Bioaccumulation and Translocation of Trace Elements in Soil-Irrigation Water-Wheat System in Arid Agricultural Areas of Xin Jiang, China

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Abstract: Pollution resulting from toxic trace elements is an increasing concern around the world especially in developing countries such as China. Rapid industrialisation, urbanisation and agricultural development are the dominant sources of anthropogenic contamination contributing to an increased potential toxicity of trace elements in the irrigation water-soil-food chain. Xin Jiang of China is a reserved cultivated land development area that could provide the most extensive strategic support for food production and arable land security in China. Thus, it is crucial to investigate the bioaccumulation and translocation of trace elements in order to assess the ecological and human health risks in the traditional oasis system of the agricultural areas in Bay Cheng County, Xin Jiang. This study analysed the levels of trace elements in different layers of the soil, the irrigation water and the wheat plants, and the relationships among them. The results indicated that cadmium (Cd) and chromium (Cr) were the primary pollutants in soils and wheats respectively, and they fell into the serious pollution category. However, no trace elements over the pollution limits were detected in irrigation water. The maximum values of trace elements appeared in the soil layers at 5–10 cm and 10–15 cm. The second pollution levels of trace elements in the soil layers were found at 0–5 cm and 0–20 cm, which were higher than those at 20–80 cm. In wheat a high amounts of absorption for Se, Cr, Zn and Cu, but low for Pb were detected in different parts of the plant. The roots of wheats were more eco- toxic to Cd, Co and Pb than other tissues, indicating that roots were more effective at absorbing Cd, Co and Pb, as these metals are usually toxic in the soil. Se, Cu and Zn showed a higher ability of being transferred from soils to the edible parts of crops. The bio-transfer factors of Zn, Mo, Cu, Mg and Mn were considerably higher than those of other elements. The average cancer risk of As, Cd, Co, Ni and TCR in wheat grains exceeded the safety reference limit

(1×10^{-4}). For the exposed population, Cr in wheat was the major contributor to total cancer risk. The average values of HQ of Cr, Mn and As, and total non-cancer risk index exceeded the corresponding effective safe reference doses ($HQ > 1$).

Key words: Bioaccumulation and translocation, bio-transfer factor, cancer risk, ecological and human health risk, toxic trace element

Introduction

Agriculture is one of the critical sectors of the worldwide economy, particularly for developing countries, and agricultural practices are related directly to food safety (Yousaf, et al. 2016). Due to urbanisation, industrialisation and climate change, most developing countries have been facing serious environmental and health problems associated with the development of agriculture (Xiao, et al. 2020). Atmospheric transport, persistence and bioaccumulation of trace elements and their contamination in agricultural soils systems have become a serious global environmental and health issue (Wang, et al. 2016). The accumulation of these trace elements in crops growing in the contaminated agricultural soils has been frequently studied (Rezapour, et al. 2019b; Zhang, et al. 2019; Zhou, et al. 2019). The translocation and bioaccumulation of trace elements in soils and crops not only harm the environment and food safety, but also have a negative influence on the immune, reproductive and nervous systems of humans and animals through the food chain (Khan, et al. 2019; Rezapour, et al. 2019a; Wang, et al. 2017). For example, continuous intake of small amounts of cadmium can result in the accumulation of cadmium in human body, and consequently reduce kidney functions or weaken bones (Rezapour, et al. 2019b; Wiggenhauser, et al. 2016). Relevant studies further indicated that the combined effect from a mixture of trace

elements, even at low concentrations, can result in endocrine disruption in both humans and animals (Ma, et al. 2016).

In China, the prevalence of trace elements in contaminated soils is considered to be the highest potential risk to food safety and human health (Chen, et al. 2016; Luo, et al. 2019). Contaminated agricultural land has been used to produce crops to meet the needs of a growing population (Ran, et al. 2016). Many studies have focused on the transformation and bioaccumulation of trace elements in soils and crops in China, but most investigations among them have been carried out in the central and southern regions of China (Cai, et al. 2019b; Cai, et al. 2019c; Chen, et al. 2016; Guan, et al. 2011; Guo, et al. 2019; Jia, et al. 2010; Jiang, et al. 2019a; Jiang, et al. 2019b; Wang, et al. 2013; Zhao, et al. 2015). However, it may be noted that very few studies have focused on the arid lands of northwest China, such as Xin Jiang, where large areas of land are being rapidly developed for agriculture using modern agricultural techniques including chemical applications (Liu, 2014). Moreover, since Xin Jiang is in a typical temperate continental climate zone, trace elements accumulate easily in the surface of the soil, which cause contamination of soils-irrigation water-crop system (Tudi et al, 2019).

Some studies in specific areas of interest in Xin Jiang have focused on trace element contamination and ecological and human health risks from an individual route, such as from the soil (Mamat, et al. 2014; Mamut, et al. 2018; Mamut, et al. 2017; Wang 2016;

Yang, et al. 2017), or water (He, et al. 2016; Zhang, et al. 2017), or crop (Sawut, et al. 2018; Zhang, et al. 2018). However, there is lack of a systematic and comprehensive study to examine the source, translocation and accumulation of multiple trace elements in soil and wheat, and the combined ecological and human health risk of these multiple trace elements in Xin Jiang. Therefore, it is necessary to examine the relationships between trace elements in soil, irrigation water and wheat, and to identify the major sources and combined ecological and human health risks caused by trace elements in Xin Jiang. The results of this study can be used to let legislators take action to reduce pollution resulting from these trace elements, to develop better environmental and food safety management practices for agriculture and natural resources, and thus ensure sustainably environmental development, food safety and public health policy in Xin Jiang.

The main aims of this work are: (1) to analyse the concentration levels of trace elements to set up their pollution indexes in soil, irrigation water and wheat; (2) to study the bio-geo-chemical, translocation pathways and bioaccumulation factors of trace elements based on the correlations of concentration levels of these elements in soils, and irrigation water with those in adjacent plant tissue structures, and (3) to assess the ecological and human health risks related to the accumulation of trace elements from wheats.

2. Materials and Methods

2.1 Study area

This study analysed trace element concentration levels in soil, irrigation water and different parts of wheat plant from Bai Cheng (Figure 1); their translocation, bioaccumulation index; and the ecological and health risk assessment.

Bai Cheng is located in the southwest of Xin Jiang Uyghur Autonomous Region. Specifically, it is between 80°37'39"–83°02'25" E and 41°24'08"–42°38'52" N (Cheng 2009; Pan 2013). Four agricultural areas, Keyir (KYR), Kariwah (KRW), Dawanqi (DW), and Yaturi (YTR) were selected for this study.

2.2. Sample Collection and Preparation

2.2.1 Soil

From each agricultural area (DW, YTR, KYR, KRW), forty soil samples were collected with a stainless-steel spatula coated with plastic materials. Seven layers of soil were collected at the following depths (0–5, 5–10, 10–15, 10–20, 20–40, 40–60, and 60–80 cm) from each site. Thus, 1120 soil samples in total were collected in this study.

The soil samples were placed into polyethylene bags, labelled and air dried. The samples were then homogenised, milled and sieved (< 2 mm) in compliance with ISO-11464 and stored in sealed bags.

2.2.2 Wheat root, stem and grain

The wheat samples were collected at the same sampling sites where the soils were sampled. Forty samples of root, stem and grain were collected respectively from each of the four agricultural sites (DW, YTR, KYR, and KRW).

The roots, stems and grains were cleaned with tap water to remove soil particles and then rinsed with deionised water. They were cut into small pieces and then dried at 75 °C in an electric oven. The dried samples were ground into fine powder and then passed through a 0.2mm sieve.

2.2.3 Irrigation water

Samples of irrigation water were collected around the sampling site along with the soil and wheat samples. Forty samples were collected at each site of the study areas (KYR, KRW, DW and YTR).

2.3 Instrumental Analysis and Quality Control

2.3.1 Elemental Analysis

A 0.05g sample of dried soil from each depth of each site was accurately weighed and placed in a Teflon microwave vessel and then digested with a solution of 5 parts concentrated HNO₃ to one part 70% HClO₄ (v/v) at temperatures between 90°C and 150 °C on an electric heating plate (Zuo, et al. 2019). The liquid prepared by the digested solutions was then diluted to 25 mL with deionised water.

Each dried wheat (root, stem and grain) sample was accurately weighed at 0.05g. Each prepared dried sample was put into a Parr Acid Digestion Vessel, digested with 5mL concentrated nitric acid and 1 mL hydrogen peroxide, and then left for 24 hours to allow the samples and the acid to mix thoroughly. The electric heating plate method was used to digest the wheat samples at 150 °C (Zeng, et al. 2015). After cooling down to room

temperature, the liquid which was prepared from the digested solutions was diluted with ultrapure water up to 25 mL, shaken for ten minutes and then stored at 4 °C.

Agilent 7700x inductively coupled plasma mass spectrometry (ICP-MS) and inductively coupled plasma-optical emission spectroscopy (ICP-OES) were used to detect the concentrations of Zn, Mg, Mn, Mo, Li, Pb, Ni, Cd, Co, Fe, Cu and Cr from soil, irrigation water and wheat samples. Atomic fluorescence (AFS) were used to detect the concentrations level of As and Se from soil, irrigation water and wheat samples.

2.3.2 Quality Control

The accuracy of analysis was checked against samples of soil and wheat with certified referenced standard materials (GBW10011, GBW07401, respectively, of the China National Centre for Standard Materials) of the selected elements in this study. In each analytical batch, 15 % of the samples were analysed twice in order to ensure the precision and accuracy of analysis. Internal reference standard materials and reagent blanks were also used in the analysis to ensure high precision and to check if there were inaccuracies in the analysis (Liu, et al. 2015).

2.4. Statistical analysis

2.4.1 Metal contamination assessment

Nemerov comprehensive pollution assessment index method

Nemerov comprehensive pollution assessment index (P_z) was used to assess metal contamination in this study as expressed in equation (1). P_z is the Nemerov

comprehensive pollution index of i trace element in soil; Max is the maximum level of trace element in soil; i is the category of trace element in soil; n is the total number of trace element to be evaluated. C_i is the concentration level of the trace element in this study. S_i is the background level of the trace element of the Xin Jiang natural soil

$$P_z = \sqrt{\left(\max \frac{C_i}{S_i}\right)^2 + \frac{1}{n} \left(\sum_{i=1}^n \frac{C_i}{S_i}\right)^2} \quad \text{Equation (1)}$$

2.4.2 Metal bioaccumulation factor and translocation factor

The bio-concentration factor² (BCF) is the proportion of trace element in different parts of the plant to the corresponding cultivated soil (Farahat, et al. 2017). Translocation Factor (TF) is the ability of a plant to move accumulated trace element from one part to another (Chen, et al. 2016) and they are expressed as:

$$BCF = C_{grain}/C_{soil} \quad ; \quad BCF = C_{root}/C_{soil} \quad ; \quad BCF = C_{stem}/C_{soil} \\ BCF = C_{irrigation\ water}/C_{soil} \quad \text{Equation (2)}$$

$$TF = C_{grain}/C_{root}; TF = C_{stem}/C_{root} \quad \text{Equation (3)}$$

2.4.3 Potential human health risk assessment

Ingestion is considered as the main pathway to human health risk of trace elements from crops. The average concentration of an exposure dose for adult is calculated using the method recommended by the US Environmental Protection Agency.

$$ADD = \frac{C * IR * ED * EF}{BW * AT} \quad (4)$$

ADD represents the average concentration of the daily dose through ingestion (mg/kg), C is the average concentration level of the trace element (mg/kg); IR is the average daily consumption of the wheat grain and its value is 456.30 g/day for an adult; ED is the exposure duration and the value is 72.4; EF is the exposure frequency and the value for the adult is 365 days; BW is the average body weight of the adult and its value is 62.5 kg; the variables were acquired from the standards of the United States Environmental Protection Agency (EPA, 2004), and the report by the Environmental Ministry of China (2010) (Table S20).

Non-carcinogenic hazard quotient (HQ)

The non-cancer risks of exposure to trace elements in wheat grain were calculated as follows (Farahat, et al. 2017).

$$HQ = \frac{ADD}{RFD} \quad \text{Equation (5)}$$

$$HI = \sum HQ_{pm} \quad \text{Equation (6)}$$

The hazard quotient ($HQ_{p, m}$) represents the non-carcinogenic risk for metal through exposure pathway. The reference doses (RFD) are taken from the United States Department of Energy's RAIS compilation (U.S. Department of Energy 2004) (Table S3). The hazard index (HI) represents the total non-carcinogenic risk for different elements.

Carcinogenic risk (CR)

The possibility of an individual developing cancer over a lifetime of carcinogenic chemical exposure is considered to be the cancer risk (Tudi, et al, 2019). In this study the cancer risks were calculated with equation (7) (Zeng, et al. 2015):

$$CR = ADD \times CSF \quad \text{Equation (7)}$$

CSF is the cancer slope factor (expressed in $\text{mg kg}^{-1} \text{ day}^{-1}$) (Table S20).

3. Results and Discussion

3.1 Trace element concentration in agricultural soils

The concentrations of trace elements from 0-5, 0-20 and 20-80 cm depths of soils in four agricultural areas of Bai Cheng County were summarized by a descriptive statistical analysis method (Tables S1, S2 and S3). These results were compared with the background levels of soils in Xin Jiang and the Soil Environmental Quality Standard of China (GB15618-1995) ($\text{pH} > 7.5$) (Table S4).

The order of the concentrations of trace elements at depths of 0-5 cm, 0-20 cm and 20-80 cm is as follows: $\text{Fe} > \text{Mn} > \text{Zn} > \text{Li} > \text{Cr} > \text{Pb} > \text{Ni} > \text{Cu} > \text{As} > \text{Co} > \text{Mo} > \text{Cd} > \text{Se}$ and the result was consistent with that reported in a previous study by Saha, et al. (2016). The average and minimum values of Cd in DW, KRW, YTR and KYR from soil at 0-5 cm and 0-20 cm depths exceeded the limit of the Soil Environmental Quality Standard of China (GB15618-1995) while those of other elements were still under the limit. At the lowest soil layers (20-80 cm) the maximum level of Cd in DW, Zn and Mn in KRW were higher than the levels recommended by Soil Environmental Quality Standard of China (GB15618-1995). At the same soil depth, the average and minimum values of Cd in KYR and KRW and YTR were higher than those of the Soil Environmental Quality Standard of China (GB15618-1995). Cd was the main pollutant that exceeded the limit set by the Chinese Environmental Protection Agency from the soil at 0-5 cm, 0-20 cm and 20-80 cm in the four agricultural areas and the results were identical to those of previous studies (Mamut, et al. 2018; Ran, et al. 2016; Yousaf, et al. 2016). Pollution by Zn and Mn also occurred in the lowest layer (20-80 cm) of agricultural land.

3.2 Soil Profile Analysis

The results of soil heavy metal analysis were shown in Table S5 and Figure 2. It showed that in the YTR region Cd revealed the highest concentration in the 5-10 cm soil layer, while its concentration in other layers was not significantly different. For Co, Cr, Cu, Mn, Mo and Ni there were no significant differences in their concentrations among any soil layers down to 60-80 cm. The Li content of the soil was present at its highest in the 15-20 cm soil layer, similar to that in the 10-15 cm layer. The maximum concentration of Pb appeared in the 5-10 cm layer, and there were no significant difference in other layers.

In the KYR region there were no significant differences in concentrations of Cd, Co, Cr, Cu, Mn, Pb, Ni in any of the soil layers down to 60–80 cm. The concentration of Li was the highest in the 40–60 cm soil layer and this result indicated that there was vertical movement through leaching of Li in the soil, but there were no significant differences among the other layers. The maximum concentration of Zn appeared in the 0–5 cm soil layer, and a high value was also obtained in the 15–20 cm and 40–60 cm layers, whereas lower values were obtained in other layers. In the KRW region, the concentrations of Cd, Cr, Cu, Li, Pb, Mo, Ni were the highest in the 0–5cm soil layer and, there were no significant differences in other layers. The maximum concentrations of Co and Zn appeared in the 5–10 cm layer, but there were no significant differences in other layers. In the DW region, the maximum concentrations of Cd, Co, Cr, Li, Pb and Cu were in the 10–15 cm soil layer, while the highest concentration of Mo was in the 0–5 cm layer.

The soil in the area studied is weakly alkaline (Sawut, et al. 2018). Most of the trace elements in the soil are in the form of elemental metals or insoluble compounds, which

do not easily migrate. With the passage of time, the accumulation of trace elements in the surface soil becomes obvious (Mariyam, et al., 2018). This showed that the soil has been polluted by exogenous trace elements over a long period of time, and thus trace elements exceed the background values of soils in Xin Jiang.

3.3 Concentration of trace elements in irrigation water

A statistical summary of the concentration levels of trace elements in irrigation water in the four selected agricultural areas (DW, KYR, KRW, YTR) of Bai Cheng County were given in Table S6 and these concentrations were compared with the background values of water such as GB 3838—2002 Standard of Surface Water Environmental Quality, the WHO Standard of Drinking water and GB5084-92 farmland irrigation water standard (Zhang, et al. 2013) (Table S7) to evaluate the degree of pollution in irrigation water.

The average levels of all the elements measured in this study did not exceed the national surface water quality standard, nor the WHO drinking water health recommendation standard, indicating that the general level of trace elements in farmland water in Bai Cheng County was low. The order of trace element concentration was Fe>Al>Ba>Li>Zn>U> Mo>Mn>Se>Ni>Cr>V>As>Co>Pb>Cd and the result was similar to that of a previous study (Zhang, et al. 2013).

3.4 Trace element concentration in wheat

Wheat is an important agricultural crop in China. Wheat absorbs essential and non-essential elements from soils, which could lead to transfer toxic elements from the soil into food chains and humans (Ran, et al. 2016). Thus, there is an urgent need to analyse

trace element concentrations in different parts of the wheat (root, stem and grain) and determine which parts were of greatest concern to health if any.

The distributions of trace elements in wheat roots of traditional agricultural areas in Xin Jiang were shown in Table S8. The order of quantities of trace element in wheat roots of DW, KRW, KYR and YTR was: $\text{Ca} > \text{Al} > \text{Fe} > \text{Mg} > \text{Mn} > \text{Cr} > \text{Pb} > \text{Zn} > \text{Cu} > \text{Ni} > \text{Li} > \text{Co} > \text{As} > \text{Mo} > \text{Se} > \text{Cd}$. For wheat stems, the distributions of trace elements in the traditional agricultural areas of Xin Jiang were shown in Table S9. The order of average concentration of heavy metals in wheat stems in DW, KRW, KYR and YTR was $\text{Ca} > \text{Al} > \text{Mg} > \text{Fe} > \text{Cr} > \text{Mn} > \text{Zn} > \text{Cu} > \text{Li} > \text{Ni} > \text{Mo} > \text{Pb} > \text{Co} > \text{Se} > \text{Cd}$. In wheat grains, the distributions of trace elements in traditional agricultural areas of Xinjiang were shown in Table S10 and they were compared with the national standards in Table S11. The order of concentrations of the elements in wheat grains in DW, KRW, KYR and YTR was $\text{Mg} > \text{Ca} > \text{Fe} > \text{Mn} > \text{Al} > \text{Zn} > \text{Cu} > \text{Cr} > \text{Li} > \text{As} > \text{Pb} > \text{Ni} > \text{Se} > \text{Co} > \text{Cd}$. Based on the results obtained in this study, the concentration levels of elements in roots, stems and wheat grains were different even in the same region.

The elements with the highest levels in all tissues of wheat were Mg, Ca, Mn, Zn and Cu, while Cd showed the lowest level in all tissues. The low Cd content was due mainly to the low Cd background value in the soil. The levels of Mg, Mn and Ca in the background values in the soil were relatively high. The levels of Zn and Cu in different

plant tissues were the highest, which were attributed to Zn and Cu being essential trace elements to plant growth (Abbas, et al. 2017). Among the trace elements, Zn is a component element of some bioactive enzymes in plants. Cu is a component of many oxidases in plants and can promote redox reactions. In addition, the chloroplasts of plants contain a large amount of Cu, which can improve the stability of chlorophyll. The levels of trace elements in different tissues of the same crop can differ, and the levels of trace elements in different areas also vary (Zhang, et al. 2018). Trace elements concentrations in soils, soil pH, cation exchange capacity, organic matter content, types and varieties of plants, and plant age all influence bioaccumulation and transference of the elements from soil to wheat (Abdelhafez and Li 2015). There is an inherent ability for many plants to metabolise a variety of trace elements based on their physiological processes (Ran, et al. 2016). These are the main reasons for the differences in the concentration levels of trace elements from different areas of this study.

3.5 Assessment of contamination by trace elements

3.5.1 Soil

The Nemerov comprehensive pollution indexes of trace elements in the soil layers at 0–5 cm, 5–20 cm and 20–80 cm are calculated using the formula (1). The results are shown in Tables S12, S13 and S14. The results were compared with the standard of the pollution grade level and are shown in Table S19.

Generally, the results of this study indicated that pollution by Co and Mn was low; marginal by Cu, Cr, Ni, Zn, Pb and As; and heavily by Cd. The previous study has indicated that trace elements tend to accumulate easily in the surface of the soil, which consequently leads to the contamination of trace elements in crops (Liu 2014), and this is the reason why there is a higher risk factor from the soil layers of 0–5 cm and 0–20 cm than from the 20–80 cm layer.

The results indicate that in the DW region, there were low levels of pollution by Cr, Co, Ni, Cu, Mn and Zn; moderate levels of pollution by Pb and As; and substantial levels of pollution by Cd in the soil layers of 0–5 cm, 5–20 cm and 20–80 cm.

In the KYR region, there were low levels of pollution by Cr, Co, Cu and Mn, moderate levels of pollution by Ni, As and Pb; and substantial levels of pollution by Cd and Zn at all soil layers. In the KRW area, there were low levels of pollution by Mn and Co at all soil layers; moderate levels of pollution by Cr, Pb, Cu, Zn, and As in the soil layers of 0–5 cm and 0–20 cm; and heavy levels of pollution by Cd and Ni in 0–5 cm, by Cd, Ni, Zn in 0–20 cm and by Cd and Zn in 20–80 cm. In the YTR area, there were low levels of pollution by Co and Mn; moderate levels of pollution by Cr, Ni, Pb, Cu, Mn and Zn; and massive levels of pollution by Cd and As in all soil layers.

3.5.2 Irrigation water

The levels of pollution in irrigation water, by trace elements, in four representative agricultural areas in Bai Cheng County were evaluated and compared with the standard

of the National Surface Water Environmental Quality (GB 3838-2002). The evaluation results showed that the single factor pollution index (P_i) and comprehensive pollution index (P_z) of heavy metals in irrigation water in the four agricultural areas (Table S15 and Table 16) were all within the parameters of safety. Therefore, they were consistent with the results of the water quality evaluation stated earlier (Section 3.2).

3.5.3 Wheat

The levels of pollution by trace elements in wheat grains in the selected agricultural areas of Bai Cheng County were evaluated against the National Standard for Food Safety (GB 2762-2012) (Table S17 and S18). The results of the Nemerov pollution assessment index showed that the pollution index values of Ni and Cd in wheat grains in DW, KYR, KRW and YTR were less than 1, indicating no pollution. The pollution index values of Pb and As in wheat grains in DW, KYR, KRW, YTR were between 1 and 2, which indicate a low light level of pollution. The pollution indices of Cr in wheat grains in DW, KYR, KRW, YTR were 3.9, 9, 10, and 2 respectively, which indicated a dangerous level of pollution.

The previous study showed that the high accumulation of trace elements in plants is due to their cultivation in soils that were contaminated by trace elements (Abbas, et al. 2017). Cr was reported as a low-level pollutant in soil but a high-level pollutant in wheat, which shows that continuous uptake and translocation of trace elements can lead to an increase in the concentration of these elements in plant parts as they are

accumulated in different tissues, even though the soil has low concentrations of these trace elements.

3.6 Analysis of the ability of bioaccumulation and translocation trace elements from soil and water to wheat

3.6.1 Bioaccumulation

Plants have the ability to take up remarkably high concentrations of trace elements through the roots from soil and water, translocating them between the different parts of the plants (Wang, et al. 2017). The accumulation coefficients of trace elements in different tissues of wheat in the selected agricultural areas of Bai Cheng County were shown in Table 1.

In KRW, KYR, YTR and DW, the order of the bioaccumulation coefficients of trace elements in wheat roots was $\text{Se} > \text{Cr} > \text{Cu} > \text{Pb} > \text{Mo} > \text{Ni} > \text{Zn} > \text{Co} > \text{Mn} > \text{Cd} > \text{Fe} > \text{As} > \text{Li}$.

The order of the bioaccumulation coefficients of trace elements in stems was $\text{Cr} > \text{Mo} = \text{Se} > \text{Zn} > \text{Cu} > \text{Ni} > \text{Cd} > \text{Co} = \text{Fe} = \text{Mn} = \text{Li} > \text{Pb}$. The order of the bioaccumulation coefficients of trace elements in grains was $\text{Se} > \text{Cu} > \text{Zn} > \text{Mo} > \text{Cu} > \text{Cr} > \text{Ni} > \text{Cd} > \text{Pb} > \text{Co}$.

The bioaccumulation coefficients of trace elements in different parts of the wheat plant were less than 1, which indicated that trace elements were not super-enriched in the plants. The result was consistent with the previous study (Chen, et al. 2016). The different parts of the wheat had high absorption ability for Se, Cr, Zn and Cu, but was weak for Pb. The roots of wheat were more eco- toxic for Cd, Co and Pb than other

tissues, indicating that roots were more effective at absorbing Cd, Co and Pb, which are more toxic in the soil. These results were similar to those of previous studies (Chen, et al. 2016; Ran, et al. 2016; Wang, et al. 2017). The elements Se, Cu and Zn had a higher ability of being transferred from soils to the edible parts of crops. Agricultural fertilizers containing Zn is the main reason for the increasing concentration of Zn in the soil leading to an increased absorption of Zn that accumulates in grains during the reproductive growth stage (Chen, et al. 2016).

The accumulation coefficients of trace elements from irrigation water to soil layers at 0-20 cm and 20-80 cm were shown in Table S20. The accumulation coefficients of trace elements from irrigation water to the soil layers of 0–20 cm and 20–80 cm were less than 1; therefore, there was no obvious element enrichment in the soil due to very low concentrations of metals in irrigation water. The order of the accumulation coefficients was Mo>Ni>Zn>Cr>Co>Mn.

All the accumulation coefficients of trace elements from irrigation water to wheat were less than 1 (Table S21), indicating that there was also no obvious element bioaccumulation phenomenon. The order of the accumulation coefficients was Mn>Pb>Co>Cr>Zn>Ni>Mo.

3.6.2 Translocation Capacity

The translocation coefficients of trace elements from the root to wheat grain and stem in KYR, KRW, DW and YTR areas in Bai Cheng County were shown in Table 2. In DW, the translocation capacity of Zn in grain and of Mo in stem were both close to 1, while the translocation coefficients of other elements of both stem and grain were lower than 1, indicating that the ability of the other elements of translocation in wheat was weaker than for Zn and Mo.

In KYR, the translocation coefficients of Li, Cr, Co, Ni, Mo, Cd, Pb, Al, and Ca in wheat stem were greater than those in grain, and the translocation coefficients of Cu, Mn, Zn, Se, and Mg in grain were greater than those in stem. The translocation coefficients of Zn in grain and Mo in wheat stem were greater than 1, and that of Mg in grain was close to 1, which indicated that the wheat stem in KYR region had a higher translocation capacity for Mo and grains had higher translocation capacities for Zn and Mg. The translocation coefficients of Li, Co, Ni, Mo, Cd, Pb, Fe, Al, and Ca in stem were higher than for these elements in grain. In contrast, the translocation capacities of Cr, Cu, Fe, Mn, Zn, Se, Ca and Mg in the grain were greater than those in stem.

In KRW, the translocation coefficients of Mo in stem and Zn in grain were greater than 1, so the stem and grain had an enrichment capacity for Mo and Zn respectively. The translocation coefficients of Li, Cr, Co, Ni, Mo, Cd, Pb, Fe, Al, and Ca in stem were greater than those in grain; while the translocation coefficients of Cu, Fe, Mn, Zn, Se, and Mg in grain were greater than those in stem.

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454 In YTR, the translocation coefficient of Mo in stem was greater than 1, so the stem had
 455 a higher ability to enrich Mo. The translocation coefficients of other elements were less
 456 than 1, indicating that the accumulation of other elements in wheat was weak in YTR.
 457 The transportability coefficients of Li, Cr, Co, Ni, Mo, Cd, Pb, Fe, Al, and Ca in the
 458 stem were greater than those in grain. Whereas the translocation abilities of Cu, Mn,
 459 Zn, Se and Mg in grain were greater than those in stem.

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461 Most of the plants have spontaneous potentiality to absorb varied and large amounts of
 462 bioavailable forms of trace elements (Luo, et al. 2019). The high rate of transpiration
 463 could lead to the absorption of trace elements from soil and transfer elements to shoot
 464 and grain (Abbas, et al. 2017; Zhou, et al. 2019; Zuo, et al. 2019). Micronutrient trace
 465 elements including Cu, Co, Fe, Mo, Zn, Ni, and Mn are essential for plant growth, but
 466 Cd and Pb have no physiological roles and impede plant growth even at low
 467 concentrations (Zhang, et al. 2019).

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469 In the studied areas, the order of transport coefficients of wheat stem was
 470 $\text{Mo} > \text{Cr} > \text{Zn} > \text{Mg} > \text{Li} > \text{Ca} > \text{Se} > \text{Mn} > \text{Cu} > \text{Fe} > \text{Al} > \text{Ni} = \text{Cd} = \text{Se} > \text{Co} > \text{Pb}$. The order of
 471 transport coefficients of wheat grain was
 472 $\text{Zn} > \text{Mo} > \text{Cu} = \text{Mg} > \text{Mn} > \text{Se} > \text{As} > \text{Cd} > \text{Cr} > \text{Fe} > \text{Ni} > \text{Co} > \text{Al} > \text{Pb}$. The bio-transfer factors of
 473 Zn, Mo, Cu, Mg and Mn were considerably higher than those of other elements. This
 474 phenomenon was observed not only in this study but also in other studies (Abbas, et al.

2017; Wang, et al. 2017; Zhang, et al. 2019). These elements are essential to the growth of wheat which has a higher capability to transfer trace elements from soils to the dietary components of the plant (Chen, et al. 2016).

3.7. Exposure and Health Risk Assessment of Trace Elements from Wheat

Exposure to chemicals including trace elements occurs through different pathways including inhalation, ingestion and dermal contact via different routes such as through water, soil, air and crops (Tudi et al., 2019). Therefore, it is necessary to assess the potential levels of exposure and associated human health risk of trace elements (Huang, et al. 2019; Ran, et al. 2016). The main pathway of exposure of these trace elements is ingestion (Cai and Song 2019). In this study, the exposure model recommended by the U. S. Environmental Protection Agency (2010) and the health risk level (carcinogenic and non-carcinogenic hazard coefficients) (Table S22) of adults were used to determine the exposure and health risk of the trace elements absorbed orally from wheat grain products in the four agricultural areas. Exposure to the trace elements was summarised in Table S23.

3.7.1 Cancer Risk

The results of cancer risk assessment for residents of KYR, KRW, DW and YTR who ingested trace elements through eating wheat products were shown in Table S24 and Figure 4. The minimum, average and maximum values of cancer risk of As, Cd, Ni, Co, and the total cancer risk index TCR (the total cancer risk) in flour from KYR, KRW,

DW and YTR exceeded the safety reference limit (1×10^{-4}) (Cai, et al. 2019b). Looking at the individual areas such as in DW, the minimum, average and maximum levels of the cancer risk index of those five elements and TCR were higher than the reference level. The average cancer risk levels of Cr, Co, Ni, Cd, As and TCR were 2.554×10^2 , 9.340×10^0 , 4.390×10^0 , 4.498×10^0 , 1.467×10^1 and 2.883×10^2 respectively. In KYR, the average cancer risk levels of Cr, Co, Ni, Cd, As and TCR were 5.572×10^2 , 1.388×10^1 , 3.171×10^0 , 5.237×10^0 , 2.860×10^1 , and 6.081×10^2 . In KRW, the average cancer risk levels of Cr, Co, Ni, Cd As and TCR were 7.341×10^2 , 1.836×10^1 , 5.895×10^0 , 5.761×10^0 , 1.778×10^1 and 7.819×10^2 respectively. In YTR, the average cancer risk of Cr, Co, Ni, Cd As and TCR were 2.659×10^2 , 1.198×10^1 , 6.320×10^0 , 1.213×10^1 , 5.953×10^0 and 3.023×10^2 respectively. Compared to the previous study conducted in other areas of Xin Jiang, the cancer risk index of trace elements was higher in this study than in previous studies (Abdelhafez and Li 2015; Cai, et al. 2019a; Sawut, et al. 2018). The average cancer risk index of trace elements through wheat consumption followed the order $Cr > As > Co > Cd > Ni$; therefore, for the exposed population, Cr contributed the most to the total cancer risk, Cr was found to be the main pollutant in wheat.

3.7.2 Non-cancer Risk

The estimated health risk index (HRI) for adults who consumed non-carcinogenic chemicals in wheat products was shown in Table S25 and Figure 5. Although the average levels of HQ for Co, Ni, Cd, Pb, Cu, Zn and Se in wheat products from the

KYR, KRW, YTR and DW agricultural areas were lower than 1 ($HQ < 1$), the average levels of HQ of Cr, Mn and As and the total non-cancer risk from the wheat products in the KYR, KRW, YTR and DW agricultural areas all exceeded the corresponding effective safe reference doses ($HQ > 1$) (Doabi, et al. 2018; Ran, et al. 2016). Our results indicated that for the exposed population, Cr, Mn and As contributed the most to the total HIF (Non-cancer risk from the flour), while Cd, Ni and Se contributed the least to HIF. Therefore, there were health implications for residents who are exposed to these contaminants from food in these areas.

Estimation of cancer and non-cancer risks of the trace elements in this study did not include the contribution of other potential contamination of rice, meat, vegetable, fruit and water that are also consumed with wheat. These foodstuffs also include additional sources of contamination (Doabi, et al. 2018). Exposure to trace elements occur through their bioavailability in foodstuffs (Liu, et al. 2017). In this study, however, exposure and health risk of the elements were calculated based on total content of trace elements rather than the bioavailability of elements. Moreover, there are potential health risks associated with inhalation and dermal contact routes; but the health risk of trace elements through inhalation and dermal contact routes were not included in this study. Therefore, further study should be conducted to analyse the levels of trace elements in other plants and environmental sources, different exposures and bioavailability of these elements, which were not considered in our present study.

4. Conclusion

The current study showed the importance of bioaccumulation and translocation of trace elements between soil-irrigation water and different parts of the wheat, and the ecological and human health risk. The results indicated that Cd was the main pollutant in the soil layers of 0-5 cm, 0-20 cm and 20-80 cm in agricultural soils, which contributed most to the potential ecological risk of the soil. The maximum values of trace element levels appeared in the 5–10 cm and 10–15cm depths of soils. The pollution indexes from the 0–5 cm and 0–20 cm soil layers were higher than in the 20–80 cm one.

The levels of Mg, Ca, Mn, Zn and Cu were higher, and the level of Cd was the lowest in all tissues of wheat. Cr was the main pollutant in wheat grains, and it fell into the serious pollution category. The bioaccumulation coefficients of trace elements in different parts of the wheat plant were all less than 1, which indicated that wheat plant was not super-enriched in these study areas. Among all the four selected areas, the whole plant showed relatively high absorption ability for Se, Cr, Zn and Cu, but weak for Pb.

The average cancer risk values of As, Cd, Ni, Co, Ni and TCR from wheat grains exceeded the safety reference limit (1×10^{-4}). For the exposed population, Cr contributed the most to the total cancer risk. The average values of HQ of Cr, Mn and As and total non-cancer risk index also exceeded the corresponding effective safe reference doses ($HQ > 1$). For the exposed population, Cr, Mn and As contributed the most to total HIF.

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Figure 1 Sampling sites of soil, irrigation water and crop in the study areas

Figure 2 Element content levels of different soil layers in four agricultural areas

Figure 3 Nemerov pollution index of soil, irrigation water and wheat

Note:

Class	PZ	Degree of pollution
1	$Pz < 0.7$	safe
2	$0.7 < Pz < 1$	warn
3	$1 < Pz < 2$	Slightly pollution
4	$2 < Pz < 3$	Moderate pollution

5	$P_z > 3$	Heavily pollution
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Figure 4 Deterministic estimates of cancer risk for adults through ingesting wheat grain in the agricultural areas of Bay County

Figure 5 Deterministic estimates of non-cancer risk for adults through ingesting wheat grain in the agricultural areas of Bay County

Table

Table 1 Accumulation index of trace elements and heavy metals (wheat/soil)

DW	Li	Cr	Co	Ni	Mo	Cd	Pb	Cu	Fe	Mn	Zn	Se	As
grain/soil	0.004	0.024	0.001	0.003	0.153	0.012	0.002	0.204	0.002	0.042	0.176	0.276	0.013
stem/soil	0.024	0.430	0.022	0.048	0.200	0.031	0.011	0.090	0.020	0.028	0.098	0.210	0.000
root/soil	0.078	0.885	0.154	0.229	0.243	0.113	0.365	0.375	0.107	0.137	0.195	0.967	0.101
KYR	Li	Cr	Co	Ni	Mo	Cd	Pb	Cu	Fe	Mn	Zn	Se	As
grain/soil	0.001	0.042	0.002	0.001	0.111	0.040	0.004	0.221	0.002	0.056	0.129	0.232	0.018
Stem/soil	0.009	0.248	0.014	0.028	0.268	0.101	0.011	0.076	0.007	0.023	0.024	0.174	0.000
root/soil	0.046	0.621	0.124	0.180	0.188	0.263	0.549	0.300	0.056	0.091	0.057	0.954	0.028
KRW	Li	Cr	Co	Ni	Mo	Cd	Pb	Cu	Fe	Mn	Zn	Se	As
grain/soil	0.001	0.040	0.003	0.002	0.081	0.026	0.003	0.164	0.001	0.051	0.123	0.218	0.011
stem/soil	0.010	0.280	0.022	0.024	0.186	0.076	0.012	0.064	0.009	0.028	0.027	0.234	0.000
root/soil	0.059	0.493	0.170	0.125	0.169	0.234	0.481	0.243	0.063	0.106	0.089	1.423	0.033
YTR	Li	Cr	Co	Ni	Mo	Cd	Pb	Cu	Fe	Mn	Zn	Se	As
grain/soil	0.002	0.012	0.001	0.003	0.231	0.057	0.002	0.185	0.002	0.062	0.113	0.278	0.005
stem/soil	0.024	0.253	0.013	0.026	0.408	0.106	0.018	0.074	0.014	0.038	0.075	0.205	0.000
root/soil	0.060	0.417	0.078	0.118	0.289	0.316	0.397	0.256	0.065	0.123	0.139	0.791	0.081

Table 2 Transfer index of trace elements and heavy metals in different parts of wheat

DW	Li	Cr	Co	Ni	Mo	Cd	Pb	Cu	Fe	Mn	Zn	Se	As	Al	Ca	Mg
grain/root	0.05	0.03	0.01	0.01	0.63	0.10	0.01	0.54	0.02	0.31	0.91	0.29	0.13	0.01	0.04	0.54
Stem/root	0.31	0.49	0.14	0.21	0.82	0.28	0.03	0.24	0.19	0.21	0.50	0.22	0.00	0.14	0.27	0.39
KYR	Li	Cr	Co	Ni	Mo	Cd	Pb	Cu	Fe	Mn	Zn	Se	As	Al	Ca	Mg
grain/root	0.02	0.07	0.02	0.01	0.59	0.15	0.01	0.74	0.03	0.62	2.28	0.24	0.65	0.01	0.05	0.81
stem/root	0.19	0.40	0.12	0.16	1.42	0.39	0.02	0.25	0.12	0.25	0.42	0.18	0.00	0.10	0.25	0.49
KRW	Li	Cr	Co	Ni	Mo	Cd	Pb	Cu	Fe	Mn	Zn	Se	As	Al	Ca	Mg
grain/root	0.02	0.08	0.02	0.01	0.48	0.11	0.01	0.68	0.02	0.48	1.39	0.15	0.33	0.01	0.07	0.78
stem/root	0.18	0.57	0.13	0.19	1.10	0.33	0.02	0.26	0.14	0.26	0.30	0.16	0.00	0.10	0.32	0.52
YTR	Li	Cr	Co	Ni	Mo	Cd	Pb	Cu	Fe	Mn	Zn	Se	As	Al	Ca	Mg
grain/root	0.04	0.03	0.02	0.02	0.80	0.18	0.01	0.72	0.03	0.51	0.81	0.35	0.06	0.01	0.05	0.82
stem/root	0.40	0.61	0.16	0.22	1.41	0.34	0.05	0.29	0.22	0.31	0.54	0.26	0.00	0.15	0.40	0.67