Health risk assessment of heavy metals (Cu, Zn, and Mn) in wild oat grown in soils amended with sediment dredged from the Joumine Dam in Bizerte, Tunisia

Imen Ben Chabchoubi^{1,2} · Slim Mtibaa^{2,3} · Mohamed Ksibi^{2,4} · Olfa Hentati^{2,4}

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Abstract

The Joumine Dam located in northern Tunisia has lost more than 20% of its initial storage capacity due to sedimentation, meaning that sediment management is necessary. The sediments at the reservoir bottom act as a sink for nutrients and chemicals originating from the upper agricultural lands and take the form of suspended particles. We proposed that the dredged sediments could be used to amend arid to semiarid soils, as this would partially cover the financial burden of dredging works and reduce the volume of these deposits. However, to check the feasibility of using the sediments as a fertilizer, it was necessary to assess the potential health risks from contaminants in the sediments. Therefore, the present study aimed to evaluate the human health risk (i.e., the hazard quotient, HQ) from heavy metals consumed due to the ingestion of *Bromus ramosus* (wild oat) grown in soil amended with the Joumine Dam sediments. Plant growth was monitored in macrocosm (amendment rate of 1.17%) and microcosm (amendment rate $\leq 10\%$) bioassays to elucidate the metal concentrations in roots, stems, leaves, and seeds. Zn, Cu, and Mn concentrations were analyzed in the plants grown in the macrocosm experiments, while the follow-up was only performed for Zn in the plants grown in the microcosm experiments. The human exposure to soil pollutants (HESP) evaluation model was adopted to evaluate the health risk (HQ) to humans through direct and indirect oral exposure to heavy metals in wild oat. At the macrocosm scale, Cu was found to be the main source of risk (HQ = 1.86) to children. At the microcosm scale, utilization of the sediment reduced the mobility and bioavailability of copper in the soil, thus decreasing the potential health risk from this metal.

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✉ Olfa Hentati
olfa.hentati@isbs.usf.tn

¹ Institut Supérieur de Biotechnologie de Monastir, Université de Monastir, Rue Taher Haddad, 5000 Monastir, Tunisie

² Laboratoire Génie de l'Environnement et Ecotechnologie (GEET), Ecole Nationale d'Ingénieurs (ENIS), Université de Sfax, Route de Soukra, Km 4, B.P. 1173, 3038 Sfax, Tunisie

³ Graduate School of Life and Environmental Science, University of Tsukuba, Tsukuba, Japan

⁴ Institut Supérieur de Biotechnologie de Sfax, Université de Sfax, Route de Soukra, Km 4, B.P. 1175, 3038 Sfax, Tunisie

Graphic abstract

Keywords Amendment · Sediment · Health risk assessment · Heavy metals · Transfer factor · Hazard quotient

Introduction

Dams and reservoirs are constructed to control floods and supply drinking and irrigation water. To date, more than 30 dams have been built in Tunisia to ensure that the demand for water is met. However, many of these hydraulic structures are suffering from pressing environmental issues such as sedimentation and water quality degradation (Mtibaa et al. 2018).

Reservoir sedimentation management is crucial to ensure the sustainable use of surface water resources. Dredging, a very effective method of suppressing sedimentation, is now needed to recover the storage capacities of many water reservoirs in Tunisia. However, this operation is expensive, so it is not performed. Mtibaa et al. (2012) suggested that reservoir sediments could be used as a soil fertilizer or soil conditioner, as this could ease the economic burden of dredging works, reduce the required amounts of other chemical fertilizers, improve soil fertility, and encourage the recycling of waste via the soil and plant cycle. Braga et al. (2019) used sediments from the Banabuiú river basin in Brazil as a soil

amendment. The aim of their study was to assess the potential reuse of sediments as a source of nutrients for agriculture in a semiarid basin in Brazil. The authors reported that the sediments supplied almost all of the nitrogen required by corn crops (*Zea mays* L.). Moreover, they found that using the sediments led to a 25% reduction in the amount spent on fertilizers.

Mulyono et al. (2019) were interested in volcanic ash, which they transformed into sediment and hardened through exposure to water. They applied an appropriate combination of the volcanic ash, biochar, and urban waste compost as fertilizer to support the growth of leaf lettuce. The use of dam sediments as a natural fertilizer for agricultural lands can also improve the quality of the water stored in downstream reservoirs (Maavara et al. 2015). In contrast, the use of chemical fertilizers in agricultural fields is the main anthropogenic driver for eutrophication in many reservoirs.

When considering the application of sediment as a soil amendment, it is important to determine the levels of zinc, copper, lead, nickel, and cadmium in the sediment, as high levels of these metals in the soil pose a major threat

to the environment (Kirchmann et al. 2017; Song et al. 2017; Braga et al. 2019). The accumulation of metals in agricultural soils is a growing concern because of food safety issues and potential health risks, as well as their adverse effects on soil ecosystems (Schlundt et al. 2020). Metals are toxic to terrestrial (Wadgaonkar et al. 2018) and aquatic (da Silva et al. 2018) life. Due to the persistence, concentration, and diffusion of metals in biological systems, considerable research has been directed into developing the most appropriate technologies for treating metal-contaminated soils (Connell 2018). Metals have unique characteristics because of their persistence, non-biodegradability, toxicity, and sometimes beneficial nature. Metals are required by or beneficial to plants at certain levels, but they are toxic when they exceed certain thresholds. They are always present at some level in the soil, as they enter the soil through natural processes such as source rock weathering and pedogenesis. They are often present in the form of cations that interact strongly with the soil matrix (Brax et al. 2017; Harms et al. 2018; Menkiti et al. 2019). As a result, metals in soils can become mobile when environmental conditions change.

Plants growing in an environment polluted with metals can accumulate those trace elements at high concentrations, resulting in a serious risk to human health when foodstuffs made from those plants are consumed (Noronha-D'Mello and Nayak 2016; Xu et al. 2018; Singh et al. 2018). This issue has generated considerable public concern.

Considering the environmental issues mentioned above, it is very important to check that sediments are safe to use as an organic fertilizer before they are applied. Yang et al. (2018) proposed that the translocation of heavy metals in soil and plant systems (i.e., plant uptake factors) and the risk from consuming vegetables and other food crops should be assessed. They discussed the different indices that are used to determine the ecotoxicological effects and health risks from eating contaminated food crops. Health risk assessments have long been developed and performed in Europe and the United States (Weber et al. 2019). However, such assessments are much more novel in Tunisia, where methods of evaluating risk are yet to be established. The study reported in the present paper is based on previous work (published in 2012 and 2016) that evaluated the possible use of sediment dredged from the Joumine water reservoir in Tunisia as a soil amendment. The present study aimed to build on that work by assessing the risk to human health of consuming heavy metals due to the ingestion of wild oat plants grown in sediment-amended soils.

Table 1 Matrix of experiments (Mtibaa et al. 2011)

Sample	Percentage of sediment	Soil salinity (g NaCl/kg of soil)	Concentration of zinc (mg/kg of soil)
1	2%	0.2	20
2	2%	0.35	30
3	2%	0.5	40
4	6%	0.2	40
5	6%	0.35	20
6	6%	0.5	30
7	10%	0.2	30
8	10%	0.35	40
9	10%	0.5	20

Materials and methods

Experimental design

Collection and preparation of sediment

The sediment samples were collected from a depth of 25 m in the Joumine reservoir, located in Bizete City in the northwest of Tunisia. The sediment samples were packed in clean plastic bags and stored at 4 °C. To prepare the samples for physicochemical property analysis, they were dried in the sun and then sieved through a 2-mm mesh. The coarse sediment fraction (> 2 mm) was used for microcosm and macrocosm tests. The fine fraction (< 2 mm) was employed for metal analysis (Mtibaa et al. 2012).

Macrocosm tests and *Bromus ramosus* growth

These experiments are reported in Mtibaa et al. (2012). The area selected to conduct the macrocosm tests was located about 10 km as the crow flies from the city of Sfax. It belongs in the administrative region of Thyna, situated on the southern side of the city. This agricultural land belongs to the state and is used to produce forage crops for dairy cows. A 3-month macrocosm (2 parcels each with a surface area of 4 m²) experiment was performed (under semicontrolled conditions) to assess the impact of amendment with sediment on wild oat growth. Two plant groups were distinguished in this experiment. The first group of plants grew in soil amended with sediment at a rate of 3.5 kg of sediment per 1 m² and at a depth of 20 cm from the soil surface. The second plant group grew in the absence of amendment, and served as a control. Both parcels were seeded with oats and irrigated every 15 days.

Microcosm tests and *Bromus ramosus* growth

The microcosm experiments were performed with agricultural soil and are reported in Mtibaa et al. (2016). After drying and homogenizing the soil, it was passed through a 2-mm sieve and contaminated with a solution of $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$ to obtain three Zn concentrations (20, 30, and 40 mg/kg of soil) (Table 1). The soils were analyzed to check the homogeneity of the contamination and Zn concentration. To obtain three modes (Table 1) of soil salinity according to Propst (1992), different concentrations (0.2, 0.35, and 0.5 g/kg soil) of NaCl were added to the soils. The nine prepared soils were carefully homogenized and amended with 2, 6, and 10% sediment to finally obtain 27 combinations (ISO 1998) (Table 1). Plants were grown in pots, and four replicates were grown for each combination. Twenty grains of wild oat were seeded into each pot at a depth of 1 cm and watered every 2 days with deionized water.

Growth was tested under controlled conditions in a culture room for a period of 25 days at a temperature of $22 \pm 3^\circ\text{C}$, a humidity of 70%, and under a light intensity of $4300 \pm 10\%$ lux according to a 16:8 (light:dark) photoperiod (ISO 2012).

Plant sample collection and metal analysis

The samples of wild oat (roots, stems, leaves, and seeds) were packed into sealed plastic bags and stored in a cold room at 4°C until analysis. Before analysis, the plants were thoroughly washed with distilled water and then dried in

air for two days. The roots, stems, leaves, and seeds were manually separated. After drying at 70°C (24 h), the organs were ground in a clean mortar. Plant tissue powder was then digested in a triacid mixture ($\text{HNO}_3\text{:H}_2\text{SO}_4\text{:HClO}_4$, 5:1:1) until the mixture became transparent (Allen et al. 1986). The heavy metal concentrations (Cu, Zn, and Mn for the macrocosm test and Zn for microcosm tests) in the filtrate were determined by atomic absorption spectrometry (ASS) using a Thermo Scientific iCE 3000 series instrument.

Exposure scenario

The human population studied consisted of people who grew plants and raised livestock in their garden or farm for their own consumption. The exposure scenario assumed that the population was exposed to the effects of pollutants year round for a period of 74.9 years (INS 2016a). The bioavailability of the ingested metals was assumed to be 100%. The bioaccumulation of heavy metals by the plants was evaluated to estimate the health risks associated with the consumption of those plants. Impact analyses were performed for different age groups, paying particular attention to the risk to children. The most likely and obvious modes of contaminant transfer from plants to humans are shown in Fig. 1.

Fig. 1 Scenario of human exposure to Joumine sediment dam amended soils via the food chain

Evaluation of health risks associated with the bioaccumulation of heavy metals in soils amended by the sediment

Bioconcentration factor (BCF)

The BCF is a key parameter for quantifying differences in metal bioavailability. The plant BCF represents the efficiency of a plant at accumulating a metal from the surrounding environment in its tissues. It is calculated via (Casas 2005)

$$\text{BCF} = C_o / C_e, \quad (1)$$

where C_o is the concentration of the trace element in the plant (mg/kg) and C_e is the environmental concentration (i.e., the concentration in the soil, in mg/kg).

Consumption of locally produced food

The human exposure to soil pollutants (HESP) evaluation model (Hazerbouck 2005) was adopted to quantify the metals that we would expect to be ingested through the consumption of plants and livestock products (meat, milk, or eggs). The amount of metal i ingested (in mg/kg/day) through exposure route j is expressed as a daily dose exposure (DDE_{ij}), which is defined via (ASTEE 2003)

$$\text{DDE}_{ij} = (CiQ_dF) / \text{bw}, \quad (2)$$

where DDE_{ij}: daily dose exposure to metal i through the exposure route j (mg/kg/day), Ci is the concentration of metal i (mg/kg) in the food consumed, which depends on the nature of the foodstuffs ingested by an individual, the bioavailability, the biotransfer factor, and the metal concentration in the pasture. Q_d is the quantity of food ingested orally per day (l/d or kg/d). It should be noted that relevant reference values or studies for Tunisian children and adolescents are unavailable; only the Q_d value for an adult is available (INS 2016b). Based on differences between the results of the INCA 2 (Individual and National Study on Food Consumption 2) investigation (Dubuisson and Lioret 2007) and Tunisian statistics for adults, food quantities were extrapolated for a Tunisian child, adolescent, man, and woman. In the equation, F is the frequency of exposure ($F=1$ in this study), and bw is the target body weight (kg). The average body weight was assumed to be 15, 30, and 70 kg, respectively, for a child, teenager, and adult (Bonnard et al. 2001) based on statistics obtained from INERIS (Bonnard et al. 2001), given that there are no relevant reference values or studies for Tunisian people.

The relevant C_i values for beef, dairy products, and poultry meat were obtained using Eqs. 3–6 below, respectively (Dupuis and Saffre 2018).

$$C_{\text{beef}} = (Q_{\text{grass}} \times C_{\text{grass}} + Q_s C_s B_s) \times \text{Ba}_{\text{beef}}, \quad (3)$$

where ‘grass’ refers to the stem and leaves, C_{beef} is the concentration of metal i in beef (mg/kg fresh meat), Q_{grass} is the total amount of grass ingested daily by the animal (60 kg of fresh grass/day; Bonnard 2003), C_{grass} is the metal concentration in the grass ingested by the animal (mg/kg fresh grass), Q_s is the quantity of soil ingested by the animal daily (0.5 kg of dry soil/day; Bonnard 2003), C_s is the metal concentration in the soil (mg/kg dry soil), B_s is the bioavailability factor from the soil ($B_s=1$), and Ba_{beef} is the biotransfer factor to beef (day/kg fresh beef; Dupuis and Saffre 2018).

$$C_{\text{milk}} = (Q_{\text{grass}} C_{\text{grass}} + Q_s C_s B_s) \times \text{Ba}_{\text{milk}}, \quad (4)$$

where C_{milk} is the concentration of metal i in the milk (mg/l milk), Q_{grass} is the total amount of grass ingested daily by the animal (80 kg fresh fodder/day; Bonnard 2003), C_{grass} is the metal concentration in the grass ingested by the animal (mg/kg fresh grass), Q_s is the quantity of soil ingested daily by the animal (0.64 kg dry soil/day; Bonnard 2003), C_s is the metal concentration in the soil (mg/kg dry soil), B_s is the bioavailability factor from the soil ($B_s=1$), and Ba_{milk} is the biotransfer factor to milk (day/l milk; Dupuis and Saffre 2018).

$$C_{\text{poultry}} = (Q_{\text{cereals}} C_{\text{cereals}} + Q_s C_s B_s) \times \text{Ba}_{\text{poultry}}, \quad (5)$$

where C_{poultry} is the concentration of metal i in poultry meat (mg/kg of fresh meat), Q_{cereals} is the total amount of cereals ingested daily by the animal (0.2 kg fresh cereals/day; Bonnard 2003), C_{cereals} is the metal concentration in the cereals ingested by the animal (mg/kg cereals), Q_s is the quantity of soil ingested daily by the animal (0.02 kg dry soil/day; Bonnard 2003), C_s is the metal concentration in the soil (mg/kg dry soil), B_s is the bioavailability factor from the soil ($B_s=1$), and $\text{Ba}_{\text{poultry}}$ is the biotransfer factor to poultry meat (day/kg fresh meat; Dupuis and Saffre 2018).

$$C_{\text{eggs}} = (Q_{\text{cereals}} C_{\text{cereals}} + Q_s C_s B_s) \times \text{Ba}_{\text{eggs}}, \quad (6)$$

where C_{eggs} is the concentration of metal i in eggs (mg/kg of fresh eggs), Q_{cereals} is the total amount of cereals ingested daily by the animal (0.2 kg fresh cereals/day; Bonnard 2003), C_{cereals} is the metal concentration in the cereals ingested by the animal (mg/kg cereals), Q_s is the quantity of soil ingested daily by the animal (0.02 kg dry soil/day) (Bonnard 2003), C_s is the metal concentration in the soil (mg/kg dry soil), B_s is the bioavailability factor from the soil ($B_s=1$), and Ba_{eggs} is the biotransfer factor to eggs (day/kg fresh eggs).

Table 2 Values of the biotransfer factors (Ba) of heavy metals into animal products used in this work (Ngo 2016)

Heavy metal	Ba (day/kg of animal product)			
	Beef meat	Cow's milk	Poultry meat	Eggs
Cu	1×10^{-2}	2×10^{-3}	5×10^{-1}	5×10^{-1}
Zn	9×10^{-5}	325×10^{-7}	875×10^{-5}	875×10^{-5}
Mn	5×10^{-4}	1×10^{-4}	5×10^{-2}	7×10^{-2}

The biotransfer factors of the metals of interest into animal products were obtained from the literature (Ngo 2016) and are listed in Table 2.

Cu, Zn, and Mn were the metals of interest regarding the direct and indirect ingestion of the plants grown in the macrocosm experiments. In the microcosm experiments, only Zn was considered for direct and indirect oral exposure routes.

Quantitative risk assessment

The risk to human health from heavy metal contamination of the soil is directly dictated by the level of human exposure to the heavy metals. In the microcosm and macrocosm tests, the health risk or hazard quotient HQ from a particular metal was determined using (Dupuis and Saffre 2018)

$$HQ = DDE/TRV, \quad (7)$$

where TRV is the toxicological reference value.

The toxicological reference values of Mn, Cu, and Zn were 14×10^{-2} (Dupuis and Saffre 2018), 37×10^{-3} (Yang et al. 2017), and 0.3 (Yang et al. 2017) mg/kg bw/day, respectively. A low HQ (< 1) suggests that toxic effects are unlikely, whereas a high HQ (> 1) means that the probability that side or toxic effects will occur cannot be excluded (Dor et al. 2005).

Results and discussion

Sediment analysis

The results for the heavy metal concentrations in the fine fraction of the sediment are presented in Table 3. The concentrations of various metals (Cu, Pb, Ni, Zn, Fe, Cu, Cd, Co, Mn) were below the limits for organic amendments set by various national standards: the Tunisian standard NT 10.44 (Grissa 2017), the French standard NFU 44-051 (AFNOR 2018), and Swiss standards (Swiss Federal Council 1998). Thus, this sediment has great potential for use as a soil fertilizer. The Tunisian and French standards have similar thresholds for the analyzed metals. The French standard is more commonly used because it is more developed and detailed, as confirmed by Bambara et al. (2019), who used different types of composts based on the French standard.

NFU 44-051 (Zdanevitch and Bour 2011; AFNOR 2018) defines the characteristics and quality of compost as well as threshold values for contaminants, in particular heavy metals (see Table 3). This standard is valid for an amendment period of 10 years.

Macrocosm tests

Concentrations of heavy metals in the amended soil

The threshold value for a particular element varies widely depending on the international or national standard considered. In the absence of a Tunisian standard for tolerable thresholds of soil metals, the values presented in Table 4 were used as thresholds to estimate the degree of soil contamination. The Chinese standard (Ministry of Environmental Protection of China 1995) is stricter than the Indian standard (Bhatnagar and Awasthi 2000) and the European Union standard (EU 2006). The concentrations of Cu, Zn,

Table 3 Heavy metal concentrations in the sediment from the Joumine Dam

Heavy metal	Concentration in sediments (mg/kg dm) (Mtibaa et al. 2012)	Limit according to NT 10.44 (mg/kg dm)	Limit according to NFU 44-051 (mg/kg dm)	Limit according to Swiss standards (mg/kg dm)
Cu	14.75 ± 0.25	300	300	100
Pb	28.5 ± 0.75	180	180	120
Ni	25.5 ± 1.75	60	60	30
Zn	95.75 ± 2.75	600	600	400
Fe	$199,991 \pm 435$	—	—	—
Cd	1.5 ± 0.25	3	3	—
Co	44 ± 1.25	—	—	—
Mn	270 ± 13	—	—	—

dm dry matter

Table 4 Heavy metal contents in macrocosm tests of soil amended with Joumine Dam sediment, and comparison with different standards

Heavy metal	Concentration in amended soil (mg/kg dm) (Mtibaa et al. 2012)	Limit according to Chinese standard (Ministry of Environmental Protection of China 1995) (mg/kg dm)	Limit according to Indian standard (Bhatnagar and Awasthi 2000) (mg/kg dm)	Limit according to European Union standard (EU 2006) (mg/kg dm)
Cu	12 ± 3	50	135–270	100
Zn	75.3 ± 15	200	300–600	300
Mn	18.1 ± 2.4	NA	NA	2000

NA not available

Table 5 Heavy metal concentrations in *B. ramosus* tissues from macrocosm tests (Mtibaa et al. 2012), and comparison to permissible limits in plants

Heavy metal	Roots (mg/kg dm)	Stems (mg/kg dm)	Leaves (mg/kg dm)	Seeds (mg/kg dm)	Maximum permissible limit (mg/kg dm)
Cu	11.3 ± 2.4	3.52 ± 1.01	11 ± 3	5 ± 1.3	73.30 ^a
Zn	89 ± 13	43 ± 15.3	73 ± 18.7	38 ± 9.4	99.40 ^a
Mn	42 ± 14	14 ± 6	12.3 ± 2.3	6.5 ± 1.8	500 ^a

^aFrom Merian et al. (2004), Kabata-Pendias (2011), and Al-Othman et al. (2016)

and Mn in the amended soil were below the thresholds set by the Chinese standard and the European Union standard. The concentration of Cu (12 mg/kg) was less than one-fourth of the limit defined by the Chinese standard (850 mg/kg), the Zn content (75.3 mg/kg) was only one-third of the limit indicated in the Chinese standard (200 mg/kg), and the Mn concentration (18.1 mg/kg) was just one-hundredth of the limit defined by the European Union standard (2000 mg/kg).

Concentrations of heavy metals in *Bromus ramosus* tissues

The results reported in Mtibaa et al. (2012) clearly showed that the roots of oat plants accumulate higher levels of heavy metals than the aerial parts. The accumulation of high levels of these metals could result in phototoxicity (Gupta et al. 2008) and cause serious intoxication (Yang et al. 2008). Zinc, an essential trace element for plants, was found at high concentrations in the roots and stems of plants grown in the amended soil. The Zn provided by the sediment enriches the soil and is translocated through the root systems of the plants, accumulating in the stems. This metal is not very toxic but it does accumulate very easily in plant tissues. Copper is also easily absorbed by plants, but this absorption is inhibited in clay soils. Among the advantages of using sediment as an amendment is that it is rich in organic matter, which facilitates the immobilization of Cu and Mn. This explains the low concentrations of these two metals, which did not exceed the permissible limits (Table 5). In this macrocosm test, heavy metals also accumulated in oat seeds. This result is consistent with the findings of He et al. (2011)

Table 6 Metal bioconcentration factors (BCFs) in seeds from *Bromus ramosus* plants grown in macrocosm tests

Plant	Organ	Heavy metal BCF		
		Cu	Zn	Mn
<i>B. ramosus</i>	Seeds	0.43	0.5	0.35

and Khan et al (2013a, b), who found that rice seeds were able to accumulate heavy metals.

Metal bioconcentration factors in *Bromus ramosus* seeds

Table 6 presents the bioconcentration factors of various heavy metals. The BCFs decreased in the following order: Zn (0.5) > Cu (0.43) > Mn (0.35). The BCF of Zn was higher than those of the other metals analyzed, in agreement with the findings of Yang et al. (2017) and Xu et al. (2013).

Potential risk of heavy metals to human health through direct and indirect ingestion of *Bromus ramosus* grown in amended soil in the macrocosm tests

In this study, we assumed that the population considered was regularly exposed to the effects of heavy metals and consumed its locally produced food at least once a day.

Results from an evaluation of the exposure to Zn, Cu, and Mn following direct and indirect consumption of oat seeds based on the corresponding HQ calculations

Table 7 Impact on human health of heavy metals consumed through the direct and indirect ingestion of *Bromus ramosus* grown in soil amended with Joumine Dam sediment

Food	Heavy metal	Child < 7 years old	Child > 7 years old	Adult man	Adult woman
Direct ingestion					
Wild oat seeds	Cu	14×10^{-2}	68×10^{-3}	43×10^{-3}	43×10^{-3}
	Zn	13×10^{-2}	63×10^{-3}	4×10^{-2}	4×10^{-2}
	Mn	46×10^{-3}	23×10^{-3}	86×10^{-3}	86×10^{-3}
Indirect ingestion					
Beef	Cu	38×10^{-2}	24×10^{-2}	16×10^{-2}	10^{-1}
	Zn	3×10^{-3}	2×10^{-3}	15×10^{-4}	1×10^{-3}
	Mn	9×10^{-3}	57×10^{-4}	37×10^{-4}	24×10^{-4}
Cow's milk	Cu	<i>1.86</i>	68×10^{-2}	27×10^{-2}	27×10^{-2}
	Zn	3×10^{-2}	1×10^{-2}	67×10^{-03}	5×10^{-03}
	Mn	4×10^{-2}	16×10^{-3}	65×10^{-4}	65×10^{-4}
Poultry meat	Cu	41×10^{-3}	31×10^{-3}	2×10^{-2}	59×10^{-3}
	Zn	7×10^{-04}	5×10^{-04}	13×10^{-05}	2×10^{-04}
	Mn	14×10^{-4}	10^{-3}	28×10^{-5}	43×10^{-5}
Eggs	Cu	26×10^{-3}	13×10^{-3}	82×10^{-4}	77×10^{-4}
	Zn	41×10^{-05}	21×10^{-05}	13×10^{-05}	12×10^{-05}
	Mn	13×10^{-4}	67×10^{-5}	59×10^{-6}	39×10^{-5}

Values in italics represent unacceptable risk ($HQ > 1$); all other values represent acceptable risk ($HQ < 1$)

for adults and children are shown in Table 7. The results show that there was no health risk ($HQ < 15 \times 10^{-2}$) from Cu, Zn, and Mn after the direct consumption of oat seeds. However, this finding should be interpreted with caution, because even toxins with no immediate effect ($HQ < 1$) may be a risk to health in the long term due to the accumulation of metals in the body. This accumulation depends on the nature and amount of the ingested substance (Xiong et al. 2020). Therefore, in the context of health security, the development of food security is now mandatory to prevent and control acute, sporadic, and chronic foodborne illnesses (Schlundt et al. 2020).

According to the abovementioned exposure scenarios, the main route of exposure to heavy metals appears to be the indirect consumption of oat seeds. Table 7 shows that the hazard ratio of Cu in children less than 7 years old is significantly higher than 1. The occurrence of toxic effects due to Cu may be expected after drinking cow's milk, which exhibited the highest transfer of this metal in the food chain. In contrast, the consumption of cow's milk does not appear to be a significant risk to human health in the other age groups ($27 \times 10^{-2} < HQ < 68 \times 10^{-2}$). Also, the risk from manganese and zinc appears to be minimal for all age groups (Fig. 1).

In what follows, we were interested in the mobility of zinc from the soil and its bioconcentration in the upper parts of *Bromus ramosus* in the presence of different NaCl concentrations and sediment rates. The tests were carried out at laboratory scale (i.e., they were microcosm tests). Results of the Zn analysis were then interpreted to assess the risk to human health from this metal.

Microcosm tests

Zinc concentrations in *Bromus ramosus* tissues

Table 8 shows the concentrations of zinc in the different organs of *Bromus ramosus* (roots, stems, leaves, and seeds). These values were obtained from data published in Mtibaa et al. (2011, 2012). We compared these values with the permissible levels of trace metals in agronomic crops set by Merian et al. (2004), Kabata-Pendias (2011), and Al-Othman et al. (2016), which suggest that the maximum permissible limit for Zn is around 99.4 mg/kg dm.

According to Table 8, the bioavailability of Zn in the plants varied according to the plant organ considered (root, stem, leaf, or seed). The bioconcentration of zinc decreased from the roots to the aerial organs. The concentrations of Zn in the roots of samples 1, 2, 3, 5, 6, and 8 exceeded the permissible limit. The sediment acts as a chelating agent, which facilitates the accumulation of metals in plant roots. Since the roots are not consumed by humans, the accumulation of metals in this part of the plant reduces the impact of the metals on human health. The results of the current study therefore suggest that the Joumine Dam sediment could be used to phytostabilize metals in contaminated soils.

Zinc bioconcentration factors in *Bromus ramosus* seeds

The calculated bioconcentration factors of zinc in the microcosm experiments are presented in Table 9. The BCFs of the samples decreased in the following order: samples 2 and 3 (0.23) > samples 1 and 8 (0.2) > sample 6 (0.17) > sample

Table 8 Zinc concentrations in *Bromus ramosus* tissues from microcosm tests and comparison with permissible limits

Sample	Roots (mg/kg dm)	Stems (mg/kg dm)	Leaves (mg/kg dm)	Seeds (mg/kg dm)	Maximum permissible limit (mg/kg dm)
1	165 ± 23	44 ± 7.5	16 ± 4	4 ± 1.5	99.40 ^a
2	296 ± 28.9	63 ± 18	29 ± 2	7 ± 2	
3	391 ± 31	109 ± 27	38 ± 3	9 ± 1.75	
4	86 ± 12	60 ± 13	8 ± 0.7	2 ± 0.5	
5	148 ± 18	35 ± 13.7	14 ± 2	3 ± 1	
6	221 ± 43	32 ± 6.54	21 ± 2.8	5 ± 0.9	
7	49.2 ± 17.9	2.5 ± 0.67	5 ± 1	1 ± 0.2	
8	330 ± 43	47 ± 13	2 ± 0.9	8 ± 2.3	
9	51.8 ± 19	18 ± 7.2	5 ± 1.5	1 ± 0.1	

^aFrom Merian et al. (2004), Kabata-Pendias (2011), and Al-Othman et al. (2016)

Table 9 Bioconcentration factors (BCFs) of Zn in seeds from *Bromus ramosus* plants grown in the microcosm test

Plant	Consumed organ	Sample	Zn BCF
<i>Bromus ramosus</i>	Seeds	1	0.2
		2	0.23
		3	0.23
		4	0.05
		5	0.15
		6	0.17
		7	0.03
		8	0.2
		9	0.05

5 (0.15) > samples 4 and 9 (0.05) > sample 7 (0.03). The experimental conditions (e.g., the sediment/soil ratio) seem to have a significant influence on the BCF of Zn in wild oat. The results show that the BCF of Zn was not influenced by the concentration of zinc in the sediment. The quantity of zinc that was transferred from the soil to the roots and accumulated in the plant organs decreased with the amount of sediment applied. This suggests that soil amendment with the sediment inhibited zinc uptake by the plants. Malik et al. (2010) considered the sediment structure to be a major influence on metal absorption by plants. The clayey sediment used in this study is rich in organic matter (Mtibaa et al. 2012). The adsorption of zinc ions onto clay minerals in the soil reduces the solubility of this metal. Also, organic matter particles can form complexes with zinc ions, which reduces the bioavailability of this metal.

It is well known that raising sodium chloride salinity levels reduces the accumulation of zinc in plants (Fritioff et al. 2005) due to the effect of osmotic stress on root function. In contrast, the present study found that the salinity level did not significantly affect the Zn BCF. This is because of the low salinity levels present in the microcosm experiments and because the roots act as a physiological barrier to metal

transfer from the soil to the roots and subsequently to aerial parts of the plant (Mitra et al. 2020).

Potential risk of zinc to human health through direct and indirect consumption of *Bromus ramosus* tissues grown in amended soil in the microcosm tests

The results of an assessment of the exposure of adults and children to zinc following direct (i.e., human consumption of seeds from oat plants grown in amended soil) and indirect (i.e., human consumption of animals that were fed on fodder grown in amended soil) consumption of *B. ramosus* grown in soil amended with Joumine Dam sediment are reported in Table 10. As also observed in the macrocosm tests, the results of the microcosm experiments show that there is no immediate health risk from the Zn consumed through the direct or indirect ingestion of oat plants grown in sediment-amended soil (HQ < 1 for all samples).

As mentioned previously, however, it is possible for elements to give HQ < 1 in microcosm and macrocosm experiments, meaning that they should not have any immediate toxic effects, but to still induce toxic effects in the long term because they accumulate in the human body over time. Indeed, according to the literature, such metal accumulation in the body could damage the kidneys (Yazgan et al. 2020) and lungs (Ivanova et al. 2020), weaken the bones (Zanetti et al. 2020), and cause hematological (Palacios et al. 2020) and cardiovascular dysfunction as well as lesions (Rosenblum et al. 2020).

Khan et al. (2015) note that the toxicological effects of metals can vary from person to person. A dependence of metal toxicity on various personal habits and exposure parameters was confirmed by Omrane et al. (2018), who considered that assessing the health risks from environmental toxicity was one of the most difficult tasks involved in establishing the dose–response relationship for a particular element.

Table 10 Impact on human health of Zn exposure due to direct and indirect ingestion of *Bromus ramosus* grown in sediment-amended soil in the microcosm experiments

Food	Sample	Child < 7 years	Child > 7 years	Adult man	Adult woman
Direct ingestion					
Wild oat seeds	1	13×10^{-3}	66×10^{-3}	5×10^{-3}	5×10^{-3}
	2	7×10^{-2}	12×10^{-3}	87×10^{-4}	87×10^{-4}
	3	9×10^{-2}	15×10^{-3}	11×10^{-3}	11×10^{-3}
	4	67×10^{-4}	33×10^{-4}	24×10^{-4}	24×10^{-4}
	5	1×10^{-2}	5×10^{-3}	37×10^{-4}	37×10^{-4}
	6	17×10^{-3}	83×10^{-4}	62×10^{-4}	62×10^{-4}
	7	33×10^{-4}	17×10^{-4}	12×10^{-4}	12×10^{-4}
	8	27×10^{-3}	13×10^{-3}	99×10^{-4}	99×10^{-4}
	9	33×10^{-4}	17×10^{-4}	12×10^{-4}	12×10^{-4}
Indirect ingestion					
Beef	1	17×10^{-4}	11×10^{-4}	83×10^{-5}	54×10^{-5}
	2	27×10^{-4}	17×10^{-4}	13×10^{-4}	84×10^{-5}
	3	43×10^{-3}	27×10^{-4}	2×10^{-3}	13×10^{-4}
	4	2×10^{-3}	13×10^{-4}	94×10^{-5}	62×10^{-5}
	5	15×10^{-4}	92×10^{-5}	69×10^{-5}	45×10^{-5}
	6	16×10^{-4}	98×10^{-5}	74×10^{-5}	49×10^{-5}
	7	23×10^{-5}	14×10^{-5}	11×10^{-5}	7×10^{-5}
	8	15×10^{-4}	92×10^{-5}	69×10^{-5}	45×10^{-5}
	9	7×10^{-4}	44×10^{-5}	33×10^{-5}	22×10^{-5}
Cow's milk	1	16×10^{-3}	57×10^{-4}	27×10^{-4}	27×10^{-4}
	2	24×10^{-3}	86×10^{-4}	4×10^{-3}	4×10^{-3}
	3	4×10^{-2}	14×10^{-3}	67×10^{-4}	67×10^{-4}
	4	18×10^{-3}	64×10^{-4}	3×10^{-3}	3×10^{-3}
	5	13×10^{-3}	47×10^{-4}	22×10^{-4}	22×10^{-4}
	6	12×10^{-3}	43×10^{-4}	2×10^{-3}	2×10^{-3}
	7	2×10^{-3}	72×10^{-5}	33×10^{-5}	33×10^{-5}
	8	13×10^{-3}	47×10^{-4}	22×10^{-4}	22×10^{-4}
	9	59×10^{-4}	21×10^{-4}	1×10^{-3}	1×10^{-3}

Table 10 (continued)

Food	Sample	Child < 7 years	Child > 7 years	Adult man	Adult woman
Poultry meat	1	91×10^{-6}	68×10^{-6}	5×10^{-5}	32×10^{-6}
	2	15×10^{-5}	11×10^{-5}	81×10^{-6}	53×10^{-6}
	3	19×10^{-5}	14×10^{-5}	1×10^{-4}	68×10^{-6}
	4	23×10^{-6}	45×10^{-7}	5×10^{-5}	32×10^{-6}
	5	72×10^{-6}	54×10^{-6}	4×10^{-5}	26×10^{-6}
	6	12×10^{-5}	87×10^{-6}	63×10^{-6}	41×10^{-6}
	7	58×10^{-6}	43×10^{-6}	32×10^{-6}	21×10^{-6}
	8	17×10^{-5}	13×10^{-5}	95×10^{-6}	62×10^{-6}
	9	44×10^{-6}	32×10^{-4}	24×10^{-6}	16×10^{-6}
Eggs	1	56×10^{-6}	29×10^{-6}	21×10^{-6}	2×10^{-5}
	2	92×10^{-6}	47×10^{-6}	34×10^{-7}	32×10^{-6}
	3	12×10^{-5}	6×10^{-5}	44×10^{-6}	41×10^{-6}
	4	56×10^{-5}	292×10^{-6}	2×10^{-5}	2×10^{-5}
	5	45×10^{-6}	23×10^{-6}	17×10^{-6}	17×10^{-6}
	6	71×10^{-6}	37×10^{-6}	27×10^{-6}	25×10^{-6}
	7	36×10^{-6}	18×10^{-6}	13×10^{-6}	13×10^{-6}
	8	11×10^{-5}	55×10^{-6}	4×10^{-5}	38×10^{-6}
	9	27×10^{-6}	14×10^{-6}	1×10^{-5}	95×10^{-7}

All values in the table represent acceptable risk ($HQ < 1$)

Heavy metals' low lethal doses could cause serious problems for the considered population. The accumulation of heavy metals in plants or animals may result in malformations that can lead to death. Therefore, a detailed evaluation of food quality is required to ensure that foods are not dangerous to human health.

Despite our thorough knowledge of the effects of each heavy metal in isolation, we do not have a deep understanding of the toxicities of metal mixtures. Also, Hembrom et al. (2020) stated that the mechanisms of action (i.e., synergistic or antagonistic) of individual chemicals present at sublethal doses in the human body are unclear.

The chemical behavior and the fate of heavy metal complexes in the environment should also be considered in this context. In the present work, plants were grown in a matrix consisting of a mixture of soil and sediment, meaning that the toxicity results obtained from the experiments are as realistic as possible and account for any unexpected toxicity.

Conclusion

This study builds on investigations into the potential use of dredging sediments as a soil amendment, as reported in two earlier papers. The application of the sediment to the soil did not appear to negatively affect crop production. Nevertheless, the concentrations of heavy metals in the plants grown in amended soil were found to be significantly different from the heavy metal concentrations in plants grown in unamended soil. The highest metal concentrations were found in the roots, and the concentrations decreased from the bottom of the plant to the top (aerial) part. In the present study, possible health risks of heavy metal ingestion due to the direct and indirect consumption of wild oat grown in soil amended with dredging sediments were assessed. The results of this assessment led us to the following conclusions:

- In the macrocosm tests, the oat grains presented the highest levels of metal accumulation. It should be noted that the probability of being contaminated or intoxicated depends on the societal level and lifestyle of the person considered. Copper contamination would be a particular risk ($HQ = 1.86$) in children younger than 7 years because of their high consumption of cow's milk.
- In the microcosm tests, the sediment affected the solubility of Zn and decreased its availability and mobility in the soil, which explains the absence of any significant risk from Zn regardless of age ($HQ < 1$). Soil salinity had no discernible effect in the experiments because the salinity was always low. To achieve a broader health risk assessment, we suggest that microcosm tests of the bioavailability of copper and manganese should be performed to evaluate the risk posed by the ingestion of these metals

due to the direct or indirect consumption of oat plants grown in sediment-amended soil.

The results gathered in this study favor the use of the studied sediment as a soil fertilizer. This would reduce the need to use phytosanitary chemicals and make it easier to manage high quantities of sediments dredged from dams.

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Compliance with ethical standards

Conflict of interest On behalf of all the authors, the corresponding author states that there are no conflicts of interest related to this work.

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