# Influence of local geological data and geographical parameters to assess regional health impact in LCA. Tomsk oblast', Russian Federation application case

Alexandra Belyanovskaya[1,2] · Bulat Soktoev[1] · Bertrand Laratte[3] · Elena Ageeva[1] · Natalia Baranovskaya[1] · Natalia Korogod[4]

## Abstract

The research paper is aimed to modify the human health impact assessment of Cr in soils. The current article presents the input of several critical parameters for the human health Impact Score ($IS_{hum}$) assessment in soils. The modification of the $IS_{hum}$ is derived using geological data — results of neutron activation analysis of soils are used in the $IS_{hum}$ calculation; research area is divided using the watersheds and population size and density. Watersheds reflect the local environmental conditions of the territory unlike the administrative units (geographical areas of the studied region) due to their geological independence. The calculations of the characterization factor value underestimate the influence of the population size and density on the final result. Default characterization factor values cannot be considered during the assessment of the potential human health impact for the big sparsely inhabited areas. In case of very low population density, the result will be overrated and underestimated in the opposite case. The current approach demonstrates that the geographical separation in the USEtox model should be specified. The same approach can be utilized for other geo zones due to the accessibility of this information (area size, population size, and density, geological, and landscape features).

**Keywords** LCIA · Heavy metals · USEtox · Cr · Regional impact assessment · Impact assessment models

Responsible Editor: Philippe Loubet

✉ Alexandra Belyanovskaya
alexandra.belyanovskaya@outlook.com

Bulat Soktoev
bulatsoktoev@tpu.ru

Bertrand Laratte
bertrand.laratte@ensam.eu

Elena Ageeva
ev_ageeva@mail.ru

Natalia Baranovskaya
nata@tpu.ru

Natalia Korogod
natalya_korogod@mail.ru

1 Division for Geology at Tomsk Polytechnic University, Tomsk, Russia

2 Laboratory of Sedimentology and Paleobiosphere Evolution, Tyumen, Russia

3 Arts et Métiers Institute of Technology, University of Bordeaux, CNRS, Bordeaux INP, INRAE, I2M, Bordeaux, F-33400 Talence, France

4 High School of Natural Science at Pavlodar State Pedagogical University, Pavlodar, Kazakhstan

## Introduction

Human health impact from the soils assessment attracts a particular scientific attention (Trujillo-González et al. 2016a; Tarasova et al. 2018; Wang et al. 2020). Heavy metals input from the soils due to their direct and indirect long-term effects (Carr et al. 2008) is investigated worldwide (Yang et al. 2018; Islam et al. 2018; Jafari et al. 2019; Li et al. 2019; Tepanosyan et al. 2020).

A significant number of studies have been devoted to the role of soil as one of the factors contributing to disease occurrence (Alloway 2013; Li et al. 2019; Sevbitov et al. 2020; Tepanosyan et al. 2020). Chemical elements entering the human body through food chains originate, to a large extent, from soils (Brevik and Sauer 2015; Trujillo-gonzález et al. 2016b; He et al. 2021). It undoubtedly requires careful study of soils' elemental composition (Zhang et al. 2021) and the potential negative effects caused by chemical elements.

Cr as a heavy metal could have a serious negative impact on human health as cancer, skin diseases (Khitrov and Jaeger 2001; Guertin 2005; Balachandar et al. 2010; Danesh Miah et al. 2010; Chatterjee et al. 2015; Sharma and Bhattacharya 2017; Sall et al. 2020; Sinha et al. 2022). The most widespread forms of the element in soils are $Cr^{3+}$, which is very stable in reducing terrain (Vodyanicky 2008; Ashraf et al. 2017), and $Cr^{6+}$, which is very unstable, easily mobilized, extremely toxic to living organisms (Brasili et al. 2020). Sources of Cr soil pollution can be both natural and man-made (Wuana and Okieimen 2011; Islam et al. 2018). The accumulation of Cr in soils depends on the local conditions. The main natural source of Cr to the environment is rock weathering (Ni et al. 2009; Tian et al. 2021). Major anthropogenic inputs of Cr into the environment include the emissions and wastes from chemical (pigments, metal finishing, leather tanning) refractory and metallurgical industries (Sheikhupura et al. 2016; Bashkin et al. 2019; Xia et al. 2019). These conditions should be considered in the processes of environmental monitoring. The importance of the local data determines the necessity of the spatially oriented investigations.

Assessing impact on human health (the Impact score - $IS_{hum}$ calculation) based on the elemental composition of soils is one widespread approach (Senesil et al. 1999; Vithanage et al. 2019; Adimalla 2020), showing its relevance and importance for human health studies. In such studies, the gross values (mass or the concentration) of heavy metals in soils are commonly utilized (Bratec et al. 2019; Sharma et al. 2021). This approach is based on the multiplication of the gross values of the pollutant in the soils on the substance specific characterization factor — CF. The characterization factor is derived by the impact assessment models. CF represents the potential toxicity of a substance (Fantke et al. 2017, 2021). CF is used as weighting factors to aggregate life cycle emissions into scores for human health damage and ecosystem health damage (de Schryver et al. 2009).

Life cycle impact assessment models provide the human health impact characterization factor for organic and nonorganic pollutants. IMPACT World + provides impact on human health, the regional separation is modeled using the USEtox regional archetypes (Bulle et al. 2019). ReCiPe provides the CF for the human non- and carcinogenic toxicity in country- or region-specific levels (Huijbregts et al. 2017). LC-IMPACT includes spatial aspects for the human health toxicity in country, continental, and a global level (Hauschild 2006; Huijbregts et al. 2016; Verones et al. 2020a).

All these models in case of the regionalized human health impact are based on the USEtox methodology. USEtox is model endorsed by UNEP's Life Cycle Initiative for characterizing human and ecotoxicological impacts of chemicals (Hauschild et al. 2008; Rosenbaum et al. 2008). The USEtox is specifically focused on the human health and the ecosystems impact assessment (Nordborg et al. 2017; Fantke et al. 2021). The USEtox model, recommended by the European Commission, has already proved its efficiency for the coupling of environmental and geochemical studies (Bratec et al. 2019) and was, therefore, chosen for our study.

USEtox model provides midpoint and endpoint characterization factors for human toxicological and freshwater ecotoxicological impacts of chemical emissions in life cycle assessment (European Commission. Joint Research Centre. Institute for Environment and Sustainability. 2011; Fantke et al. 2017). The USEtox model is constructed to provide characterization factors for human health and freshwater ecological damage for contaminant emissions to indoor air, urban air, rural air, freshwater, and agricultural soil (Fantke et al. 2017). The human health CF is given in the USEtox model is widely used in the Life cycle assessment (Walser et al. 2014; Liang et al. 2019; Luo et al. 2021; Alejandrino et al. 2021).

One of the main advantages of the USEtox is that the spatial aspect is considered at different scale (17 sub-continental regions); however, there is a lack of the local environmental information in the calculations (Shaked 2011). The LCIA is usually carried out in the regional scale (Hauschild and Potting 2000). At the same time, the environmental studies are performed at the local level. The model includes sub-continental regions, as "Central Asia," which is heterogeneous from the geological point of view. The regional information in the USEtox about these areas is rather generic.

At the same time, previous investigations show that the environmental fate and the exposure of the chemicals at the local level strongly depends on the geological structure of the area (river flows, maternal rocks compositions, etc.) and the anthropogenic tension (Franke et al. 2005; Mirmiran et al. 2009; Kim et al. 2017; He et al. 2019; Verones et al. 2020b). These parameters are local, and they affect the environmental conditions of the research area, and consequently influence the population health.

The other spatial aspect of the impact modeling is the division of the geo areas. As it was previously mentioned, the USEtox model includes 17 sub-continental regions. The separation is organized based on the level of the administrative units. The previous investigations of the research group (Belyanovskaya et al. 2019, 2020) were also based on the administrative borders. However, such division of the regions in the impact assessment usually ignores natural conditions. Meanwhile, the watersheds reflect the landscape and the geological structure (Solntsev 2001; Kvasnikova 2003). Thus, we propose using the watersheds to reduce the regional limitation, mentioned above.

The other underestimated parameter of the model is a population density (PD). In the USEtox model, the population density of the area is rather generic. Population density depends on the type of the area, as rural or urbanized zones. For example, in Russia, the PD varies from 4956 person/$km^2$ in Moscow to 0.07 person/$km^2$ in Chukotka Autonomous Region (Federal State Statistics Service [Rosstat]). For the comparison, in the USEtox model in the continental scale, the PD of the "Central Asia" is 14 person/$km^2$ (Fantke et al. 2017). We suppose that overpopulated areas and the regions with a low level of urbanization should be considered differently unlike it is performed in the model dataset.

The approach also considers the exposure of Cr with meat products through the food chain. In the article, the modification of the indirect exposure factor ($XF_{indirect}$) is developed. The paper is the continuation of the previous investigations of the research group. The indirect human exposure factor calculation modification was already developed earlier (Belyanovskaya et al. 2019, 2020).

The previous works were extended with the following:

1) The $CF_{hum}$ calculated for the geologically oriented zones (watersheds) of Tomsk oblast' — to highlight the importance of the geological parameter in the LCIA, we compared the administratively divided zones with the interfluves;
2) 78 samples of organs and tissues of the domestic pig were analyzed with the instrumental neutron activation analysis — INAA (in the previous research 18 samples analyzed with the inductive coupled plasma spectrometry - ICP-MS were proceeded);
3) Exposure factor $_{indirect}$ modified using the local population density for each researched zone of the oblast'.

Exposure factor $_{indirect}$ (XF) reflects the intake of chemicals through the meat products via soils (Rosenbaum et al. 2011; Fantke et al. 2017). The chemical composition of food, such as meat or dairy products, reflects the state of the environment (Baroni et al. 2011; Kim et al. 2017; Pu et al. 2017; Rikhvanov et al. 2019). Based on the biomagnification principle through the food chain, meat products reflect soil compositions as well. Thus, concentration of heavy metals in meat products can indicate the exposure of living organisms to them from polluted mediums (Kim et al. 2017; Panichev et al. 2021). This modification is expressed in the article by exposure factor modification (Fig. 1).

To reflect the heterogeneity of geological conditions inside one geo zone, Tomsk oblast' in Russia was chosen for the case study. The method is based on indicators that are customized for each area without reference to a specific territory. Tomsk oblast' is used as an example of the current application case.

The region is an area with complex environmental conditions. It includes natural anomalies. There are manifestations of brown coal deposits, more than 100 hydrocarbon deposits and about 18% of Russian peat reserves (Arbuzov et al. 1999; Arbuzov and Ershov 2007). The main oil and gas districts of the region are Aleksandrovsky, Kargasoksky, and Parabelsky. There are also mineral ore deposits: iron ore Bakcharsky deposit (Nikolaeva 1967); zircon-ilmenite deposits (Rikhvanov et al. 2001) bauxite, zinc, gold, antimony, uranium, and many more (Evseeva 2001).

At the same time, the research results of A.M. Mezhibor (Mezhibor 2009) showed that the accumulation of elements in peat is influenced not only by natural factors but also by the impact of technogenic factors (Baranovskaya, 2011). The infrastructure of the Tomsk region is formed by more than 200 large and medium-sized industrial enterprises. The main sources of large-scale pollution in the Tomsk region are the Tomsk Petrochemical Plant (the largest in the Russian Federation), the Siberian Chemical Plant (in Russian SKHK), agro-industrial complexes (Mezheninovskaya, Tuganskaya, Tomsk pig farms), as well as industrial landfills and household waste (Krivov et al. 2019) ash dumps, quarries, treatment facilities, and others. Tomsk oblast' includes urbanized regions with high population density and sparsely inhabited zones.

The proposed approach is applicable for the further investigations with no direct connection with the research area.

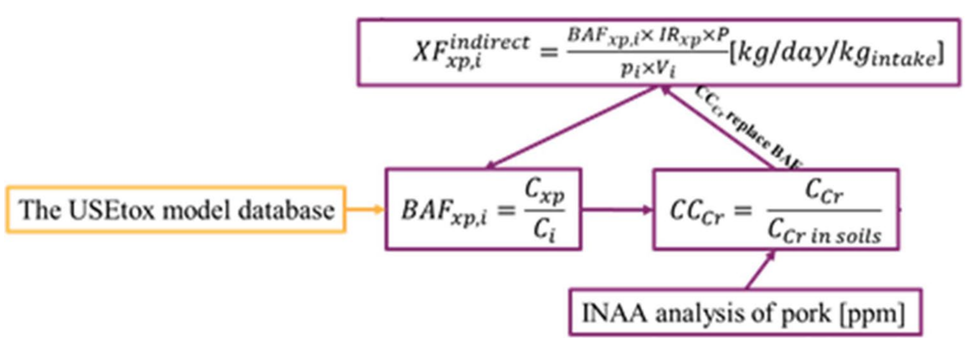



**Fig. 1** The indirect exposure factor calculation (Fantke et al. 2017) and modification, (Belyanovskaya et al. 2019, 2020). $XF_{indirect\ xp,i}$, exposure factor; $BAF_{xp,i}$, bioaccumulation factor; IR, individual ingestion rate of a food substrate corresponding to exposure pathway xp; P, population head count; $p_i$, bulk density of medium i [$kg_i/m_i^3$], $V_i$, volume of medium i linked to the exposure pathway xp $BAF_{xp,i}$, bioaccumulation factor; $C_{xp}$, concentration of an element in the food substrate corresponding to the xp exposure pathway; $C_i$, concentration in the environment (soil, air); $CC_{Cr}$, concentration coefficient; $C_{C\ r}$, concentration of Cr ($C_{Cr}$) [$mg/kg_{xp}$] in pork meat (according to the results of chemical analysis); $CC_{Cr\ in\ soils}$, average concentration of Cr in soils; INAA, instrumental neutron activation analysis

The analytical data depend on the local conditions of the environment and the type of the chemical analysis. Different chemical analysis can provide a wide range of chemical elements in the natural environments under study. Geographical indicators such as population density and area size are available for each area.

The available analytical data allows us to characterize the degree of impact on human health, combining different methods of assessing the ecological condition of urban areas (Bratec et al. 2019): (1) geological approach and (2) impact assessment, which reflects the novel character of the study.

## Study area

Tomsk oblast' is a region of the Russian Federation with a total area of 316.9 thousand km$^2$, located in the southeastern part of the Western-Siberian Plain on both sides of the Ob River (The official internet portal of the Administration of the Tomsk region, https://tomsk.gov.ru/). The climate is strong continental with a prevalent South-West wind destination (Fig. 2). The region includes a large sparsely inhabited area with non-developed infrastructure (e.g. the northern part). The southern part (Tomsk region - N 14, Shegarsky region – N 16, Kozhevnikovsky region N 7 in Fig. 2) of Tomsk oblast' is an industrial center where the bulk of the population lives.

There are 6 types of soil in the Tomsk region. The North and Northeast of the region are composed of podzolic and boggy soils. West and southeast are represented by sod-podzolic and swampy soils. The southern part of the region is formed by grey forest and chernozem soils. Floodplain soils form the area around the Ob, Chulym, and Tom rivers (Soil map of the Tomsk region, 1989).

Studies showed that the territory of Tomsk oblast' is characterized by significant geochemical heterogeneity due to both natural and technogenic factors (Rikhvanov et al. 2006; Rikhvanov et al. 2011). Another factor influencing the potential accumulation of chemical elements is cross-border transport carried by a dense river flows located in the region. Water masses move from the south to the north. Transit flow from the Kemerovo region (the rivers Tom, Yaya, and Kiya) and the Krasnoyarsk Territory (Chulym, the upper Keti, Cheti, and Tyma) make up 50% of the water flow.

This heterogeneity contributes to the accumulation of chemical elements by organisms living in this territory.

The investigation combines two environmental impact assessment approaches for spatial orientation: administrative units of Tomsk region and watershed areas. An interfluve area is the territory situated between streams of rivers. These two types of spatial differentiation can be equally used in the impact assessment investigations. Administrative areas reflect the dominative type of industries developed in each district, meanwhile the interfluvial areas are comparable with soil types and geology. In addition, all the settlements of Tomsk oblast' are situated along rivers.

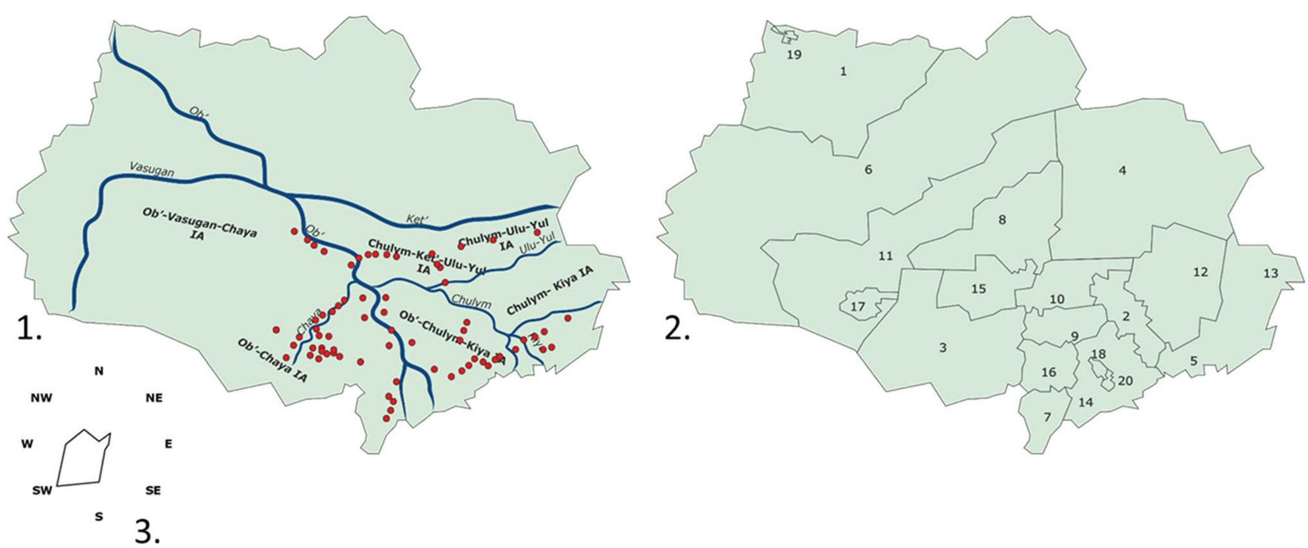



**Fig. 2** The map of Tomsk oblast' with interfluve areas (1), administrative map (2), and wind destination (3) ("Archive of weather in Tomsk," 2020) Note: Districts: 1. Aleksandrovsky; 2. Asinovsky; 3. Bakcharsky; 4. Verkhneketsky; 5. Zyryansky; 6. Kargasoksky; 7. Kozhevnikovsky; 8. Kolpashevsky; 9. Krivosheinsky; 10. Molchanovsky; 11. Parabelsky; 12. Pervomaisky; 13. Teguldetsky; 14. Tomsky; 15. Chainsky; 16. Shegarsky; 17. Kedrovy; 18. Closed city Seversk; 19. Strezhevoy city; 20. Tomsk city Map 1: red points, sampling points; blue lines, river flows; map 2: administrative regions; 3: wind destination of the Tomsk oblast'

## Material and methods

### Soil sampling

Soil sampling was carried out in the last decade of April — the first 10 days of May, by the "envelope" method of five points, the depth of which was about 10 cm, i.e., the upper fertile layer. During the sampling, the presence or absence of organic fertilizer use was registered. Spot samples taken at the same sampling site were combined, thereby achieving their mixing and homogenization. Sample preparation included preliminary drying of the soil, removal of foreign matter. The dataset includes a total of 189 samples of soils of Tomsk oblast'.

For the investigation, the settlements of the Tomsk region located within the interfluve of the Ob River and its large tributaries are considered. There are 6 inter-stream areas in Tomsk oblast' and 47 settlements are included in the research area.

In the following table, the list of the districts included in the interfluves is given, information about the number of settlements in each administrative district is given in the annex (Table 1).

As can be seen from Table 1, some interfluve areas include settlements included administratively in the same district, others overlap administrative districts. We exclude the double-counting of the same districts by using the concentration of Cr from different villages.

### Meat sampling

The sampling was carried out by the researchers from the Division for Geology of Tomsk Polytechnic University. The total quantity of samples is 78 samples of organs and tissues of 2 animals. Organs and tissues of 2 domestic pigs *Sus scrofa domesticus* were taken from private farms in Tomsk region of Tomsk oblast' (Russia).

The samples of organs and tissues of the domestic pig represent the whole organism of the animal and all parts that can be consumed as food. The food samples were taken on private farms, raising animals for sale to the native population in the local markets.

The representability of biomaterials of domestic pigs as a sufficient environmental indicator was already presented in a previous investigation by the research group of Tomsk Polytechnic University (Baranovskaya and Rikhvanov, 2011; Belyanovskaya et al. 2019). Results of the chemical analysis are presented in the corresponding table, under the 'Annex' section (Annex, Table 2).

## Sample preparation and analysis

Soil and pork samples were analyzed by Instrumental Neutron Activation Analysis (INAA). The INAA analysis has an advantage as a direct non-destructive analysis without chemical decomposition of samples. In the published papers, the accuracy of the analysis is proven (Arbuzov et al. 2016, 2019; Arbuzov 2017).

Sample preparation for the INAA takes place in several stages: a package of aluminum foil (size 3 cm x 3 cm), its pretreatment with an alcohol, a bag formation with tweezers, then weighing the foil bag (mg) on an electronic balance. A sample code is affixed to the bag, the sample is poured into bags on electronic scales to determine the weight of the sample (ideally 100 mg) and the total weight.

The analysis of the samples is carried out at the "IRT-T" research nuclear reactor in the nuclear geochemical laboratory of the Division for Geology of the National Research Tomsk Polytechnic University (accreditation certificate RA.RU.21AB27 of 04/08/2015). Analysis was carried out by A.F. Sudyko and L.F. Bogutskaya according to the instructions of NSAM VIMS No. 410-YAF.

The thermal neutron flux density in the irradiation channel is $2*10^{13}$ neutrons ($cm^2*s$), and the duration of sample irradiation is 20 hours. The measurements were carried out on a gamma spectrometer with a germanium-lithium detector DGDK-63A. The detection limit of Cr in soils by the INAA is 0.2 ppm.

**Table 1** The list of regions settled in each interfluve area

| | Interfluve area | Districts of Tomsk oblast | N |
|---|---|---|---|
| 1 | Vasyugan-Chaya | Bakcharsky, Kolpashevsky, Parabelsky | 4 |
| 2 | Ob'-Chaya | Bakcharsky, Kozhevnikovsky, Molchanovsky, Chainsky, Shegarsky | 31 |
| 3 | Chulym-Ulu-Yul | Pervomaisky | 1 |
| 4 | Chulym-Ket'-Ulu-Yul | Verhneketsky, Kolpashevsky, Molchanovsky | 12 |
| 5 | Ob'-Chulym-Kiya | Zuryansky, Asinovsky, Tomsky | 11 |
| 6 | Chulym-Kiya | Zuryansky, Teguldetsky | 10 |

*N*, the total number of settlements included in the interfluve area

## Calculation

Processing and generalization of the obtained analytical data was carried out on a personal computer using the office suite Microsoft Office (Excel, Word 2013) and the program "Statistica 7". To build the graphic material, the software "Surfer 10" and "CorelDraw" were used. Samples were organized for Tomsk oblast', using both the administrative approach of spatial recognition and by considering the divisions according to the interfluve areas to which they belong.

### The statistical analysis

Statistical processing of data (with a reliability level of 95%) is carried out.

When calculating the average contents of elements from the total sample, "hurricane samples" were removed, but they are shown in the scatter of values. When some elements were present in concentrations below the detection limit of the analysis, half of the threshold value is used in the calculation (Mikhalchuk and IAzikov 2014). Regardless of the nature of the distribution of elements, we took the arithmetic mean values of the sample as average levels of content, which, with both normal and asymmetric distribution, gives the most consistent estimate of the concentration values (Tkachev and IUdovich 1975).

The significance of the differences in the sample sets is estimated using the Kolmogorov-Smirnov statistical nonparametric analysis method. The differences were considered significant at a $p$-level $p < 0.001$.

### Methodology for assessing the toxicity of elements

The basics of the USEtox model developed on the Microsoft Excel platform (Fig. 1, Annex).

According to the USEtox, Impact Score ($IS_{hum}$) (Fig. 3, formula I) is a LCIA impact score used for characterizing human toxicity that is expressed as a number of cancer or non-cancer disease cases at midpoint level and as a number of disability-adjusted life years [DALY] at endpoint level (Fantke et al. 2017).

Midpoint indicators focus on single environmental problems in the case-effect chain, endpoint indicators show the environmental impact on higher aggregation levels (Bare et al. 2000; Huijbregts et al. 2016).

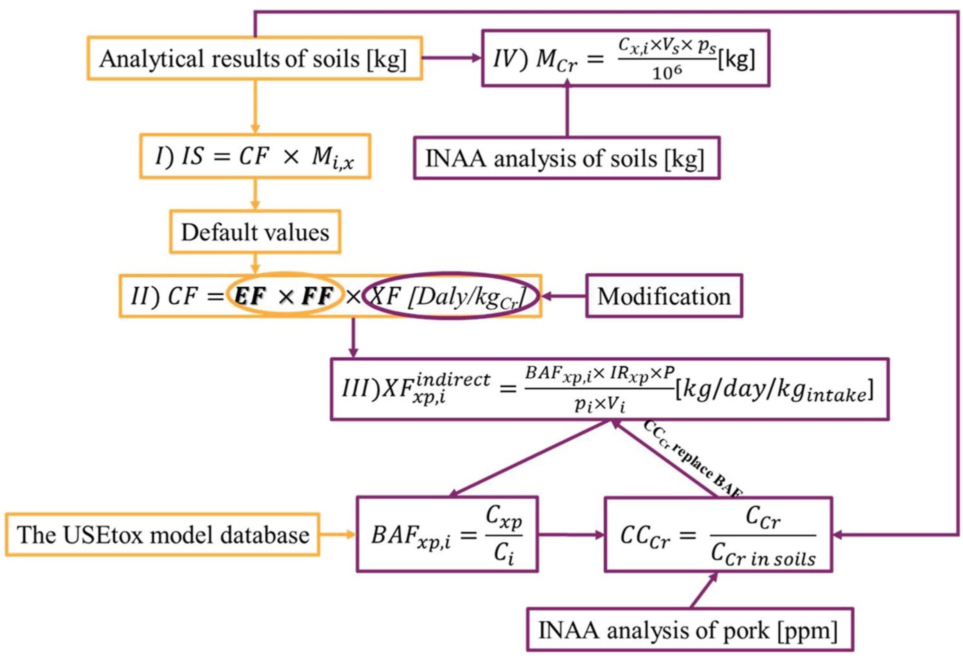



**Fig. 3** The framework of the investigation, according to (Fantke et al. 2017; Belyanovskaya et al. 2019; Bratec et al. 2019). Roman numbers on the figure refer to formulas. (I) IS, impact score; CF, characterization factor, $M_{i,x}$, the total mass of the element. (II) CF, characterization factor; EF, effect factor; XF, exposure factor. (III) $XF_{indirect\ xp,i}$, exposure factor; $BAF_{xp,i}$, bioaccumulation factor; IR, individual ingestion rate of a food substrate corresponding to exposure pathway xp; 4) P, population head count; 4) $p_i$, bulk density of medium i [$kg_i/m_i^3$], $V_i$, volume of medium i linked to the exposure pathway xp; 5) $BAF_{xp,i}$, bioaccumulation factor; 6) $C_{xp}$, concentration of an element in the food substrate corresponding to the xp exposure pathway; 7) $C_i$, concentration in the environment (soil, air); 8) $CC_{Cr}$, concentration coefficient; 9) $C_{C r}$, concentration of Cr ($C_{Cr}$) [mg/$kg_{xp}$] in pork meat (according to the results of chemical analysis); 10) $CC_{Cr\ in\ soils}$, average concentration of Cr in soils. (IV) $M_{Cr}$, total mass of the element; $C_{x,i}$, Cr concentration in agricultural soils; $V_s$, soils volume; 4) $p_s$, bulk density of soils [$kg_i/m_i^3$]

The $IS_{hum}$ for potential impacts of Cr is calculated using a weighted summation of pollutants released from potential pollution sources and characterization factors for the damage (Fig. 3, formula I). The characterization factor needed for the impact score calculation was derived using the USEtox model dataset.

For the modification of the characterization factor and the Impact score, two types of local samples are used.

1) Tomsk oblast' soils. These are used for the characterization factors and the impact score calculation and modification (Fig. 3, formulas I, II);
2) Pork sampled in two settlements of Tomsk oblast'. This data is extrapolated into the exposure factor modification (Fig. 3, formula III).

The total mass of the element in soils ($M_{Cr}$) is calculated according to the formula developed by (Bratec et al. 2019) (Fig. 3, formula IV).

Where:

- $C_{x,i}$ is the concentration of Cr in agricultural soils in each studied area. $C_{x,i}$ is taken from the own analytical results;
- $p_s$ is the bulk density of soils, which is the table value taken from the USEtox documentation [$kg_{soil}/m^3{}_{soil}$];
- $V_s$ is the volume of soils of each considered region [$m^3$].

The characterization factor (CF) is calculated by USEtox documentation. Characterization factor for the potential human health damages at the endpoint is expressed in DALY/kg $_{emitted}$ – disability adjusted years per kg $_{emitted}$. The CF is derived as the multiplication of three factors:

Effect factor (EF) [$kg_{intake}$/day] reflects the impact on human health due to the arrival of a chemical element substance in the living organism in various ways (through air, water, soil, or food).

Fate factor (FF) [$kg_{in\ compartment}$ per $kg_{emitted}$/day] represents the persistence of a chemical in the environment (e.g., in days) as well as the relative distribution.

Exposure factor (XF) [$kg_{intake}$/day per $kg_{in\ compartment}$] describes the effective human intake of a specific environmental medium– soil – through ingestion.

In the current investigation, we use the default values of effect and fate factors, but with the modification of exposure factor using the analytical data of the concentration of Cr in the pork meat (Belyanovskaya et al. 2019). This reflects the effective intake of elements via soil or air into the human body when eating meat products.

The exposure factor is calculated according to the formula given in the framework of the investigation (Fig. 3, formula 5), where the bulk density ($p_i$) of the soils and the individual consumption rate (IR) are tabular values and are taken from the model for calculation. The volume of soils ($V_i$ [$m^3$]) is calculated by the following formula:

$$V_i = h_i\ [m] \times S_i\ \left[m^2\right]$$

Formula 1: The volume of medium *i* calculation. Where, $h_i$ [m] is the height of medium i (continental and global air, or soil), the table value presented in the model, and $S_i$ [$m^2$] is the area of agricultural soils, depending on the geographical features of the studied region.

In order to take into account the environmental features of the region, the bio-transfer factor (BTF) is replaced by the ratio of the concentration of Cr ($C_{Cr}$) [$mg/kg_{xp}$] in pork (according to the results of chemical analysis), and the concentration of Cr in soils of each studied region (Fig. 3, formula 6) [mg/kg]. Where, the bio-transfer factor BTF [days/$kg_{substrate}$] is the steady-state ratio between the concentration $C_{substrate}$ in meat or milk respectively and the intake *i* of a chemical (Cr) by the animal.

In previous investigations, the concentration ratio was normalized to the percent abundance (Glazovsky clarke of Cr in biosphere (Glazovsky 1982)). In the current investigation, the Cr concentration in soils is taken for the ratio.

Official data is used for the total square footage and population calculation of the administrative areas and interfluves (2020). The area between the biggest rivers of Tomsk oblast, forming the interfluves, is used for the square footage calculation. The geographical information obtained is given in the annex section.

## Results

### Statistical analysis results

Results of statistical analysis demonstrate abnormal distribution of Cr concentration in soils of Tomsk oblast, according to the variation coefficient (V) (Table 2), where V=70%. In most samples, Cr concentration ranges from 65 to 116 ppm.

The literature analysis shows that the average concentration of Cr in Tomsk region topsoil is above most of the literature values (Fig. 4).

The database was divided into groups — interstream areas. The maximum values of Cr content are detected in the soils of (the Southeast part of Tomsk oblast) — the Chulym-Kiya interfluve area (Table 3, Fig. 5). The Chulym-Ulu-Yul interfluve is highlighted as an area with the lowest Cr content. However, it can be noted, that only one settlement and 5 samples from these zones were studied. Topsoil of the South-West part of Tomsk oblast' (Ob'-Vasugan-Chaya and Ob'Chaya interfluve zones) also contains low Cr concentrations.

**Table 2** The statistical parameters of chromium concentrations in soils of Tomsk oblast

| Cr total | Mean | St. error | Median | Mode | St. dev. | Min | Max | V | N |
|---|---|---|---|---|---|---|---|---|---|
| | 119 | 6 | 98 | 94 | 84 | 13 | 618 | 70 | 189 |

*mean*, arithmetical mean [ppm]; *St. error*, standard error of the arithmetical mean; *St. dev.*, standard deviation of the arithmetical mean; *min*, minimum value [ppm]; *max*, maximum value [ppm]; *V*, variation coefficient, [%]; *N*, total number of samples

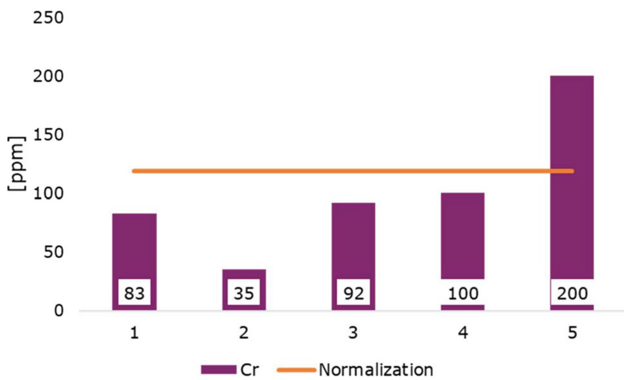



**Fig. 4** Diagram of Cr distribution in soils of Tomsk oblast, 189 samples in total, [ppm]. Note: 1. Lithosphere Clarke (Vinogradov 1962); 2. Lithosphere clarke (Taylor and McLennan 1985); 3. Lithosphere Clarke (Grigorev 2009); 4. World soils (Bowen 1979) 5. World soils, (Vinogradov 1957); Normalization is analytically obtained data

Using ranges of chemical elements, we can see that in the southeast side of Tomsk oblast, soils concentrate more Cr than samples taken in the south-western part.

Soils taken in the southern part of Tomsk oblast' accumulate more Cr than in the northern part of the oblast.

However, the maximum total concentration coefficient of chemical elements in soils is observed in samples of areas around the Ob' river and the Chulym-Ulu-Yul interstream area. Besides Cr, there is intensive accumulation of other heavy metals (As, Fe, Co), radioactive elements (U), rare earth elements (Lu, Yb, La, Ce, Eu), noble-metals (Ag, Au), and Sb, Sr, Br (Table 4).

Accumulation of elements forming significant correlations with Cr, whose accumulation is noted in most of the regions studied (Table 5). The elements having the strong positive correlation with Cr are accumulating in soils as well, and their potential toxicity should be considered for the impact assessment.

Comparative analysis of correlations between chemical elements allows the differences between elemental interactions in soils from areas around different rivers to be clearly seen. Cr forms positive and negative correlations with heavy metals whose toxicity is underestimated (Sb, Ba). In soils taken from the southeast side of Tomsk oblast, rare earth

**Table 3** The statistical parameters of the chromium concentration in soils sampled in interfluve areas of Tomsk oblast'

| Interfluve areas | S | Mean | SE | Me | Mo | SD | Min | Max | V | N |
|---|---|---|---|---|---|---|---|---|---|---|
| Chulym-Kiya | 6608 | 219 | 27 | 190 | N/d | 144 | 14 | 619 | 66 | 29 |
| Ob'-Vasyugan-Chaya | 88780 | 94 | 9 | 93 | N/d | 27 | 51 | 144 | 28 | 8 |
| Ob'-Chaya | 26141 | 97 | 4 | 97 | 108 | 35 | 38 | 173 | 36 | 62 |
| Chulym-Ulu-Yul | 24391 | 33 | 5 | 37 | N/d | 11 | 21 | 44 | 34 | 5 |
| Chulym-Ket'-Ulu-Yul | 24391 | 137 | 14 | 129 | N/d | 64 | 42 | 298 | 47 | 20 |
| Ob'-Chulym-Kiya | 20327 | 99 | 7 | 89 | N/d | 53 | 14 | 619 | 62 | 65 |

*S*, square footage [km$^2$]; *mean*, arithmetical mean [ppm], *SE*, standard error, *Me*, median, *Mo*, mode, *SD*, standard deviation, *min*, the minimum value [ppm], *max*, the maximum value [ppm], *V*, coefficient of variation [%], *N*, the number of samples, *N/d*, no data

**Fig. 5** The distribution of Cr in soils sampled at the interfluve areas of Tomsk oblast, [ppm]

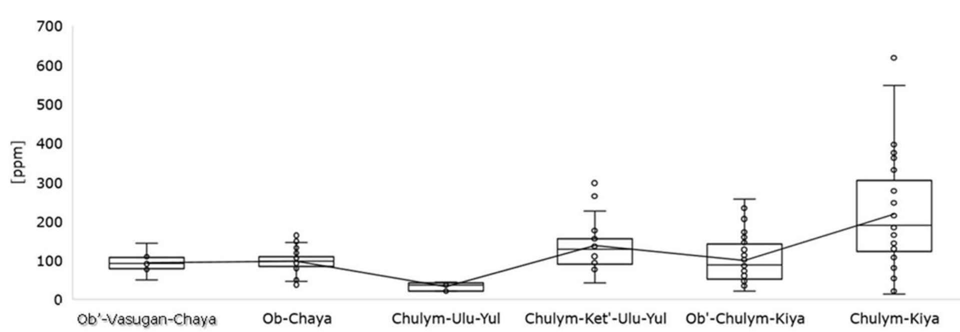


**Table 4** The values of the concentration coefficients of chemical elements relative to the average content of elements in the sample

| Interfluve area | Chemical elements | $\sum CC>1$ |
|---|---|---|
| Chulym-Kiya | $As_{1.4}$-$\mathbf{Cr_{1.2}}$=Au-$Ca_{1.1}$-$Na_1$=Fe=Sb=Yb=Lu=U=Ba=Sr | 12.9 |
| Ob'-Chulym-Kiya | $Au_{1.2}$-$Sb_1$=Lu=Fe=Sc=Ba=U=Yb=Na=La=**Cr**=Ca=Rb | 12.2 |
| Chulym-Ket'-Ulu-Yul | $Sr_{1.6}$=Ag-$Hf_{1.2}$-$Na_{1.1}$=Ba-$\mathbf{Cr_1}$ | 7.6 |
| Ob-Chaya | $Br_{1.7}$-$Ta_{1.5}$-$Co_{1.3}$=Th=Cs-$Sc_{1.2}$=Fe=Rb=La=Ce=Sm=Tb=Eu-$Ag_{1.1}$=Yb=Lu=U=Hf-$Na_1$=Sb=Ba=Sr…-$\mathbf{Cr_{0.8}}$ | 15.5 |
| Ob'-Vasugan-Chaya | $Ag_{1.8}$-$Hf_{1.6}$-$Eu_{1.4}$-$Na_{1.2}$=Br=Ce=Th=Ba=Cs=Sc=Fe=Co=Sm=Tb-$La_1$=U=Sr=Ta…-$\mathbf{Cr_{0.8}}$ | 15.3 |
| Chulym-Ulu-Yul | $Sr_{2.2}$-$As_{2.1}$-$Ca_2$-$Rb_{1.7}$-$Sb_{1.6}$-Lu-$Au_{1.5}$-$Na_{1.4}$-$Yb_{1.3}$=Ba=Tb=Ta-$U_{1.2}$-$La_1$=Sm=Hf…-$\mathbf{Cr_{0.3}}$ | 19.3 |

$\sum CC>1$, the sum of the concentration coefficient exceeding 1

**Table 5** Correlation interactions in soils sampled in Tomsk oblast according to the Spearman method, $p_{0.05}$

| N | Interfluve area | Correlation with Cr | |
|---|---|---|---|
| | | Positive correlation | Negative correlation |
| 1 | Chulym-Kiya | - | Br, Eu |
| 2 | Ob'-Chulym-Kiya | Ba, Eu, As | Na, Ca, Rb, Br, Sm, Yb, Lu, U, Au, Sr |
| 3 | Chulym-Ket'-Ulu-Yul | Sr | Au |
| 4 | Ob-Chaya | Ce, Ba, Tb, Eu, As | - |
| 5 | Ob'-Vasugan-Chaya | Sb, Au | |
| 6 | Chulym-Ulu-Yul | Tb | |

*r*, critical value of the Pearson correlation

elements, Au, Ba, As, and Sb create a significant positive correlation with Cr.

The graphical interpretation as distribution map is the common approach to estimate the potential sources of the heavy metals and soil qualities (Duan et al. 2020; Fathizad et al. 2020; Zhang et al. 2021). The Cr distribution in soils of Tomsk oblast' (Fig. 6) allows us to see the spatial distribution. We can observe the main halo of the Cr accumulation in the southeastern part of the oblast around the Ulu-Yul, Chulym and Kiya rivers. The area with the highest concentrations of Cr is a border area with Kemerovsky oblast.

Areas of elevated Cr concentration cross four border districts of Tomsk oblast': Pervomaisky, Teguldetsky,

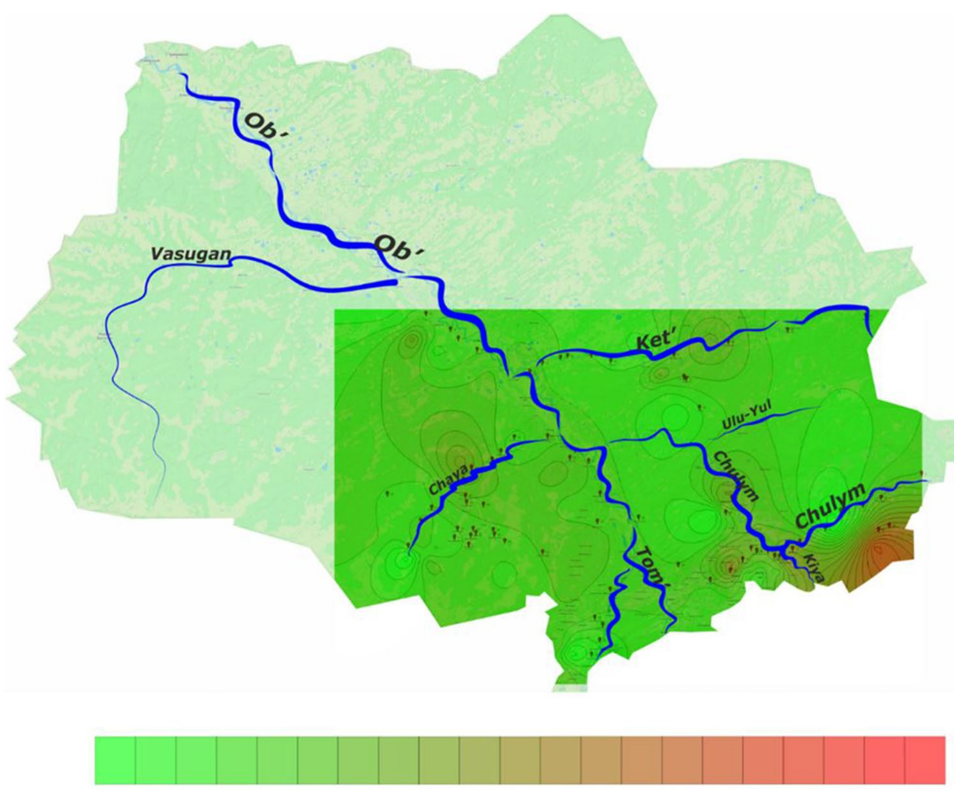



**Fig. 6** Map of the total concentration of Cr in the territory of Tomsk oblast, [ppm], scale 10 to 1

Asinovsky, and Zuryansky. Soils sampled from the northern part of Tomsk oblast' contain lower concentrations of Cr, but with some exceptions. There are halos with medium concentrations of Cr in agricultural soils above the Ket' river divided between Verkhneketsky, Kolpahsevsky, and Parabelsky distrticts.

Points of high Cr concentration are situated on the border areas between different administrative units with no connection with internal division of Tomsk oblast, which confirms the advantages of using the interfluve spatial organization of the research.

Comparing the distribution of Cr in soils according to the administrative divisions of Tomsk oblast', a certain heterogeneity of concentration is also seen (Fig. 7).

The central part of Tomsk oblast', Bakcharsky, Krivosheinsky, and Shegarsky districts are the areas where the lowest variation coefficient is observed. The biggest variation in the dataset is found in the Teguldetsky district.

As discussed before, the heterogeneity of given results is probably connected with the mixed environmental condition of the region, caused by the mix of anthropogenic influence and natural conditions.

## The human health characterization factor the Impact score assessment

The results of our studies show that soils of Tomsk oblast' accumulate a significant number of elements, including toxic and conditionally toxic ones, such as Cr, in the impact area, which poses a potential threat to human health. In this regard, it is necessary to assess the toxicity of individual elements for the human body.

The modified characterization factor varies significantly between different interfluve areas (Fig. 8). The sequence of the factor does not correlate with the value of the Cr concentration in soils. Investigated zones are ranged in the following order according to the value of the human health CF: Chulym-Ulu-Yul> Ob'- Chaya> Ob'-Chulym - Kiya> Chulym-Ket'-Ulu-Yul> Chulym-Kiya> Ob'-Vasugan-Chaya.

The modified human health characterization factors for Cr vary from the CF proposed by the USEtox model. However, for the soils of the Ob'-Chulym-Kiya and Ob'-Chaya interfluve areas, the values of modified human health CF are close to the default characterization factor.

The human health impact score was calculated using the modified and default characterization factors (Fig. 9).

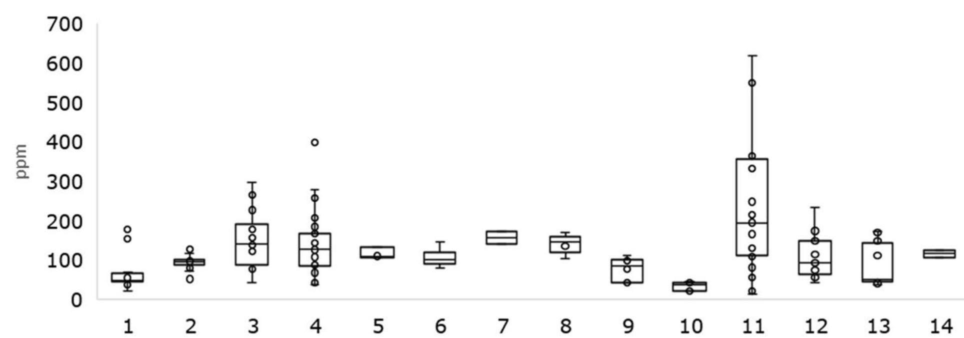



**Fig. 7** The distribution of Cr in soils according to the administrative divisions of Tomsk oblast', [ppm]. Districts: 1. Asinovsky region, 2. Bakcharsky, 3. Verkhneketsky, 4. Zyryansky, 5. Kozhevnikovsky, 6. Kolpashevsky, 7. Krivosheinsky, 8. Molchanovsky, 9. Parabelsky, 10. Pervomaisky, 11. Teguldetsky, 12. Tomsky, 13. Chainsky, 14. Shegarsky

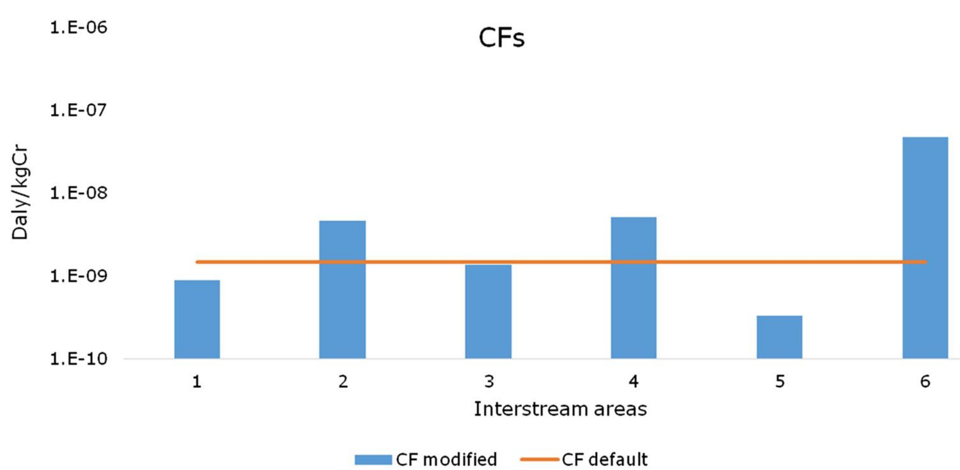
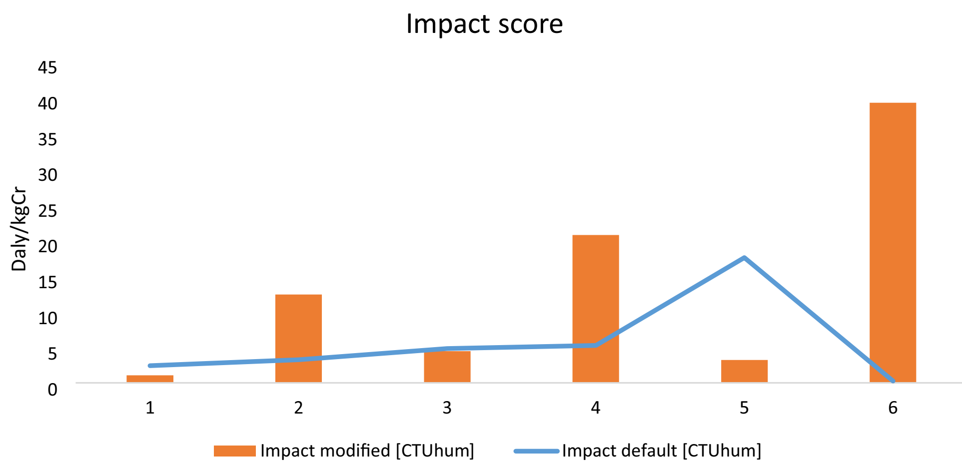



**Fig. 8** The human health characterization factors - $CF_{hum}$ (modified and default) of Cr in interfluve areas, soils [Daly/$kg_{Cr}$]. $CF_{hum}$ default is the table value provided in the USEtox model. 1. Chulym-Kiya, 2. Ob'-Chulym-Kiya; 3. Chulym-Ket'-Ulu-Yul; 4. Ob'-Chaya; 5. Ob'-Vasyugan-Chaya; 6. Chulym-Ulu-Yul

Fig. 9 The human health impact score modified and default of Cr in interfluve areas, [Daly/kg$_{Cr}$], Lg scale. 1. Chulym-Kiya, 2. Ob'-Chulym-Kiya; 3. Chulym-Ket'-Ulu-Yul; 4. Ob'-Chaya; 5. Ob'-Vasyugan-Chaya; 6. Chulym-Ulu-Yul




We can see that the Chulym-Ulu-Yul interfluve area has the highest Impact score among all studied districts of Tomsk oblast. The impact score value is determined by the concentration of Cr in soils. The source of soil pollution in settlements below the Chulym river is situated in the south-eastern part of Tomsk oblast.

The impact score calculated with the modified characterization factor is also higher than the default value. Significant variation between default and modified results is observed for the Ob'-Vasyugan-Chaya and Chulym-Ulu-Yul interfluve areas. These zones are characterized by the high heterogeneity of the population density. We can assume that the USEtox model underestimates the value of the characterization factors for big, sparsely inhabited areas.

Considering the limitation of the square footage of each interfluve determination, the calculation of CF and IS according to administrative divisions was performed (Figs 11 and 12). The population density of studied areas is available in the official governmental sources.

To simplify the reading of the resulting charts, we repeat the map of Tomsk oblast' (Fig. 10).

Making a comparison between the values of the characterization factors (Fig. 11) calculated for the same region, but on the basis of administrative spatial divisions, we can observe that for Tomsky (Ob'-Chulym-Kiya interfluve) and Verkhneketsky (Chulym-Ket'-Ulu-Yul) regions modified factors are lower than default data. Other modified values are higher.

The similar trend is observed for the impact score calculation, but for Tomsky and Pervomaisky districts (Fig. 12). These zones are situated in the eastern part of the Tomsk oblast around the Ob' and the Chulym rivers.

Proving that the administrative divisions-oriented approach to the impact assessment is too generic, we can make a conclusion. In the resulting map (Fig. 6), we see that only some parts of the regions have soils with a high concentration of Cr. Similar environmental conditions are artificially divided into 4 zones. This division affects the conclusions about the state of the environment in the whole district.

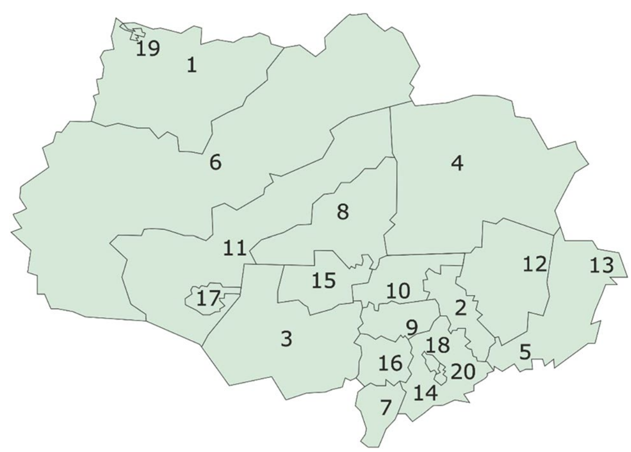



Fig. 10 The administrative map of Tomsk oblast'. Districts : 1. Aleksandrovsky; 2. Asinovsky; 3. Bakcharsky; 4. Verkhneketsky; 5. Zyryansky; 6. Kargasoksky; 7. Kozhevnikovsky; 8. Kolpashevsky; 9. Krivosheinsky; 10. Molchanovsky; 11. Parabelsky; 12. Pervomaisky; 13. Teguldetsky; 14. Tomsky; 15. Chainsky; 16. Shegarsky; 17. Kedrovy; 18. Closed city Seversk; 19. Strezhevoy city; 20. Tomsk city

## Discussions

There are plenty of factors affecting Cr as a heavy metal concentration in soils, such as use of fertilizers, atmospheric deposition, industrial emissions, and soil parent materials (Ke et al. 2017; Lv and Wang 2018; Hedberg et al. 2019).

In the current application case, we can highlight two factors as well:

1. Man-made sources. Anthropogenic sources of Cr pollution are situated mainly in the south of Tomsk oblast'– Tomsk region. Soils of the Tomsk region, as a zone of increased technogenesis, have been studied in the most detail (Zhornyak 2009). The average Cr content of

Fig. 11 The human health characterization factors - $CF_{hum}$ (modified and default) of Cr in in areas of Tomsk oblast', soils [Daly/$kg_{Cr}$], Lg scale. Lg, logarithmic scale. 1. Asinovsky; 2. Bakcharsky; 3. Verkhneketsky; 4. Zyryansky; 5. Kozhevnikovsky; 6. Kolpashevsky; 7. Krivosheinsky; 8. Molchanovsky; 9. Parabelsy; 10. Pervomaisky; 11. Teguldetsky; 12. Tomsky; 13. Chainsky; 14. Shegarsky

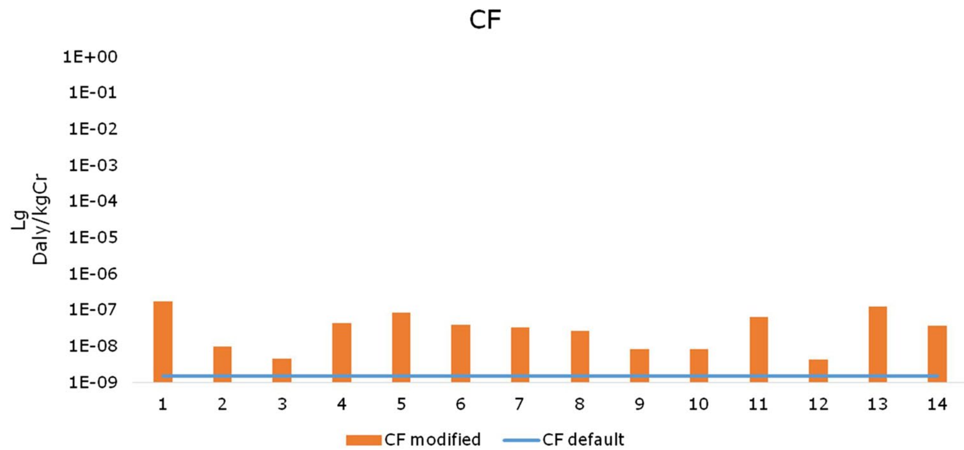
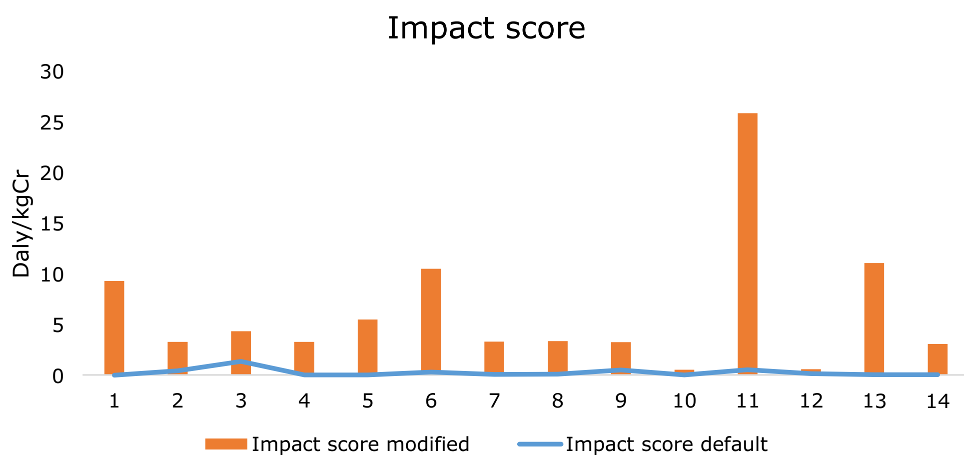



Fig. 12 The human health impact score (modified and default) of Cr in areas of Tomsk oblast', [Daly/$kg_{Cr}$]. 1. Asinovsky; 2. Bakcharsky; 3. Verkhneketsky; 4. Zyryansky; 5. Kozhevnikovsky; 6. Kolpashevsky; 7. Krivosheinsky; 8. Molchanovsky; 9. Parabelsy; 10. Pervomaisky; 11. Teguldetsky; 12. Tomsky; 13. Chainsky; 14. Shegarsky




Tomsk city soils is 104 ppm (Zhornyak 2009), the own results is 1.1 times higher. Also comparing analytical results with abundance ratios of Cr in lithosphere, we established a high level of Cr cumulation in the studied topsoil. The south-eastern halos of the concentration have also probably an anthropogenic nature. We can assume that the most polluted point in the border area with Kemerovo oblast could relate to the wind transfer of pollutant from the opencast coal mines (Arbuzov 2017) situated in the area to the south ("Weather archive in Kemerovo for months and seasons," 2020).

2. Natural sources. There are several geological factors of Cr accumulation to be noted. According to V. Goldshmidt, Cr is correlated with Fe in geochemical processes in the environment (Goldshmidt 1952). Halos of Cr concentration in the left bank of Ob' river reflect the bedding of the iron-ore assets. The south of Tomsk oblast' is formed with the Tom'- Koluvan' bow area, where magma is not covered with the platform mantle and can be a source of Cr in soils (Milanovskii 1996). As the content of clay minerals and organic matter increases in the southern part of Tomsk oblast', the content of heavy metals in the soil increases (Tu et al. 2011; Jia et al. 2020; Qu et al. 2020). Research on the heavy metal content of forage fodder and topsoil of the southwest part of Tomsk region demonstrated low accumulations of heavy metals in grey forest soils (Nikolaeva 2020).

The results show the trend of the Cr accumulation in all parts of the studied region. Gross concentrations of elements in soils do not express the level of the impact on the public health. Although soils are a critical repository for numerous deleterious pollutants (Doyi et al. 2018), which could be transferred to plants, living organisms, and groundwaters (Alloway 2013; Nag et al. 2022). Polluted soils could be the source that poses the greatest threat to human health (Cuajungco and Lees 1998; Bare 2006; Başaran et al. 2012; Brown et al. 2016; Turbinsky and Bortnikova 2018; Wang et al. 2018; Shen et al. 2021). Correlation of Cr content in soils of Tomsk region with prevalence of sarcoidosis is proven (Denisova et al. 2016). Thus, the accumulation of Cr in soils, its monitoring, and mapping has great importance for the human health impact assessment.

Using the LCIA model allows us to evaluate and predict the impact. Analyzing obtained results, we can make several conclusions.

Use of impact assessment models often leads to disparate results, and therefore we observe the contradiction between modified and default factors. The difference between the characteristic factors of the model modified with analytical data and the default results is mentioned in other scientific studies (Adam et al. 2013; Hedberg et al. 2019; Xiao et al. 2020) including our own case studies (Belyanovskaya et al. 2019, 2020).

The obtained results differ from the model data to a greater or lesser extent. However, the impact of analytically obtained local data is undeniable. In this paper, we observe a strong disparity between the characterization coefficients modified with our data and the ones proposed in the default model. The same disparity is observed for the impact score. We assume that this dispersion highlights the contradiction between generosity of the USEtox model dataset and the high specificity of analytically obtained data.

The modified exposure factor provides information about chemical components in food consumed in the region. The possibility that the state of the environment may significantly affect the content of pollutants in meat or dairy products is underestimated in the model. The USEtox includes the different types of meat products depending on such parameters as the level of fat in meat. However, this information is rather generic. The pollutant transfer mechanisms through the trophic chain still needed to be investigated. In the USEtox dataset, the bio-transfer factor expressing the accumulation of the elements does not vary according to the region. Thus, the BTF given for the "Central Asia" region is generic for all areas.

Continental levels of CF of soils given in the USEtox cannot reflect the environmental features of local areas. The values of CFs $_{\text{default}}$ and consequent ISs depend on many parameters like the chemical properties of elements, their effect on human organisms, and geographic features of the region. We see that the population density is the most critical parameter affecting the results. (Annex, Table 8). In this case, using the administratively organized spatial orientation is a better approach, because the square footage and the population is updated every year by the government. At the same time, this type of spatial organization does not reflect the landscape, geology, and ecology of the area. Natural, historically formed, environmental conditions apply to the zones of a given geological formation, with similar geographic conditions and climate. Applying only the administrative approach, the potential toxicity score is artificially divided between regions. In this case study, interfluves represent the naturally made locations.

The current investigation suffers from several limitations of sampling and data processing technique:

I. Limitations in representativeness of the statistical dataset:

1. One settlement from Chulum-Ulu-Yul interfluve area is taken for the investigation (Pervomaisky village);
2. Two soil samples were taken in the Krivosheinsky and Shegarsky districts, and three in Kozhevnikovsky;
3. The indirect exposure factor modification is carried out using analytical data about Cr content in 78 organs and tissues of 2 pigs;

II. Limitations in the indirect exposure factor calculation:

1. The Cr content in the pork taken for the indirect Exposure factor modification is the same for each settlement of Tomsk oblast — it might reduce the accuracy of the local data;
2. There is uncertainty in the interfluve areas square and population density calculations, which are not precisely documented — the population density may differ.

III. Limitations in the human health impact score calculation:

1. For the calculation of the characterization factor, only the non-cancerogenic effect was considered — the human health impact calculation for cancerogenic effect is not covered in the research;
2. Default fate factor and effect factor from the USEtox model documentation are taken for the calculation of the CF -fate factor and effect factors do not describe the local conditions.

## Conclusions

The current research highlights the importance of local information in environmental monitoring and the environmental impact assessment modeling. It is important to note, that the current case study has not directly correlated with the particular area; thus, the approach can be further utilized.

Analysis of Cr in soils enables its calculation in spatial soil distributions. We conclude that the mapping of Cr accumulation halos is an effective tool to divide Tomsk oblast' in particular zones. The efficiency of spatial orientation with interfluves in environmental monitoring is also visible. We see that Cr accumulation ranges follow the river and the wind destination.

Administrative separation inside one region makes a supplementary limitation for pollution monitoring. We recommend keeping to geographical and geological approaches to delimitate the region. Both approaches have certain limitations and advantages, and they are complementary to one another in the impact assessment processes.

However, in the current project, we refer to the naturally recognized locations more, because they properly reflect the geography of the region.

We particularly highlight the importance of the population density values in the characterization factor modification. Population density calculation should be based on the official governmental data, to avoid data inconsistencies. We recommend avoiding a comparison between urbanized areas with a high population density and the countryside with low-populated settlements.

Future perspectives of the work include the development of the database of the impact score of Tomsk oblast' with other mediums such as water and air. To improve the representativeness of the statistical dataset, more sampling data should be proceeded. Otherwise, outlier grades may affect the results. Using the outliers leads to the underestimation of the environmental monitoring. The capability of the neutron activation analysis allows the other non-organics from the USEtox model dataset (Zn, Ba, As, Sb) to be measured. We consider the ISs and CFs modification for four additional pollutants for our future research. The studied area can be also regionalized according to the concentration of other pollutants, and the value of their ISs and CFs.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s11356-022-21784-9.

**Author contribution** Alexandra I. Belyanovskaya: Conceptualization, Data curation, Writing - original draft, Formal analysis.
Bulat R. Soktoev: Writing - original draft, Formal analysis.
Bertrand Laratte: Conceptualization, Supervision, Methodology.
Elena V. Ageeva: Writing - original draft, Formal analysis.
Natalia V. Baranovskaya: Conceptualization, Supervision.
Natalia P. Korogod: Conceptualization.

**Funding** The statistical data processing is supported by State program RF «Science». Project FSWW-0022-2020. The impact assessment with the USEtox model is supported by the RSF grant (N 20-64-47021). The mapping of Cr spatial distribution was carried out within the framework of a grant from the Russian Science Foundation (project No. 22-27-00748).

**Data availability** All relevant data generated during the study are included in the article.

## Declarations

**Ethics approval** The authors declare that all applicable international, national, and institutional guidelines for the care and use of animals were followed. Sampling of biomaterial was carried out as part of the slaughter of the livestock in a private farm.

**Consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

## References

Adam V, Quaranta G, Loyaux-Lawniczak S (2013) Terrestrial and aquatic ecotoxicity assessment of Cr(VI) by the ReCiPe method calculation (LCIA): application on an old industrial contaminated site. Environ Sci Pollut Res 20:3312–3321. https://doi.org/10.1007/s11356-012-1254-9

Adimalla N (2020) Heavy metals pollution assessment and its associated human health risk evaluation of urban soils from Indian cities: a review. Environ Geochem Health 42:173–190. https://doi.org/10.1007/s10653-019-00324-4

Alejandrino C, Mercante I, Bovea MD (2021) Life cycle sustainability assessment: lessons learned from case studies. Environ Impact Assess Rev 87:106517. https://doi.org/10.1016/j.eiar.2020.106517

Alloway BJ (ed) (2013) Heavy Metals in Soils. Springer, Netherlands, Dordrecht

Arbuzov S, Ershov V, Potzeluyev A, Rikhvanov L (1999) Rare elements in Kuznetsk basin coals. Committee of Natural Resources for the Kemerovo region, Kemerovo

Arbuzov SI (2017) Rare-earth elements (La, Ce, Sm, Eu, Tb, Yb, Lu) in the coals of the North Asia (Siberia, Russian Far East, North China, Mongolia, Kazakhstan). Geosfernye issledovaniya 6–27. https://doi.org/10.17223/25421379/5/1

Arbuzov SI, Chekryzhov IY, Finkelman RB et al (2019) Comments on the geochemistry of rare-earth elements (La, Ce, Sm, Eu, Tb, Yb, Lu) with examples from coals of north Asia (Siberia, Russian far East, North China, Mongolia, and Kazakhstan). Int J Coal Geol 206:106–120. https://doi.org/10.1016/j.coal.2018.10.013

Arbuzov SI, Ershov VV (2007) Geochemistry of rare elements in Siberian coals [Geokhimiia redkikh elementov v ugliakh Sibiri]. Print, Tomsk

Arbuzov SI, Mezhibor AM, Spears DA et al (2016) Nature of tonsteins in the Azeisk deposit of the Irkutsk Coal Basin (Siberia, Russia). Int J Coal Geol 153:99–111. https://doi.org/10.1016/j.coal.2015.12.001

Ashraf A, Bibi I, Niazi NK et al (2017) Chromium(VI) sorption efficiency of acid-activated banana peel over organo-montmorillonite in aqueous solutions. Intl J Phytorem 19:605–613. https://doi.org/10.1080/15226514.2016.1256372

Balachandar V, Arun M, Mohana Devi S et al (2010) Evaluation of the genetic alterations in direct and indirect exposures of hexavalent chromium [Cr(VI)] in leather tanning industry workers North Arcot District, South India. Int Arch Occup Environ Health 83:791–801. https://doi.org/10.1007/s00420-010-0562-y

Bare JC (2006) Risk assessment and Life-Cycle Impact Assessment (LCIA) for human health cancerous and noncancerous emissions: integrated and complementary with consistency within the USEPA. Hum Ecol Risk Assess 12:493–509. https://doi.org/10.1080/10807030600561683

Bare JC, Hofstetter P, Pennington DW, de Haes HAU (2000) Midpoints versus endpoints: the sacrifices and benefits. Int J Life Cycle Assess 5:319. https://doi.org/10.1007/BF02978665

Baroni MV, Podio NS, Badini RG et al (2011) How much do soil and water contribute to the composition of meat? A case study: meat from three areas of Argentina. J Agric Food Chem 59:11117–11128. https://doi.org/10.1021/jf2023929

Başaran N, Duydu Y, Bolt HM (2012) Reproductive toxicity in boron exposed workers in Bandirma, Turkey. J Trace Elem Med Biol 26:165–167. https://doi.org/10.1016/j.jtemb.2012.04.013

Bashkin VN, Galiulin RV, Galiulina RA, Arabsky AK (2019) Risk of soil contamination by heavy metals through gas-dust emissions. Issues of. Risk Anal 16:42–49. https://doi.org/10.32686/1812-5220-2019-16-42-49

Belyanovskaya A, Laratte B, Perry N, Baranovskaya N (2019) A regional approach for the calculation of characteristic toxicity factors using the USEtox model. Sci Total Environ 655:676–683. https://doi.org/10.1016/j.scitotenv.2018.11.169

Belyanovskaya AI, Laratte B, Rajput VD et al (2020) The innovation of the characterisation factor estimation for LCA in the USETOX model. J Clean Prod 122432. https://doi.org/10.1016/j.jclepro.2020.122432

Bowen HJM (1979) Environmental chemistry of elements. H. J. Bowen. -N.Y.: Acad. Press, p 333

Brasili E, Bavasso I, Petruccelli V et al (2020) Remediation of hexavalent chromium contaminated water through zero-valent iron nanoparticles and effects on tomato plant growth performance. Sci Rep 10:1920. https://doi.org/10.1038/s41598-020-58639-7

Bratec T, Kirchhübel N, Baranovskaya N et al (2019) Towards integrating toxicity characterization into environmental studies: case study of bromine in soils. Environ Sci Pollut Res 26:19814–19827. https://doi.org/10.1007/s11356-019-05244-5

Brevik EC, Sauer TJ (2015) The past, present, and future of soils and human health studies. Soil 1:35–46. https://doi.org/10.5194/soil-1-35-2015

Brown SL, Chaney RL, Hettiarachchi GM (2016) Lead in urban soils: a real or perceived concern for urban agriculture? J Environ Qual 45:26–36. https://doi.org/10.2134/jeq2015.07.0376

Bulle C, Margni M, Patouillard L et al (2019) IMPACT World+: a globally regionalized life cycle impact assessment method. Int J Life Cycle Assess 24:1653–1674. https://doi.org/10.1007/s11367-019-01583-0

Carr R, Zhang C, Moles N, Harder M (2008) Identification and mapping of heavy metal pollution in soils of a sports ground in Galway City, Ireland, using a portable XRF analyser and GIS. Environ Geochem Health 30:45–52. https://doi.org/10.1007/s10653-007-9106-0

Chatterjee J, Kumar P, Sharma PN, Tewari RK (2015) Chromium toxicity induces oxidative stress in turnip. Indian J Plant Physiol 20:220–226. https://doi.org/10.1007/s40502-015-0163-6

Cuajungco MP, Lees GJ (1998) Brain Res. 799

Danesh Miah M, Farhad Hossain Masum M, Koike M (2010) Global observation of EKC hypothesis for CO2, SO and NO emission: a policy understanding for climate change mitigation in Bangladesh. Energy Policy 38:4643–4651. https://doi.org/10.1016/j.enpol.2010.04.022

de Schryver AM, Brakkee KW, Goedkoop MJ, Huijbregts MAJ (2009) Characterization factors for global warming in life cycle assessment based on damages to humans and ecosystems. Environ Sci Technol 43. https://doi.org/10.1021/es800456m

Denisova OA, Chernogoryuk GE, Egorova KK et al (2016) The role of geo-ecological factors in development of sarcoidosis morbidity in Tomsk and the Tomsk region. Zdravookhranenie Rossiiskoi Federatsii (Health Care of the Russian Federation, Russian journal) 60:147–151. https://doi.org/10.18821/0044-197

Doyi I, Essumang D, Gbeddy G et al (2018) Spatial distribution, accumulation and human health risk assessment of heavy metals in soil and groundwater of the Tano Basin, Ghana. Ecotoxicol Environ Saf 165:540–546. https://doi.org/10.1016/j.ecoenv.2018.09.015

Duan X-C, Yu H-H, Ye T-R et al (2020) Geostatistical mapping and quantitative source apportionment of potentially toxic elements in top- and sub-soils: a case of suburban area in Beijing, China. Ecological Indicators 112:106085. https://doi.org/10.1016/j.ecolind.2020.106085

European Commission. Joint Research Centre. Institute for Environment and Sustainability. (2011) International reference life cycle data system (ILCD) handbook general guide for life cycle assessment: provisions and action steps. Publications Office

Evseeva N.S. (2001) Geography of the Tomsk region. Natural conditions and resources Tomsk. Tomsk Polytechnic University, Tomsk

Fantke P, Bijster M, Guignard C, et al (2017) USEtox® 2.0, Documentation version 1

Fantke P, Chiu WA, Aylward L et al (2021) Exposure and toxicity characterization of chemical emissions and chemicals in products: global recommendations and implementation in USEtox. Int J Life Cycle Assess 26:899–915. https://doi.org/10.1007/s11367-021-01889-y

Fathizad H, Ardakani MAH, Heung B et al (2020) Spatio-temporal dynamic of soil quality in the central Iranian desert modeled with machine learning and digital soil assessment techniques. Ecol Indic 118:106736. https://doi.org/10.1016/j.ecolind.2020.106736

Federal State Statistics Service [Rosstat]. https://rosstat.gov.ru. Accessed 13 Jan 2021

Franke BM, Gremaud G, Hadorn R, Kreuzer M (2005) Geographic origin of meat-elements of an analytical approach to its authentication. Eur Food Res Technol 221:493–503. https://doi.org/10.1007/s00217-005-1158-8

Glazovsky N. F. (1982) Tekhnogennye potoki veschestva v biosfere Technogenic flows of matter in bioshepere. Dobytcha water resources and their future 7–28

Goldshmidt V.M. (1952) Geochemical principles of the distribution of trace elements [Geokhimicheskie printsipy raspredeleniia redkikh elementov]. Москва

Grigorev N. A. (2009) Distribution of chemical elements in the upper part of the continental crust [Raspredelenie khimicheskikh elementov v verkhnei chasti kontinentalnoi kory]. UB RAS, Ekaterinburg

Guertin J (2005) Toxicity and health effects of chromium (all oxidation states). Chromium (VI) Handbook 215–234. doi:https://doi.org/10.1201/9780203487969.ch6

Hauschild M (2006) Spatial differentiation in life cycle impact assessment: a decade of method development to increase the environmental realism of LCIA. Int J Life Cycle Assess 11:11–13. https://doi.org/10.1065/lca2006.04.005

Hauschild M, Potting J (2000) Spatial differentiation in life cycle impact assessment - the EDIP2003 methodology. Report for the Danish Environmental Protection Agency. 1–195

Hauschild MZ, Huijbregts M, Jolliet O et al (2008) Building a model based on scientific consensus for life cycle impact assessment of chemicals: the search for harmony and parsimony. Environ Sci Technol 42:7032–7037. https://doi.org/10.1021/es703145t

He B, Wang W, Geng R et al (2021) Exploring the fate of heavy metals from mining and smelting activities in soil-crop system in Baiyin, NW China. Ecotoxicol Environ Saf 207:111234. https://doi.org/10.1016/j.ecoenv.2020.111234

He B, Zhao X, Li P et al (2019) Lead isotopic fingerprinting as a tracer to identify the pollution sources of heavy metals in the southeastern zone of Baiyin, China. Sci Total Environ 660:348–357. https://doi.org/10.1016/j.scitotenv.2018.11.339

Hedberg J, Fransson K, Prideaux S et al (2019) Improving the life cycle impact assessment of metal ecotoxicity: importance of chromium speciation, water chemistry, and metal release. Sustainability 11:1655. https://doi.org/10.3390/su11061655

Huijbregts M, Steinmann Z, Elshout P, et al (2016) ReCiPe2016: a harmonized life cycle impact assessment method at midpoint and endpoint level. RIVM Report 2016-0104. Bilthoven, The Netherlands

Huijbregts MAJ, Steinmann ZJN, Elshout PMF et al (2017) ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess 22:138–147. https://doi.org/10.1007/s11367-016-1246-y

Islam M, Karim M, Zheng X, Li X (2018) Heavy metal and metalloid pollution of soil, water and foods in Bangladesh: a critical

review. Int J Environ Res Public Health 15:2825. https://doi.org/10.3390/ijerph15122825
Jafari A, Ghaderpoori M, Kamarehi B, Abdipour H (2019) Soil pollution evaluation and health risk assessment of heavy metals around Douroud cement factory, Iran. Environ Earth Sci 78:250. https://doi.org/10.1007/s12665-019-8220-5
Jia Z, Wang J, Zhou X et al (2020) Identification of the sources and influencing factors of potentially toxic elements accumulation in the soil from a typical karst region in Guangxi, Southwest China. Environ Pollut 256:113505. https://doi.org/10.1016/j.envpol.2019.113505
Ke X, Gui S, Huang H et al (2017) Ecological risk assessment and source identification for heavy metals in surface sediment from the Liaohe River protected area, China. Chemosphere 175:473–481. https://doi.org/10.1016/j.chemosphere.2017.02.029
Khitrov G (The ROPD of D, Jaeger R (The ROPD of D (2001) Chromium toxicity. http://www.nyu.edu/classes/jaeger/chromium_toxicity.htm. Accessed 13 Jan 2021
Kim JS, Hwang IM, Lee GH et al (2017) Geographical origin authentication of pork using multi-element and multivariate data analyses. Meat Sci 123:13–20. https://doi.org/10.1016/j.meatsci.2016.08.011
Krivov MA, Luneva IU V., ZHuravleva E V. (2019) State report on the state and protection of the environment of the Tomsk region in 2019 [Gosudarstvennyi doklad o sostoianii i okhrane okruzhaiushchei sredy Tomskoi oblasti v 2019 godu]. Tomsk
Kvasnikova Z (2003) Geochemical landscapes of the Tom-Yay interfluves: within the Tomsk region [Geohimicheskie landshafty Tom'-Jajskogo mezhdurech'ja: V predelah Tomskoj oblasti]. Tomsk State University
Li C, Zhou K, Qin W et al (2019) A review on heavy metals contamination in soil: effects, sources, and remediation techniques. Soil Sediment Contam Int J 28:380–394. https://doi.org/10.1080/15320383.2019.1592108
Liang L, Wang Y, Ridoutt BG et al (2019) Agricultural subsidies assessment of cropping system from environmental and economic perspectives in North China based on LCA. Ecol Indic 96:351–360. https://doi.org/10.1016/j.ecolind.2018.09.017
Luo Y, Song K, Ding X, Wu X (2021) Environmental sustainability of textiles and apparel: a review of evaluation methods. Environ Impact Assess Rev 86:106497. https://doi.org/10.1016/j.eiar.2020.106497
Lv J, Wang Y (2018) Multi-scale analysis of heavy metals sources in soils of Jiangsu Coast, Eastern China. Chemosphere 212:964–973. https://doi.org/10.1016/j.chemosphere.2018.08.155
Mezhibor A M (2009) Ecogeochemistry of trace elements in highmoor peats of the Tomsk region [Ekogeokhimiia elementov-primesei v verkhovykh torfakh Tomskoi oblasti]
Mikhalchuk AA, IAzikov EG (2014) Multivariate statistical analysis of ecological and geochemical measurements. Part II. Computer workshop. [Mnogomernyi statisticheskii analiz ekologo-geokhimicheskikh izmerenii CHast II Kompiuternyi praktikum]. TPU, Tomsk
Milanovskii EE (1996) Geology of Russia and the near abroad (Northern Eurasia) [Geologiia Rossii i blizhnego zarubezhia Severnoi Evrazii]. MSU, Moscow
Mirmiran P, Noori N, Zavareh MB, Azizi F (2009) Fruit and vegetable consumption and risk factors for cardiovascular disease. Metabolism 58:460–468. https://doi.org/10.1016/j.metabol.2008.11.002
Nag R, O'Rourke SM, Cummins E (2022) Risk factors and assessment strategies for the evaluation of human or environmental risk from metal(loid)s – a focus on Ireland. Sci Total Environ 802:149839. https://doi.org/10.1016/j.scitotenv.2021.149839
Ni S, Ju Y, Hou Q et al (2009) Enrichment of heavy metal elements and their adsorption on iron oxides during carbonate rock weathering process. Prog Nat Sci 19:1133–1139. https://doi.org/10.1016/j.pnsc.2009.01.008
Nikolaeva NYu (2020) Accumulation of heavy metals in soil and in fodder products in the southeast of the Tomsk region [Akkumuliatsiia tiazhelykh metallov v pochve i v kormovoi produktsii iugo-vostoka Tomskoi oblasti]. In: III National (All-Russian) Scientific Conference "Theory and Practice of Modern Agrarian Science." Novosibirsk, pp 514–517
Nikolaeva I V. (1967) Bakcharskoe oolitic iron ore deposit [Bakcharskoe mestorozhdenie oolitovykh zheleznykh rud]. 129
Nordborg M, Arvidsson R, Finnveden G et al (2017) Updated indicators of Swedish national human toxicity and ecotoxicity footprints using USEtox 2.01. Environ Impact Assess Rev 62:110–114. https://doi.org/10.1016/j.eiar.2016.08.004
Panichev AM, Baranovskaya NV, Seryodkin IV., et al (2021) Landscape REE anomalies and the cause of geophagy in wild animals at kudurs (mineral salt licks) in the Sikhote-Alin (Primorsky Krai, Russia). Environmental Geochemistry and Health. https://doi.org/10.1007/s10653-021-01014-w
Pu Y, Laratte B, Marks RS, Ionescu RE (2017) Impact of copper nanoparticles on porcine neutrophils: ultrasensitive characterization factor combining chemiluminescence information and USEtox assessment model. Mater Today Commun 11:68–75. https://doi.org/10.1016/j.mtcomm.2017.02.008
Qu S, Wu W, Nel W, Ji J (2020) The behavior of metals/metalloids during natural weathering: a systematic study of the mono-lithological watersheds in the upper Pearl River Basin, China. Sci Total Environ 708:134572. https://doi.org/10.1016/j.scitotenv.2019.134572
Rikhvanov L, Baranovskaya N, Korogod N, et al (2019) Elemental composition of biological water as an indicator of technogenesis. Izvestiya Tomskogo Politekhnicheskogo Universiteta Inziniring Georesursov 330: https://doi.org/10.18799/24131830/2019/2/122
Rikhvanov L, Baranovskaya N, Soktoev B, Mongolina T (2011) Evaluation of drinking water according to geochemical composition of its salt deposition. 8th International Conference on Environmental Engineering, ICEE 2011 337–342
Rikhvanov, L., Yazikov E, Sukhikh J, et al (2006) Особенности of Natural Environments of Tomsk District and Diseases. Tomsk
Rikhvanov LP, Kropanin SS, Babenko SA (2001) Zircon-ilmenite placer deposits - as a potential source of development of the West Siberian region [TSirkon-ilmenitovye rossypnye mestorozhdeniia - kak potentsialnyi istochnik razvitiia Zapadno-Sibirskogo regiona]. SARS, Kemerovo
Rosenbaum RK, Bachmann TM, Gold LS et al (2008) USEtox—the UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. Int J Life Cycle Assess 13:532–546. https://doi.org/10.1007/s11367-008-0038-4
Rosenbaum RK, Huijbregts MAJ, Henderson AD et al (2011) USEtox human exposure and toxicity factors for comparative assessment of toxic emissions in life cycle analysis: sensitivity to key chemical properties. Int J Life Cycle Assess 16:710–727. https://doi.org/10.1007/s11367-011-0316-4
Sall ML, Diaw AKD, Gningue-Sall D et al (2020) Toxic heavy metals: impact on the environment and human health, and treatment with conducting organic polymers, a review. Environ Sci Pollut Res 27:29927–29942. https://doi.org/10.1007/s11356-020-09354-3
Senesil GS, Baldassarre G, Senesi N, Radina B (1999) Trace element inputs into soils by anthropogenic activities and implications for human health. Chemosphere 39:343–377. https://doi.org/10.1016/S0045-6535(99)00115-0
Sevbitov A, Kuznetsova M, Dorofeev A et al (2020) Dental anomalies in people living in radionuclide-contaminated regions. J Environ Radioact 216:106190. https://doi.org/10.1016/j.jenvrad.2020.106190
Shaked S (2011) Multi-continental multimedia model of pollutant intake and application to impacts of global emissions and globally traded goods. Ph.D., University of Michigan

Sharma N, Sodhi KK, Kumar M, Singh DK (2021) Heavy metal pollution: insights into chromium eco-toxicity and recent advancement in its remediation. Environ Nanotechnol Monit Manag 15:100388. https://doi.org/10.1016/j.enmm.2020.100388

Sharma S, Bhattacharya A (2017) Drinking water contamination and treatment techniques. Appl Water Sci 7:1043–1067. https://doi.org/10.1007/s13201-016-0455-7

Sheikhupura D, Muhammad A, Rakhshan K, et al (2016) Effect of heavy metals from tannery effluent on the soil and groundwater using multivariate analysis in district Sheikhupura, Pakistan

Shen W, Hu Y, Zhang J et al (2021) Spatial distribution and human health risk assessment of soil heavy metals based on sequential Gaussian simulation and positive matrix factorization model: a case study in irrigation area of the Yellow River. Ecotoxicol Environ Saf 225:112752. https://doi.org/10.1016/j.ecoenv.2021.112752

Sinha R, Kumar R, Sharma P et al (2022) Removal of hexavalent chromium via biochar-based adsorbents: state-of-the-art, challenges, and future perspectives. J Environ Manag 317:115356. https://doi.org/10.1016/j.jenvman.2022.115356

Soil map of the Tomsk region (1989) Novosibirsk: Main Directorate of Geodesy and Cartography [GUGK]

Solntsev NA (2001) The study of landscape: selected works. Moscow State University Publisher, Moscow

Tarasova N, Makarova A, Fantke P, Shlyakhov P (2018) Estimating chemical footprint: contamination with mercury and its compounds. Pure Appl Chem 90:857–868. https://doi.org/10.1515/pac-2017-1102

Taylor SR, McLennan SM (1985) The continental crust: its composition and evolution. Blackwell Press, Oxford

Tepanosyan G, Sahakyan L, Maghakyan N, Saghatelyan A (2020) Combination of compositional data analysis and machine learning approaches to identify sources and geochemical associations of potentially toxic elements in soil and assess the associated human health risk in a mining city. Environ Pollut 261:114210. https://doi.org/10.1016/j.envpol.2020.114210

Tian H, Zhang C, Qi S et al (2021) Concentration and spatial distribution of potentially toxic elements in surface soil of a peak-cluster depression, Babao Town, Yunnan Province, China. Int J Environ Res Public Health 18:3122. https://doi.org/10.3390/ijerph18063122

Tkachev IUA, IUdovich IAE (1975) Statistical processing of geochemical data [Statisticheskaia obrabotka geokhimicheskikh dannykh]. Nauka, Leningrad

Trujillo-González JM, Torres-Mora MA, Keesstra S et al (2016a) Heavy metal accumulation related to population density in road dust samples taken from urban sites under different land uses. Sci Total Environ 553:636–642. https://doi.org/10.1016/j.scitotenv.2016.02.101

Trujillo-gonzález JM, Torres-mora MA, Keesstra S et al (2016b) Science of the Total Environment Heavy metal accumulation related to population density in road dust samples taken from urban sites under different land uses. Sci Total Environ 553:636–642. https://doi.org/10.1016/j.scitotenv.2016.02.101

Tu C, He T, Liu C et al (2011) Accumulation of trace elements in agricultural topsoil under different geological background. Plant Soil 349:241–251. https://doi.org/10.1007/s11104-011-0866-z

Turbinsky VV, Bortnikova SB (2018) Proportions of arsenic and antimony in biogeochemical provinces as health risk factors. Scientific reviews Health. Risk Anal 3:136. https://doi.org/10.21668/health.risk/2018.3.15

Verones F, Hellweg S, Antón A et al (2020a) LC-IMPACT: A regionalized life cycle damage assessment method. J Ind Ecol 24:1201–1219. https://doi.org/10.1111/jiec.13018

Verones F, Hellweg S, Antón A et al (2020b) LC-IMPACT: A regionalized life cycle damage assessment method. J Ind Ecol 24. https://doi.org/10.1111/jiec.13018

Vinogradov AP (1957) Geochemistry of rare and trace elements in soils [Geokhimiia redkikh i rasseiannykh elementov v pochvakh]. AS USSR

Vinogradov AP (1962) Chemical composition of living matter in connection with the chemistry of the Earth's crust [Srednee soderzhanie khimicheskikh elementov v gornykh porodakh]. Geochemistry 7:555–571

Vithanage M, Kumarathilaka P, Oze C et al (2019) Occurrence and cycling of trace elements in ultramafic soils and their impacts on human health: a critical review. Environ Int 131:104974. https://doi.org/10.1016/j.envint.2019.104974

Vodyanicky YuN (2008) Heavy metals and metalloids in soils [Geokhimiia redkikh i rasseiannykh elementov v pochvakh]. GNU Soil Science Institute. V.V. Dokuchaeva RAAS, Moscow

Walser T, Juraske R, Demou E, Hellweg S (2014) Indoor exposure to toluene from printed matter matters: complementary views from life cycle assessment and risk assessment. https://doi.org/10.1021/es403804z

Wang H, Wu Q, Hu W et al (2018) Using multi-medium factors analysis to assess heavy metal health risks along the Yangtze River in Nanjing, Southeast China. Environ Pollut 243:1047–1056. https://doi.org/10.1016/j.envpol.2018.09.036

Wang H, Yilihamu Q, Yuan M et al (2020) Prediction models of soil heavy metal(loid)s concentration for agricultural land in Dongli: a comparison of regression and random forest. Ecol Indic 119:106801. https://doi.org/10.1016/j.ecolind.2020.106801

Wuana RA, Okieimen FE (2011) Heavy metals in contaminated soils: a review of sources, chemistry, risks and best available strategies for remediation. ISRN Ecology 2011:1–20. https://doi.org/10.5402/2011/402647

Xia S, Song Z, Jeyakumar P et al (2019) A critical review on bioremediation technologies for Cr(VI)-contaminated soils and wastewater. Crit Rev Environ Sci Technol 49:1027–1078. https://doi.org/10.1080/10643389.2018.1564526

Xiao X, Zhang J, Wang H et al (2020) Distribution and health risk assessment of potentially toxic elements in soils around coal industrial areas: a global meta-analysis. Sci Total Environ 713:135292. https://doi.org/10.1016/j.scitotenv.2019.135292

Yang Q, Li Z, Lu X et al (2018) A review of soil heavy metal pollution from industrial and agricultural regions in China: pollution and risk assessment. Sci Total Environ 642:690–700. https://doi.org/10.1016/j.scitotenv.2018.06.068

Zhang H, Yin A, Yang X et al (2021) Use of machine-learning and receptor models for prediction and source apportionment of heavy metals in coastal reclaimed soils. Ecol Indic 122:107233. https://doi.org/10.1016/j.ecolind.2020.107233

Zhornyak L V. (2009) Ecological and geochemical assessment of the territory of Tomsk on the basis of the data of soil research [Ekologo-geokhimicheskaia otsenka territorii g Tomska po danym izuchenia pochv]. Tomsk Polytechnic University