



HAL
open science

The depth of the soil's horizons profile has an effect on the human health impact score

Alexandra Belyanovskaya, Daria Vorobeva, Natalia Guseva, Bertrand Laratte

► To cite this version:

Alexandra Belyanovskaya, Daria Vorobeva, Natalia Guseva, Bertrand Laratte. The depth of the soil's horizons profile has an effect on the human health impact score. *Journal of Cleaner Production*, 2023, pp.136134. 10.1016/j.jclepro.2023.136134 . hal-03979994

HAL Id: hal-03979994

<https://hal.science/hal-03979994>

Submitted on 9 Feb 2023

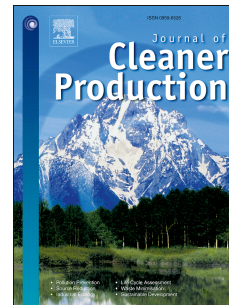
HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Journal Pre-proof

The depth of the soil's horizons profile has an effect on the human health impact score

Alexandra Belyanovskaya, Daria Vorobeva, Natalia Guseva, Bertrand Laratte



PII: S0959-6526(23)00292-5

DOI: <https://doi.org/10.1016/j.jclepro.2023.136134>

Reference: JCLP 136134

To appear in: *Journal of Cleaner Production*

Received Date: 25 March 2021

Revised Date: 22 July 2022

Accepted Date: 18 January 2023

Please cite this article as: Belyanovskaya A, Vorobeva D, Guseva N, Laratte B, The depth of the soil's horizons profile has an effect on the human health impact score, *Journal of Cleaner Production* (2023), doi: <https://doi.org/10.1016/j.jclepro.2023.136134>.

This is a PDF file of an article that has undergone enhancements after acceptance, such as the addition of a cover page and metadata, and formatting for readability, but it is not yet the definitive version of record. This version will undergo additional copyediting, typesetting and review before it is published in its final form, but we are providing this version to give early visibility of the article. Please note that, during the production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

© 2023 Published by Elsevier Ltd.

Alexandra I. Belyanovskaya: Conceptualization, Data curation, Writing - original draft, Formal analysis.

Daria Vorobeva Writing - original draft, Formal analysis.

Bertrand Laratte: Conceptualization, Supervision, Methodology.

Natalia Guseva: Conceptualization, Supervision.

Journal Pre-proof

1 **The depth of the soil's horizons profile has an effect on the human health impact score**

2

3 **Authors**

4 ^{1,2} **Alexandra Belyanovskaya** alexandra.belyanovskaya@outlook.com

5 ¹ **Daria Vorobeva** vorobeyda18@gmail.com

6 ¹ **Natalia Guseva** gusevanv@tpu.ru

7 ³ **Bertrand Laratte** bertrand.laratte@ensam.eu

8

9 ¹ Division for Geology of School of Earth Sciences & Engineering, Tomsk Polytechnic University,
10 30, Lenin Avenue, Tomsk, 634050, Russia

11 ² Laboratory for Sedimentology and Paleobiosphere Evolution University of Tyumen, Russia

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

14

15 Abstract

16 The chemical composition of soils reflects the degree of industrial exposure. Cu and Ni concentrations
17 in soils of the «Severonickel» plant vicinity are higher than remote ones. In the impact area, the mean
18 concentration of the heavy metals in the subsoils is 55 [ppm] for Ni and 33 [ppm] for Cu. Soils'
19 chemical composition varies over different mineral horizons. The subsoil layer is the main
20 accumulator of chemical elements, including pollutants. Erosion of the surface layer and technogenic
21 disturbance of the soil profile can lead to subsoil spreading and a significant increase in the human
22 health Impact Score. At the same time, the default IS calculation is focused on the 0.1 [m] depth for
23 all zones. In the paper two factors are considered in the impact modeling modification. The human
24 health Impact Score is calculated specifically for each genetic soil layer with the respective depth of
25 the profile (from 0.05 [m] to 0.2 [m]) and for soils from background and impact areas. The
26 discrepancies between default and modified Impact Scores are observed. In the Impact area, the
27 highest IS_{hum} for Ni is 60, for Cu is 5.6 [DALY]; in the Background area, it is 11 and 3.1 [DALY]
28 respectively. The importance of using the regionally modified values in population health impact
29 monitoring is highlighted.

30

31 Keywords

32 Arctic soils, impact assessment, characteristic factors, USEtox, Kola region, copper, nickel, regional

33 LCIA

34

35

36 **Introduction**

37

38 The Arctic zone is characterized by extreme natural and climatic conditions, the focal nature of
39 industrial and economic exploration of the territory, low population density, and the vulnerability of
40 nature and public health from industrial activity. The Kola Peninsula is Russian Arctic territory where
41 the wealth of mineral resources has become the basis for the growth of mining and metallurgical
42 industries. At the same time, northern ecosystems are highly sensitive to the intake of technogenic
43 origin chemical elements. Many metal ions are potentially toxic, so it is important to understand their
44 transport and distribution in the environment and the routes through which they may be transferred
45 to humans (Spurgeon et al., 2011). Nickel (Ni) and copper (Cu). Ni and Cu are chosen for the research
46 because they are the main pollutants in the North-West of Russia (Barsova et al., 2019; Kyllönen et
47 al., 2020; Moiseenko et al., 2006; Sandimirov, 2020). Exposure to heavy metals can cause a lot of
48 health problems in humans. Long-term exposure is linked to several neurological disorders (Alquezar
49 et al., 2020; Chin-Chan et al., 2015). Therefore, the question of assessing the impact of pollutants on
50 individual elements of ecosystems arises, air, water, soil, including on humans and their health.

51 Current article is focused on the soil pollution. Soil is a biogeochemical barrier for chemical elements
52 input to ecosystems from the polluted atmosphere. Soil is a depositing medium that accumulates
53 chemical elements. This property becomes especially important under conditions of long-term
54 anthropogenic load (Barsova et al., 2019). Soil is a critical repository for numerous deleterious
55 pollutants, thereby serving as a good matrix for assessing the status quo of environmental pollution
56 (Doyi et al., 2018). Soils degradation leads to a decrease in their sorption capacity and, consequently,
57 to groundwater contamination with heavy metals (Shumilova and Petrov, 2016). Heavy metal
58 pollution affects the soil's ecological function (Li et al., 2021; Yuan et al., 2021). Heavy metals
59 emanate from a myriad of sources in the environment, including industrial wastes, and particularly in
60 areas of the intersection of enterprises (Wuana and Okieimen, 2011; Zhang et al., 2020). Recently a
61 lot of research has been devoted to human health impact assessment of heavy metals in mediums such

62 as soils, sediment, or dust. Because of their persistence and non-biodegradability, heavy metals can
63 easily accumulate in the environment and could be transferred to plants, living organisms, and
64 groundwaters (Alloway, 2013).

65 When assessing the pollution of natural environments, the gross value of chemical elements in the
66 components of the natural environment is the most frequently determined indicator (F. Bratec et al.,
67 2019; Perminova, 2017; Sharma et al., 2021). Nevertheless, it does not allow a comparative impact
68 assessment between different chemical elements or components of the natural environment. For this
69 reason, many authors now use modern methods and models of the impact and environment
70 geocological state assessment based on the calculation of the various indexes (Liang et al., 2015;
71 Makarova et al., 2018; Zhang et al., 2020).

72 In this study, we consider assessing of the human toxicity with calculation of the life cycle impact
73 assessment Impact Score (IS) calculation as the approach to quantify the human health impact
74 (European Commission -- Joint Research Centre -- Institute for Environment and Sustainability,
75 2010). The Impact score is calculated using the total mass of the pollutant and the substance specific
76 characterization factor. The characterization factors calculation is taken from the USEtox model.

77 USEtox is a scientific consensus model for comparative assessment of toxics of goods and services
78 (Wu and Su, 2020). USEtox is model endorsed by UNEP's Life Cycle Initiative for characterizing
79 human and ecotoxicological impacts of chemicals (Hauschild et al., 2008; Rosenbaum et al., 2008).

80 The USEtox is specifically focused on the human health and the ecosystems impact assessment
81 (Nordborg et al., 2017).

82 However, there are a lot of uncertainties connected with the LCIA models, and the USEtox in
83 particular:

84 1. The inventory of metals in the model dataset needed to be developed. In the USEtox
85 inorganics are all specified as 'indicative', reflecting the relatively high uncertainty associated with
86 estimates of fate, exposure and effects for this substance group (Fantke et al., 2017). The CFs for
87 metals in the USEtox are classified as interim (Pizzol et al., 2011). Variations in transport properties

88 for inorganic substances depend in complex ways on a range of media properties. However, there are
89 not local geological information in the model. In the article we propose to reduce this limitation with
90 the analytical results of Ni and Cu concentration in soils of Kola peninsula.

91 2. In the USEtox model only the concentration of the pollutant in the surface layer is considered
92 for the Impact Score calculation (Fantke et al., 2017). However, the surface soil layer can be
93 disturbed, or the natural genetic layer can be changed (Elsukova et al., 2019; Kashulina et al., 2014,
94 2010). The default IS calculation is focused on the 0.1 [m] depth for all zones. We extend the model
95 dataset leaning on media properties as different soils profile horizons (from 0.05 [m] to 0.2 [m]).

96 Considering all limitations, we can propose following hypothesis, it is necessary to consider local
97 features of the landscape: natural differentiation and technogenic transformation of the soil profile. It
98 allows adjusting the result of the impact assessment on the living organism and adapting it for regional
99 conditions (Belyanovskaya et al., 2022, 2019, 2020).

100 To investigate this hypothesis, we compare soil layers' potential toxicity for human health by
101 calculation of the Impact score. The Impact score is calculated both in the area of influence and in
102 the background area. It emphasizes the combined influence of natural and anthropogenic factors,
103 which demonstrates how in small, contiguous territories there can be a sharp change in IS as a result
104 of the variability of lithogeochemical conditions and the presence of industrial facilities. This
105 approach allows the IS values to be taken as another factor for identifying the zone of impact of
106 industrial enterprises from the perspective of human health impact assessment. To compare the level
107 of impact the background area was chosen as well.

108 The background zone is remoted from the emission source. Studies of soil chemistry in this area
109 revealed minimal concentrations of nickel and copper (Guseva N.V. et al., 2020; Vorobeva D. and
110 Guseva N.V., 2021). It was difficult to locate the background zone farther because of the variable
111 lithogeochemical background and the presence of other large industrial facilities. This approach is in
112 accordance with studies by other authors (Opekunova et al., 2006).

113 Modification of the Impact score calculation allows us to characterize the degree of impact on human
114 health (IS_{hum}), combining different methods of assessing the ecological condition of urban areas:
115 geological approach and impact assessment, which reflect the novelty of the research. On the one
116 hand, studies of the geological characteristics of areas exposed to industrial impact reflect the changes
117 occurring in the natural environment due to technogenesis. On the other hand, the application of a
118 wealth of geological data allows for the expansion of the database of impact assessment models and
119 a more complete assessment of the quality of the natural environment. The application of an
120 interdisciplinary approach is based on the principles of ecogeochemistry, human health, and
121 ecosystem impact assessment.

122

123 **1. Study area**

124

125 **1.1 Natural conditions**

126

127 The Lake Imandra catchment is the central part of the Murmansk region (Figure 1-2). Murmansk
128 region is a constituent entity of the Russian Federation with a total area of 144.900 thousand km²,
129 located in the north-west of Russia. Sampling points refer to three administrative units of the
130 Murmansk region: the Apatity, Kirovsk, Mochegorsk catchment areas.

131 Almost the entire territory lies north of the Polar Circle and is located on the Kola Peninsula. The
132 climate is a temperate cold climate, with average annual precipitation and an annual temperature of
133 553 mm and -0.8°C, respectively. The prevailing wind direction is from north to south in summer and
134 from south to north in winter.

135 The eastern part area is occupied by the alkaline Khibiny Massif, and the western part of the territory
136 is a hilly plain with a section of industry-disturbed landscape. The geological structure here is
137 represented by basic and ultrabasic rocks, overlapped by moraine lake-glacial and fluvioglacial

138 deposits. The study area as a zone of ores extraction is investigated; the mineralographic map is
139 following (Figure 1).

140

141

142 Figure 1. Mineralographic map of the research area, 1:200000

143 Compiled on the basis of materials from GIS-Atlas «Subsoil of Russia» as of 01.09.2019.

144

145 According to the mineralographic map of the area there are natural depositions of Ni, Cu, Cr, and Pt
146 in the area of smelter vicinity (Monchegorsk city). The impact and the background areas are placed
147 in the boundaries of the established nonferrous metals depositions. There are non-metal minerals
148 resources around Kirovsk city.

149 The geological and climatic features of the region determine the soil characteristics. Four types of
150 soils have developed on the Kola Peninsula: tundra, podzol, boggy, to a small extent soddy and
151 derived from them. Most typical of the Kola Peninsula is podzol soil type. The mechanical
152 composition is dominated by sandy and sandy loam soils, largely heaped (Elkshina and Kupriyanova,
153 1970).

154

155 **1.2 Industrial influence**

156

157 Landscapes of the Kola Peninsula have been already investigated due to the high level of
158 anthropogenic tension (Kashulina, 2017; Revich, 2020). This impact leads to massive air, soil, and
159 water pollution (Bazova, 2013; Dauval'ter and Kashulin, 2015).

160 The presented results allow us to evaluate the impact of the copper-nickel plant on the chemical
161 composition of the components of the natural environment through the polluted atmosphere.
162 Emissions in 2016 were Ni 245 t/yr Cu 462 t/yr (Barkan and Lyanguzova, 2018). In the zone of
163 impact of copper-nickel factory emissions, atmospheric precipitation contains significant amounts of

164 pollutants: Ni 262 $\mu\text{g/l}$, Cu 540 $\mu\text{g/l}$ (Evtyugina and Asming V., 2013). In surface waters (Ni 46 $\mu\text{g/l}$,
165 Cu 17 $\mu\text{g/l}$) concentrations of these elements are significantly higher than in groundwater (Ni 4.9
166 $\mu\text{g/l}$, Cu 0.56 $\mu\text{g/l}$) (Evtyugina et al., 2016). When atmospheric precipitation infiltrates through the
167 soil, most of the heavy metals are bound in the soil horizons, where they accumulate (Ni 54.99 ppm,
168 Cu 33.26 ppm) (Table 7, Annex). The soil is thus a natural buffer that protects groundwater from
169 aerotechnogenic nickel and copper intrusion. Therefore, the stage of infiltration of atmospheric
170 precipitation through the soil plays a significant role in the chemical composition of groundwater,
171 and soils themselves.

172 There are extremely high concentrations of Ni and Cu in the organogenic soil horizons and the
173 medium peat layers (Kashulina, 2017). According to the investigation of (Koptsik et al., 2015) soils
174 of technogenic wastelands formed under the influence of long-term emissions of Severonickel
175 Combine are acidic, depleted in nutrients, polluted with heavy metals, and badly eroded Natural
176 illuvial humic podzols have lost their upper organogenic and podzolic horizons as a result of erosion
177 and removal of protective vegetation cover. Atmospheric air pollution with SO_4 , disruption of
178 vegetation cover and changes in the morphological composition of soils increases their ability to
179 accumulate heavy metals (Kashulina et al., 2014, 2010). Accumulation of Ni and Cu in soils correlates
180 with winter fallouts (Kashulina, 2017).

181 The concentration and the composition of the pollutants in soils correlate with the emission from local
182 industry (Barkan and Lyanguzova, 2018). Smelters are one of the largest sources of environmental
183 pollution (Opekunova, 2016, 2004; Opekunova et al., 2006). The study is restricted to one of the
184 major industrial enterprises of the Murmansk region. The copper-nickel smelting plant
185 «Severonickel» (The Kola Mining and Metallurgical Company) built in the 1930s is located in
186 Monchegorsk at an altitude of about 123 m. Currently, copper-nickel matte is processed at this site.
187 The reconstruction of the production in Monchegorsk resulted in a 56.6% reduction in nickel
188 emissions from 2013 (Revich, 2020). Emissions from The Kola Mining and Metallurgical Company
189 («Severonickel» in Monchegorsk and «Pechenganickel» Nickel-Zapolayrniy) decreased from 1627.1

190 tons in 1998 to 348.9 in 2017 for Ni, and from 1062.2 to 486.9 tons for Cu over the same period. A
191 certain indicator of atmospheric air pollution by metals is their content in the surface soil layer (Ettler,
192 2015a; Evdokimova et al., 2011; Evseev and Krasovskaya, 2017). The content of copper and nickel
193 in Monchegorsk soil exceeds MAC up to 5 times (Opekunova et al., 2006).
194 Mixed environmental conditions (natural anomalies and anthropogenic impact) generate the need to
195 assess the impact of the environment on public health.

196

197 **2. Materials and methods**

198 **2.1 Methods of soil sampling**

199

200 This research paper is focused on Ni and Cu distribution and the impact assessment in soils of the
201 Kola Peninsula, taking into account their concentration in impact and background areas (Figure 2).
202 Impact areas are normally more polluted than remote areas (Ettler, 2015). The background zone was
203 taken 30-50 km from the emission source while observing a decrease in the concentration of the main
204 pollutants (Ni and Cu).

205 According to the prevailing wind direction, 13 soil sections (0-60 cm) were sampled by layer during
206 the expedition in July 2016 (total number of samples 28). The sampling locations are shown in Figure
207 2 and Table 2 in the Annex.

208

209

210 Figure 2. Sampling locations (A.) and study area (B.), industry-disturbed landscape (C.) and main
211 wind direction of Monchegorsk city (D.)

212

213 To assess the accumulation of heavy metals in different types of soils, the structure of their vertical
214 profile (from the surface of the soil down to the parent rock) is of particular importance. As a rule,
215 the soil profile consists of several layers, called genetic horizons, as they were formed as a result of

216 soil-forming processes caused by the genesis of the soil (National Atlas of Soils of the Russian
217 Federation [Nacional'nyj atlas pochv Rossijskoj Federacii], 2011).

218 All the samples we studied were taken at points belonging to the podzol soil type formed in cold areas
219 with a good leaching regime. On the Kola Peninsula, podzols with a low thickness of 15-50 cm are
220 typical. Podzols with higher thicknesses (layer of more than 50 cm) are not widespread (Elkshina and
221 Kupriyanova, 1970).

222 Podzols are characterized by a differentiated profile (Figure 3) consisting of litter 3–8 cm thick;
223 whitish, lightened due to the removal of coloring iron compounds, and humus of the podzolic or
224 eluvial horizon (topsoil) with a thickness of 2 to 20-30 cm; illuvial horizon (subsoil) of brown or
225 ocher tones, formed as a result of the illuvial accumulation of aluminum-ferruginous-humus complex
226 compounds, gradually turning into the parent rock (substratum) (National Atlas of Soils of the
227 Russian Federation [Nacional'nyj atlas pochv Rossijskoj Federacii], 2011).

228

229

230 Figure 3. Genetic horizon of podzol

231

232 Each soil layer plays a particular role in the accumulation processes of pollutants. In the current
233 research, we turn attention in particular to the subsoil. The smaller number of topsoil samples is due
234 to the eroded upper horizons at some sites, and the smaller number of substratum samples is due to
235 the highly cluttered area and the inability to deepen the soil section (Table 1). Thus, the majority of
236 samples are taken from the depth of 0.06-0.2 m – the subsoil. This depth corresponds to the illuvial
237 horizon according to the Russian classification of soils (National Atlas of Soils of the Russian
238 Federation [Nacional'nyj atlas pochv Rossijskoj Federacii], 2011). The subsoil is the main mineral
239 horizon that accumulates inorganic components, coming from the overlying layers (Adams and
240 Moore, 1983).

241

242 Table 1. Soil horizons collected for the investigation

N	Soil layer	Depth [m]	Quantity of samples
1	Topsoil	0.06-0.08	6
2	Subsoil	0.06-0.2	16
3	Substratum	0.2-0.3	5

243

244 Sampling was carried out taking into account the local features of the structure of the soil profile: by
 245 in accordance with the genetic horizons, but not evenly spaced in depth. Some samples taken at the
 246 same depth belong to different genetic horizons (Annex, Table 3).

247 Soils intended for the determination of heavy metals are sampled with tools that do not contain metals.

248 Soil samples are packed in containers ensuring the preservation of small soil particles (bags made of
 249 synthetic film, dense fabric, or water-resistant paper).

250

251 **2.2. Sample preparation and analysis**

252

253 Chemical analysis and sample preparation was conducted in the Research Laboratory for
 254 Hydrogeochemistry (Tomsk Polytechnic University, Tomsk, Russia).

255 Sample preparation. Soil samples were naturally air-dried in the room prevented chemical pollution.

256 Debris was removed, and they were then sieved through a sieve (mesh size 1 mm) for later use.

257 To determine the total metal concentration, a soil sample of 2-3 g was weighed, placed into a PP

258 digestion vessel, and then concentrated HNO₃ of high purity at a ratio of 1:10. Sample decomposition

259 is carried out in a microwave oven with a blank sample at 110-115°C in 5-7 steps for 2 minutes. Then

260 the solution is diluted with 20% HNO₃.

261 Then chemical elements were measured by an inductively coupled plasma mass spectrometer (ICP-

262 MS method) NexION 300D (PerkinElmer, USA).

263 Two heavy metals (Ni and Cu) were chosen for the research. These chemicals have similar toxic
264 properties, and they are the main pollutants of the area (Motuzova et al., 2004).

265 **Nickel** and its compounds are toxic and carcinogenic (Rabinovitch and Rizhova, 2016). The most
266 common types of health impairment caused by Ni are respiratory, skin and cardiovascular diseases
267 (Chashschin et al., 1994). The increased nickel content in soils leads to endemic diseases: ugly forms
268 appear in plants and in animals; eye diseases are associated with the accumulation of nickel in the
269 cornea (McIlveen and Negusanti, 1994). The clark of nickel in World soils by Vinogradov is 40
270 mg/kg (Dobrovol'skij V.V., 2003). More recent clark estimates coincide with this value (Butovsky,
271 2005). In U.S. soils, Ni clark is much lower than world clark - 17 mg/kg (Dobrovol'skij V.V., 2003).
272 Nickel enters the soil as a result of fuel combustion and industrial emissions. In soils Ni accumulates
273 strongly in agrodern-podzolic gley soil (Vodyanitsky, 2008).

274 **Copper** is the third most used metal in the world ("VCI, Copper history/Future, Van Commodities
275 Inc.," 2011). This metal has dual nature: essential at an optimum level, while toxic at high levels
276 (Ameh and Sayes, 2019). Cu expresses organophilic properties (McBride, 1989). Cu clark in U.S.
277 soils coincides with world clark and is equal to 20 mg/kg (Dobrovol'skij V.V., 2003). The main
278 source of copper in the soil is copper-nickel smelters (Ilyin, 1991).

279

280 **3. Data processing technique**

281 **3.1. Descriptive statistics**

282

283 Descriptive data analysis, including mean, standard deviation (SD), minimum and maximum
284 concentrations, variation coefficient, etc., was carried out. Together with SD, variation coefficient
285 (VC), which is $SD/mean$, was used to reflect the degree of discrete distribution of different metal
286 element concentrations, and to indicate indirectly the activeness of the selected element in the
287 examined environment. Histograms were also utilized to show the distributions of the metals (Annex,
288 Figure 1).

289 The accumulation of Ni and Cu has a similar nature in the research areas, thus for the rank correlation
290 analysis, the whole sampling was used. To calculate the correlation between Ni, Cu, and other heavy
291 metals, the whole sampling variety was taken.

292

293 **3.2 The Impact assessment and Characteristic factors calculation with the USEtox model**

294 **3.2.1 General framework**

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

296 According to the USEtox model, Impact score (IS, Formula 2) - the LCIA impact score for human
297 toxicity is expressed at midpoint level as cancer or non-cancer disease cases and endpoint level as
298 several of disability-adjusted life years [DALY] (Fantke et al., 2017). The LCIA impact score for
299 potential impacts of the chosen elements (Cu, Ni) is calculated using a weighted summation of the
300 released pollutants – Ni and Cu in soils (the mass – M , [kg], Formula 2) and substance specific
301 characterization factors (CF) obtained with the USEtox model (Formula 1).

302

$$303 \quad IS = CF \times M_{x,i}$$

304 Formula 1. The Impact Score calculation (Fantke et al., 2017)

305 *Note: CF – characterization factor, M - the total mass of the element*

306

307 Characterization factors for the potential human health damage [DALY/kg] of Ni (II) and Cu (II) for
308 the geo-zone «Central Asia» is taken from the USEtox model (Fantke et al., 2017) (Annex, Table 1).

309 The total mass of the element in soils (M) (Formula 2) is calculated according to the formula
310 developed by T. Bratec (F. Bratec et al., 2019; T. Bratec et al., 2019; Perminova et al., 2017). The
311 total mass of the pollutant is derived from the concentration of the chemical element in soils ($C_{x,i}$) in
312 each studied area. This data is obtained analytically with the ICP-MS– geological data.

313

$$314 \quad M = \frac{C_{x,i} \times V_s \times p_x}{10^6} [\text{kg}]$$

315 Formula 2. M - total mass of the element calculation (F. Bratec et al., 2019; T. Bratec et al., 2019;
316 Perminova et al., 2017)

317 *Note: $C_{x,i}$ – metals concentration in soils; V_s - soils volume; 4) p_s - bulk density of soils [kg/m^3].*

318

319 **3.2.2 Impact score calculation modifications**

320 In the current paper, we present the approach to modify the Impact score calculation. The
321 modification leads to reduce the lack of geological data limitation of the USEtox method. In the
322 USEtox only the topsoils (0.1 [m]) are considered in the CF calculation. In the research paper, we
323 modify the total soils volume calculation with different heights of the soil layer (Formula 3).

324

$$325 \quad V_i = h_i \times S_i$$

326 Formula 3. The volume of soils calculation

327 *Note: h_i – the height of soils, [m]; S_i – the square footage of the research area, [m^2]*

328

329 Physical parameters of the soils are taken into account. For each studied area, the total volume of
330 soils is considered (Formula 3, V_s [m^3]). The volume of soils here represents square footage (S_i) of
331 the studied region and the height of the soil's horizon (h_i). The bulk density of soils (p_i), which is the
332 table value taken from the USEtox documentation [$\text{kg}_{\text{soil}}/\text{m}^3_{\text{soil}}$], and V_s is the volume of soils of each
333 considered region [m^3].

334 The areas under research (background and impact areas) belong to 3 administrative units of the
335 Murmansk region: Kirovsk, Apatity, Monchegorsk catchment areas. Different sizes of the regions are
336 taken into account with the square footage parameter (S_i) (Annex, Table 2).

337

338 4. Results and discussions

339 4.1 Statistical analysis results

340

341 Analysis of the chemical composition of the mineral horizons of the Kola Peninsula soils shows that
342 the subsoil horizon accumulates the majority of the estimated pollutants (heavy metals, radioactive,
343 and REEs) (Annex, Table 4) in all sampling points. A large number of these pollutants have high
344 concentration coefficients (CC <2;3;5). Maximum CC is also noted in subsoils. The main components
345 of emissions to the environment (Ni, Cu) (Opekunova et al., 2006) are characterized by a high
346 concentration in all the considered mineral horizons of soils, both in the control and in the zone of
347 influence. On the leeward side 5 km from the mill, there is a decrease in Ni and Cu concentrations
348 (Figure 4-5), these elements accumulate the most.

349

350

351 Figure 4. The Ni concentrations in the Background (B) and in the Impact (I) areas, in different
352 distance from the source of the pollution

353 *Note: Clark - S.R. Taylor, S.M. McLennan, 1985 – average concentration of Ni and Cu in the upper*
354 *continental crust (Taylor and McLennan, 1985)*

355 *N – number of sampling point, Distance [km] – distance from the source of pollution*

356

357

358 Figure 5. The Cu concentrations in the Background (B) and in the Impact (I) areas, in different
359 distance from the source of the pollution

360 *Note: Clark - S.R. Taylor, S.M. McLennan, 1985 – average concentration of Ni and Cu in the upper*
361 *continental crust (Taylor and McLennan, 1985)*

362 *N – number of sampling point, Distance [km] – distance from the source of pollution*

363

364 Ni and Cu in this case or represent the most stable components of emissions or they are accumulated
365 due to natural factors.

366 Minimal concentrations of Ni and Cu ($CC < 1$) are noted in soils of the background area, while other
367 heavy metals, radioactive and rare-earth elements in these samples have $CC > 1$. The wide spectrum
368 of element accumulation in soils of the Kola Peninsula in points distant directly from the production
369 site is explained by its mixed geocological situation. Data analysis demonstrates the difficult
370 ecological and geochemical situation in the study area. Opekunova et al. (Opekunova et al., 2006)
371 also revealed the content of a group of heavy metals in soils in the vicinity of Monchegorsk. Since
372 this work is devoted to the accumulation of heavy metals, further attention in the work is focused on
373 this group of chemical elements.

374 The wide range of accumulation of heavy metals in the soils of the Kola Peninsula is also
375 characterized by the presence of significant correlations between them. Heavy metals in general and
376 Ni and Cu as the main industrial pollutants of the research area have close chemical properties and
377 correlate in the soil (Figure 6). There is the strongest positive correlation between Cu and Ni
378 (Spearman rank correlation coefficient $p_{0.05} = 0.9$), (Annex, Figure 2). Heavy metals (Cr, Cd, Co) have
379 significant positive correlations with Cu and Ni. These elements according to factor loading analysis
380 are under the influence of one factor (Annex, Figure 3). Due to the absence of the other deposition,
381 but Cu and Ni in the area, the main factor affecting the whole group of the heavy metals is probably
382 industrial.

383 In the following diagram (Figure 6), we observe the graphical expression of the Ni-Cu correlation.
384 The strong positive correlation of these metals can be explained by the same source of accumulation
385 as well as their chemical mechanisms. There is probably a mix of the industrial specificities of the
386 area supports and the natural sources.

387

388

389 Figure 6. Cu - Ni correlation diagram, polynomial trend line ($n_{\text{samples}}=17$), R^2 - reliability of
390 approximation

391
392 The statistical interpretation of the obtained results demonstrates the distribution of Ni and Cu in the
393 sampling variability. Ni and Cu concentrations in soils follow the lognormal distribution in the studied
394 soils (Figures 7-8). The lognormal distribution and the high variety coefficient reflect the
395 heterogeneity of the metal accumulation in soils. They are usually formed when several dependent
396 causes are present. Thus, it can be caused by the massive intake of chemicals from industrial
397 contamination and the natural deposition of the elements in the area. Due to the lognormal distribution
398 of the data the nonparametric statistics were applied to the sampling.

399
400
401 Figure 7. The Cu and Ni distribution in soils of the Impact zone [ppm] Figure 8. The Cu and Ni distribution in soils of
402 the Background zone [ppm]

403 According to the Mann-Whitney U test (Annex, Table 5); the averages of the compared sampling
404 varieties (Ni and Cu in soil background and impact zones) have a significant difference (Table 2).
405 The values of Ni and Cu in two investigated areas were compared, therefore.

406 Descriptive statistics of Ni and Cu concentrations in soils are presented for impact and background
407 areas in Table 2. The average concentration of Ni varies from 24.24 – 88.17 [ppm] in the Impact area,
408 and from 3.34 to 12.62 [ppm] in the background; Cu concentrations are in the gap from 14.17 to 60.66
409 [ppm] in the Impact and 6.76 -24.60 [ppm] in the background. For further comparison, the
410 arithmetical means were taken to avoid the underestimation of the results and to show the local
411 anomalies of the metal accumulation.

411 Table 2. Descriptive statistics

	Impact area		Background area	
	Ni	Cu	Ni	Cu
Mean	55.0	33.3	9.3	11.4
SE	7.8	4.7	1.2	2.3
Min	24.2	14.2	3.3	6.8
Max	88.2	60.7	12.6	24.6
Median	50.4	30.1	9.7	9.7
VC	45	44	33	53
*S.R. Taylor, S.M. McLennan, 1985	20	25	20	25

412 *Note: mean – arithmetical mean [ppm], SE - Standard error, SD – standard deviation, CV – variation*
413 *coefficient [%], * S.R. Taylor, S.M. McLennan, 1985 – average concentration of Ni and Cu in the*
414 *upper continental crust (Taylor and McLennan, 1985)*

415
416 The leading role of the anthropogenic nature of the heavy metal accumulations in the soils of the
417 impact area is supported in the Table 2. First, the mean concentrations of Ni - Cu by soil profile for
418 impact areas significantly over their concentration in soils of the background area. Ni arithmetic mean
419 concentration in soil impact areas is nearly 6 times higher than the background value. Whereas Cu is
420 approximately 3 times. The composition of the industrial pollution of the ecosystem from the
421 «Severonickel» vicinity includes Cu_2S , CuFeS_2 , $(\text{Ni, Fe})_9\text{S}_8$, metallic Ni, and Cu (Barkan V.Sh.,
422 2008). Thus, pollutant composition is reflected in the high concentration of heavy metals in soils. The
423 mean values of Ni-Cu in the plant vicinity increase the continental crust as well (Taylor and
424 McLennan, 1985), at the same time values of the conditionally clean area is lower than literature data.
425 The anthropogenic origin of the pollution is supported by the fact that one of the largest industrial
426 enterprises in the Murmansk region is located in the study area (Sandimirov, 2020).

427 The background soils exceeding the maximum permitted concentration of the heavy metals in soils
428 are probably polluted too. Unlike the impact area, where the depositions of Ni and Cu are reported
429 (Figure 1) soils of the conditionally clean area have no natural occurrence of these metals. At the
430 same time wind destination is the main factor in the pollutants spread.

431 The intensive pollution of the area with heavy metals reported by many (Evseev and Krasovskaya,
432 2017; Kashulina, 2017; Kyllönen et al., 2020; Liisa et al., 1997) and significant level of the pollution
433 leads us to propose the anthropogenic nature of their accumulation and distribution.

434 We assume that the industrial intake of Cu and Ni corresponds to the general trend of their
435 concentration. In this case, the spatial distribution from the source of pollution should be investigated.

436 Therefore, the variation of the heavy metals accumulation in different sampling points is observed.

437 As we can see the distance from the source of pollution is a critical parameter of any environmental
438 monitoring. Data represented in the table was also compared according to the sampling point
439 (background: clean area). The graphical interpretation of the obtained results demonstrates the main
440 trends of the distribution of heavy metals in the vicinity of the industrial plants (Figure 4-5).

441 We observe that Ni and Cu follow the same distribution trend. We see that the majority of the soils
442 taken in the zones far from the source of the industrial pollution contain lower concentrations of both
443 metals.

444 As we can see from the wind direction vector, the climate of the research area determines the equal
445 influence of wind transfer. At the same time, zones of landscape degradation reflect the main wind
446 destination (Figure 2) and the pollution flow too. Thus, the sampling point 5 km (point N 12, Annex,
447 Table 3) away from the source of the contamination is placed in the Impact area but from the leeward.
448 Consequently, we observe the reduction of Ni and Cu concentrations at this point.

449 Massive intake of the pollutants is usually characterized by the heterogeneity of their accumulation,
450 with the consequent augmentation of the concentration coefficient. Here, we see that the
451 concentration of Ni and Cu calculated for soils from the background vary less than for the impact

452 area. This can be explained by the multiple inputs (pollution and natural deposition) of those
453 chemicals in the anthropogenic loaded area.

454 Accumulation of heavy metals is also changed by the genetic characteristics of the soil's horizons.
455 Investigated in the current paper «B» horizon of soils or «subsoil» are normally covered with the litter
456 and top-soils and less contaminated (Elsukova et al., 2019). However, leaning on the obtained results
457 subsoil horizons of the Imandra lake vicinity are also polluted. Pollutants migrate from the surface
458 layer to the deeper horizons. Similar processes are noted in zones of industrial vicinity by other
459 authors (Kim et al., 2020).

460 The accumulation capability of the deeper soil layers highlights the necessity of their investigation as
461 a possible source of pollution. The results of our studies show that soils of the Kola Peninsula
462 accumulate a significant value of Cu and Ni, in the impact and background areas, which poses a
463 potential threat to human health. In this regard, it is necessary to assess the toxicity of individual
464 elements for the human body.

465

466 **4.2 Human health impact assessment**

467

468 Site-specific characteristics of the researched areas (as maternal rock composition) and massive
469 environmental pollution of the area with Ni and Cu determine negative conditions for the population
470 health in the area.

471 To simplify the reading of the resulting charts, we repeat the sampling map below (Figure 10).

472 We observe 2 trends in the obtained results:

473 1) The trend of Ni and Cu gross values (concentrations) distribution correlates with the IS values.

474 The first mineral horizon (topsoils) shows the lowest element's concentrations (Annex, Table 3). It
475 is logical to assume that IS of the surface layer will be the lowest one. We conclude, that scoping the
476 “active” layer only (0.1 [m]) (de Souza et al., 2017), when heavy metals vary greatly depending on
477 the local properties of the soil considered (Hellweg et al., 2005; Stoessel et al., 2018), can lead to an

478 underestimation of the negative influence on the population health. Local data propose an approach
479 to counteract over- and underestimation of metal toxicity in the default USEtox assessment (Hedberg
480 et al., 2019). Despite the fact that USEtox model succeeds in mimicking the results of the spatially
481 differentiated model (Kounina et al., 2014), soil parameters as thickness of the topsoil layer, or linking
482 soils with subsoil (Karim et al., 2019) should be considered.

483 2) When heavy metals concentrations depend on the soil profile properties, consequent variation
484 between default and modified IS values is observed. That supports the hypothesis that consideration
485 of specific features of the soil profile-such as erosion of the upper horizons significantly changes the
486 results of the human health impact assessment. Obtained results show that the distribution of elements
487 in soil profiles is characterized by an increase in Cu, Ni content with depth. Thus, dusting of the
488 topsoil horizons can be considered as specific geographic conditions of the studied area. Models
489 should be adapted and parameterized for different local conditions (Gentil et al., 2020).

490

Figure 9. Ni (A.), and Cu (B.) Impact score calculation modified (m) and default (d) calculated for different soil layers in the Background and Impact area

Note: h, [m] – height of the soil horizon, N – number of sampling point,

Distance [m] – distance from the source of pollution

492 Specific geographic conditions of the studied area do not allow the calculation of the standard height
493 of the soil horizon to be done. Due to the geographical conditions in the vicinity of Lake Imandra low
494 power podzols with poorly developed humus layer and litter are formed. These soils due to their depth
495 of ~0.1 [m] may correspond to the B horizon, which accumulates the main mass of chemical elements.
496 Also, the topsoils can be disturbed by industrial activity and intensive environmental pollution, that
497 leads to subsoils scalping (Wu et al., 2020; Yu et al., 2014). Soils from the deeper horizons can be
498 spread with the wind flow and consequently affect the local population. Environmental fate of the
499 pollutants as their distribution through the soil horizon should be connected with the human toxicity
500 assessment (Núñez and Finkbeiner, 2020). It is important to admit the geological and ecological
501 characteristics of the region in the impact assessment process. For example, for further impact
502 assessment research such site-specific characterization as landscape conditions or their technogenic
503 disruption.

504

505 **5. Conclusion**

506

507 Studies of heavy metal pollution in the Kola Peninsula are relevant, in terms of assessing the state of
508 the environment and in terms of the impact on public health. Pollution of the surroundings of
509 Severonickel Plant by heavy metals is undeniable and is emphasized both by this work and by other
510 authors (Bazova, 2013; Evseev and Krasovskaya, 2017; Kashulina, 2018; Kyllönen et al., 2020; Liisa
511 et al., 1997).

512 The results of our work demonstrate a wide range of accumulation of chemical elements in the subsoil
513 horizon, both in the area adjacent to the plant and in the conditional background area. Factor and the
514 correlation analysis between Ni and Cu and a similar trend of their accumulation, allow us to propose
515 that they have similar source of origin. The results emphasize the role of subsoils in the accumulation
516 of the main number of pollutants in the studied soils. To ensure a more comprehensive and accurate
517 assessment of metal contamination results, two assessment methods of impact score, and
518 characteristic factors calculation with the USEtox model were applied.

519 As it was noted earlier, the research area is characterized by man-made disturbance of the soil profile
520 and erosion of the upper horizons. While the results of the work highlight the features and height of
521 soil horizons in the profile as a critical parameter to assess the impact on the environment. For such
522 areas it is necessary to make an adapted calculation of the human health Impact Score, taking into
523 account the characteristics of the local landscape.

524

525 **Acknowledgments**

526

527 The statistical data processing is supported by State program RF «Science», project FSWW-35 0022-
528 2020.

529

530 **References**

- 531 Adams, F., Moore, B.L., 1983. Chemical Factors Affecting Root Growth in Subsoil Horizons of
532 Coastal Plain Soils. *Soil Science Society of America Journal* 47, 99–102.
- 533 Alloway, B.J. (Ed.), 2013. *Heavy Metals in Soils, Environmental Pollution*. Springer Netherlands,
534 Dordrecht. <https://doi.org/10.1007/978-94-007-4470-7>
- 535 Alquezar, C., Felix, J.B., McCandlish, E., Buckley, B.T., Caparros-Lefebvre, D., Karch, C.M., Golbe,
536 L.I., Kao, A.W., 2020. Heavy metals contaminating the environment of a progressive
537 supranuclear palsy cluster induce tau accumulation and cell death in cultured neurons. *Scientific*
538 *Reports* 10, 569. <https://doi.org/10.1038/s41598-019-56930-w>
- 539 Ameh, T., Sayes, C.M., 2019. The potential exposure and hazards of copper nanoparticles: A review.
540 *Environmental Toxicology and Pharmacology*. <https://doi.org/10.1016/j.etap.2019.103220>
- 541 Barkan V.Sh., 2008. Soil Pollution with Nickel and Cu-prum Caused by the Industrial Source
542 (Metallurgical Dust) [Zagryaznenie pochvy nikelom i medyu ot promyshlennogo istochnika
543 metallur-gicheskikh pyley], in: *Ecological Problems in the Northern Regions and the Ways to*
544 *Solve Them: Proceedings of Russian Research Conference with in-Ternational Participation*.
545 Apatity, pp. 46–51.
- 546 Barkan, V.SH., Lyanguzova, I.V., 2018. Change of contamination level of organogenic horizon of
547 al-fe-humus podzols with reduction of aerotechnogenic load (Kola Peninsula) [Izmenenie
548 urovnya zagryazneniya organogennogo gorizonta al-fe-gumusovykh podzolov pri umen'shenii
549 aerotekhnogennoj nagruzki. *Eurasian Soil Science [Pochvovedenie]* 338–346.
550 <https://doi.org/10.7868/S0032180X18030085>
- 551 Barsova, N., Yakimenko, O., Tolpeshta, I., Motuzova, G., 2019. Current state and dynamics of heavy
552 metal soil pollution in Russian Federation—A review. *Environmental Pollution* 249, 200–207.
553 <https://doi.org/10.1016/j.envpol.2019.03.020>
- 554 Bazova, M.M., 2013. Metals and Metalloids in Natural Waters of the Kola North and Their
555 Environmental Hazard [Metally i metalloidy v prirodnykh vodah Kol'skogo severa i ih
556 ekologicheskaya opasnost']. *Vesntik of the Tyumen State University* 12, 189–198.
- 557 Belyanovskaya, A., Laratte, B., Perry, N., Baranovskaya, N., 2019. A regional approach for the
558 calculation of characteristic toxicity factors using the USEtox model. *Science of the Total*
559 *Environment* 655, 676–683. <https://doi.org/10.1016/j.scitotenv.2018.11.169>
- 560 Belyanovskaya, A., Soktoev, B., Laratte, B., Ageeva, E., Baranovskaya, N., Korogod, N., 2022.
561 Influence of local geological data and geographical parameters to assess regional health impact
562 in LCA. Tomsk oblast', Russian Federation application case. *Environmental Science and*
563 *Pollution Research*. <https://doi.org/10.1007/s11356-022-21784-9>
- 564 Belyanovskaya, A.I., Laratte, B., Rajput, V.D., Perry, N., Baranovskaya, N. v., 2020. The Innovation
565 of the characterisation factor estimation for LCA in the USETOX model. *Journal of Cleaner*
566 *Production* 122432. <https://doi.org/10.1016/j.jclepro.2020.122432>
- 567 Bratec, F., Bratec, T., Marty, P., Troussier, N., Diaz-Pichardo, R., 2019. Spatial Variability of Human
568 Health Impacts: Application to a Biorefinery Process Implementation. *Proceedings of the Design*
569 *Society: International Conference on Engineering Design* 1, 985–994.
570 <https://doi.org/10.1017/dsi.2019.104>

- 571 Bratec, T., Kirchhübel, N., Baranovskaya, N., Laratte, B., Jolliet, O., Rikhvanov, L., Fantke, P., 2019.
572 Towards integrating toxicity characterization into environmental studies: case study of bromine
573 in soils. *Environmental Science and Pollution Research* 26, 19814–19827.
574 <https://doi.org/10.1007/s11356-019-05244-5>
- 575 Butovsky, R.O., 2005. Heavy metals as technogenic chemical pollutants and their toxicity for soil
576 invertebrates. *Agrochemistry* 4, 73–91.
- 577 Chashschin, V.P., Artunina, G.P., Norseth, T., 1994. Congenital defects, abortion and other health
578 effects in nickel refinery workers. *Science of the Total Environment*, The 148, 287–291.
579 [https://doi.org/10.1016/0048-9697\(94\)90405-7](https://doi.org/10.1016/0048-9697(94)90405-7)
- 580 Chin-Chan, M., Navarro-Yepes, J., Quintanilla-Vega, B., 2015. Environmental pollutants as risk
581 factors for neurodegenerative disorders: Alzheimer and Parkinson diseases. *Front Cell Neurosci*
582 9, 124. <https://doi.org/10.3389/fncel.2015.00124>
- 583 Dauval'ter, V.A., Kashulin, N.A., 2015. Influence of mining and metallurgical enterprises on
584 chemical composition of bottom sediments of Imandra Lake, Murmansk Region [Vliyanie
585 deyatel'nosti gorno-metallurgicheskikh predpriyatij na himicheskij sostav donnyh otlozhenij
586 ozera Imandra, Murmanskaya . *Biosfera* 7, 295–313.
- 587 de Souza, E.S., Texeira, R.A., da Costa, H.S.C., Oliveira, F.J., Melo, L.C.A., do Carmo Freitas Faial,
588 K., Fernandes, A.R., 2017. Assessment of risk to human health from simultaneous exposure to
589 multiple contaminants in an artisanal gold mine in Serra Pelada, Pará, Brazil. *Science of The*
590 *Total Environment* 576, 683–695. <https://doi.org/10.1016/j.scitotenv.2016.10.133>
- 591 Dobrovol'skij V.V., 2003. *Basics of Biogeochemistry [Osnovy biogeohimii]*. ACADEMIA,
592 Moscow.
- 593 Doyi, I., Essumang, D., Gbeddy, G., Dampare, S., Kumassah, E., Saka, D., 2018. Spatial distribution,
594 accumulation and human health risk assessment of heavy metals in soil and groundwater of the
595 Tano Basin, Ghana. *Ecotoxicology and Environmental Safety* 165, 540–546.
596 <https://doi.org/10.1016/j.ecoenv.2018.09.015>
- 597 Elkshina, YU.A., Kupriyanova, V.V. (Eds.), 1970. *Surface water resources of the USSR. T. 1. Kola*
598 *Peninsula [Resursy poverhnostnyh vod SSSR. T. 1. Kol'skij poluostrov]*. Hydrometeorological
599 publishing house, Leningrad.
- 600 Elsukova, E.Yu., Opekunova, M.G., Opekunov, A.Yu., 2019. Technogenic transformation of heavy
601 metal streams in soils in regions under influence of copper-nickel production. *International*
602 *research journal* 12, 118–124. <https://doi.org/10.23670/IRJ.2019.90.12.024>
- 603 Ettler, V., 2015. Soil contamination near non-ferrous metal smelters: A review. *Applied*
604 *Geochemistry* 64, 56–74. <https://doi.org/10.1016/j.apgeochem.2015.09.020>
- 605 European Commission -- Joint Research Centre -- Institute for Environment and Sustainability, 2010.
606 *International Reference Life Cycle Data System (ILCD) Handbook -- General guide for Life*
607 *Cycle Assessment -- Detailed guidance, Constraints*. <https://doi.org/10.2788/38479>
- 608 Evdokimova, G.A., Mozgova, N.P., Kalabin, G.V., 2011. Contents and toxicity of heavy metals in
609 soils of the zone affected by aerial emissions from the Severonikel enterprise. *Eurasian Soil*
610 *Science* 44, 237–244.

- 611 Evseev, A. V., Krasovskaya, T.M., 2017. Toxic metals in soils of the Russian North. *Journal of*
612 *Geochemical Exploration*. <https://doi.org/10.1016/j.gexplo.2015.05.018>
- 613 Evtyugina, Z., Asming V., 2013. Osobennosti formirovaniya sostava infil'tracionnyh vod v usloviyah
614 aerotekhnogenogo zagryazneniya. *Vestnik of MSTU : Scientific journal of Murmans State*
615 *Technical University* 16, 73–80.
- 616 Evtyugina, Z.A., Guseva, N.V., Kopylova, J.G., Vorobeva, D.A., 2016. Chemical composition of
617 natural waters of contaminated area: The case for the Imandra Lake catchment (the Kola
618 Peninsula). *IOP Conference Series: Earth and Environmental Science* 33.
- 619 Fantke, P., Bijster, M., Guignard, C., Hauschild, M., Huijbregts, M., Jolliet, O., Kounina, A., Magaud,
620 V., Margni, M., McKone, T., Posthuma, L., Rosenbaum, R.K., van de Meent, D., van Zelm, 2,
621 R., 2017. USEtox® 2.0, Documentation version 1. <https://doi.org/10.11581/DTU:00000011>
- 622 Gentil, C., Fantke, P., Mottes, C., Basset-Mens, C., 2020. Challenges and ways forward in pesticide
623 emission and toxicity characterization modeling for tropical conditions. *The International*
624 *Journal of Life Cycle Assessment* 25, 1290–1306. <https://doi.org/10.1007/s11367-019-01685-9>
- 625 Guseva N.V., Vorobeva D.A., Evtyugina Z.A., 2020. Features of interaction in the water–rock
626 system: a case study of the Imandra lake catchment (the Kola peninsula). *Bulletin of the Tomsk*
627 *Polytechnic University. Geo Assets Engineering* 331, 177–188.
628 <https://doi.org/10.18799/24131830/2020/8/2779>
- 629 Hauschild, M.Z., Huijbregts, M., Jolliet, O., Macleod, M., Margni, M., van de Meent, D., Rosenbaum,
630 R.K., McKone, T.E., 2008. Building a Model Based on Scientific Consensus for Life Cycle
631 Impact Assessment of Chemicals: The Search for Harmony and Parsimony. *Environmental*
632 *Science & Technology* 42, 7032–7037. <https://doi.org/10.1021/es703145t>
- 633 Hedberg, J., Fransson, K., Prideaux, S., Roos, S., Jönsson, C., Odnevall Wallinder, I., 2019.
634 Improving the Life Cycle Impact Assessment of Metal Ecotoxicity: Importance of Chromium
635 Speciation, Water Chemistry, and Metal Release. *Sustainability* 11, 1655.
636 <https://doi.org/10.3390/su11061655>
- 637 Hellweg, S., Fischer, U., Hofstetter, T.B., Hungerbühler, K., 2005. Site-dependent fate assessment in
638 LCA: transport of heavy metals in soil. *Journal of Cleaner Production* 13, 341–361.
639 <https://doi.org/10.1016/j.jclepro.2003.10.003>
- 640 Ilyin, V.B., 1991. Heavy metals in the soil - plant system [Tyazhelye metally v sisteme pochva -
641 rastenie]. Nauka, Siberian Branch, Novosibirsk.
- 642 Karim, R.-A., Deschênes, L., Bulle, C., 2019. Regionalized aquatic ecotoxicity characterization factor
643 for zinc emitted to soil accounting for speciation and the transfer through groundwater. *The*
644 *International Journal of Life Cycle Assessment* 24, 2008–2022. <https://doi.org/10.1007/s11367-019-01633-7>
- 646 Kashulina, G., Caritat, P. de, C.Reimann, 2014. Snow and rainchemistry around the “Severonikel”
647 industrial com-plex, NW Russia: Current status and retrospective anal-ysis. *Atmospheric*
648 *Environment*. 89, 672–682.
- 649 Kashulina, G.M., 2018. Monitoring of soil contamination with heavy metals in the vicinity of a
650 copper-nickel plant on the Kola Peninsula [Monitoring zagryazneniya pochv tyazhelymi

- 651 metallami v okrestnostyah medno-nikelevogo predpriyatiya na Kol'skom poluostrove]. Eurasian
652 Soil Science [Pochvovedenie] 493–505. <https://doi.org/10.7868/S0032180X1804010X>
- 653 Kashulina, G.M., 2017. Extreme pollution of soils by emissions of the copper–nickel industrial
654 complex in the Kola Peninsula. Eurasian Soil Science 50, 837–849.
655 <https://doi.org/10.1134/S1064229317070031>
- 656 Kashulina, G.M., Pereverzev, V.N., Litvinova, T.I., 2010. Transformation of the soil organic matter
657 under the extreme pollution by emissions of the Severonikel smelter. Eurasian Soil Science 43,
658 1174–1183.
- 659 Kim, H., Lee, M., Lee, J.-H., Kim, K.-H., Owens, G., Kim, K.-R., 2020. Distribution and extent of
660 heavy metal(loid) contamination in agricultural soils as affected by industrial activity. Applied
661 Biological Chemistry 63, 31. <https://doi.org/10.1186/s13765-020-00517-x>
- 662 Koptsik, G.N., Smirnova, I.E., Koptsik, S.V., Zakharenko, A.I., Turbaevskaya, V.V., 2015.
663 Efficiency of remediation of technogenic barrens around the “Severonikel” works in the Kola
664 peninsula. Moscow University Soil Science Bulletin 2, 42–48.
- 665 Kounina, A., Margni, M., Shaked, S., Bulle, C., Jolliet, O., 2014. Spatial analysis of toxic emissions
666 in LCA: A sub-continental nested USEtox model with freshwater archetypes. Environment
667 International 69, 67–89. <https://doi.org/10.1016/j.envint.2014.04.004>
- 668 Kyllönen, K., Vestenius, M., Anttila, P., Makkonen, U., Aurela, M., Wängberg, I., Nerentorp
669 Mastromonaco, M., Hakola, H., 2020. Trends and source apportionment of atmospheric heavy
670 metals at a subarctic site during 1996–2018. Atmospheric Environment 236.
671 <https://doi.org/10.1016/j.atmosenv.2020.117644>
- 672 Li, M., Zhang, J., Yang, X., Zhou, Y., Zhang, L., Yang, Y., Luo, L., Yan, Q., 2021. Responses of
673 ammonia-oxidizing microorganisms to biochar and compost amendments of heavy metals-
674 polluted soil. Journal of Environmental Sciences 102, 263–272.
675 <https://doi.org/10.1016/j.jes.2020.09.029>
- 676 Liang, S., Wang, Y., Cinnirella, S., Pirrone, N., 2015. Atmospheric mercury footprints of nations.
677 Environmental Science and Technology 49, 3566–3574. <https://doi.org/10.1021/es503977y>
- 678 Liisa, M.R., Kashulina, G., Bogatyrev, I., 1997. Mobility and retention of heavy metals, arsenic and
679 sulphur in podzols at eight locations in northern Finland and Norway and the western half of the
680 Russian Kola Peninsula, Journal of Gewhemical Exploration.
- 681 Makarova, A., Shlyakhov, P., Tarasova, N., 2018. Estimating Chemical Footprint on High-resolution
682 Geospatial Grid. Procedia CIRP 69, 469–474. <https://doi.org/10.1016/j.procir.2018.01.001>
- 683 McBride, M.B., 1989. Reactions Controlling Heavy Metal Solubility in Soils. pp. 1–56.
684 https://doi.org/10.1007/978-1-4613-8847-0_1
- 685 McIlveen, W.D., Negusanti, J.J., 1994. Nickel in the terrestrial environment. Science of the Total
686 Environment, The 148, 109–138. [https://doi.org/10.1016/0048-9697\(94\)90390-5](https://doi.org/10.1016/0048-9697(94)90390-5)
- 687 Moiseenko, T.I., Voinov, A.A., Megorsky, V. V., Gashkina, N.A., Kudriavtseva, L.P., Vandish, O.I.,
688 Sharov, A.N., Sharova, Y., Koroleva, I.N., 2006. Ecosystem and human health assessment to
689 define environmental management strategies: The case of long-term human impacts on an Arctic
690 lake. Science of the Total Environment 369, 1–20.
691 <https://doi.org/10.1016/j.scitotenv.2006.06.009>

- 692 Motuzova, G. V., Lukina, N. V., Nikonov, V. V., Dauval'ter, M. V., Zorina, A. V., 2004. Effect of
693 natural and anthropogenic factors on soils, soil water, and subsoil water in Kola Peninsula. *Water*
694 *Resources* 31, 297–302. <https://doi.org/10.1023/B:WARE.0000028699.06469.9a>
- 695 National Atlas of Soils of the Russian Federation [Nacional'nyj atlas pochv Rossijskoj Federacii],
696 2011. . Astrel': AST, Moscow.
- 697 Núñez, M., Finkbeiner, M., 2020. A Regionalised Life Cycle Assessment Model to Globally Assess
698 the Environmental Implications of Soil Salinization in Irrigated Agriculture. *Environmental*
699 *Science & Technology* 54, 3082–3090. <https://doi.org/10.1021/acs.est.9b03334>
- 700 Opekunova, M.G., 2016. Bioindication of contamination [Bioindikaciya zagryaznenij]. Saint
701 Petersburg State University, Saint Petersburg.
- 702 Opekunova, M.G., 2004. Bioindikacija zagryaznenij, SP. ed. Sankt-Peterburg University, Sankt-
703 Peterburg.
- 704 Opekunova, M.G., Yu, E.E., Chekushin, V.A., Tomilina, O.V., Salminen, R., Reimann, C., 2006.
705 Environmental condition monitoring in the districts of industrial complex «Severonikel». I.
706 Migration and accumulation of chemical elements in soils in Monchegorsk-city. *Vestnik Sankt-
707 Peterburgskogo Universiteta, Seriya Geologiya i Geografiya* 96–103.
- 708 Perminova, T.A., 2017. Bromine in natural environments of the Tomsk region and its toxicity
709 assessment.
- 710 Perminova, T.A., Baranovskaya, N. v., Laratte, B., Sudyko, A., 2017. Bromine in the soils of Tomsk
711 region. *Bulletin of the Tomsk Polytechnic University* 328, 33–45.
- 712 Pizzol, M., Christensen, P., Schmidt, J., Thomsen, M., 2011. Impacts of “metals” on human health:
713 A comparison between nine different methodologies for Life Cycle Impact Assessment (LCIA).
714 *Journal of Cleaner Production* 19, 646–656. <https://doi.org/10.1016/j.jclepro.2010.05.007>
- 715 Rabinovitch, L.M., Rizhova, L.M., 2016. To the question about carcinogenic properties of nickel and
716 some of its derivatives. *Vestnik Vserossijskogo nauchno-issledovatel'skogo instituta zhirov* 53–
717 54.
- 718 Revich, B.A., 2020. Health risks in “hot spots” from chemical contamination of the Arctic macro-
719 region [Riski zdorov'yu naseleniya v «goryachih tochkah» ot himicheskogo zagryazneniya
720 Arkticheskogo makroregiona]. *Soc Probl* 148–157.
- 721 Rosenbaum, R.K., Bachmann, T.M., Gold, L.S., Huijbregts, M.A.J., Jolliet, O., Juraske, R., Koehler,
722 A., Larsen, H.F., MacLeod, M., Margni, M., McKone, T.E., Payet, J., Schuhmacher, M., van de
723 Meent, D., Hauschild, M.Z., 2008. USEtox—the UNEP-SETAC toxicity model: recommended
724 characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact
725 assessment. *The International Journal of Life Cycle Assessment* 13, 532–546.
726 <https://doi.org/10.1007/s11367-008-0038-4>
- 727 Sandimirov, S.S., 2020. Influence of the service water system at the Kola Nuclear Power Plant on the
728 heavy metals content in Lake Imandra. *Water and Ecology* 26, 93–103.
729 <https://doi.org/10.23968/2305-3488.2020.25.2.93-103>
- 730 Sharma, N., Sodhi, K.K., Kumar, M., Singh, D.K., 2021. Heavy metal pollution: Insights into
731 chromium eco-toxicity and recent advancement in its remediation. *Environmental*

- 732 Nanotechnology, Monitoring & Management 15, 100388.
733 <https://doi.org/10.1016/j.enmm.2020.100388>
- 734 Shumilova, M.A., Petrov, V.G., 2016. The study of sorption processes arsenite-ion by some types of
735 Udmurt republic soil. *Chemical Physics and Mesoscopy Journal* 18, 147–153.
- 736 Spurgeon, D.J., Lawlor, A., Hooper, H.L., Wadsworth, R., Svendsen, C., Thomas, L.D.K., Ellis, J.K.,
737 Bundy, J.G., Keun, H.C., Jarup, L., 2011. Outdoor and indoor cadmium distributions near an
738 abandoned smelting works and their relations to human exposure. *Environmental Pollution* 159,
739 3425–3432. <https://doi.org/10.1016/j.envpol.2011.08.028>
- 740 Stoessel, F., Sonderegger, T., Bayer, P., Hellweg, S., 2018. Assessing the environmental impacts of
741 soil compaction in Life Cycle Assessment. *Science of The Total Environment* 630, 913–921.
742 <https://doi.org/10.1016/j.scitotenv.2018.02.222>
- 743 Taylor, S.R., McLennan, S.M., 1985. *The continental crust: its composition and evolution*. Blackwell
744 Press, Oxford.
- 745 VCI, Copper history/Future, Van Commodities Inc. [WWW Document], 2011. URL
746 <http://trademetal futures.com/copperhistory.html>
- 747 Vodyanitsky, Yu.N., 2008. Heavy metals and metalloids in soils. Dokuchaev Soil Science Institute.
748 RAAS., Moscow.
- 749 Vorobeva D., A., Guseva N.V., 2021. Geochemical characteristics of soils: a case study of territory
750 with a high aerotechnogenic load. *Bulletin of the Tomsk Polytechnic University. Geo Assets*
751 *Engineering* 332, 149–159. <https://doi.org/10.18799/24131830/2021/6/3245>
- 752 Wu, Y., Su, D., 2020. Review of Life Cycle Impact Assessment (LCIA) Methods and Inventory
753 Databases, in: *Sustainable Product Development*. Springer International Publishing, Cham, pp.
754 39–55. https://doi.org/10.1007/978-3-030-39149-2_3
- 755 Wu, Z., Lei, S., Lu, Q., Bian, Z., Ge, S., 2020. Spatial distribution of the impact of surface mining on
756 the landscape ecological health of semi-arid grasslands. *Ecological Indicators* 111, 105996.
757 <https://doi.org/10.1016/j.ecolind.2019.105996>
- 758 Wuana, R.A., Okieimen, F.E., 2011. Heavy Metals in Contaminated Soils: A Review of Sources,
759 Chemistry, Risks and Best Available Strategies for Remediation. *ISRN Ecology* 2011, 1–20.
760 <https://doi.org/10.5402/2011/402647>
- 761 Yu, H., Ni, S.J., He, Z.W., Zhang, C.J., Nan, X., Kong, B., Weng, Z.Y., 2014. Analysis of the spatial
762 relationship between heavy metals in soil and human activities based on landscape geochemical
763 interpretation. *Journal of Geochemical Exploration* 146, 136–148.
764 <https://doi.org/10.1016/j.gexplo.2014.08.010>
- 765 Yuan, X., Xue, N., Han, Z., 2021. A meta-analysis of heavy metals pollution in farmland and urban
766 soils in China over the past 20 years. *Journal of Environmental Sciences* 101, 217–226.
767 <https://doi.org/10.1016/j.jes.2020.08.013>
- 768 Zhang, R., Chen, T., Zhang, Y., Hou, Y., Chang, Q., 2020. Health risk assessment of heavy metals in
769 agricultural soils and identification of main influencing factors in a typical industrial park in
770 northwest China. *Chemosphere* 252, 126591.
771 <https://doi.org/10.1016/j.chemosphere.2020.126591>

Journal Pre-proof

Contaminated Arctic soils human health Impact assessment: A regional Life Cycle Impact Assessment approach

A. Belyanovskaya, D. Vorobeva, N. Guseva, B. Laratte

Annex

CALCULATION of CHARACTERIZATION FACTORS
 Enter a single substance to see set of matrices below or enter range of rows to create series of results in 'Results multiple substances'

SINGLE SUBSTANCE or FIRST ROW		FINAL ROW		FIND A SUBSTANCE RowNr	
RowNr	24	RowNr		Search term:	RowNr
Substance	Cr(III)	Substance		<input type="text"/>	Substance
CAS	18085-83-1	CAS		<input type="button" value="Run Series"/>	<input type="button" value="Search"/>
				<input type="button" value="Apply"/>	<input type="button" value="Apply"/>
Substance running	Cr(III)	REGION		INDOOR EXPOSURE	
RowNr	24	RegionRowNr	8	HomeName	OECD countries average
Model	USEtox® 2.02 [built 28-June-2018]	RegionName	Central Asia	OccupationName	Industry, OECD
Date of run	15-Oct-2021			CROP RESIDUES	
				CropName	wheat

Figure 1. The USEtox model interface

Table 1. Characterization factors for the potential human health damages, CF [DALY/kg]

CF hum	Ni (II)	Cu (II)
Nat.soilC	9.0E-07	1.2E-07

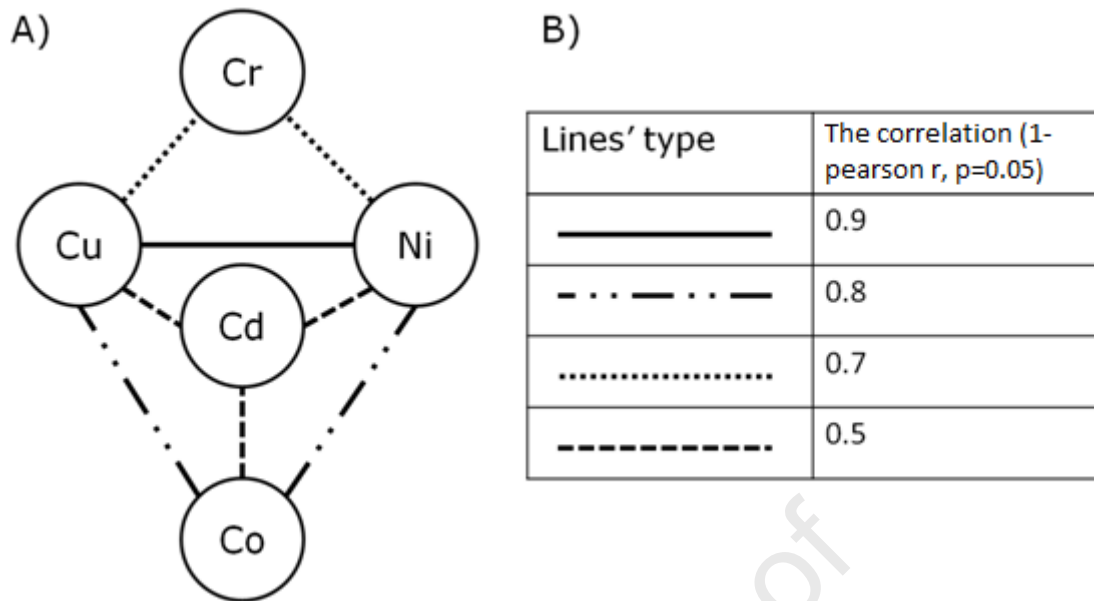
Table 2. Square of sampling areas

N	Sampling area	S [km ²]	Sampling points
1	Apatity catchment area	2500	1, 13
2	Monchegorsk catchment area	3400	5, 6, 7, 12, 8, 9, 10, 2
3	Kirovsk catchment area	3600	4, 3

15 Table 3. Ni and Cu gross values and calculation results of IS

Point	Horizon	Distance [m]	h [m]	Ni		Cu		Point	Horizon	Distance [m]	h [m]	Ni		Cu	
				C in soils [ppm]	IS [Daly/kg]	C in soils [ppm]	IS [Daly/kg]					C in soils [ppm]	IS [Daly/kg]	C in soils [ppm]	IS [Daly/kg]
Impact area								Background area							
5	Subsoils	2000	0.2	88.2	60	60.7	5.5	11	Topsoils	34500	0.1	1.2	0.3	1.2	0.04
6	Topsoils	2000	0.1	53.9	17	33.0	1.4		Subsoils		0.1	9.7	7	7.8	0.7
	Subsoils		0.2	87.8	28	32.1	1.6		Subsoils		0.3	9.3	4	9.0	0.5
7	Substratum	2000	0.4	61.9	57	33.1	4		Substratum		0.4	4.6	4	5.9	0.6
12	Topsoils	5000	0.2	32.5	12	20.0	1	13	Subsoils	33000	0.2	12.6	2	10.4	0.2
	Subsoils		0.3	36.0	26	27.3	2.6		Topsoils		0.1	1.0	0.2	0.4	0.01
	Subsoils+Substratum		0.5	29.5	28	25.9	3.3		Subsoils		0.2	7.6	3	9.7	0.5
8	Topsoils	7000	0.1	7.7	2	24.9	1.1	Subsoils	0.3	10.9	4	11.3	0.6		
	Subsoils		0.2	61.2	45	57.8	5.6		Substratum	0.5	10.6	7	14.7	1.3	
9	Subsoils	7500	0.1	75.8	28	32.4	1.6	4	Subsoils	44500	0.3	3.3	1	6.8	0.2
	Subsoils		0.1	70.7	29	22.1	0.8	3	Subsoils	47500	0.2	11.3	11	24.6	3.1
	Substratum		0.3	45.8	54	30.3	4.8								
10	Topsoils	14700	0.1	12.3	3	9.8	0.4								
	Subsoils		0.1	24.2	8	14.2	0.6								
	Subsoils		0.2	37.1	12	29.9	1.3								
	Substratum		0.4	30.8	34	31.6	4.6								
2	Subsoils	27500	0.2	39.5	27	30.3	2.7								

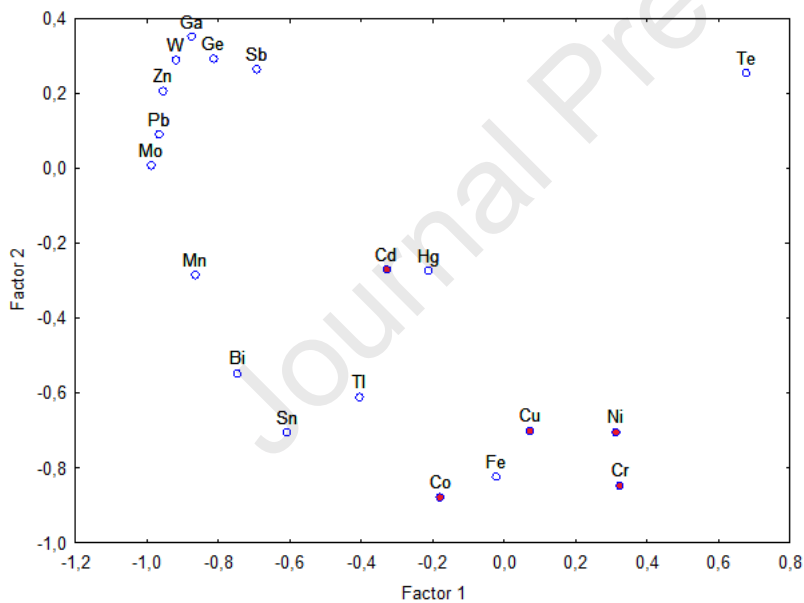
16



17

18 Figure 2. Correlations cluster between heavy metals in Arctic soils, N= 17.

19



20

21 Figure 3. The factor loading (unrotated) analysis

22

23 Table 4. The concentration coefficient (normalized to the mean of the sampling variety) of chemical
 24 elements in soils of the Impact area (a), and the Background area (b)

N	Concentration coefficient			
	A2	B		C
		B1	B2	
The Impact area				
2		Mo _{5,6} -Mn _{5,1} -Tl _{3,9} -Cs _{3,4} -Co _{3,2} =Sn-Li ₃ -Ti _{2,7} -V _{2,5} =Bi-Fe _{2,4} -Pb _{2,1} -Rb ₂ -Cr _{1,9} -As _{1,7} =W=U-Zn _{1,6} =In-Cu _{1,4} =Sb-Ni _{1,3} -Sc _{1,2} -Hg _{1,1} =Th-Cd ₁		
5		Ni _{2,8} =Cu-Cd _{1,8} -Co _{1,7} -Cr _{1,6} =Bi-Re _{1,5} -V _{1,4} =Ir=Hg=Th-Sc _{1,3} -Al _{1,2} =Fe=In=Sn-Li _{1,1}		
6	Ni _{1,7} -Cu _{1,5} =Cd-Bi _{1,3} -Pb _{1,2} -Sb ₁	Sc _{3,4} -Al _{3,3} -Hg _{3,1} -Ni _{2,8} -Cr _{2,7} -In _{2,6} -Ir _{2,5} -Sb _{2,4} -Re _{2,3} -V _{2,2} -As ₂ -Fe _{1,9} -Sn _{1,8} -Ti _{1,7} =Os-Cu _{1,5} =Ga=Au-Pt _{1,4} -Bi _{1,3} -Co _{1,2} -Mo _{1,1} =Cd		
7				Cr _{2,1} =Co-Ni ₂ -Sc _{1,7} -Tl _{1,6} -Cu _{1,5} =Rb-V _{1,3} =Mn=Ba-Fe _{1,2} -In _{1,1} -Bi ₁
8	Au _{1,3} -Sb _{1,2} =Re-Cu _{1,1} =Pb-Os ₁	Cd _{3,4} -Cr _{2,6} =Cu-Sb _{2,1} -Hg ₂ =Ni-In _{1,8} -Fe _{1,6} -Al _{1,4} =V=Co=Ga=Ir=Bi-Sn _{1,3} -Sc _{1,2} =Os-As _{1,1} =Au-Pb ₁		
9		Ni _{2,4} -Cd _{2,3} -Sc ₂ =Hg-Al _{1,9} -Co _{1,8} -Cr _{1,6} =Fe=Re=Ir-Cu _{1,5} =In-V _{1,4} -Ti _{1,2} -Li _{1,1} =Mn=Ga=Sn-Zn ₁	Ni _{2,3} -Co _{1,7} -Sc _{1,6} -Cd _{1,5} -Al _{1,4} -Cr _{1,2} =Fe-V _{1,1} -Li ₁ =Cu=In=Re=Ba	Rb _{1,7} =Tl-Co _{1,6} -Ni _{1,5} -Cu _{1,4} -Ba _{1,3} -Sc _{1,2} =Ti-Li _{1,1} =V=Cr=Mn=Fe=Hg-Al ₁
10	Pb ₂ -Bi _{1,2} -Cd _{1,1}	In _{2,7} -Au _{2,6} -Ti _{2,5} -Fe _{2,3} -V _{2,2} -Cr _{2,1} -Hg ₂ -Sc _{1,8} =Sn-Cs _{1,4} -Al _{1,3} =Tl-Co _{1,2} =Ga=Rb-Li _{1,1} -Cd=Lu-Mn ₁	Re ₂ -Tl _{1,5} -Li _{1,4} =Co=Cu-Sc _{1,3} -Ni _{1,2} -Rb _{1,1} =In-Al ₁ =Ba=Cs	Tl _{1,6} -Co _{1,4} =Cu-Sc _{1,3} =Lu=Re=Hg-Rb _{1,2} =Y=Ce=Yb-Li _{1,1} =Ba=Er=Tm
12	Ti _{1,2} =V-Sn _{1,1} -Ni ₁	V _{1,6} =Cr-Ti _{1,5} -Sn _{1,4} -Fe _{1,3} -Li _{1,2} =Cu-Co _{1,1} =Ni=Cs=Tl=Bi-Rb ₁	Tl _{1,9} -Rb _{1,8} -Cr _{1,2} =Cu-Li _{1,1} =V=Ag=Cs-Co ₁	
The Background area				
11		Li _{1,4} -Fe _{1,3} -Ti _{1,2} =V-Sn _{1,1} -In ₁ =Bi	Li _{1,1}	
1		Na ₁₅ -Sr _{5,6} -K _{4,1} -B ₄ -Pd _{3,8} -Be ₃ -Hf _{2,8} -As _{2,6} =Ba-		

N	Concentration coefficient			
	A2	B		C
		B1	B2	
		Zr _{2.5} -Ca _{2.4} -La _{2.3} =Nd-Ce _{2.2} =Pr-Th _{2.1} =Rb-Eu ₂ -Sm _{1.9} =U-Ho _{1.8} =Gd=Tb=Dy-Y _{1.7} =Rh-Pt _{1.6} =Yb=Er-Au _{1.5} =Tm-Zn _{1.4} =Lu=Mn-Ta _{1.3} =Ga=Ge=Nb-Cs _{1.2} -Si _{1.2} -P _{1.1} -...-Cu _{0.5} -Ni _{0.4}		
13	Sn _{1,2}	Fe _{2,3} -In _{2,1} -V _{1,9} -Li _{1,7} =Al=Sc=Ti-Pb _{1,5} -Cr _{1,3} =Th-Ga _{1,2} =Hg-Bi ₁	Li _{1,9} -Sc _{1,4} =In-Fe _{1,3} -Al _{1,2} -Ti=Cr	Li _{1,2} -Th _{1,1}
4		Sr _{8.4} -Sb _{8.3} -I _{6.5} -Be _{6.1} -W _{5.7} -Ta _{5.2} -Br ₅ -Pd _{4.9} -P _{4.7} -Nb _{4.6} -Mo _{4.5} -Cs _{4.3} -Ga _{3.7} -Rh _{3.5} -Ca _{3.4} -Zr _{3.2} -La _{3.1} =Hf-Rb ₃ =Zn=Ru-Na _{2.8} =Ag=Hg-Al _{2.7} =SO ₄ -Cl _{2.6} -Ce _{2.3} =Pr-Pt _{2.2} -As _{2.1} =Nd=U=Cd-B _{1.9} -Pb _{1.8} =Ge-Eu _{1.7} =Gd=K=Tb-Ba _{1.6} =Sm=Bi=Y-Er _{1.5} =Dy=Au=Ho=Tm-Mn _{1.4} =Lu=Yb-Sn _{1.1} -Ti ₁ -...-Cu _{0.3} -Ni _{0.1}		
3		Zr ₂₁ -Hf ₂₀ =Nb-Ta ₁₇ =Eu-Pr ₁₆ =La=Pd=Sm=Nd-U ₁₅ =Gd=Tb=Dy=Ho=Ce=Er=Y=Tm-Yb ₁₄ =W-Ag ₁₃ =Pt=Ge-Sr ₁₂ =Lu-Be ₁₁ -Th _{9.9} -Os _{9.4} -Mo _{9.2} -As _{8.3} -Ba ₈ -B _{6.1} Ga _{5.3} -Mn _{4.9} -Rh _{4.8} -Ca _{4.7} -Sb _{4.4} -Pb _{4.2} =Zn-P _{4.1} =Cs-Rb _{3.5} -Al ₃ -Na _{2.7} -K _{2.5} -Cd ₂ =Ru-Sn _{1.9} =Bi=Li=Cl=Se-Ir _{1.8} =Ti-Si _{1.6} -Tl _{1.5} =Au-I _{1.4} -In _{1.2} =Hg=Mg-Co _{1.1} =Cu=Fe=Sc-SO ₄ ₁ -...-Ni _{0.4}		

25

26

27 Table 5. Mann-Whitney U Test

	Rank Sum I	Rank Sum B	U	Z	p-value	Z	2*1sided
Cu	123	30	2.00	3.17	0.002	3.17	0.0004
Ni	125	28	0.00	3.37	0.001	3.37	0.0001
The critical value, p _{0.05} = 14							

28 Note: I – impact area (N=10); B – Background area (N=7)

29

30 Table 6. The sampling points with the distance from the pollution source

N	N of sampling point	The distance [km]	Height of the soil horizon [m]
The Impact area			
1	5	2.00	0.15
2	6	2.00	0.08
3	12	5.00	0.16
4	12	5.00	0.21
5	8	7.00	0.16
6	9	7.50	0.08
7	9	7.50	0.06
8	10	14.70	0.07
9	10	14.70	0.07
10	2	27.50	0.15
The Background area			
11	11	34.5	0.5
12	11	34.5	0.5
13	1	33	0.5
14	13	37.5	0.4
15	13	37.5	0.5
16	4	44.5	0.4
17	3	47.5	1.6

31

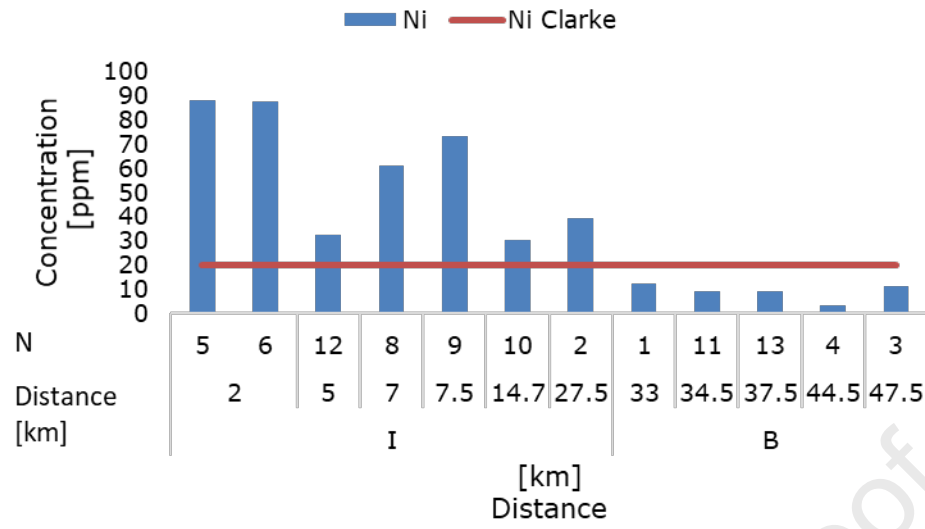
32 Table 7. Ni and Cu emissions in the studied area

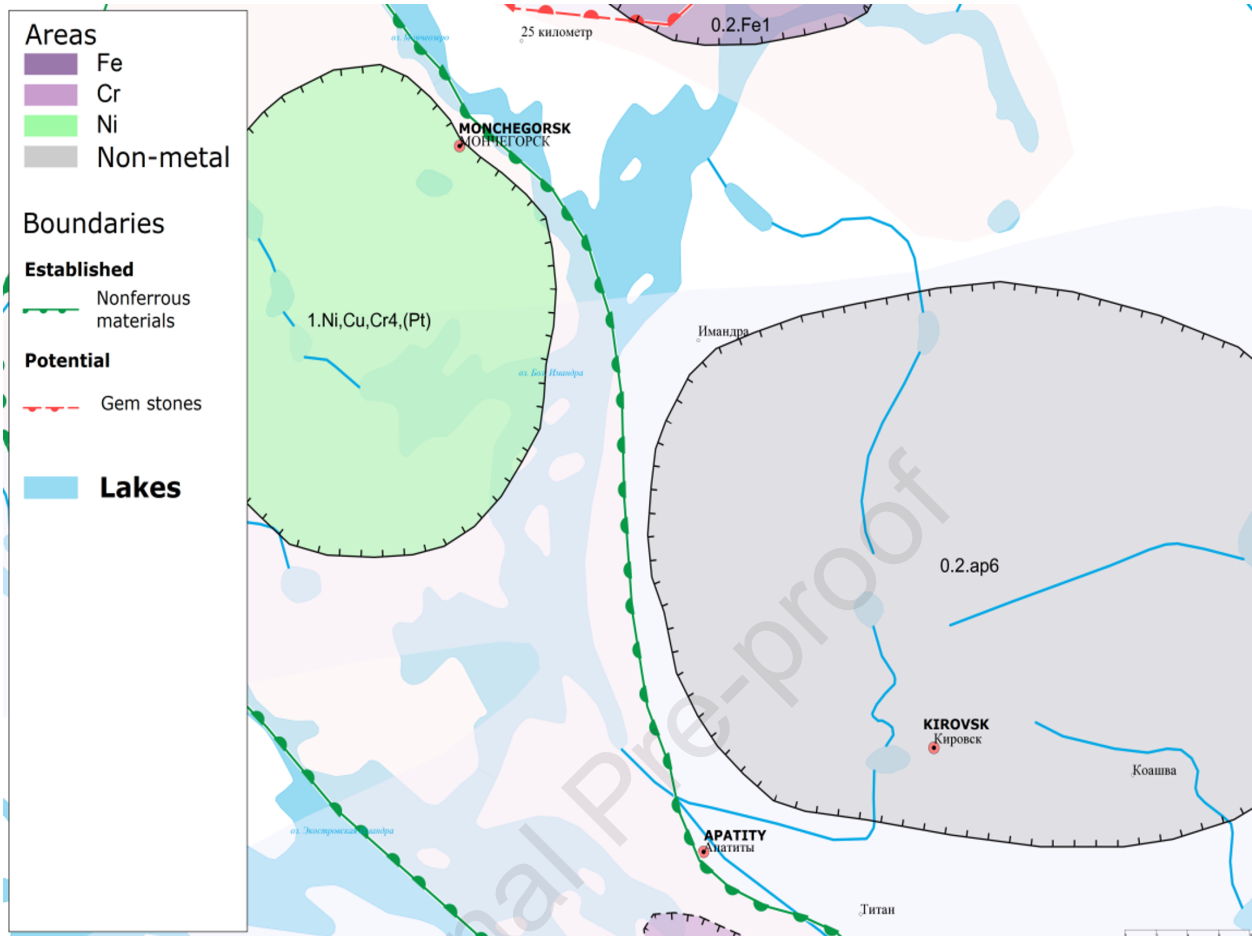
Area	Impact area		Background		References
	Ni	Cu	Ni	Cu	
Emission, ton/year	245	462			(Barkan and Lyanguzova, 2018)

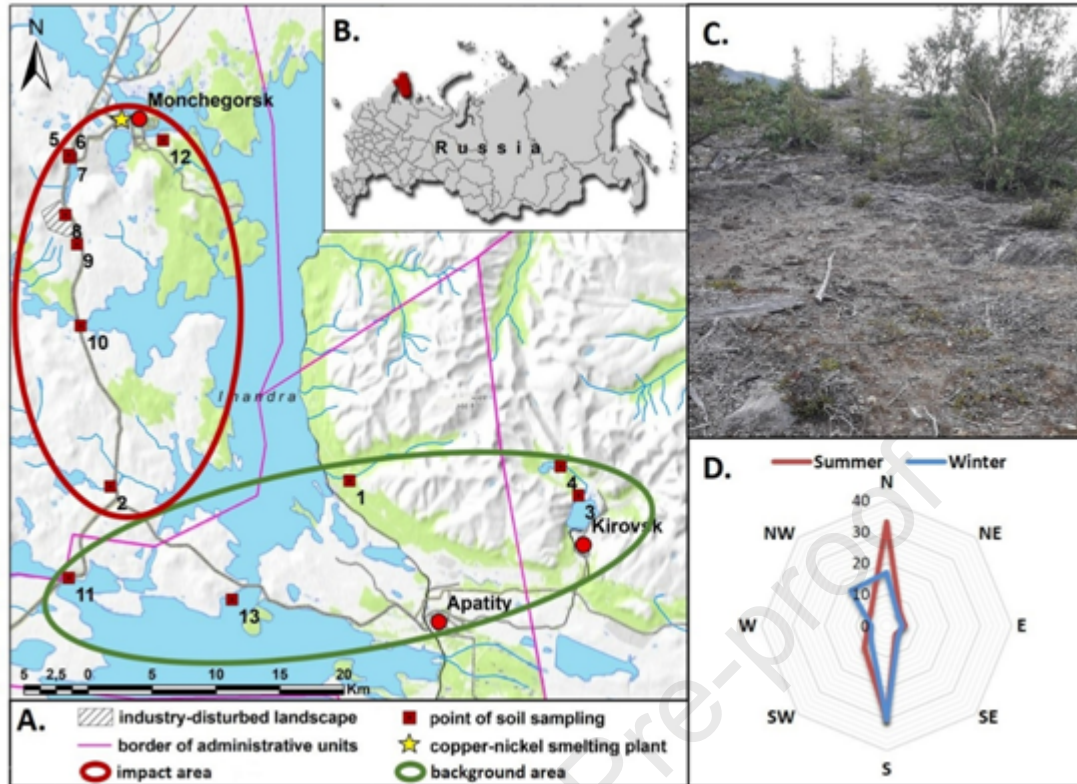
Precipitation, $\mu\text{g/l}$	262	540	14.3	19.4	(Evyugina and Asming V., 2013)
Surface water, $\mu\text{g/l}$	46.0	17.0	0.1	0.3	(Evyugina et al., 2016)
Groundwater, $\mu\text{g/l}$	4.9	0.6	0.02	0.1	
Soil, ppm	55.0	33.3	9.3	11.4	Own results

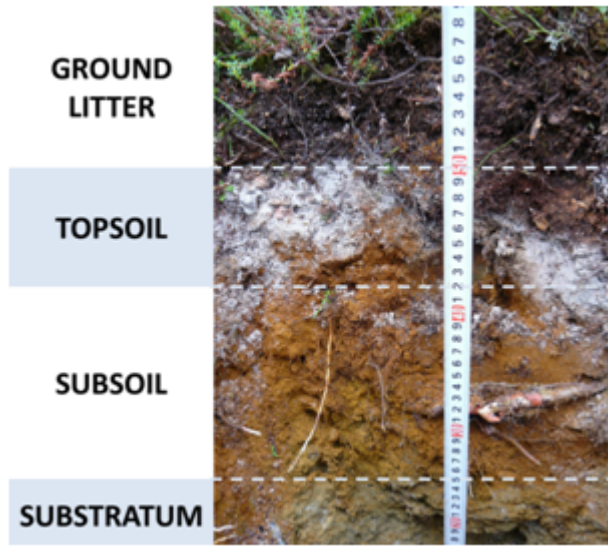
33

Journal Pre-proof

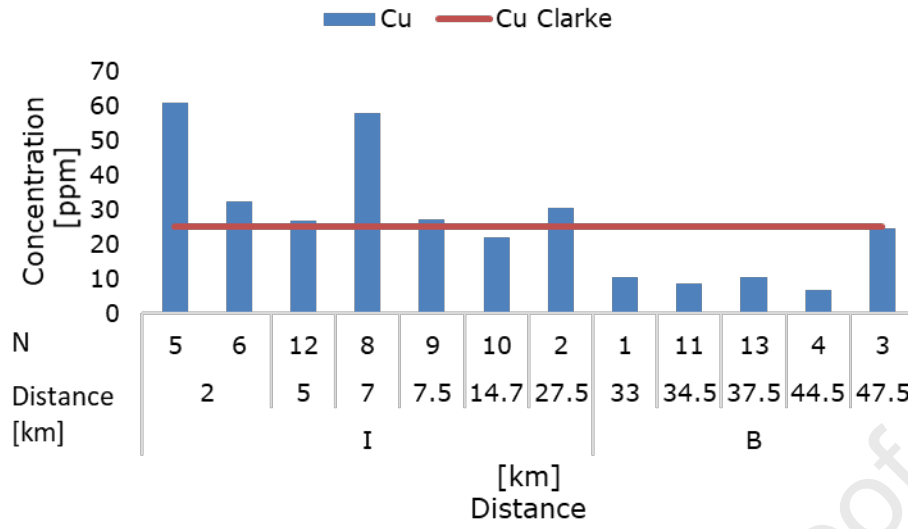


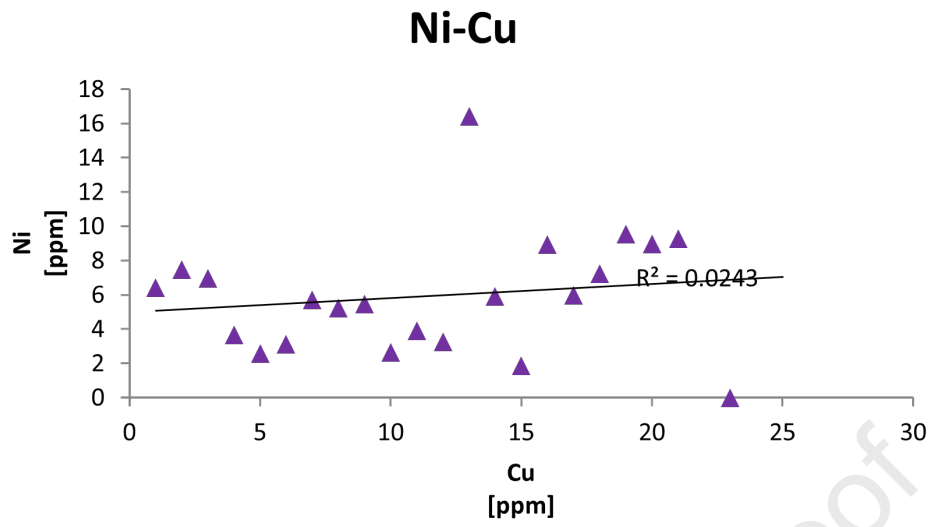


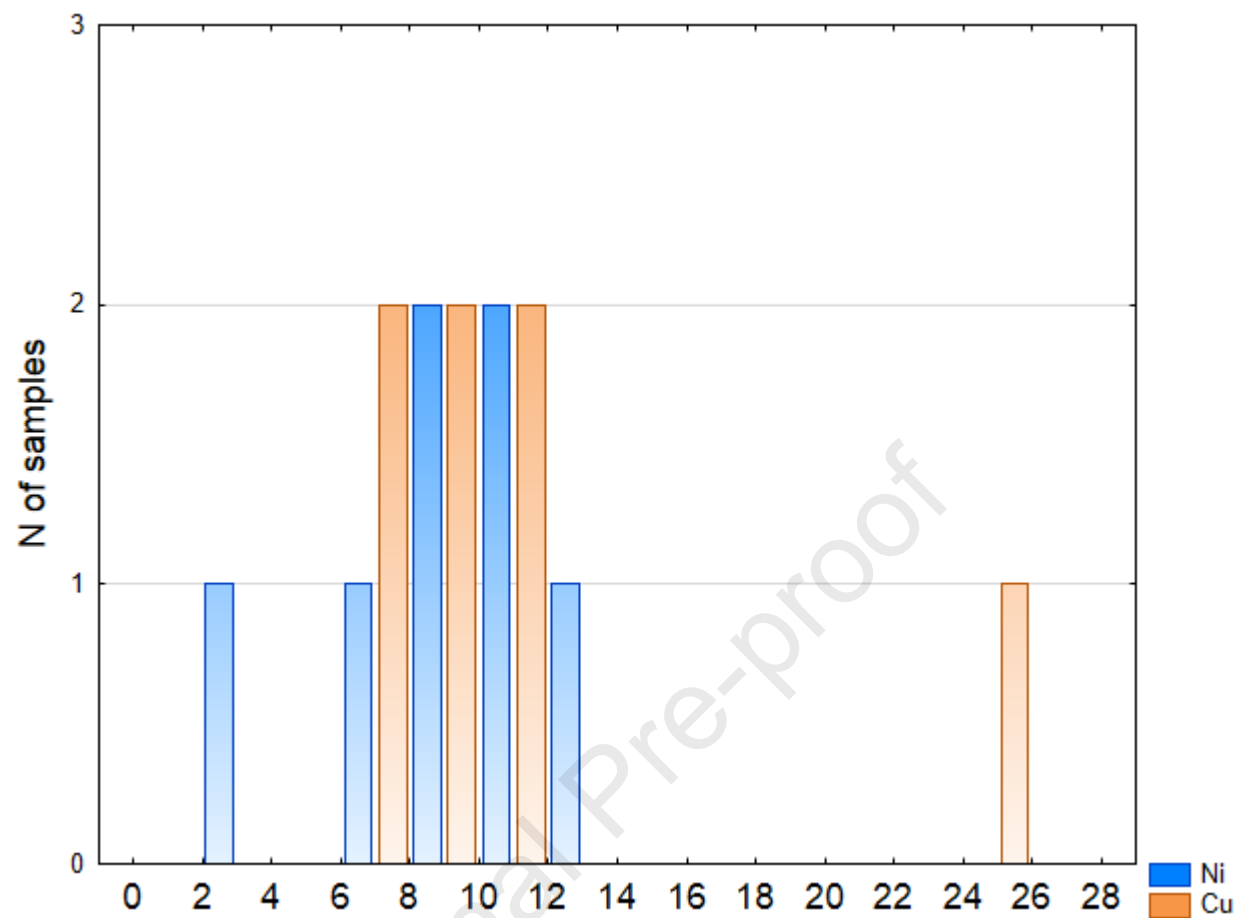




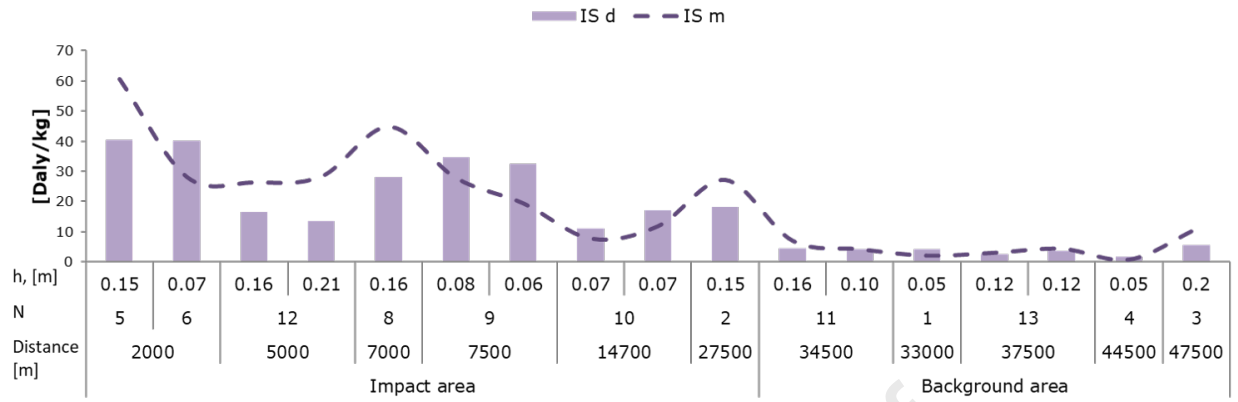
Journal Pre-proof



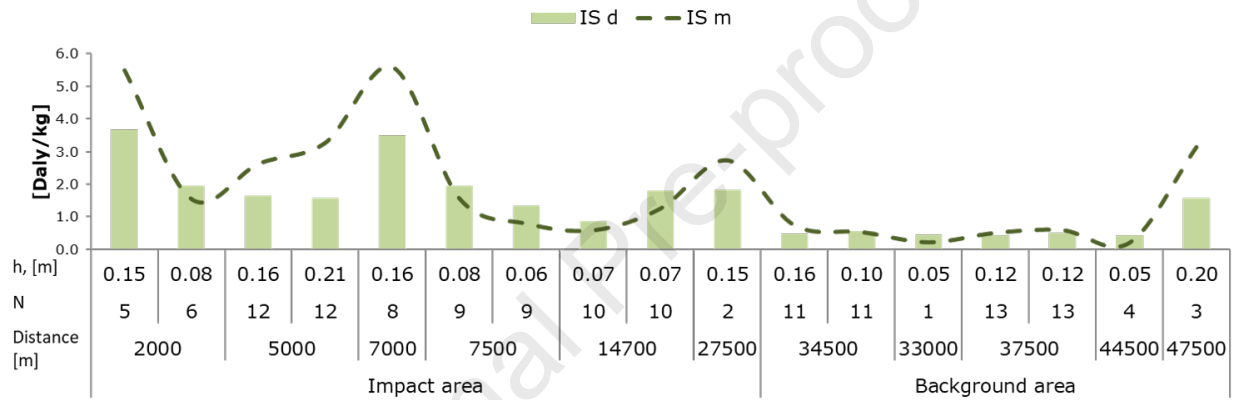


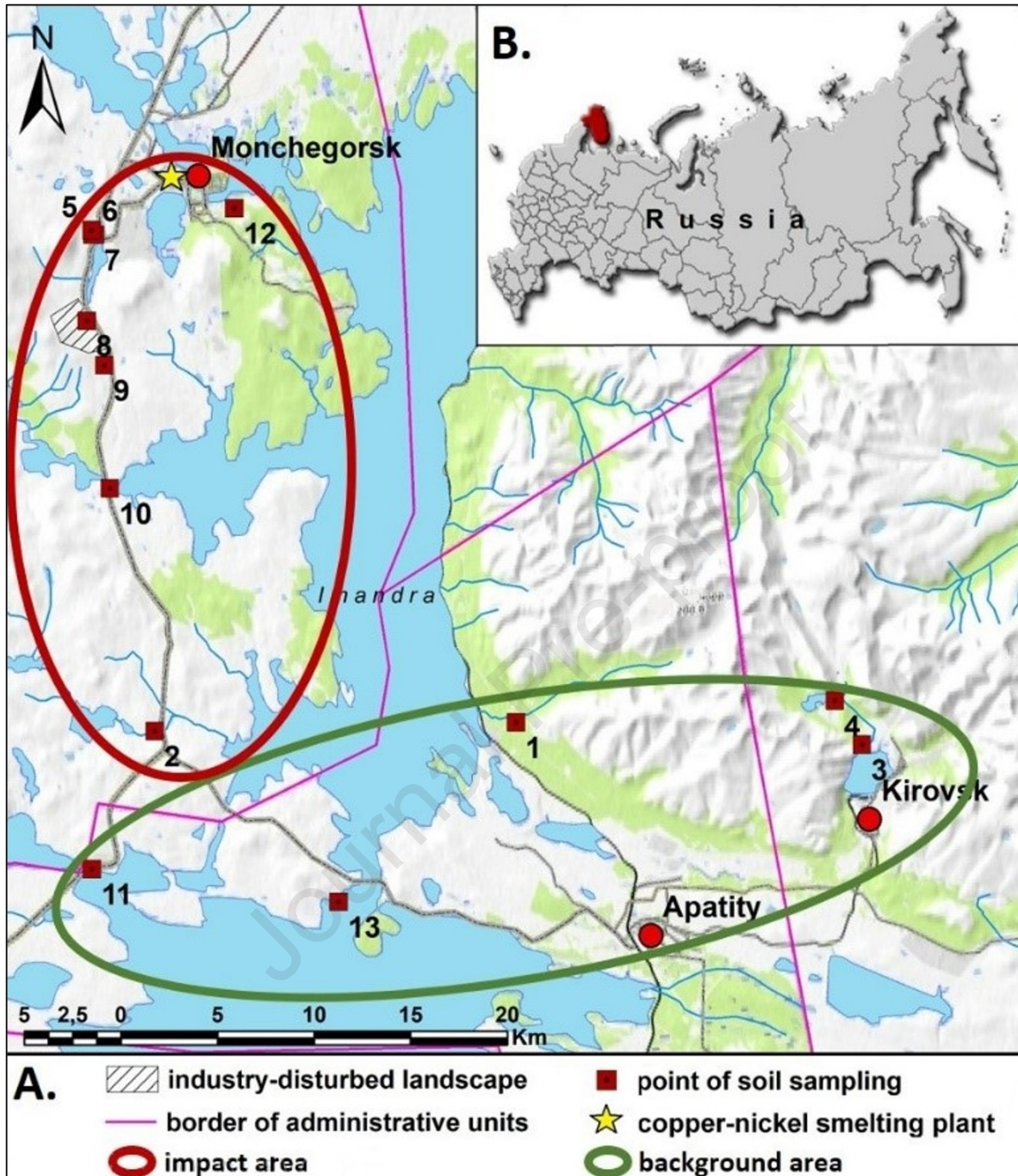


A) Ni



B) Cu





Highlights

- Soils of «Severonickel» plant vicinity accumulate Ni and Cu in the impact and the background areas;
- The genetic soil profile of the Severonickel» plant vicinity is characterized with eroded upper horizons;
- The subsoil horizon accumulates the majority of the estimated pollutants;
- Human health Impact Scores for arctic soils increase in the subsoil horizon;
- The depth of the soil's horizons profile is a critical parameter for the human health impact score calculation.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Journal Pre-proof