Assessment of risk to health of the population from soil pollution by heavy metals: theoretical-methodological and ecological aspects

Valentyna I. Trigub, Svitlana V. Domuschy

Odesa I. I. Mechnykov National University, Odesa, Ukraine, v.trigub07@gmail.com

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Abstract. Existing methodological approaches to assessing the risk to public health from the effects of heavy metal pollution are highlighted. This article considers the influence of emissions from motor transport and industrial enterprises on the level of soil contamination by movable forms of heavy metals in different functional zones of the Odessa city. The degree of technogenic and chemical pollution of urban soils is determined by ecological indicators: concentration coefficient (Kc), hazard coefficient (Kn) and total pollution indicator (Zc). It is established that the indicators of the content of heavy metals in the humus horizons of the soils of Odessa city have a high variability and depend on the degree of industrial and transport impact. It was found that only the soils of the Botanical Garden have an optimal content of heavy metals. It is established that the soils are the most polluted by emissions from road transport in terms of lead (18 TVL), zinc (23 TVL) and cadmium (15 TVL). Accumulation of heavy metals was found in all studied soils of the city. The ecological condition of soils varies from optimal (park zone) to unsatisfactory condition (zone of joint influence of motor transport and industrial enterprises). In terms of total pollution, soils within the impact of road transport and industrial enterprises have a very high (extremely dangerous) level of pollution. The highest values of the total indicator of soil pollution were determined within the impact of road transport (Zc = 758.72) and the combined impact of industrial enterprises and road transport (Zc = 921.6). For the first time, a method was used to assess the risk to the health of the population of the Odessa city from the effects of soil contamination with heavy metals according to the probit regression model. It was determined that the study area of the city mainly has a high and dangerous risk to public health. The conducted researches allowed us to reveal the level of toxicity of the city soils and the level of danger to the health of the population, which will contribute to the implementation of appropriate measures to reduce pollution of the urban environment. The methodology for assessing the health risk from urban soil pollution by heavy metals is a promising approach to quality control of the system «environment – human health» and requires further research.

Keywords: heavy metals, Odessa city, urban soils, industrial enterprises, motor transport, risk to public health.

Оцінка ризику для здоров’я населення від забруднення грунтів важкими металами: теоретико-методологічні та екологічні аспекти

В.І. Тригуб, С.В. Домуська

Одеський національний університет імені Іллі Ілліча Мечникова, Одеса, Україна, v.trigub07@gmail.com

Анотація. Висвітлено існуючі методологічні підходи щодо оцінки ризику для здоров’я населення від впливу забруднення довкілля важкими металами. Розглянуто вплив викидів автомобільного транспорту та промислових підприємств на рівень забруднення грунтів хімічним та техногенними формами важких металів різних функціональних зон міста Одеси. Визначено ступінь техногенно-хімічного забруднення міських грунтів за екологічними показниками: коефіцієнтом концентрації (Кс), коефіцієнтом небезпеки (Kn) та сумарним показником забруднення (Zc). Виявлено, що лише грунти Ботанічного саду мають оптимальний стан щодо вмісту важких металів. Встановлено, що найбільш забрудненими є грунти у межах впливу викидів автомобільного транспорту за вмістом свинцю (18 ГДК), цинку (23 ГДК) та кадмію (15 ГДК). Загалом грунти характеризуються високим (небезпечним) рівнем забруднення. Найвищі значення сумарного показника забруднення грунтів визначено в межах впливу автомобільного транспорту (Zc=758,72) та спільного впливу промислових підприємств і автомобільного транспорту (Zc=921,6). Вперше використано метод оцінки ризику для здоров’я населення міста Одеси від впливу забруднення грунтів важкими металами за моделлю пробіт-регресії. Визначено, що лише грунти Ботанічного саду мають оптимальний стан щодо впливу викидів автомобільного транспорту за вмістом свинцю (18 ГДК) та сумарним показником забруднення (Zc=921,6). Загалом грунти характеризуються високим (небезпечним) рівнем забруднення. Найвищі значення сумарного показника забруднення грунтів визначено в межах впливу автомобільного транспорту (Zc=758,72) та спільного впливу промислових підприємств і автомобільного транспорту (Zc=921,6). Вперше використано метод оцінки ризику для здоров’я населення від забруднення грунтів важкими металами за моделлю пробіт-регресії.

Ключові слова: важкі метали, місто Одеса, міські грунти, промислові підприємства, автотранспорт, ризик для здоров’я населення.
Introduction

It is well known that environmental pollution from industrial emissions and road transport is a significant factor influencing the ecological state of the environment and public health. Despite the decline in industrial production in Ukraine, the level of air pollution, soil cover of large cities and industrial regions remains high (Jakovenko and Molodgeva, 2013).

The analysis of literature sources allows us to identify the main current environmental problems of large industrial cities – a high concentration of industrial potential and population in a very limited area and a powerful trucking industry (Anan‘yeva, 2017; Voloshyn and Lepkyy, 2003; Marchenko et al., 2017; Sitdikova et al., 2015; Chernychenko et al., 2017). According to the Ministry of Ecology and Natural Resources of Ukraine, 63.2% and 36.8% of pollutants are released into the atmosphere from stationary and mobile sources, respectively (Natsional‘na dopovid…, 2018). Among mobile sources of pollution, the share of road transport is 88.7% (Statystychnyy zbiryk…, 2017).

Today, the world’s car fleet exceeds 600 million units, of which 83–85% are cars, 15–17% – trucks and buses. The share of vehicles in urban air pollution reaches 70–90%, which creates a fairly stable and significant areas of air pollution, sanitary and hygienic standards which can be exceeded several times (Sitdikova et al., 2015).

The specificity of mobile sources of pollution (vehicles) is manifested primarily in the low location of pollution emissions (at the level of population respiration), their distribution in an indefinite area and in close proximity to residential areas.

Among the “priority” air pollutants entering the urban atmosphere with exhaust gases of cars are: lead (80% of emissions), carbon monoxide (59%), nitrogen oxides (32%), gasoline (a) pyrene, volatile hydrocarbons and other moderately and highly toxic substances (Sitdikova et al., 2015). The composition of the exhaust gases of vehicles depends on the type of engine, its mode of operation, technical condition and fuel quality. To date, more than 200 components of vehicle exhaust have been studied, including heavy metal (HM) compounds.

It is known that the most stable component of the environment on the one hand, and the “storage” of chemical compounds – on the other, is the soil. Among modern pollutants the leading place is occupied by heavy metals, compounds of which negatively affect the vital activity of soil microorganisms, growth and development of plants, animals, groundwater and surface water quality and harm human health (Anan‘yeva, 2017; Berestenko and Grigor’ev, 2011; Krjazhev et al., 2015; Lim et al., 2011; Lyzhina et al., 2018; Marchenko et al., 2017; Rybalova et al., 2019).

The most toxic HMs are lead (Pb), cadmium (Cd), zinc (Zn), which belong to the first hazard class; cobalt (Co) and copper (Cu) – to the second class, manganese (Mn) – the third class of danger. Excessive amounts, both Mn, Cu and Zn, are both excessive and insufficient, leading to increased morbidity, impaired physical development and other adverse health effects (Voloshyn and Lepkyy, 2003).

Urban soils can have both indirect and direct effects on public health. First, soils are a potential source of secondary pollution of surface and groundwater, air and crop products, both from heavy metals and other toxic substances. Secondly, HMs have a significant proportion of aerosol components of air, which can penetrate into the lungs and blood of person, as well as accumulate in various organs. The direct impact of soil pollution on the health of the population, especially children, is manifested through the entry of soil particles into the body during walks, games and more.

In view of the above information, the assessment of the risk to the health of the population of the city of Odessa from the impact of soil pollution by heavy metals is relevant primarily to determine the level of environmental hazards and develop appropriate environmental measures.

The aim of the study is to determine the impact of road transport and industrial enterprises on the accumulation of mobile forms of heavy metals in urban soils and to assess the risk to public health of the city from their pollution by HM.

To achieve this goal, the following tasks were set: to analyze modern methodological approaches to assessing the risk of human health from the effects of environmental factors; assess the degree of man-made chemical pollution of the city’s soils by environmental indicators (concentration factor (Kc), hazard factor (Kn) and total pollution rate (Zc)); determine the level of risk to public health from soil contamination by heavy metals.

The state of study of the issue

The roots of the study of the impact of environmental factors on the health of the population date back to antiquity. Thus, the famous ancient Greek philosopher Paracelsus believed that there is a link between disease and health, which depends on the harmony of nature and man. According to the philosopher Hippocrates, “everything is medicine and everything is a poison that depends only on their number” (Gartman, 2009).

Special attention was paid to the study of the dependence of public health on the quality of drinking water, air, soil, and plant products at the end of the 20th century and now. In the works of domestic and foreign scientists (Vasil’ev et al., 2013; Berestenko and Grigor’ev, 2011; Jakovenko et al., 2013; Vasil’ev et al., 2015; Lyzhina et al., 2018; Afshari et al., 2016, 2017; V. I., Domuschy S. V. Journ. Geol. Geograph. Geoecology, 31(1), 152–162
Salem et al., 2016; Boccia and Margiotta, 2015) a hygienic assessment of chemicals in food raw materials and food products was conducted, an air pollution index calculated, information and analytical programs developed that allow processing and evaluation of measurements of physical and chemical pollution and conducting of integrated indicators of exposure, taking into account synergistic effects that exceed the total impact. The work of physicians, ecologists and soil scientists is devoted to the study of the dependence of pollution of certain components of the environment with heavy metals, fluorine and their impact on morbidity. In particular, the content of fluorine and heavy metal compounds in the soils of Odessa region and their impact on population morbidity are discussed in (Trigub and Lyashkova, 2018; Trigub et al., 2020).

Over the last two decades, the work of foreign and domestic scientists has focussed not only on the impact of environmental factors on public health, but also on the assessment and possible risk to public health from pollution of certain components of the environment (Anan’yeva, 2017; Daukaev et al., 2015, Krijazhev et al., 2015; Lyzhina et al., 2018; Maj and Klein, 2011; Marchenko et al., 2017; Rybalova et al., 2019; Stepanova et al., 2014; Surzhikov et al., 2019; Chernychenko et al., 2017; Boccia and Margiotta, 2015; Salem et al., 2016).

Currently, the assessment and management of public health risk is enshrined in law in all EU countries, the United States, Canada, Australia and recommended by leading international organizations – the World Health Organization (WHO), the International Labor Organization (ILO), the Organization for Economic Development Cooperation and Development (OECD).

Methodological approaches to assessing the risk to human health from the effects of environmental factors are relatively new, but are actively used in many countries around the world and can solve a wide range of problems of environmental protection and public health; allow us to combine and take into account the medical, environmental, social and economic problems of the regions (Avaliani et al., 2010).

The most common methodological approaches to assessing the risk to public health from the effects of air, surface water and soil pollution are: determining the risk assessment of air pollution by enterprises according to the WHO methodology (Otsinka ryzyku..., 2007); the methodological approach of the American Environmental Protection Agency (EPA), which is used in many countries around the world; methodology for assessing the health risk of the population of urban areas, taking into account the combined effects of physical and chemical factors using proprietary information technology and software (Zabolotskikh et al., 2016); method of assessing the risk to public health from the effects of soil contamination with heavy metals on the model of probation-regression (Rybalova et al., 2019).

Risk assessment methodology includes: risk assessment, risk management and risk communication. Risk management is a logical continuation of risk assessment for public health, which aims to justify the choice of the best solutions in a particular situation to eliminate or minimize it (Otsinka ryzyku..., 2007).

The advantages of using a risk assessment methodology are that it can be used in those areas of pollution where there is no or only irregular data on population morbidity (epidemiological and clinical) and allows one to identify negative factors of environmental pollution (Bekshin, 2014). Currently, methodological approaches and methods of risk assessment for public health are used in the environmental assessment of various components of the environment: air, soil, natural waters, due to emissions from industrial enterprises, road transport and other sources of pollution (Bekshin, 2014; Zabolotskikh et al., 2016; Madzhd et al., 2016).

The vast majority of current research on public health risk assessment has addressed the impact of air pollution on the environment and human health (Stepanova et al., 2014; Marchenko et al., 2017; Chernychenko et al., 2017; Maj and Klein, 2011; Vasil’ev et al., 2015; Anan’yeva, 2017; Golikov et al., 2018).

Risk assessment for public health is also used to characterize the level of environmental hazards of soils contaminated by industrial emissions and road transport. Thus, according to Rybalova et al. (2019) it is necessary to determine the risk to public health separately for areas of agricultural use using translocation MPCs, which show the risk of heavy metals from the soil into vegetation, and for other areas — by determining the excess of heavy metals over background concentrations regression.

In the context of intensive growth of road transport (including private), the problem of soil pollution in large cities and risk assessment of public health is relevant and requires detailed study.

Materials and methods of research

General scientific research methods (system, analysis, observation) and special (laboratory-analytical, comparative-geographical, statistical, cartographic) were used to determine the impact of road transport on HM soil pollution and possible risk to the health of the city population.

Soil samples were taken by the envelope method in accordance with the normative document DSTU 4287: 2004 “Soil quality. Sampling ” (DSTU 2005, 2005) taking into account the functional zoning of the city: conditionally “clean” zone (control within the city, Botanical Garden), park, country, intensive influence of industrial enterprises, motor transport and zone of joint influence of industrial enterprises and automobile transport (Fig. 1).
In order to determine the degree of soil contamination in Odessa, we used the content of mobile forms of heavy metals (Pb, Zn, Co, Cd, Cu) in the buffer ammonium acetate extract with a pH of 4.8 on the atomic absorption spectrophotometer AAS in Odessa branch of the Institute of Soil Protection of Ukraine according to DSTU 4770.2: 2007, DSTU 4770.3: 2007, DSTU 4770.5: 2007, DSTU 4770.6: 2007, DSTU 4770.9: 2007 (DSTU…, 2005).

The degree of man-caused chemical pollution of the city was determined by the following environmental indicators: coefficient of concentrations (Cc), coefficient of danger (Cd) and total pollution rate (Zc) (Saet, 1990; Madzhd et al., 2016).

The coefficient of concentrations (Cc), which characterizes the degree of accumulation of HM in the soil relative to the selected standard (control), was calculated by the formula:

\[ Cc = Cc / Cs, \]  

where \( Cc \) is the content of the substance in the component, \( Cs \) is the content of the substance in the standard (control), mg / kg.

The ecological condition of the soil by the value of the concentration coefficient was assessed separately for each chemical element on a scale: the optimal ecological condition — exceeding \( Kh \leq 1.0 \); normal — \( K = 1.0–2.9 \); satisfactory — \( K = 3.0–5.0 \); unsatisfactory — \( K \geq 5.0 \) (Saet, 1990).

The level of contamination of the soil cover with mobile forms of heavy metals (coefficient of danger (Cd)), which is used to assess the degree of danger of the pollutant element in relation to migration in the soil-plant system, was calculated by the formula:

\[ Cd = Ci / MAC, \]  

where \( Ci \) is the concentration of HM in the soil, mg/kg;

MAC — an indicator of the maximum allowable concentration of HMs in the soil, mg/kg.

Comprehensive assessment of soil contamination by a set of heavy metals was calculated according to the formula of the total soil contamination index (Zc), taking into account the actual content of a certain chemical element in the soil and the maximum allowable concentration of contaminants:

\[ Zc = \sum_{i=1}^{n} Cc_i - (n - 1) \]  

where \( n \) is the amount of pollutants,

\( Cc \) — coefficient of concentrations of pollutants.

Estimation of the level of soil contamination with heavy metals by the complex according to Zc was evaluated on a scale: Zc = <16 – permissible level, Zc = 16–32 – moderately dangerous, Zc = 32–128 – dangerous; Zc = 128 – very dangerous.

The risk to public health from the effects of heavy metal pollution of the city was determined by the formula:

\[ P_{rob} = -1.32 + 1.45 lg C / C_{by}, \]  

where \( Cb \) – background concentration;

\( Ci \) – pollutant in the soil, mg/kg.
The action of several chemical elements causes a total harmful effect, which depends on the route and duration of entry into the body, dose levels or concentrations of compounds. If several elements cause an impact through one of the components of the environment, then such an impact is combined. The risk of public health with such exposure to environmental pollution is assessed by the rule of multiplication of probabilities, where the multiplier is not the magnitude of health risk, but the values that characterize the probability of its absence and is calculated by the formula:

$$\text{Risk}_{\text{tot}} = 1 - (1 - \text{Risk}_1) (1 - \text{Risk}_2) \ldots (1 - \text{Risk}_n),$$  \hspace{1cm} (5)

where Risk is the risk of the combined effects of heavy metal contamination on public health, Risk$_1$, …, Risk$_n$ – risk of exposure to each individual pollutant (Rybalova et al., 2019).

Estimation of risk indicators for public health and their characteristics are presented in Table 1.

<table>
<thead>
<tr>
<th>Significance of risk to public health (Risk)</th>
<th>Danger class</th>
<th>Risk characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01–0.19</td>
<td>1</td>
<td>Minor risk to public health</td>
</tr>
<tr>
<td>0.20–0.39</td>
<td>2</td>
<td>Increased risk to public health (extreme chronic effects on human health)</td>
</tr>
<tr>
<td>0.40–0.59</td>
<td>3</td>
<td>Significant risk to public health (severe chronic effects on human health)</td>
</tr>
<tr>
<td>0.60–0.79</td>
<td>4</td>
<td>High risk to public health (severe acute effects on human health)</td>
</tr>
<tr>
<td>0.80–1.00</td>
<td>5</td>
<td>Dangerous risk to human health (very large impact on human health)</td>
</tr>
</tbody>
</table>

### Research results and their discussion

Currently, the greatest environmental impact is on large cities, where anthropogenic impact manifests itself in various forms: microclimate change, air pollution, water, soil and vegetation by domestic and hazardous industrial emissions. Pollution from mobile sources, including private vehicles, is growing particularly fast. Geochemical anomalies with high content of various toxic substances, including heavy metals, are formed near highways. Both industrial and transport impacts are long-lasting and irreversible (Stoyko and Koynova, 2012).

The city of Odessa is characterized by a strong port economy, maritime complex, international transport activities of sea, rail, road, air transport. Within the city there are more than 300 basic industrial enterprises and more than 1000 small enterprises of various forms of ownership, which occupy about 26% of the city (Topchiyev, 2012). Among them are environmentally hazardous enterprises of I–III hazard classes: LLC “Industrial Company” KIK “- asphalt concrete products – enterprise of I hazard class, which requires a 1000-kilometer sanitary protection zone (SPZ), LLC “Olympus Circle “for the production of copper sulfate (III class, SPZ – 300 m), LLC “Cement” (I class, SPZ – 1000 m), PJSC “Odessa Refinery” – oil refining (I class, SPZ – 1000 m), PJSC “VO” Stalkanat-Silur “(III class, SPZ – 300 m), LLC FC “Biotransfer” “(I class, SPZ – 1000 m), JSC “Eskimnetoprodut “(II class, SPZ – 500 m), LLC Ukflckdsystems “- transshipment of propane, butane (II class, SPZ – 500 m), OPO JSC “Uktransnafta “- oil pumping (II class, SPZ – 500 m), JSC” Odessa CHP “(II class, SPZ – 500 m); “Interchem” – for the production of pharmaceutical substances (Class I, SPZ – 1000 m) and others (Topchiyev, 2012).

A significant share of modern air and soil pollution is due to the growth of the city’s car fleet. Thus, on the city highways, excesses over the maximum permissible concentrations (MPC) of chemicals in the air were recorded at 12 observation points (Rehional’na dopovid ‘…, 2018). The upper horizons of urban soils are the most polluted.

According to our research (Fig. 2), the content of heavy metals in the humus horizons of the city soils is characterized by significant fluctuations. The most polluted in terms of soluble forms of content of all studied pollutants are soils within the joint influence of industrial enterprises and road transport. Thus, the maximum lead content is 33 times higher than the MPC and 108 times the background content (key area № 12, st. Mykolayiv road, zone of joint influence of industrial enterprises and motor transport). The maximum levels of zinc, cobalt, cadmium and copper also significantly exceed the maximum allowable concentrations and are respectively 10 MPC, 4.5 MPC, 2.4 MPC and 30 MPC. High levels of zinc (hazard class I) and copper (hazard class I) have soils within the impact of road transport emissions. Thus, their maximum content is 6.5 and 29 MPC, respectively (key area № 11, Shevchenko Avenue, the impact zone of road transport). Only the soils of the Botanical Garden (key area № 1, French Boulevard, control) have a favourable ecological status, where the content of mobile forms of heavy metals is much lower than the maximum allowable concentrations, and the content of lead, cobalt, cadmium and copper – and background content.
To assess the ecological condition of soils and identify local man-made anomalies, the value of the concentration coefficient was calculated, which may indicate the activity of accumulation (K_s > 1) of heavy metals in the city soils. According to the value of the concentration coefficient (Fig. 3), only the soils of the Botanical Garden (control) have an optimal condition in terms of lead, cobalt, cadmium and copper. The insignificant accumulation of zinc (compared to other study areas) is due to the proximity of the highway. Accumulation of heavy metals was found in all other studied soils of the city. Thus, in terms of lead content, the ecological condition of soils varies from optimal (park zone) to unsatisfactory (zone of joint impact of emissions from motor transport and industrial enterprises; in terms of zinc and copper, soils in all studied areas of the city (83%), except the park zone. In terms of cobalt and cadmium content, about 60% of the soils of the study area have an unsatisfactory ecological condition.

The coefficient of danger (Cd) of the studied soils, which is determined by the level of excess pollutants in relation to the MPC varies from 0.01–0.19 (key section № 1, street French Boulevard, control) to 6.40–9.96, respectively, in content of lead and copper (zone of double impact of emissions from industrial enterprises and road transport) (Fig. 4). The corresponding pattern is determined for other heavy metals, which indicates a high degree of danger of heavy metals and the possibility of their migration in the soil-plant system.
Fig. 4. The coefficient of danger of heavy metals in the soils of Odessa

Comprehensive environmental assessment of soil pollution by a set of heavy metals was determined by the indicator of total soil pollution (Zc) (Fig. 5).

As can be seen from the presented figure, only the soils of the Botanical Garden (control) have a low danger (permissible). 60% of the study area of the city has a very high (extremely dangerous) level of pollution. The highest values of the total rate of soil pollution are determined within the impact of road transport (Zc = 758.72) and the combined impact of industrial enterprises and road transport (Zc = 921.6), which can adversely affect public health.

Therefore, according to the research aimed at assessing the ecological condition of urban soils, there was a significant excess of the maximum allowable concentration of all pollutants studied. In order to comprehensively assess the ecological condition of urban areas and develop appropriate environmental measures, it was important to assess the risk to public health due to heavy metal contamination of the soil. According to the developed gradation (Rybalova et al. 2019), only the territory of the city’s Botanical Garden has a small risk to public health, 40% of the study area – high and significant, 53% – high and dangerous risk to public health (Fig. 6).
The maximum risk indicator (Risk = 0.99) was determined on Mykolaivska Doroga Street (Luzanivka Beach) – one of the favorite places for recreation of Odessa residents and guests. The high pollution of the study area is due to the long-term impact of road transport (parking near the beach).

So, the assessment of the risk to public health allows us to identify the most dangerous areas where staying for a long time is dangerous to human health.

Conclusions

Therefore, studies show that:

1. The methodology for assessing the risk to human health from the impact of environmental factors, which is a new, relatively young scientific interdisciplinary field and is developing rapidly around the world, can solve a wide range of environmental and public health problems. The method of using the probit regression model to assess the risk to public health in comparison with traditional methodological approaches to determining the hazard index has significant advantages and allows one to identify negative factors of environmental pollution, to determine the possible degree of risk to human health.

2. The obtained values of the main ecological indicators showed that the soils of the city of Odessa in the territories adjacent to the transport routes and within the influence of industrial enterprises suffer from significant man-made impact. This is evidenced by the accumulation, primarily of lead, copper and zinc, to a lesser extent cobalt and cadmium. It was found that more than 90% of the studied areas in terms of total pollution exceed the permissible danger, which can significantly adversely affect human health.

3. 73% of the study area of Odessa city has a significant risk to public health, which indicates the need for continuous monitoring and measures to reduce pollution of the urban environment.

4. The methodology for assessing the risk of public health from pollution of urban soils with heavy metals is a promising approach to quality control of the system “environment – human health” and requires further research.

5. To assess the medical and environmental condition of the system “soil-human health” it is necessary to conduct additional studies that will identify the degree of correlation between the impact of soil pollution of the city HM on individual diseases.

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