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Particulate Air Pollution in Central Serbia and some Proposed Measures for the Restoration of Degraded and Disturbed Mining Areas

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biocrusts
cyanobacteria

ABSTRACT

Mining causes soil degradation, particle emission, and air and water quality deterioration. This study estimates some health risks in districts of Central Serbia affected by surface mining activities, and proposes measures for land restoration. The epidemiological risk assessment was based on data for seven cancers and three cardiovascular diseases during 2010 - 2020. Results showed a statistically significant increase in the incidence of lung and bronchial cancer in critical districts. Borski district stood out with the highest incidence rates for cardiovascular diseases. The suspected role of particulate air pollution from the mining industry in health deterioration calls for intensified air quality monitoring and development of mitigation technologies. A restoration strategy called the Pan-Life-Carpet technology is proposed for the restoration of mining areas and for air and water pollution control.

Introduction

Land is a vital resource for human social and economic wellbeing. However, many parts of land ecosystems are under climatic and anthropogenic pressure. Anthropogenic climate changes accelerate natural and induce anthropogenic land degradation (Talukder et al., 2021). Land degradation leads to the deterioration of terrestrial and aquatic ecosystems and decrease of biodiversity. It presents one of the most severe ecological challenges of to-

day (Perović et al., 2021) that leads to the reduction or loss of the biological or economic productivity and complexity of the land (UNCCD, 1994). Besides natural processes, main causes of land degradation are improper soil and vegetation management, overgrazing, industrial activities, waste deposition and mining, urbanization and infrastructure development, release of airborne pollutants, disturbance of the water cycle (UNDP, 2022), while climate

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change further amplifies the impact of drivers of land degradation (IPBES, 2018).

One of the most visible processes of soil degradation is soil erosion (UNDP, 2022). Soil erosion is a major environmental problem, threatening human safety and global socio-economic development (Sun et al., 2013; Jiang et al., 2019). Soil erosion can affect water and air quality. Erosive and unprotected soil presents a source of particulate pollution, while soil particles can contain other pollutants such as metals and organic pollutants (Goudie, 2014; Giltrap et al., 2021). The global emission of dust from the soil to the atmosphere has been estimated to be 3000 million tons annually (Katra, 2020).

Mining modifies, degrades and pollutes land (Padro et al., 2022). Surface mining induces immediate loss of soil, formation of waste (ash, slag, and tailings) and wastewater resulting from tailing processing (Pavlović et al., 2017). A major problem of mining is the mining waste, i.e. deposits of ash, slag and tailing that are usually disposed of without further utilization (Pavlović et al., 2017). Serbia produces about 40 million tons of mining waste every year (Official Gazette of the Republic of Serbia, No 12/2022). Mining is one of the main processes connected with soil loss and degradation in Serbia (Ličina et al., 2011; Pavlović et al., 2017). Emission of the soil particles to the atmosphere deteriorates air quality of the surroundings and remote areas (Goudie, 2014; Giltrap et al., 2021). Tian et al. (2019) showed that more than half of road dust sieved to 10 μm , collected at different distances to the mine and tailings, originate from the mine.

The primary pollutant produced by surface mining is particulate matter (PM) (Kumar Patra et al., 2016). PM consists of heterogeneous components, formed due to chemical reactions between inorganic and organic substances (soot, dust, soil components, vehicle exhaust gases, combustion products, etc.) (Manisalidis et al., 2020; Matić Savićević, 2020). According to the size PM are divided into three groups: PM₁₀ (coarse particles, between 2.5–10 μm), PM_{2.5} (fine particles, < 2.5 μm) and PM_{0.1} (ultra-

fine particles, < 100 nm) (Franck et al., 2011; USEPA, 2016). The carbon core of PM can adsorb various chemicals such as aromatic and aliphatic compounds, biological allergens, endotoxins, heavy metals (e.g. Pb, As, Cd, Ni) etc. (Matić Savićević, 2020; Knežević et al., 2021) (Figure 1).

PM are associated with various health issues (Kelly & Fussel, 2015), and according to the International Agency for Research on Cancer (IARC) of the WHO, they belong to the Group 1 carcinogens, together with outdoor pollution (Loomis et al., 2013; IARC, 2016). It is estimated that exposure to air pollution, especially PM, results in millions of deaths annually (Kelly & Fussel, 2015; WHO, 2019; 2021). The effect of PM on the human body is determined by size (Valavanidis et al., 2008). Particles larger than 10 μm are generally trapped in the mucous membrane of the nose and throat and can be swallowed (Giltrap et al., 2021). Most PM₁₀ are deposited in the upper airways (Brown et al., 2002) and can get deposited in the lungs where they cause inflammatory processes (Knežević et al., 2021). PM_{2.5} penetrate deep lung tissue (Giltrap et al., 2021) (Figure 1). Particle shape (International Commission on Radiological Protection, 1995; Sankaran et al., 2023), adsorbed substances (Valavanidis et al., 2008), origin, chemical compositions (Valavanidis et al., 2008; Xing et al., 2016), exposure time (Yang et al., 2019; Orellano et al., 2020), mechanisms of toxicity (Valavanidis et al., 2008) medical condition (e.g. preexisting heart and lung disease, diabetes) and stage of life (elderly and children) (Sacks et al., 2011; Manisalidis et al., 2020) determine the effects of PM on the human body, also.

PM is an important pollution in open mine areas, especially PM₁₀ (Bui et al., 2019). In recent years, the concentration of PM₁₀ in Serbia has been higher than the allowed 50 $\mu\text{g}/\text{m}^3$ (WHO, 2019). Mining has a long-standing tradition in the Republic of Serbia with potential to expand (Popović et al., 2015). Kumar Patra et al. (2016) summarized medical evidence of health deterioration due to inhalation of PM pollution from surface mines. Mining impacts cardiovascular and respiratory systems, contributes to the neurological disorders and kidney damages (Ku-

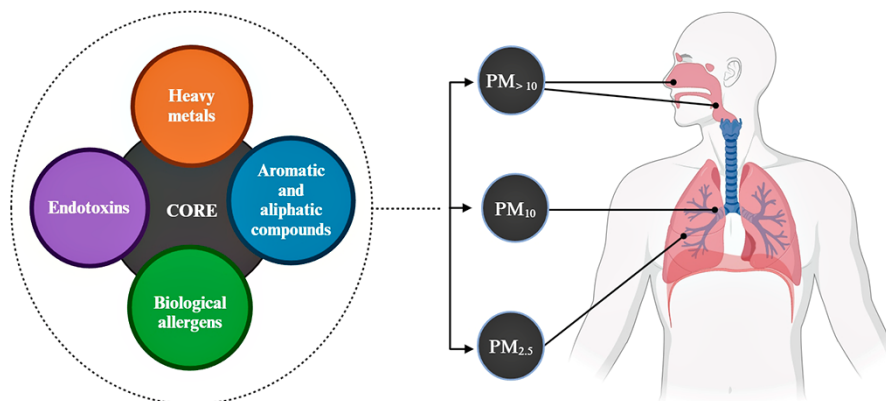


Figure 1. Description of heterogeneity of PM in the air and their impact on the respiratory system depending on the size of the PM (made with <https://www.biorender.com/>)

mar Patra et al., 2016; da Silva-Rego et al., 2022). One of the Sustainable Development Goals (SDGs) in the Agenda 2030 is to “substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination” by 2030 (UN, 2015). There-

fore, this work aims to estimate the health risk in the districts of Central Serbia that are affected by surface mining and mining waste disposal, as well as to propose measures for simultaneous mining land restoration, air pollution reduction and health risk decrease.

Data and methods

Databases for epidemiological analyses

The epidemiological risk assessment was based on the incidences of cancers and cardiovascular diseases. According to the Batut definition, standardized incidence and mortality rates represent theoretical values obtained through a specific technical process involving the introduction of a standard population. Typically, this standard population can be the world population (ASR-W), the European population (ASR-E), or a truncated population (ASR-TRUNC). These standardized rates overcome differences (most commonly by sex and age) that exist in different populations, making them suitable for comparisons (Batut, 2023c). The possible relation between PM pollution in degraded/disturbed areas and incidence of cancers and cardiovascular diseases in Central Serbia was based on data published by the Institute of Public Health of Serbia, ‘Dr Milan Jovanović Batut’ (Batut, 2023, 2023b, 2023c).

The seven examined cancers and three cardiovascular diseases are listed in Table 1, including corresponding abbreviations, as well as their codes from the 10th revision of the International Statistical Classification of Diseases and Related Health Problems (ICD), a medical classification list by the World Health Organization (WHO). The collected data concerning the mentioned diseases covered the period 2010 - 2020. The data included information concerning cancers in both males and females, except for the

Table 1. Examined cancers and cardiovascular diseases with abbreviations

Abbr.	ICD - 10 codes	Cancer and cardiovascular diseases
C1	C00 - C14	Malignant neoplasm of lip, oral cavity and pharynx
C2	C32	Malignant neoplasm of larynx
C3	C34	Malignant neoplasm of bronchus and lung
C4	C67	Malignant neoplasm of bladder
C5	C71	Malignant neoplasm of brain
C6	C91 - C95	Leukemia
C7	C00 - C97	Malignant neoplasms
CV1	I21	Acute myocardial infarction
CV2	I20.0	Unstable angina pectoris
CV3	I24.9	Acute coronary syndrome

Source: <https://icd.who.int/browse10/2019/en#/C06.9> (Internet 1).

cancers of pharynx, oral cavity, and larynx, for which data on females was not available.

Regional division of Central Serbia

According to the administrative division, Central Serbia has 18 districts. The investigated districts and corresponding abbreviations are presented in Table 2. The incidence of investigated types of cancers and cardiovascular diseases are documented by districts. Thus, it is possible to estimate the occurrence of diseases in degraded mining areas.

Table 2. Investigated districts of Central Serbia and the total number of inhabitants for the period 2010 – 2020 per district

Nº	District	Average number of inhabitants per district 2010 - 2020
1	Kolubarski	168612
2	Mačvanski	289074
3	Raški	305209
4	Moravički	205360
5	Zlatiborski	276884
6	Rasinski	231362
7	Šumadijski	286174
8	Pomoravski	205571
9	Braničevski	174794
10	Podunavski	192521
11	Zaječarski	113092
12	Borski	118762
13	Nišavski	367036
14	Pčinjski	204323
15	Jablanički	208448
16	Toplički	87473
17	Pirotski	88156
18	Beograd	1541347

Statistical analysis

A division was made into critical and non-critical districts. For critical districts were considered those which are affected by soil degradation and dust pollution from main mining sites of Central Serbia. The minings in Bor, Majdanpek, Kostolac and Kolubara as well as mining waste

disposals 'Nikola Tesla A' and 'Nikola Tesla B' were considered as main degraded mining sites (Figure 2, circled). The influence of dominant winds was also considered in districts categorisation. Among the 18 examined districts, ten were critical and represented the first group in the statistical comparison (Beograd city, Podunavski, Borski, Moravički, Kolubarski, Šumadijski, Mačvanski, Braničevski, Zaječarski and Pomoravski). The rest of the districts of Central Serbia were considered as non-critical districts (Pčinjski, Rasinski, Jablanički, Nišavski, Raški, Toplički, Pirotski and Zlatiborski).

Results

Degraded mining areas in Serbia as particulate matter air pollution source

According to the analysis of the map showing damaged and degraded areas in Serbia with prominent main mining areas (Figure 2), following districts could be consid-

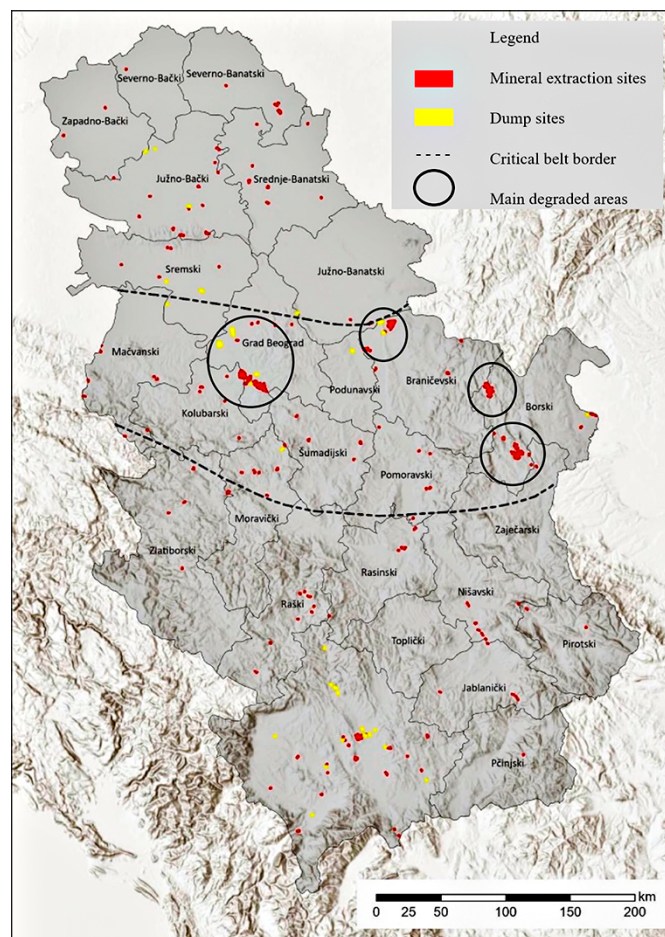


Figure 2. Map of damaged and degraded areas as a source of particulate air pollution in Serbia with ten affected districts in Central Serbia (based on Corine Land Cover 2018 (V2020_20U1), European Environment Agency (EEA))

The values of the incidences of selected cancers and cardiovascular diseases were statistically analyzed using Student's t-test. Survey results were obtained using statistically significant differences between critical and non-critical districts in Serbia with a reliability of 95% ($p = 0.000 < 0.05$). The normality of the distribution was determined using the Shapiro-Wilk test. Derived values are presented in diagrams in order to visualize possible relationships between the incidences of seven types of cancers and three types of cardiovascular diseases with degraded mining areas which are a source of PM air pollution.

ered as most exposed to the PM air pollution from mining areas: Beograd city district, Mačvanski district, Kolubarski district, Moravički district, Šumadijski district, Podunavski district, Pomoravski district, Braničevski district, Borski district and Zaječarski district.

Epidemiological analyses

The ratio of the incidence of cancer and cardiovascular diseases was determined by district in Central Serbia for the period 2010 - 2020. Critical districts showed a statistically significant association with an increased incidence of lung and bronchial cancer compared to the non-critical districts ($p = 0.027$, $p < 0.05$) (Figure 3a). The highest mean incidence of lung and bronchial cancer was determined in the following critical districts: the Beograd city (75.86) and Podunavski (70.15) districts. Statistical analyses showed the association of critical districts with an increased incidence of cancer of the oral cavity and pharynx (cavitas and pharynx) was marginally significant ($p = 0.086$, $0.05 \leq p < 0,1$) (Figure 3b). However, incidence analysis for other investigated cancers (C2, C4, C5, C6, C7) showed that there is

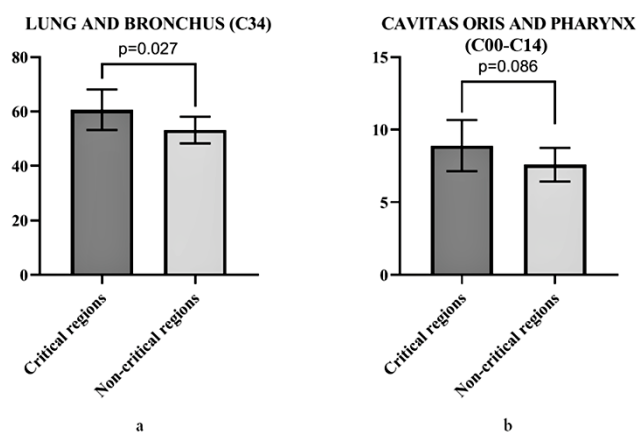


Figure 3. Incidence of lung and bronchial cancer (a), oral cavity and pharynx cancers (b) in Central Serbia for the period 2010 – 2020

no statistically significant difference between the critical and non-critical districts.

The incidence analysis for the examined cardiovascular diseases (CV1, CV2, CV3) showed that there is no statistically significant difference between the selected critical and non-critical districts. Due to the fact that cardiovascular diseases are the most common cause of death in Serbia in 2019 (Vasić et al., 2022), the incidence values among all districts in Central Serbia were compared, whereby the Borski district stood out in particular. Based on the incidence values, this district took the first place in the case of acute coronary syndrome, the second place in the case of unstable angina pectoris, and the third place in the case of acute myocardial infarction. Owing to the fact that this district is the most affected by soil (surface) degradation, the incidence values of the Borski district in the period from 2010 - 2020. years were compared with each district individually as well. Analyses proved that there is no statistically significant difference between the Borski district on one side and the districts with the highest incidence values.

Acute coronary syndrome disease in Borski district, with a standardized incidence rate of 200.768 per 100,000 inhabitants, ranks this district with the highest incidence compared to other districts (Figure 4). Statistical processing of the data did not show statistical significance difference in comparison with Zaječarski district that belongs to the group of critical districts as well ($p = 0.466$).

In the case of unstable angina pectoris, the Borski district, with standardized incidence rate values of 64.077 per 100,000 inhabitants in the observed period, ranked second in terms of the incidence, after the Nišavski district (incidence value = 76.064) and ahead with the Zaječarski district (incidence value = 58.732) (Figure 5). Statistical analyses show no significant difference between the Borski district and Nišavski ($p = 0.426$), Zaječarski ($p = 0.574$) and the Beograd city district ($p = 0.505$) on the other side. Results show that Borski, Zaječarski and the Beograd city districts, belonging to critical districts, are among the leading districts for unstable angina pectoris according to incidence values.

In the case of acute myocardial infarction, the Borski district, with standardized incidence rate values of 135.964 per 100,000 inhabitants in the observed period, ranked third in incidence, after Šumadijski and Raški districts with incidence values of 146.305 and 137.084 respectively (Figure 6). There is no statistically significant difference in the incidence values for the acute myocardial infarction between Borski and some other critical districts: Šumadijski ($p = 0.615$), Raški ($p = 0.327$), Rasinski ($p = 0.515$), Toplički ($p = 0.557$), Zaječarski ($p = 0.484$), Pčinjski ($p = 0.405$), Pirotski ($p = 0.420$), Mačvanski ($p = 0.346$) and Kolubarski ($p = 0.283$). Still, Borski district stood out as the district with the leading high incidence for analyzed cardiovascular disease in the observed period.

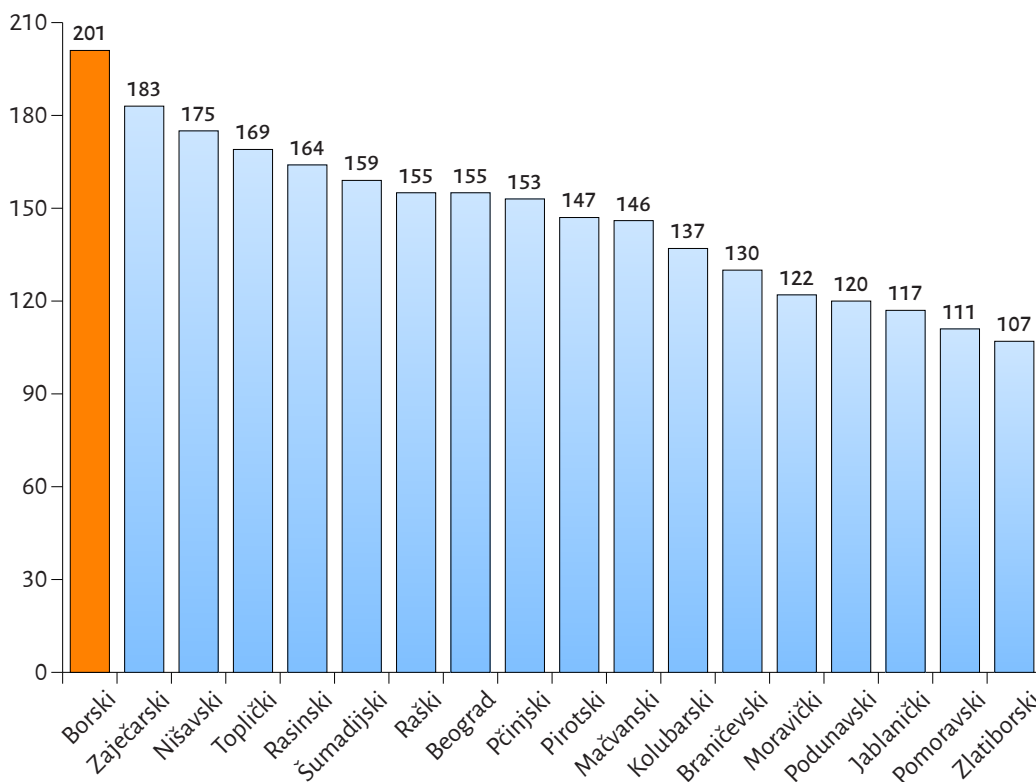


Figure 4. Standardized incidence rates (per 100,000 inhabitants) of acute coronary syndrome disease in Central Serbia for the period 2010 – 2020

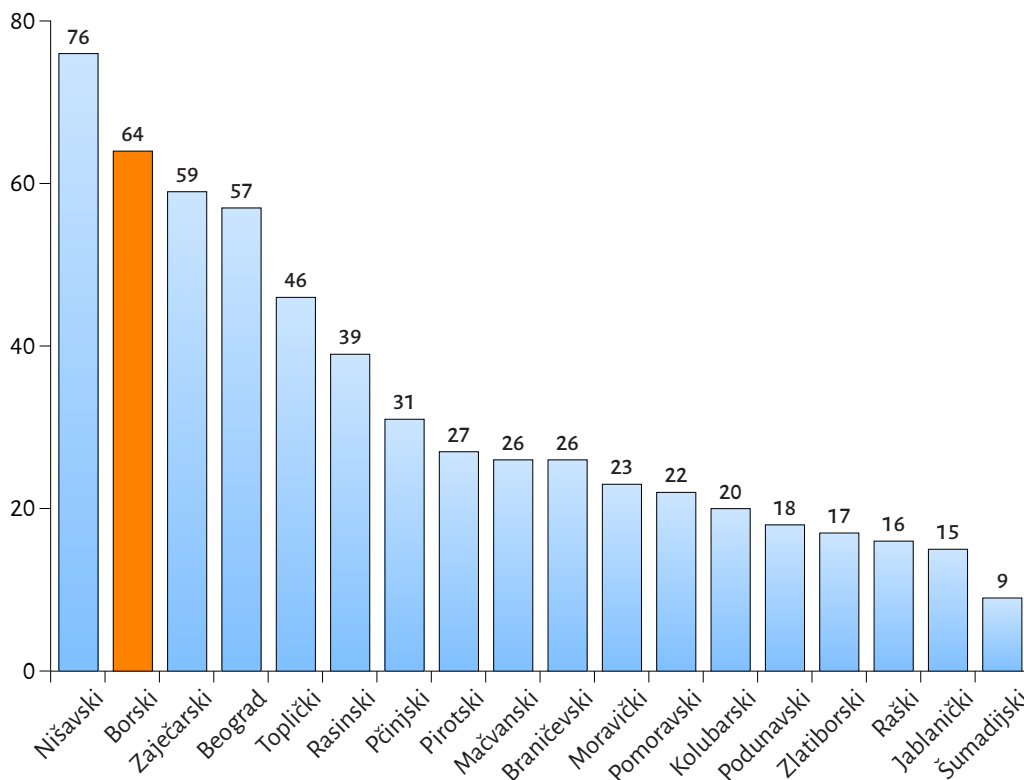


Figure 5. Standardized incidence rates (per 100,000 inhabitants) of unstable angina pectoris in Central Serbia for the period 2010 – 2020

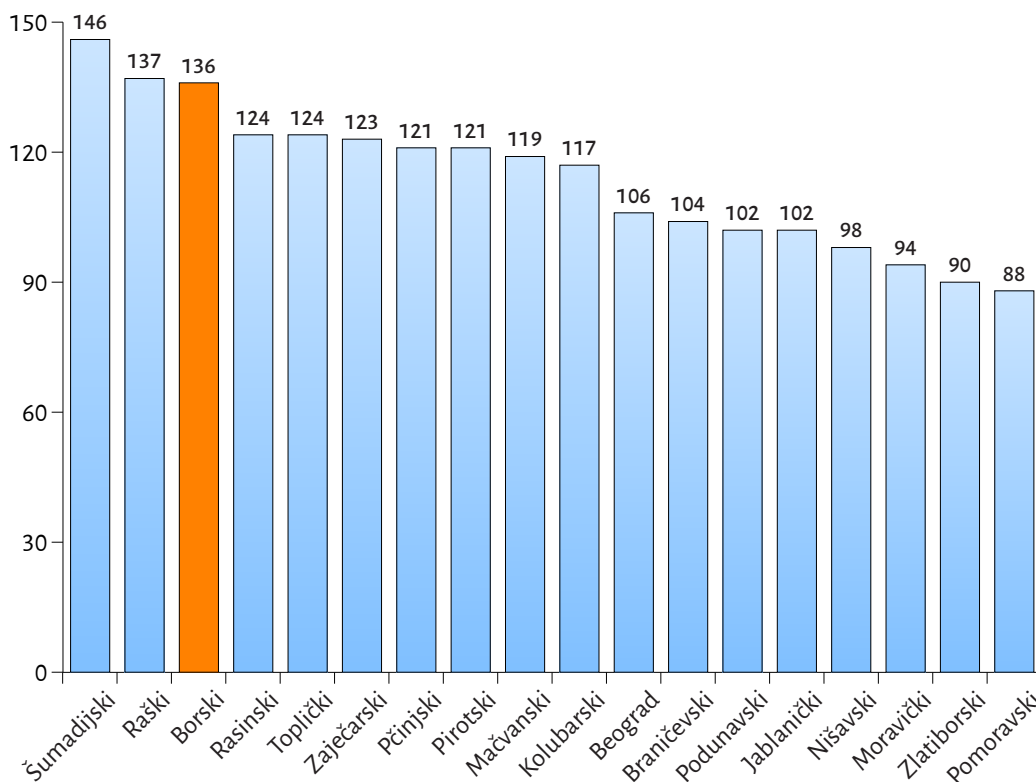


Figure 6. Standardized incidence rates (per 100,000 inhabitants) of acute myocardial infarction in Central Serbia for the period 2010 – 2020

Discussion

Mining activities as a health risk in Central Serbia

Land degradation is a world-wide problem. Serbia is under a high risk of land degradation and associated consequences, with an expected increase in the future (Pavlović et al., 2017; UNDP, 2022). The most pronounced process of soil degradation in Serbia and many other European countries is soil erosion (Pavlović et al., 2017; SEPA, 2018). Degraded soil presents a source of air pollution (Giltrap et al., 2021). Soil degradation by mining activities and tailings and waste disposals plays an important role in the generation of atmospheric dust with respect to the quantity of the particulates generated (Csavina et al., 2012). Based on the map of damaged and degraded areas in Serbia (Figure 2), districts around the main mining areas in Central Serbia could be considered as the most exposed districts suffering from PM air pollution from surface mining activities, and thus they have been regarded as critical districts in this study. Regardless of the presence of the surface mines in Vojvodina, this region was not taken into consideration in this study due to high industrialization and agricultural areas. Agricultural areas in Serbia are mostly located in Vojvodina, where more than 60% of the area is in the category of hazardous sensitivity and 36% in the category of medium sensitive to wind erosion (Baumgertel et al., 2019). Mines in Bor and Majdanpek (Figure 2, circled) are one of the main surface mining areas in Serbia. They are located in the borderline of Borski district with surrounding Zaječarski, Pomoravski and Braničevski districts. Kostolac mine (Figure 2, circled) is located in Braničevski district, close to Podunavski district. Kolubara mine (Figure 2, circled) and 'Nikola Tesla A' and 'Nikola Tesla B' mine waste disposals (Figure 2, circled) in Beograd city district are surrounded by Mačvanski, Kolubarski, Moravički, Šumadijski and Podunavski districts. The geographical positions of the mentioned districts, in relation to mines and mine waste disposals, indicate their exposure to mine-originating PM air pollution. Therefore, the mentioned districts form a potential critical belt with the increased risk of exposure to PM air pollution from degraded mining lands and mining waste disposal sites.

Statistical analyses indicated a statistically significant association between an increased incidence of lung/bronchial cancer in the critical districts for the period 2010 - 2020 (Figure 3a). Beograd city district showed the highest incidence of lung and bronchial cancer during the observed period of 11 years compared to other districts of Central Serbia. Main mining and degraded areas impacted Beograd city district are Kolubara coal basin with total area of about 600 km² (Milanović et al., 2017) and thermal power plant ash disposal sites 'Nikola Tesla A' with an area

of 400 ha (Gajić, 2014) and 'Nikola Tesla B' with an area of 600 ha (Nišić et al., 2015). Opencast coal mines in Serbia are mainly located in areas of fertile alluvial soils and occupy about 12,000 ha, with an expected increase of 200 ha each year (Pavlović et al., 2017). The eight thermal power plants in Serbia produce 8 Mt of ash annually (Electric Power Industry of Serbia, Technical Report 2010), while only 2.7% of the ash in Serbia is utilized for other purposes, mainly in the construction industry (Pavlović et al., 2017). Mining waste that is not subjected to further utilization is usually deposited in the open air (Pavlović et al., 2017). Large areas of deposited mining waste and opencast mines are exposed to the environmental erosive forces, e.g. wind erosion. Wind directions reported for the meteorological stations Beograd and Valjevo (Republic Hydrometeorological Service of Serbia) can contribute to the dispersion of particles from ash disposals and the Kolubara mine degraded land (Figure 7). Studies have shown increased lung cancer risk among miners with exposure to coal dust (Une et al., 1995; Hosgood et al., 2012; Tomaskova et al., 2012). Minowa et al. (1988) showed a higher lung cancer mortality in administrative units with coal mines in Japan. Fly coal ash has also been recognised as a health risk factor for lung cancer development (Whiteside & Herndon, 2018). Thus, the results of this study and current knowledge of the role of coal dust and fly ash in lung cancer development indicate that district Beograd city, where Kolubara coal mine and ash disposals ('Nikola Tesla A' and 'Nikola Tesla B') are located as, well as surrounding districts could be considered as risk areas for lung cancer development. Besides cancers, coal mine dust (Ross & Murray, 2004; Laney & Weissman, 2014) and fly ash (Shrivastava et al., 2015) are promoting other respiratory diseases in the affected areas. Tomaskova et al. (2012) showed increased lung cancer risk in coal miners with pneumoconiosis, compared to those without pneumoconiosis. This indicates a greater susceptibility to developing lung cancer in people with an already impaired immune system. Examining the health status of the population in the territory of the municipality of Lazarevac, district affected by Kolubara mining activities, Muratović (2015) pointed out the importance of air pollution of the mining areas in the development of respiratory diseases such as bronchitis, asthma and pneumonia. This study did not include the mentioned diseases due to the lack of official data. Therefore, monitoring and future research should cover a wider spectrum of respiratory diseases in relation to target districts due to the significant contribution of mine activities to air pollution.

This study showed that there is a statistically significant but marginal association between elevated incidence of cancer of the oral cavity and pharynx in the male popu-

lation and critical districts. Due to lack of data, this study did not include the female population in examining the association of cancer of the oral cavity and pharynx in the critical districts. There are studies that showed the association of pharynx cancer with exposure to coal dust (Goldberg et al., 1997; Laforest et al., 2000). Thus, the contribution of PM air pollution from mine sites in development of this cancer should not be underestimated, but deserves more attention in further research.

According to the World Health Organization, particulate air pollution is significantly associated with cardiopulmonary diseases and mortality (WHO, 2021). Cardiovascular diseases are one of the main causes of death in Serbia (Vasić et al., 2022) and world-wide (Gaziano, 2001; Gaidai et al., 2023; Samuel et al., 2023; Woodruff et al., 2024). This study showed that there is no statistically significant difference between the selected critical and non-critical districts in analyzed cardiovascular diseases. One of the reasons could be that the development of cardiovascular diseases is influenced by an array of factors (Dahlöf, 2010), and not only by air pollution originating from surface mining activities. Still, among all districts in Central Serbia, Borski district has the leading high incidence for analyzed cardiovascular disease. Most of the land degraded by surface mining in Serbia is located in Borski district and it is caused by copper mining in Majdanpek and Bor (Pavlović et al., 2017). The mining activity has degraded areas of about 1110 ha in Bor and 12,060 ha in Majdanpek which is about 60% of the total agricultural land (Pavlović et al., 2017). Wind directions meas-

ured from the meteorological station Crni Vrh (Republic Hydrometeorological Service of Serbia) in Borski district indicate possible contribution of wind to the emission of particles from mine degraded lands to neighbor and remote sites (Figure 7). Bor is one of the most air polluted regions in Serbia and beyond. Air quality monitoring for Bor showed that annual arsenic concentrations exceeded the proposed limit value at all measuring sites and annual lead and cadmium concentrations frequently exceeded the proposed limit value for the period from 2009 to 2015 (Serbula et al., 2017). Mining activities in Majdanpek also negatively impacted the environment, and consequently air quality (Ilić Krstić et al., 2020). Study conducted by Nkosi et al. (2016) showed that elderly people exposed to pollution arising from mine dumps in South Africa had a significantly higher prevalence of cardiovascular and respiratory diseases and that living close to mine dumps was significantly associated with asthma, hypertension, pneumonia, emphysema, arrhythmia, and myocardial infarction. Higher mortality rates from chronic cardiovascular disease compared to non-mining areas have also been observed in mining areas of Central Appalachian States (Esch & Hendryx, 2011). Based on the known negative impact of air pollution from mining areas on the cardiovascular system (e.g. Esch & Hendryx, 2011; Nkosi et al., 2016.) and results of this study, mining activities and consequent heavy metal pollution should be considered as important risk factors for development of cardiovascular diseases.

Despite the existence of the Kostolac mine in Braničevski district, the low incidence of analyzed diseases can be

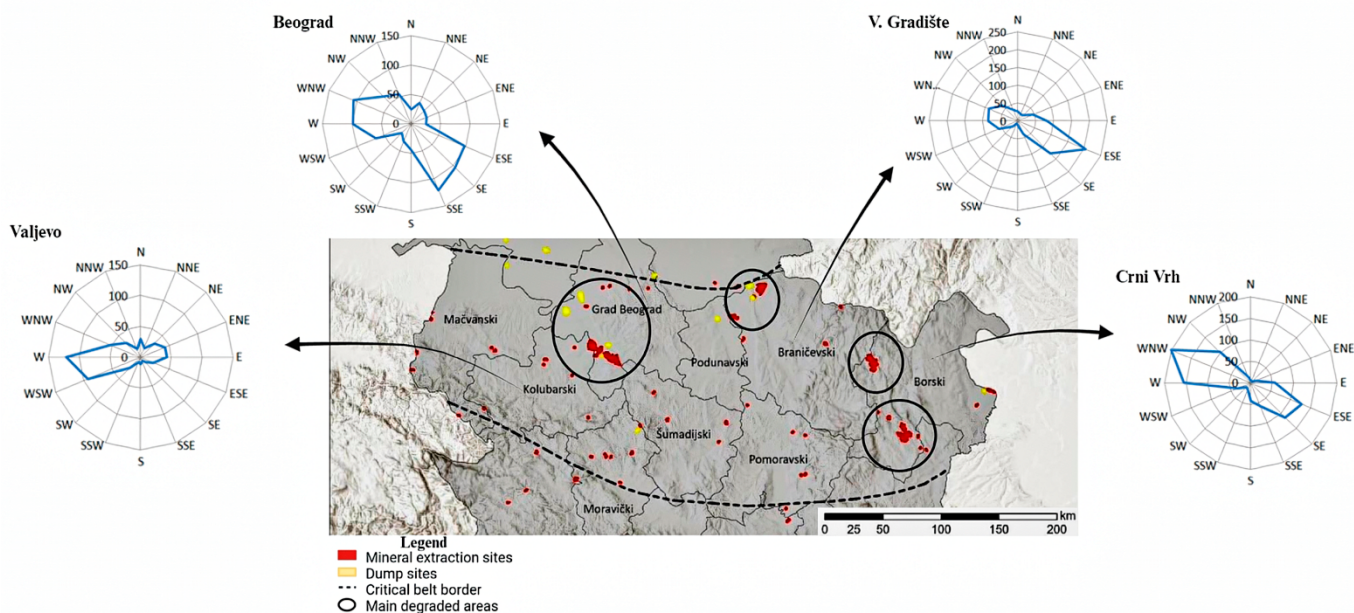


Figure 7. Representative relative frequencies of wind directions in per mille (1981 - 2010) for critical belt: Borski district (meteorological station Crni Vrh), Braničevski district (meteorological station V. Gradište), Beograd city district (meteorological station Beograd) and Kolubara district (meteorological station Valjevo) (based on Corine Land Cover 2018) (V2020_20u1), European Environment Agency (EEA), (Republic Hydrometeorological Service of Serbia)

due to its position in the border zone and the dominant east-southeast wind (ESE wind, Veliko Gradište meteorological station) (Republic Hydrometeorological Service of Serbia) (Figure 7).

Mining activities such as excavation, crushing, grinding, separation, smelting, refining, and tailings are important sources of contaminated dust that can be wind-transported to neighbour places (Serbula et al., 2010; Csavina et al., 2012; Zanetta-Colombo et al., 2022). Local copper mining activities in northern Chile are connected to the increased metal concentrations in dust collected from roofs and windows of indigenous villages (Zanetta-Colombo et al., 2022). However, in Serbia there is an insufficient monitoring of particle pollution (Matić Savićević & Stojanović, 2019), even though air pollution harms the economy of the country through lower labour output (World Bank, 2016), increased health expenses, damage to crops and infrastructure, and costs related to climate change and environmental protection (WHO, 2021). Total treatment costs in 2017 were 30% higher compared to 2010, and amounted to circa €1.7 billion and €1.4 billion, respectively. The modern way of living is considered to have a huge impact on the increase in the cost of treating cardiovascular diseases. According to the WHO, particulate air pollution is significantly associated with cardiopulmonary diseases and mortality, and other health conditions (WHO, 2021). In studies from other countries (Minowa et al., 1988; Une et al., 1995; Goldberg et al., 1997; Laforest et al., 2000; Ross & Murray, 2004; Esch & Hendryx, 2011; Hosgood et al., 2012; Tomaskova et al., 2012; Laney & Weissman, 2014; Shrivastava et al., 2015; Nkosi et al., 2016; Whiteside & Herndon, 2018) and this study from the Republic of Serbia indicate the role of the particulate air pollution from the mine industry in health deterioration. Thus, intensified monitoring of PM air pollution originating from mining activities, assessment of their influence on the health and combating particulate air pollution is of environmental, health, economic and social importance in Serbia and world-wide.

Proposed measures for restoration of degraded and disturbed mining areas to combat particulate air pollution

Even though there have been made certain efforts towards improving restoration practice in Serbia, restoration activities in Serbian mining basins are considered poorly applied in practice (Randelović et al., 2017). Natural recovery of the vegetation cover could take a long time and the success of land restoration by higher plants in these environments could be limited. The process of natural recovery of satisfactory vegetation cover on mine wastes could last from 50 to 100 years (Bradshaw, 1997). Restoration of the mine tailings and waste deposits by recultivating higher plants is limited because of adverse environmental factors

present in these environments, such as water and nutrient deficiency, high temperatures, adverse chemical properties of the substrates (Pavlović & Mitrović, 2013; Pavlović et al., 2017; Li & Liber, 2018). Li & Liber (2018) study showed that low levels of soil moisture and available nitrogen were the major limiting factors affecting plant community development on the coal gob pile, not metal toxicity.

Dominant biological cover in the environments where development of higher vegetation is hindered is represented by biological soil crusts (biocrusts) (Veste, 2005). Biocrusts are bio-sedimentary complexes of organisms (cyanobacteria, mosses, lichens, fungi and bacteria) and soil particles (Eldridge & Green, 1994; Williams et al., 2012). This community is highly tolerant to desiccation and long-term drought (Veste, 2005). Biocrust characterizes successional development that begins with cyanobacterial colonization of the soil (Lan et al., 2012; Williams et al., 2012). Several cyanobacteria genera are nitrogen fixers within biocrusts (Belnap & Lange, 2003). They produce protective layers of exopolysaccharides that have multiple roles in the biocrust community such as binding the soil particles, retaining water and nutrients (Colica et al., 2014; Rossi & De Philippi, 2015; Mugnai et al., 2017). Cyanobacteria and their exopolysaccharides form a complex protective network with incorporated soil particles over the soil surface (Dulić et al., 2017; Palanački Malešević et al., 2021). They trap (Malam Issa et al., 2001; Williams et al., 2012; Svirčev et al., 2013; 2019; Dulić et al., 2017; Palanački Malešević et al., 2021), metabolize and stabilize the airborne particles (Dulić et al., 2017; Palanački Malešević et al., 2021; Svirčev et al., 2013; 2019). Accordingly, colonization of the surface of the substrate by biocrusts provides essential ecosystem functions. They control water and nutrient availability and soil stability in the environment (Chamizo et al., 2016; 2018; Palanački Malešević et al., 2021).

Artificially induced biocrusts have been proposed to fight land degradation in adverse environmental conditions, and cyanobacterial inoculation have been introduced as a potential solution (e.g. Wang et al., 2009; Rossi et al., 2017; Chamizo et al., 2018; Antoninka et al., 2020; Rossi, 2020). Some of the latest studies employing cyanobacteria for the restoration of degraded land and the mitigation of adverse environmental conditions are reviewed in the study by Palanački Malešević et al. (2024). The importance of biocrusts and cyanobacteria in the land restoration after soil disturbance induced by mining has been recognized (Doudle & Williams, 2010; Doudle et al., 2011; Williams et al., 2019). Cyanobacterial inoculation induces biocrusts development on mine tailings, which further mitigates wind erosion and enhances tailing fertility enabling establishment of vegetation cover (Rezasoltani et al., 2023). However, biocrusts development in the field conditions can be hindered by adverse environmental factors. Water is a primary factor affecting biocrust growth (Bu et

al., 2014) and drought is common in most mine environments (Zhu et al., 2022). Dew enables physiological activity of cyanobacteria and maintenance of biocrust biomass, but for biocrust biomass growth a higher amount of water than dew is needed (Rao et al., 2009). Since the restoration process could take a long time due to the lack of moisture during the initial phase of biocrust development, it is necessary to find strategies for acceleration of the biocrusts establishment and further growth. Assisted development of artificially induced biocrusts through mitigation of key limiting factors could provide promotion of inoculum viability and growth rate. Biocrust carpet engineering could enable quick, sustainable and environmentally friendly solutions to mining land restoration.

The role of biocrust carpet engineering, through assisted development of artificially induced biocrusts, in the restoration of mine tailings and waste deposits of mining to control air pollution should not be neglected. To provide a quick, sustainable, and environmentally friendly solution, some requirements must be met:

- Providing *interaction of dust particles with cyanobacteria* would lead to particle capture into the sticky cyanobacterial biofilm and their further entrapment in this community during dry and wet environmental conditions (Svirčev et al., 2013; 2019; Palanački Malešević et al., 2021). Inoculation of cyanobacterial biomass in the affected environments would promote this interaction.
- Providing an *extended wet period* would enable longer metabolic activity of cyanobacteria and thus active collection of air particles by sticky biofilm. During wet environmental conditions, metabolically active cyanobacteria trap, metabolize and deposit airborne particles as part of their life strategy in providing minerals for biocrusts growth (Williams et al., 2012; Svirčev et al., 2013; 2019). Polysaccharide support to cyanobacterial inoculum could improve water availability, provide extended wet period, and

promote cyanobacterial metabolic activity and biocrusts growth. There are studies that indicate the potential of superabsorbent polymer (Park et al., 2014) and nanocomposite (Chi et al., 2020; Li et al., 2021) as soil fixing and water retention agents in promoting biocrust growth.

Attention should be paid to the technical feasibility of the polysaccharide-supported inoculation of cyanobacteria in the field. A physical support to the polysaccharide-cyanobacterial carpet should be engineered to enable easier carpet applicability at the field. This polysaccharide-cyanobacterial carpet with physical support creates microenvironmental conditions for the accelerated initiation and growth of biocrusts. This technology could be called the Pan-Life-Carpet (PLC) concept, i.e. a carpet for the initiation of life on mining and other degraded land areas.

Degraded land is a source for dust emission and pre-condition for sediment erosion. Such land directly causes air pollution by dust emission to the atmosphere and water pollution by soil and sediment erosion to neighboring water bodies (Figure 8a). Airborne particles from polluted air are carried by the wind to distant regions and very often end up in water ecosystems. In this way, water bodies are also indirectly polluted by airborne particles from polluted air. Therefore, there is a need for sustainable solutions to the problems of land degradation and consequent air and water pollution in such challenging environments. Cyanobacteria and their sticky exopolysaccharides, that are part of PLC technology, are known to capture, accumulate and stabilize airborne particles (Svirčev et al., 2013; 2019; Palanački Malešević et al., 2021). Implemented PLC technology and consequent accelerated biocrust development stabilize soil surface, prevent dust emission and sediment erosion, providing land restoration and prevention of air and water pollution, respectively (Figure 8b). The sticky structure of PLC provided by cyanobacterial exopolysaccharide

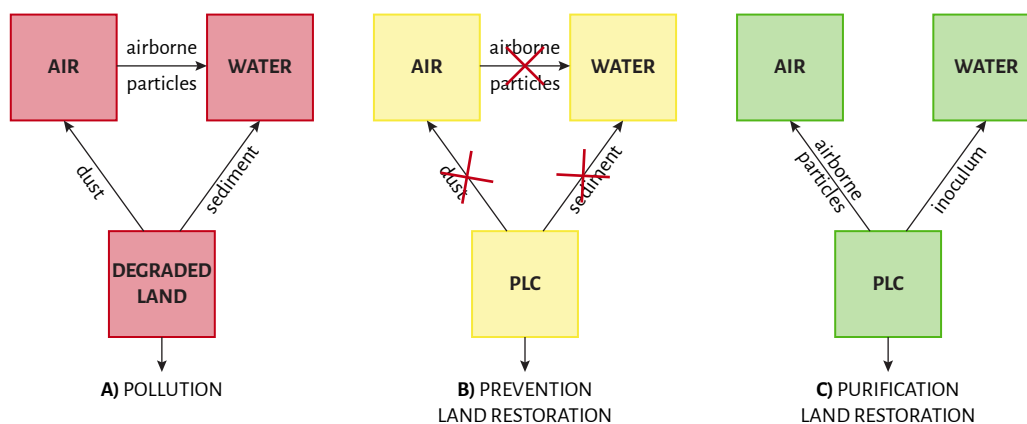


Figure 8. The role of Pan-Life-Carpet (PLC) in land restoration, prevention of air and water pollution as well as air and water purification (made with <https://www.biorender.com/>)

captures airborne particles from polluted air, decreases their concentration in the air and thus provides air purification (Figure 8c). Cyanobacterial biomass from polluted water bodies can be taken away from water ecosystems and used as inoculum for PLC development, which further contributes to water purification (Figure 8c).

The PLC technology thus exhibits a double impact on air quality: 1) by stabilizing substrate surfaces it prevents dust particle emission to the atmosphere and thus prevents air pollution (Figure 8b); 2) by capturing and further stabilizing airborne particles it purifies already pol-

luted air (Figure 8c). The PLC technology exhibits similar benefits for the water ecosystems: 1) by preventing air pollution and purifying air it prevents indirect pollution of water ecosystems (Figure 8b); 2) the use of cyanobacterial biomass from eutrophic lakes for PLC preparation purifies water ecosystems, as well (Figure 8c). Thus, biocrust carpet engineering, i.e. the PLC concept, by providing land restoration, air and water pollution prevention as well as air and water purification addresses global environmental problems of land degradation and air and water pollution.

Conclusion

The present study addressed the health risk assessment in districts of Central Serbia due to exposure to PM pollution originating from degraded mining areas. Epidemiological estimation was based on the incidence of seven types of cancers and three types of cardiovascular diseases in 18 districts of Central Serbia for the period 2010 – 2020. Locations of surface mines, mine disposals and ash disposal sites, as well as frequencies of wind directions, were also observed.

The obtained results showed a statistically significant increase in lung and bronchial cancer incidence in critical districts affected by soil degradation and dust pollution from main mining sites compared to non-critical districts. Among them, Beograd city had the highest incidence due to the proximity and wind impact from thermal

power plant ash disposal sites 'Nikola Tesla A', 'Nikola Tesla B', and Kolubara coal basin. Based on the incidence values, the Borski district, where most of the land was degraded by copper mining (Bor and Majdanpek), stood out among the top three districts for examined diseases.

According to the results of the study, intensified monitoring of air pollution originating from mining areas, as well as mitigation technology for restoration of such degraded land, are necessary. Pan-Life-Carpet technology based on artificially induced biocrusts, with the dominance of cyanobacteria, has been proposed as a potential quick, sustainable, and environmentally friendly solution for mining land restoration and air and water pollution control. The PLC concept is becoming ready for field testing and expected to facilitate processing of degraded land surfaces.

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