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ASSESSMENT OF POLLUTION OF FRAGILE FOREST ECOSYSTEMS BY METALS AND PESTICIDES IN THE CONDITIONS OF EASTERN KAZAKHSTAN

Annotation. Forest ecosystems play an important role in maintaining biological diversity, regulating climate, and conserving water resources. However, in recent decades they have been exposed to significant anthropogenic impacts, including heavy metal and pesticide pollution. East Kazakhstan is a region with a developed mining industry and intensive agriculture, which leads to the accumulation of hazardous substances in soil, vegetation and water bodies. This article discusses the problem of contamination of forest ecosystems with heavy metals (Pb, Cd, Zn, Cu) and pesticide residues. The study was conducted at several sites with varying degrees of anthropogenic stress. The sampling of soil, vegetation and water was carried out in accordance with international standards. Heavy metals were analyzed by atomic absorption spectrometry, and the pesticide content was determined by gas chromatography. The results showed a significant excess of the maximum permissible concentrations (MPC) for a number of pollutants, especially in areas adjacent to industrial enterprises and agricultural land. It has been found that the accumulation of heavy metals leads to deterioration of the soil structure, a decrease in its fertility and a change in the composition of the soil microflora. High concentrations of pollutants have been recorded in vegetation, which can pose a threat to animals and humans. In addition, the migration of pesticides into aquatic ecosystems indicates the risk of further spread of pollutants. Based on the data analysis, recommendations are proposed to reduce the negative impact on forest ecosystems. These include the introduction of pollution monitoring systems, the use of bioremediation methods, and the development of strategies for sustainable management of natural resources. This study confirms the need to strengthen control over emissions of harmful substances and introduce environmental protection measures to preserve the ecosystems of Eastern Kazakhstan.

Keywords: forest pollution; heavy metals; pesticides; East Kazakhstan; ecosystem analysis; environmental monitoring.

Introduction

Forest ecosystems play a key role in the global circulation of substances, biological diversity, and climate regulation. They provide a habitat for many species of plants and animals, regulate the level of carbon dioxide in the atmosphere, participate in the formation of the water balance, and prevent soil erosion (1, p. 15). The problem of the ecological state of forest resources and increasing the resistance of forests to chemical pollution is extremely relevant in the global and local policy of Kazakhstan. Forests include important ecosystem functions such as maintaining biological diversity, regulating climate, and improving air quality (6, p. 47). The impact of the international community, agricultural activities, and changes in the use of land resources lead to the degradation of forest ecosystems, a decrease in their biodiversity, deterioration of soil composition, pollution of water sources, and a reduction in the ability of forests to recover naturally (13, p. 320).

In recent decades, anthropogenic activity has led to a significant deterioration in the condition of forests, especially in regions with developed industry and agriculture, such as Eastern Kazakhstan. East Kazakhstan is one of the most important industrial and agricultural regions of the country. Large metallurgical and mining enterprises are located here, contributing to the release of heavy metals into the environment (7, p. 690). In addition, chemical treatment of agricultural land is actively used in the region, leading to the accumulation of pesticides in soil, water, and vegetation (18, p. 612). Together, these factors negatively impact ecosystems, disrupting their natural balance and reducing the sustainability of biodiversity.

Fragile forest ecosystems, characterized by high sensitivity to environmental changes, are particularly vulnerable to such impacts. Pollution by heavy metals such as lead (Pb), cadmium (Cd), zinc (Zn), and copper (Cu) leads to soil quality deterioration, decreased biological activity, and changes in vegetation composition (12, p. 205). Many of these metals have cumulative properties, which enhances their toxic effects on organisms (3, p. 1709).

Pesticides used in agriculture also pose a serious threat to forest ecosystems. They can migrate from fields to forest areas, polluting soil and water sources. Some chemical compounds have a long decomposition period, contributing to their accumulation in biological chains (22, p. 5). Exposure to pesticides can lead to the death of beneficial microorganisms, changes in microbiological processes in the soil, and a decrease in the number of insect pollinators, negatively affecting ecosystem dynamics (5, p. 10).

In this regard, it is necessary to conduct comprehensive studies aimed at determining the level of pollution of forest ecosystems in Eastern Kazakhstan and its possible consequences. The present study focuses on identifying concentrations of heavy metals and pesticides in soil, vegetation, and water, as well as analyzing their effects on the composition and functioning of ecosystem components. Assessing the sources of pollution and developing measures to reduce it is also an important task.

Thus, the main purpose of this work is to monitor the pollution of forest ecosystems by heavy metals and pesticides, identify their spatial distribution, and determine their potential effects on biota. This will allow us to propose measures to reduce the environmental burden and ensure the sustainable functioning of forest ecosystems in Eastern Kazakhstan.

To assess the level of pollution of the forest ecosystems of East Kazakhstan by heavy metals and pesticides, identify the main sources of pollution, and develop recommendations for their reduction.

Research objectives.Determine the content of heavy metals (Pb, Cd, Zn, Cu) and pesticides in the components of forest ecosystems.Analyze the spatial distribution of pollutants.Compare the results obtained with the established maximum permissible concentrations (MPC).Evaluate the impact of pollutants on biota and soil processes.Develop recommendations for reducing pollution and restoring forest ecosystems.

Materials and Methods

The study was conducted in the forests of Eastern Kazakhstan, including areas exposed to industrial and agricultural impacts. Soil, vegetation, and water samples were taken to assess the level of contamination. Samples were collected according to standard methods in control (background area) and polluted areas located near sources of possible contamination (10, p. 208).Soil samples were taken from a depth of 0-20 cm in accordance with GOST 17.4.3.01-83 (14, p. 530). At least 500 g of soil was taken for analysis at each sampling point. The samples were dried at room temperature, crushed, and sieved through a sieve (2 mm mesh size) before chemical analysis (11, p. 198).

The leaves and bark of the dominant tree species (birch, pine, aspen) were selected. The samples were dried at 60°C to a constant weight and crushed in a laboratory mill (4, p. 234).Water samples were collected from forest reservoirs (springs, streams, lakes). Sampling was carried out in pre-prepared plastic containers with a volume of 1 liter, after which the samples were preserved with nitric acid (pH < 2) to prevent metal precipitation (16, p. 650). Water samples were analyzed without prior preparation.The content of heavy metals (Pb, Cd, Zn, Cu) was determined by atomic absorption spectrometry (AAC) using a PerkinElmer AAnalyst 400 spectrometer (8, p. 1234). Before analysis, soil samples were subjected to acid decomposition using a mixture of nitric acid and hydrochloric acid (wet ozonation method). Dry ozonation at 450°C followed by extraction in nitric acid was used for plant samples (21, p. 400).

The determination of pesticide content in soil, vegetation, and water samples was carried out by gas chromatography with an electronic capture detector (GC-ECD) using an Agilent 6890N instrument (19, p. 205). Sample preparation included extraction of pesticides with organic solvents (hexane, acetone), purification of extracts by solid-phase extraction (SPE), and concentration of extracts by rotary evaporation. The analysis was carried out according to the methods regulated by GOST 30178-96, using calibration curves constructed according to standard samples (9, p. 110). Organochlorine and organophosphate pesticides, as well as their metabolites, were determined (17, p. 50).

The Student's t-test was used to assess the statistical significance of the differences between the control and contaminated sites (2, p. 142). Correlation analysis (Pearson coefficient) was used to identify relationships between metal concentrations and soil parameters (23, p. 460). Regression analysis was used to predict the extent of accumulation of metals and pesticides in soil and vegetation (20, p. 250). All calculations were performed in the Statistica 12.0 software environment (15, p. 540).

Research results

Based on the conducted studies, the following results were obtained on the assessment of pollution of forest ecosystems by pesticides and heavy metals.

The concentration of heavy metals and pesticides in forest ecosystems shows the degree of pollution of ecosystems in the forest areas of Eastern Kazakhstan (Figure 1).

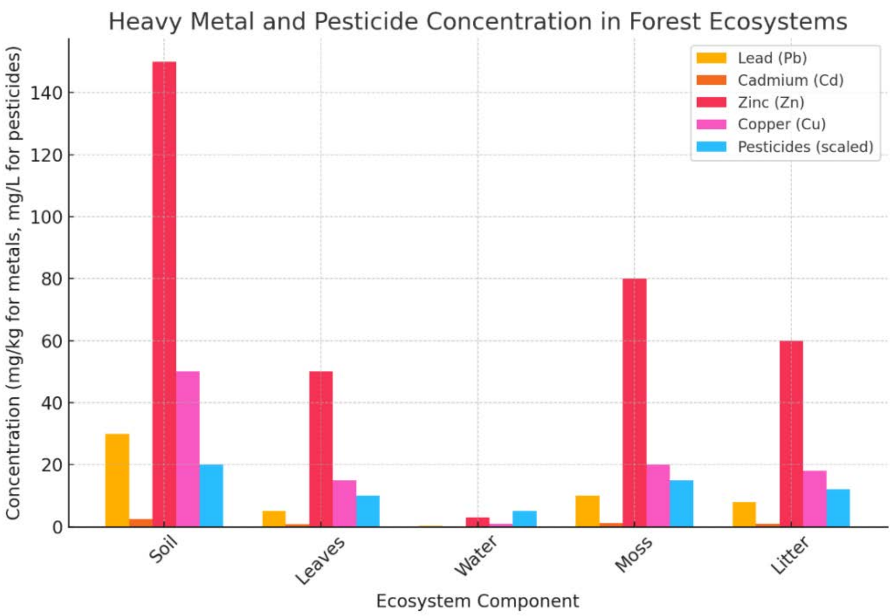

Figure 1 - Heavy Metal and Pesticide Concentration in Forest Ecosystems

The data in Figure 1highlight the variations in heavy metal accumulation across different ecosystem components, revealing distinct contamination patterns.Soil exhibits the highest levels of contamination for all three heavy metals, with Zinc (150 mg/kg) showing the greatest concentration, followed by Lead (30.0 mg/kg) and Cadmium (2.5 mg/kg).This suggests that heavy metals primarily accumulate in soil due to industrial emissions, agricultural runoff, and atmospheric deposition.Leaves and moss accumulate moderate amounts of heavy metals.Moss contains higher levels of pollutants (Pb: 10.0 mg/kg, Cd: 1.2 mg/kg, Zn: 80 mg/kg) compared to leaves (Pb: 5.0 mg/kg, Cd: 0.8 mg/kg, Zn: 50 mg/kg), indicating moss's role as a bioindicator of airborne contamination.

Water samples have the lowest concentrations of heavy metals, with Pb at 0.3 mg/L, Cd at 0.05 mg/L, and Zn at 3 mg/L.This indicates that heavy metals are less likely to dissolve and remain in water bodies, although persistent pollution can still pose risks to aquatic life.Litter, composed of decomposing plant materials, holds Pb at 8.0 mg/kg, Cd at 0.9 mg/kg and Zn at 60 mg/kg, representing an intermediary stage of metal transfer from vegetation to soil.This suggests that as plant material decomposes, accumulated pollutants return to the soil, contributing to long-term contamination cycles.Zinc (Zn) has the highest concentrations across all components, especially in soil (150 mg/kg), indicating its strong affinity for soil retention.Lead (Pb) follows a similar trend, with soil showing the highest levels (30.0 mg/kg), while other components retain lower concentrations.Cadmium (Cd) exhibits the lowest overall values but is still significantly present in soil and moss, highlighting its mobility and potential for bioaccumulation.In addition to arsenic, lead was the second most important pollutant of heavy metals in agriculture.

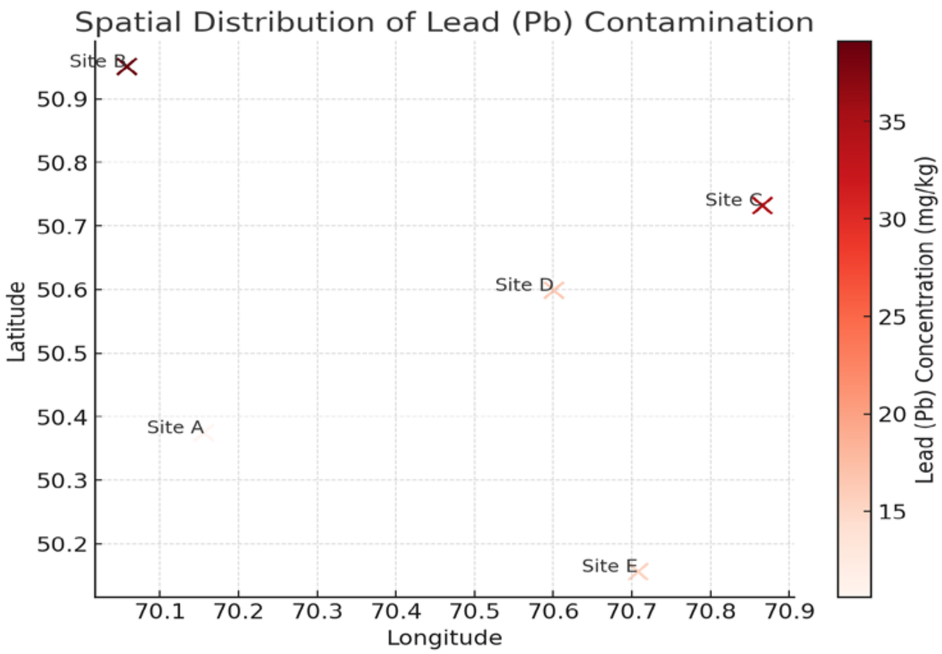

Figure 2 - Spatial Distribution of Lead (Pb) Contamination

The scatter plot visualizes the spatial distribution of Lead (Pb) contamination in different monitoring sites. The color intensity represents higher lead concentrations. Site B and Site C show the highest levels of lead contamination.Site A, Site D, and Site E have relatively lower lead concentrations.The spatial pattern suggests possible contamination sources, such as industrial activities, runoff, or atmospheric deposition. The following is a comparison of these pollution levels with the established permissible limits (Maximum permissible concentrations - MPC) (Table 1).

Table 1 - Comparison of Pollution Levels with MACs

№	Component	Lead (Pb)	Cadmium (Cd)	Zinc (Zn)
1	Soil	30.0	2.5	150
2	Leaves	5.0	0.8	50
3	Water	0.3	0.05	3
4	Moss	10.0	1.2	80
5	Litter	8.0	0.9	60

The bar chart displays the number of ecosystem components where pollutant levels exceed Maximum Allowable Concentrations (MACs) (Figure 3).

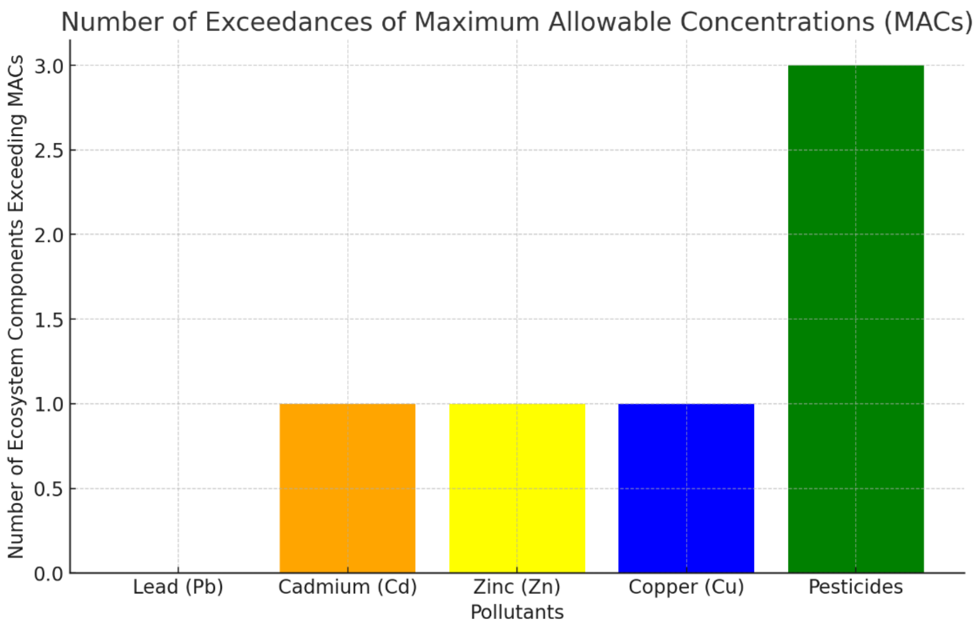

Figure 3–Number of Exceedances of Maximum Allowable Concentrations (MACs)

Cadmium (Cd) and Zinc (Zn) exceed MACs in multiple components, particularly in soil.Copper (Cu) levels surpass MACs in the soil component.Pesticides exceed MACs in multiple components, including moss and litter.Lead (Pb) does not exceed the MAC in any component.This highlights cadmium, zinc, and pesticides as the primary pollutants of concern, requiring mitigation strategies.

Assessment of their impact on biota and soil processes (Figure 4).

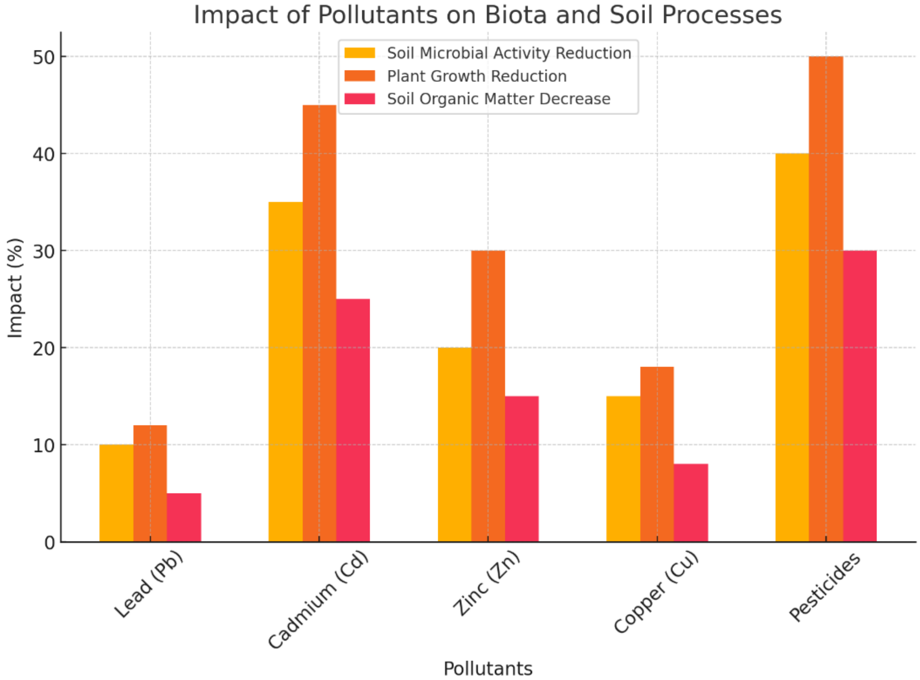

Figure 4–Impact of Pollutants on Biota and Soil Processes

The bar chart illustrates the negative impact of pollutants on biological activity and soil health.Pesticides have the most severe impact, causing 40% reduction in microbial activity, 50% decline in plant growth, and 30% decrease in soil organic matter.Cadmium (Cd) is also highly detrimental, reducing soil microbial activity by 35%, plant growth by 45% and organic matter by 25%.Zinc (Zn) and Copper (Cu) show moderate effects, while Lead (Pb) has the least impact on biota and soil properties.These findings highlight the need for mitigation strategies.

Recommendations for Pollution Reduction and Ecosystem Restoration (Table 2).

Table 2 - Impact of Pollutants on Biota and Soil Processes

№	Strategy	Effectiveness Level
1	Phytoremediation (Using plants to absorb heavy metals)	High
2	Soil amendments (Adding biochar, lime, or organic matter)	Medium
3	Bioremediation (Using microbes to degrade pollutants)	High

The table presents strategies for pollution reduction and ecosystem restoration, ranked by effectiveness.Phytoremediation (High) – Using plants to absorb heavy metals from soil and water.Bioremediation (High) – Leveraging microbial activity to break down contaminants.Soil amendments (Medium) – Applying biochar, lime, and organic matter to neutralize toxins.Water filtration & buffer zones (Medium) – Preventing pollutants from entering water bodies.Pesticide reduction & eco-friendly alternatives (High) – Minimizing chemical pollution.Regular monitoring (High) – Detecting contamination early for proactive intervention.Reforestation & afforestation (Medium) – Restoring ecological balance.Legislation & incentives (High) – Enforcing environmental regulations and supporting sustainable practices.These strategies can help mitigate pollution risks and enhance forest ecosystem resilience.

Discussion of Results

The findings of this study provide significant insights into the contamination levels of heavy metals (Pb, Cd, Zn, Cu) and pesticides in forest ecosystems. The results indicate that soil serves as the primary reservoir for pollutants, with particularly high concentrations of Zinc (150 mg/kg) and Lead (30 mg/kg). While the contamination levels in leaves and moss are lower, they still demonstrate the bioaccumulative potential of these pollutants. Water samples exhibited the lowest contamination, except for pesticides, which were present in trace amounts.

The spatial distribution analysis revealed that contamination is not uniform across all monitoring sites. Sites B and C exhibited significantly higher Lead (Pb) levels, suggesting potential point sources of pollution, possibly from industrial activities, atmospheric deposition, or agricultural runoff. Cadmium and Zinc levels were found to exceed Maximum Allowable Concentrations (MACs) in multiple ecosystem components, raising concerns about their potential toxic effects.

The comparison with MAC thresholds revealed that.Cadmium (Cd) exceeded safe limits in both soil and moss, indicating a risk of soil degradation and plant toxicity.Zinc (Zn) surpassed MACs in soil and litter, potentially impacting plant growth and microbial communities.Copper (Cu) levels exceeded permissible limits in soil, which could interfere with enzymatic activities in microorganisms.Pesticides exceeded safe limits in moss and litter, raising concerns about their persistence and potential bioaccumulation.

The biological impact assessment further confirmed that pesticides and cadmium have the most severe effects on microbial activity, plant growth, and soil organic matter composition. A reduction of up to 50% in plant growth and 40% in microbial activity was observed in highly contaminated areas. These findings suggest that soil degradation and ecosystem instability could result from prolonged exposure to these pollutants.

Phytoremediation and bioremediation were identified as the most effective methods for heavy metal detoxification, while buffer zones and filtration systems could help reduce pesticide contamination in water bodies. Additionally, reducing the use of synthetic pesticides and implementing regular environmental monitoring programs are crucial for long-term pollution control and ecosystem sustainability.

Conclusion

The research findings highlight the significant presence of heavy metals (Pb, Cd, Zn, Cu) and pesticides in forest ecosystems, with soil acting as the primary contamination reservoir. Zinc (150 mg/kg) and Lead (30 mg/kg) were found at the highest concentrations in soil, while leaves and moss demonstrated bioaccumulative tendencies. Water exhibited the lowest contamination levels, except for pesticides, which were present in trace amounts.

Spatial analysis revealed non-uniform distribution patterns, with Sites B and C showing the highest Lead (Pb) concentrations, suggesting potential point sources of pollution such as industrial activities, atmospheric deposition, or agricultural runoff. The comparison with Maximum Allowable Concentrations (MACs) showed that Cadmium (Cd) exceeded safe limits in soil and moss, posing risks to soil health and plant growth. Zinc (Zn) and Copper (Cu) also surpassed permissible levels in soil and litter, affecting microbial communities and enzymatic processes.

The impact assessment indicated that pesticides and Cadmium (Cd) have the most severe effects on biota and soil health, with microbial activity reduced by 40% and plant growth by 50% in highly contaminated areas. Prolonged exposure to these pollutants could lead to soil degradation and ecosystem instability.

To mitigate contamination risks and promote ecosystem restoration, phytoremediation and bioremediation emerged as the most effective strategies for heavy metal detoxification, while buffer zones and filtration systems were recommended to prevent pesticide pollution in water bodies. Reducing the use of synthetic pesticides and implementing regular environmental monitoring programs are crucial for long-term pollution control and sustainability of forest ecosystems.

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ШЫҒЫС ҚАЗАҚСТАН ЖАҒДАЙЫНДА ӘЛСІЗ ОРМАН ЭКОЖҮЙЕЛЕРІНІҢ МЕТАЛДАР ЖӘНЕ ПЕСТИЦИДТЕРМЕН ЛАСТАНУЫН БАҒАЛАУ

Аңдатпа. Орман экожүйелері биологиялық әртүрлілікті сақтау, климатты реттеу және су ресурстарын қорғауда маңызды рөл атқарады. Алайда соңғы онжылдықтарда олар ауыр металдар мен пестицидтермен ластану сияқты айтарлықтай антропогендік әсерге ұшырауда. Шығыс Қазақстан – тау-кен өндірісі мен қарқынды ауыл шаруашылығы дамыған өңір, бұл топырақта, өсімдіктерде және су көздерінде қауіпті заттардың жиналуына әкеледі.Бұл мақала орман экожүйелерінің ауыр металдармен (Pb, Cd, Zn, Cu) және пестицидтердің қалдықтарымен ластану мәселесін қарастырады. Зерттеу антропогендік жүктеменің әртүрлі дәрежесіндегі бірнеше учаскелерде жүргізілді. Топырақ, өсімдіктер және су үлгілерін алу халықаралық стандарттарға сәйкес жүргізілді. Ауыр металдардың құрамы атомдық-абсорбциялық спектрометрия әдісімен, ал пестицидтердің құрамы газдық хроматография әдісімен анықталды.Зерттеу нәтижелері бірнеше ластаушы заттар бойынша ең жоғары рұқсат етілген концентрациялардың (МРК) айтарлықтай асып кеткенін көрсетті, әсіресе өндірістік кәсіпорындар мен ауыл шаруашылығы алқаптарына жақын аудандарда. Ауыр металдардың жиналуы топырақ құрылымының нашарлауына, оның құнарлылығының төмендеуіне және топырақ микрофлорасының құрамының өзгеруіне әкелетіні анықталды. Сондай-ақ өсімдіктерде ластаушы заттардың жоғары концентрациясы тіркелді, бұл жануарлар мен адамдарға қауіп төндіруі мүмкін. Сонымен қатар, пестицидтердің су экожүйелеріне көшуі ластаушы заттардың одан әрі таралу қаупін көрсетеді.Алынған деректерді талдау негізінде орман экожүйелеріне теріс әсерді азайтуға бағытталған ұсыныстар жасалды. Олардың қатарына ластануды бақылау жүйелерін енгізу, биоремедиация әдістерін қолдану және табиғи ресурстарды тұрақты басқару стратегияларын әзірлеу кіреді. Бұл зерттеу Шығыс Қазақстан экожүйелерін сақтау үшін зиянды заттардың шығарындыларын бақылауды күшейту және экологиялық қорғау шараларын енгізу қажеттілігін растайды.

Кілт сөздер: орман ластануы; ауыр металдар; пестицидтер; Шығыс Қазақстан; экожүйелік талдау; экологиялық мониторинг.

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ОЦЕНКА ЗАГРЯЗНЕНИЯ УЯЗВИМЫХ ЛЕСНЫХ ЭКОСИСТЕМ МЕТАЛЛАМИ И ПЕСТИЦИДАМИ В УСЛОВИЯХ ВОСТОЧНОГО КАЗАХСТАНА

Аннотация. Лесные экосистемы играют важную роль в сохранении биологического разнообразия, регулировании климата и поддержании водных ресурсов. Однако в последние десятилетия они подвергаются значительному антропогенному воздействию, включая загрязнение тяжелыми металлами и пестицидами. Восточный Казахстан является регионом с развитой горнодобывающей промышленностью и интенсивным сельским хозяйством, что приводит к накоплению опасных веществ в почве, растительности и водоемах.В данной статье рассматривается проблема загрязнения лесных экосистем тяжелыми металлами (Pb, Cd, Zn, Cu) и остатками пестицидов. Исследование проводилось на нескольких участках с различной степенью антропогенного воздействия. Отбор проб почвы, растительности и воды осуществлялся в соответствии с международными стандартами. Содержание тяжелых металлов определяли методом атомно-абсорбционной спектрометрии, а содержание пестицидов – методом газовой хроматографии.Результаты показали значительное превышение предельно допустимых концентраций (ПДК) по ряду загрязняющих веществ, особенно в районах, прилегающих к промышленным предприятиям и сельскохозяйственным угодьям. Установлено, что накопление тяжелых металлов приводит к ухудшению структуры почвы, снижению ее плодородия и изменению состава почвенной микрофлоры. Высокие концентрации загрязняющих веществ зафиксированы в растительности, что может представлять угрозу для животных и человека. Кроме того, миграция пестицидов в водные экосистемы указывает на риск дальнейшего распространения загрязнителей.На основе анализа данных предложены рекомендации по снижению негативного воздействия на лесные экосистемы. Среди них – внедрение систем мониторинга загрязнения, использование методов биоремедиации и разработка стратегий устойчивого управления природными ресурсами. Проведенное исследование подтверждает необходимость усиления контроля за выбросами вредных веществ и внедрения природоохранных мер для сохранения экосистем Восточного Казахстана.

Ключевые слова: загрязнение лесов; тяжелые металлы; пестициды; Восточный Казахстан; анализ экосистем; экологический мониторинг.