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MACHINE LEARNING FOR MODELLING THE IMPACT OF GEO-ENVIRONMENTAL FACTORS ON NATURAL RESOURCE ALLOCATION

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Abstract. *Relevance.* Effective forest ecosystem management requires an understanding of the influence of geo-environmental factors on vegetation cover. Climate change, human impact, and wildfires are transforming forest types, especially in mountainous regions. In this context, intelligent systems capable of identifying key dependencies and predicting forest cover types are becoming increasingly important. *Objective.* This study aims to develop a classification model for forest cover types based on environmental and topographic parameters using the Random Forest algorithm. ***Methods.*** The model was built using data from the open UCI Machine Learning Repository. The dataset includes elevation, aspect, slope, distances to hydrological and fire-related features, and road proximity. Correlation analysis was conducted, and a Random Forest model was trained. The model's performance was evaluated using Accuracy, Precision, Recall, and F1-score metrics. *Results and conclusions.* The model achieved an overall accuracy of 91%. Elevation and distance to roadways were found to be the most influential features. Classes 1, 2, and 7 showed high classification accuracy, while classes 4 and 5 had higher misclassification rates. The results are useful for adaptive forest management, risk prediction, and biodiversity conservation. This study confirms the applicability of machine learning in supporting sustainable forest ecosystem analysis. Future research will aim to enhance the model by incorporating additional climatic and anthropogenic factors.

Keywords: machine learning, mountain resources, geological exploration, environmental factors, data analysis, resource modeling

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ГЕОЭКОЛОГИЯЛЫҚ ФАКТОРЛАРДЫҢ ТАБИҒИ РЕСУРСТАРДЫ БӨЛУГЕ ӘСЕРІН МОДЕЛЬДЕУГЕ АРНАЛҒАН МАШИНАЛЫҚ ОҚЫТУ

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Аннотация. *Өзектілігі.* Орман экожүйелерін тиімді басқару геоэкологиялық факторлардың өсімдік жамылғысының құрылымына әсерін түсінуді талап етеді. Климаттың өзгеруі, антропогендік әсер және табиғи өрттер орман түрлерін әсіресе таулы аймақтарда түбегейлі өзгертеді. Бұл жағдайда негізгі тәуелділіктерді анықтауға және орман жамылғысының түрлерін болжауға қабілетті интеллектуалды жүйелердің рөлі артады. *Мақсаты.* Зерттеудің мақсаты — кездейсоқ орман алгоритмін қолдана отырып, экологиялық және топографиялық параметрлерді талдау негізінде орман жамылғысын жіктеу моделін құру. *Әдістері.* Модельді құру үшін UCI ашық репозиторийінен алынған мәліметтер пайдаланылды. Үлгіде биіктік, экспозиция, еңіс, жолдардан қашықтық, гидрологиялық және пирологиялық нысандар туралы ақпарат бар. Корреляциялық талдау жүргізілді және Random Forest моделі салынды. Дәлдікті бағалау Accuracy, Precision, Recall және F1-score көрсеткіштері бойынша жүргізілді. *Нәтижелер мен қорытындылар.* Модель 91% дәлдікке жетті. "Биіктік" және "жол қашықтығы" параметрлері ең маңызды болып шықты. 1, 2 және 7 сыныптар жоғары дәлдікпен танылды, ал 4 және 5 сыныптар үшін қателер байқалды. Нәтижелер орман ресурстарын адаптивті басқару, тәуекелдерді болжау және биоәртүрлілікті сақтау үшін пайдаланылуы мүмкін. Ұсынылған зерттеу орман экожүйелерін тұрақты талдау үшін машиналық оқытудың қолданылуын растайды. Болашақта қосымша климаттық және антропогендік факторлар есебінен модельді кеңейту көзделеді.

Түйін сөздер: машиналық оқыту, тау ресурстары, геологиялық барлау, экологиялық факторлар, деректерді талдау, ресурстарды модельдеу

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МАШИННОЕ ОБУЧЕНИЕ ДЛЯ МОДЕЛИРОВАНИЯ ВЛИЯНИЯ ГЕОЭКОЛОГИЧЕСКИХ ФАКТОРОВ НА РАСПРЕДЕЛЕНИЕ ПРИРОДНЫХ РЕСУРСОВ

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Аннотация. *Актуальность.* Эффективное управление лесными экосистемами требует понимания влияния геоэкологических факторов на структуру растительного покрова. Изменение климата, антропогенное воздействие и природные пожары радикально трансформируют типы лесов, особенно в горных районах. В этих условиях возрастает роль интеллектуальных систем, способных выявлять ключевые зависимости и прогнозировать типы лесного покрова. *Цель.* Целью исследования является построение модели классификации лесного покрова на основе анализа экологических и топографических параметров с использованием алгоритма случайного леса. *Методы.* Для построения модели использовались данные из открытого репозитория UCI. В выборке содержится информация о высоте, экспозиции, уклоне, удалённости от дорог, гидрологических и пирологических объектах. Проведен корреляционный анализ и построена модель Random Forest. Оценка точности осуществлялась по метрикам Accuracy, Precision, Recall и F1-score. *Результаты и выводы.* Модель достигла точности 91%. Параметры «высота над уровнем моря» и «расстояние до дорог» оказались наиболее значимыми. Классы 1, 2 и 7 были распознаны с высокой точностью, тогда как для классов 4 и 5 наблюдались ошибки. Результаты могут быть использованы для адаптивного управления лесными ресурсами, прогнозирования рисков и сохранения биоразнообразия. Представленное исследование подтверждает применимость машинного обучения для устойчивого анализа лесных экосистем. В дальнейшем предполагается расширение модели за счёт дополнительных климатических и антропогенных факторов.

Ключевые слова: машинное обучение, горные ресурсы, геологоразведка, экологические факторы, анализ данных, моделирование ресурсов

Introduction. One of the most important ecosystems on the planet is the forest ecosystem. It has a significant impact on climatic conditions, biodiversity, and environmental sustainability (Malozyomov et al., 2024; Evsyukov et al., 2024). Identifying the factors that influence forest cover types is key to understanding how forest ecosystems respond to environmental changes and anthropogenic impacts. In the context of global climate change and increased pressure on natural resources, forests play a crucial role in maintaining ecological balance by providing essential ecosystem services such as regulating the water cycle, maintaining soil fertility, and preserving biodiversity (Kurashkin et al., 2024; Kapanski et al., 2025)]. Understanding these factors is particularly important for ecologists and foresters to develop sustainable forest management strategies.

Moving on to the consideration of the diversity of forest ecosystems, it is important to note that globally there is a great variety of forest types, determined by a combination of climatic, topographic, and soil conditions (Kaung et al., 2024; Malozyomov et al., 2024; O'Brien et al, 2022). In this context, increasing species diversity in forests can significantly enhance their resilience to changes in natural conditions, including climate fluctuations. Such diversity also contributes to the preservation of breeding potential and improvement of tree species, ensuring the maintenance of important functions in the ecosystem (Xu et al., 2023). Forests with high species diversity exhibit higher productivity and resistance to diseases and pests, making them a key element in biodiversity conservation strategies.

To effectively manage such diverse forest ecosystems, forests are classified based on climatic variables and vegetation index data. This allows for the identification of unique forest types such as tropical forests, taiga, and temperate forests. These ecosystems require specific management and conservation approaches that consider their unique characteristics and needs (Bosikov et al., 2024). Understanding these differences helps develop strategies aimed at the long-term preservation and restoration of forest ecosystems.

It is worth noting that forests play a key role in the carbon cycle, providing carbon storage and climate regulation (Silaev et al., 2023). They also contribute to the conservation of water resources and prevent soil erosion (Schulze, et al., 2022). In this context, forest biodiversity has a significant impact on their functioning: studies show that forests with high species diversity are more resilient and productive compared to monocultures (Filina et al., 2023). Thus, preserving biodiversity becomes a central task in forest resource management.

Climate change, in turn, has a significant impact on the distribution of forest ecosystems around the world. Rising temperatures and changing precipitation patterns lead to shifts in forest zone boundaries, especially in mountainous regions. For example, mountain forests may gradually move up the slopes in response to warming, resulting in changes in tree species composition and the loss of unique high-altitude ecosystems (Zhu et al., 2021). These changes underscore the need to develop adaptive forest management strategies in a changing climate (Muraviev et.al., 2012; Beisembetov et.al., 2012).

Moreover, forest fires are an important natural factor that shapes the structure of forest ecosystems. The frequency and intensity of fires directly affect the composition of tree species and forest structure, which in turn influences their ability to absorb carbon and regulate the climate (Tynchenko et al., 2024). To mitigate the consequences of uncontrolled forest fires, it is important to use prescribed burns as a management measure that can maintain the resilience of forest ecosystems.

At a global level, forest cover continues to change under the influence of various factors. In developing countries such as South America and Africa, there is a significant reduction in forest areas due to urbanization, expansion of agricultural lands, and climate change. These changes occur despite efforts for forest restoration and conservation. At the same time, developed countries like Europe and North America are experiencing the opposite trend: forest restoration associated with changes in land-use patterns and active environmental protection policies (Bastin et al., 2020).

Ultimately, studying the factors that influence forest cover types is necessary for developing effective strategies for forest conservation and restoration. This is especially relevant in the context of sustainable natural resource management and adaptation to climate change. Scientific studies conducted in this area provide valuable data that can be used to create more sustainable and efficient forest management models (Galachieva et al., 2023), contributing to their long-term preservation.

Materials and methods. The parameters under study were taken from the UCI Machine Learning Repository project. The data are open for various research purposes. The dataset contains the following parameters:

- Elevation
- Aspect
- Slope
- Horizontal Distance To Hydrology
- Vertical Distance To Hydrology
- Horizontal Distance To Roadways
- Hillshade 9am
- Hillshade Noon
- Hillshade 3pm
- Horizontal Distance To Fire Points
- Wilderness Area (1–4)
- Cover Type—the output parameter consisting of 7 classes. Each class corresponds to a specific forest type.

To assess the linear dependence between two or more variables, correlation analysis was applied. This method allows for identifying variables that are important to the model by measuring the influence of one parameter on another (Koteleva et al., 2024; Tynchenko et al., 2024).

For data analysis, the machine learning algorithm Random Forest is used, which consists of multiple independent decision trees. Each tree is built independently, using a random sample of data and features. This results in a diversity of trees, which can increase the overall prediction accuracy compared to the accuracy of a single tree. The classification model results were evaluated using the following metrics:

- Accuracy—the ratio of the number of correct predictions to the total number of predictions made by the model.
- Precision—the proportion of correctly classified positive class objects among all objects predicted as positive.
- Recall—the proportion of true positive results relative to the total number of cases in the positive class that the model should have identified.
- F1-score—the harmonic mean between precision and recall, providing a balance between them.

Results and discussion. Conducting the correlation analysis was performed after data preprocessing, which included removing missing values, data normalization, and error correction. The result of the correlation analysis is presented in Figure 1.

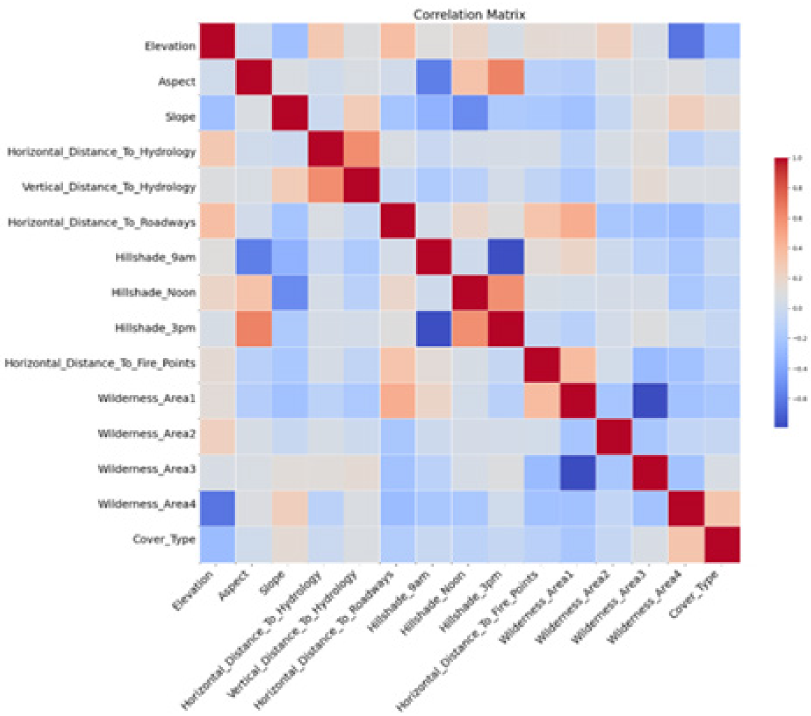
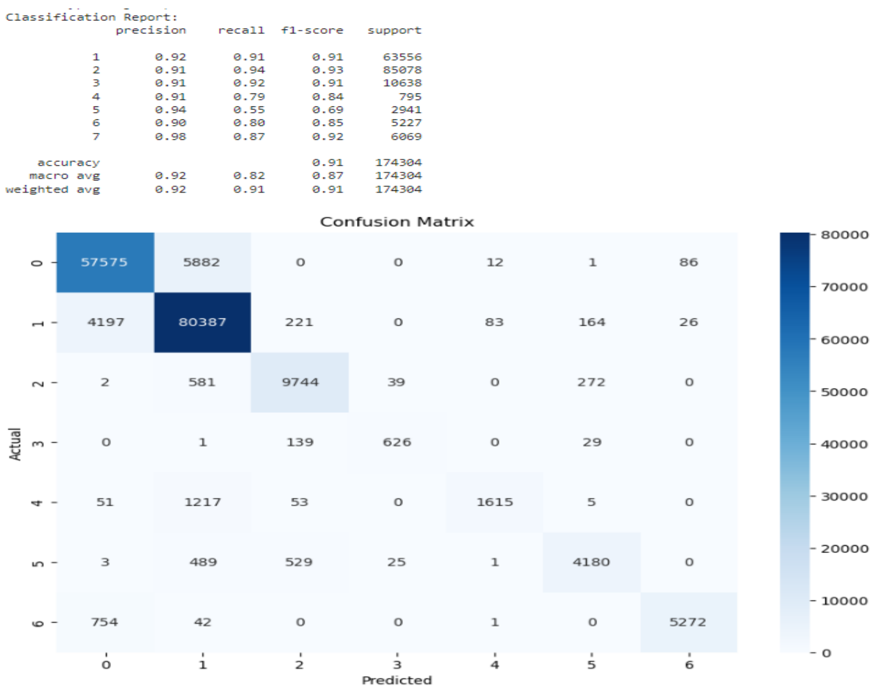


Figure 1. Correlation Analysis

Using correlation, it was found that the attributes Hillshade_9am and Hillshade_3pm, as well as Wilderness_Area1 and Wilderness_Area3, have a strong negative correlation between them. From these dependencies, it follows that the illumination of the area at different times changes with the position of the sun, and that areas of the first wilderness area almost never overlap with those of the third wilderness area.

The presence of a large number of weak correlations between factors indicates the possible presence of nonlinear dependencies that cannot be accounted for in a linear model. To find complex dependencies in the data, the Random Forest method was applied. The classification matrix of the obtained model is presented in Figure 2. The model report is provided in Table 1.



Classification Report:

	precision	recall	f1-score	support
1	0.92	0.91	0.91	63556
2	0.91	0.94	0.93	85078
3	0.91	0.92	0.91	10638
4	0.91	0.79	0.84	795
5	0.94	0.55	0.69	2941
6	0.90	0.80	0.85	5227
7	0.98	0.87	0.92	6069
accuracy			0.91	174304
macro avg	0.92	0.82	0.87	174304
weighted avg	0.92	0.91	0.91	174304

Figure 2. Classification Matrix

Table 1. Model Report

Class	Value	Recall	F1-score	Support
1	0.92	0.91	0.91	63556
2	0.91	0.94	0.93	85078
3	0.91	0.92	0.91	10638
4	0.91	0.79	0.84	795
5	0.94	0.55	0.69	2941
6	0.90	0.80	0.85	5227
7	0.98	0.87	0.92	6069
Precision			0.91	174304
Macro-average	0.92	0.82	0.87	174304
Weighted average	0.92	0.91	0.91	174304

The classification matrix is used to evaluate the performance of the classification algorithm, where the rows represent the actual classes and the columns represent the predicted classes. Each element of the matrix shows the number of examples that were predicted to belong to the class indicated by the column but actually belong to the class indicated by the row. Diagonal values represent correct predictions for each class. Off-diagonal values represent misclassifications. Using the classification matrix, it was possible to identify classes that are more difficult to distinguish than others. By comparing the values in the obtained matrix, it was noticed that classes 4 and 5 have more false positives than others. This may be due to the presence of common or ambiguous features.

The overall accuracy of the model, showing the proportion of all correct predictions made by the model, is 0.91. Classes with a large amount of support (for example, classes 1 and 2) have high values across all metrics, indicating good model performance with frequently occurring classes. Class 5 shows low recall (0.55), which may indicate that the model has difficulty detecting this class, possibly due to a small amount of training data or insufficient feature distinction.

Let us proceed to the analysis of the model's feature importance (Figure 3).

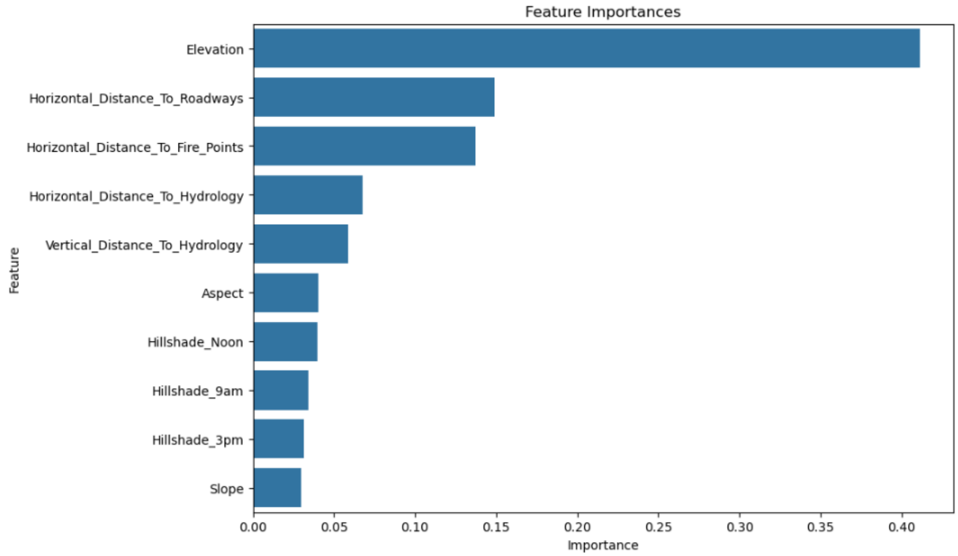


Figure 3. Feature Importance of the Model

This type of visualization shows that the most significant feature is Elevation (height above sea level). Horizontal_Distance_To_Roadways (horizontal distance to the nearest road) and Horizontal_Distance_To_Fire_Points (horizontal distance to the location where a fire occurred) are less important features.

These results underscore the importance of topographic and geographic factors in forest cover studies. For example, elevation can affect types of vegetation, water availability, climatic conditions, and consequently, the type of forest cover.

Similarly, the horizontal distance to roads influences human accessibility and the level of anthropogenic impact, which can lead to changes in forest communities and their structure. Likewise, the distance to the nearest fire points may indicate risks associated with forest fires, which can radically change the composition and structure of forests.

Conclusion. In the course of this study, ecological parameters influencing forest cover types were analyzed using the Random Forest method. The constructed model has an accuracy of 91%. Based on data on elevation above sea level, horizontal distance to roads, and fire points, it was possible to significantly improve the understanding of the relationships between landscape characteristics and the distribution of various forest types.

The obtained results can be used to optimize forest resource management, develop measures to prevent fires, and conserve biodiversity. Further research can expand our knowledge of the influence of other anthropogenic and natural factors, such as waterlogging, land-use changes, and pollution. This will allow for the development of more effective strategies for adapting forest ecosystems to changing environmental conditions.

In conclusion, this study confirmed that a comprehensive analysis of ecological parameters using machine learning methods opens up new prospects for understanding the dynamics and resilience of forest ecosystems under global changes.

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