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AGROCHEMICAL PROPERTIES AND FERTILITY POTENTIAL OF MOUNTAIN-FOREST SOILS IN THE LANKARAN-ASTARA REGION SUPPORTING PERSIAN IRONWOOD (*PARROTIA PERSICA*) AND CASPIAN LOCUST (*GLEDITSIA CASPICA*)

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Abstract. This study investigates the relationship between the distribution patterns of two relict tree species-ironwood *(Parrotia persica)* and Caspian locust *(Gleditsia caspica)* - and soil conditions in the mountain forest ecosystems of the Lankaran-Astara economic region. The research was conducted between 2022 and 2025. A total of 112 soil samples were collected from 28 soil profiles and analyzed for total organic carbon (TOC), FTIR spectroscopy, pH, particle size distribution (laser diffraction), trace element composition (ICP-MS), and clay mineral composition (XRD). The results indicate that *P. persica* reaches its maximum density (410 trees/ha) on northern slopes at elevations of 600–800 m, whereas *G. caspica* attains higher density (265 trees/ha) on southeastern slopes at 400–600 m. Mountain forest brown soils formed under *P. persica* show higher humus content (6.2%), TOC (4.2%), and slightly acidic pH (6.0), while mountain forest yellow and brown soils under *G. caspica* are characterized by moderate humus content (3.5%), TOC (2.4%), and neutral pH (6.5). Soils under *P. persica* are enriched in Zn (54 mg/kg) and Cu (14.5 mg/kg), whereas those under *G. caspica* contain higher concentrations of Fe (5400 mg/kg) and Mn (400 mg/kg). The soils under *P. persica* exhibit high potential for organic farming, while those under *G. caspica* have neutral pH, making them suitable for a wide range of crops.

Keywords: Persian Ironwood, Caspian locust, soil conditions, agrochemistry, soil fertility, micronutrients.

INTRODUCTION

The Lankaran-Astara economic region is located in southeastern Azerbaijan, along the western coast of the Caspian Sea [1]. This area encompasses the main part of the Hyrcanian forests, which represent one of the country's most important natural resources [2]. The Hyrcanian forests are a globally significant natural complex, rich in relict and endemic species originating from the Tertiary period . Their evolutionary history spans millions of years, and they represent rare ecosystems that survived Quaternary glaciations and persist to the present day [3].

The international importance of the Hyrcanian forests was officially recognized in 2019, when the portions located in Iran were inscribed on the UNESCO World Heritage List [4]. In 2023, the Azerbaijani parts of the Hyrcanian forests were added to this list [5]

Criterion (ix): The forests demonstrate uninterrupted evolutionary processes since the Quaternary glaciation, enabling the specification of various plant and animal species.

Criterion (x): The area provides critical habitat for endangered species, such as the Persian leopard (*Panthera pardus tulliana*), and numerous endemic tree species, including Persian Ironwood (*Parrotia persica*), Caspian Locust (*Gleditsia caspica*), wingnut (*Pterocarya fraxinifolia*), and Zelkova (*Zelkova carpinifolia*).

Parrotia persica (ironwood) is not only one of the most typical representatives of the Hyrcanian forests but also a living relic of the Tertiary period [6]. Fossil remains of this species have been discovered in Middle Miocene layers in Austria, indicating that it once had a much wider distribution [7]. Currently, its natural range is largely confined to the Hyrcanian forests along the southwestern coast of the Caspian Sea [8]. Its distribution extends northward to the southeastern regions of Azerbaijan (Lankaran, Astara) and southward to the Elburz Mountains in Iran [9]. The exceptional hardness of its wood makes it suitable for the construction of bridges, tool handles, and telephone poles [10]. The widespread presence of *Parrotia persica* within Hirkan National Park has played a significant role in the inclusion of these areas on the UNESCO World Heritage List . The exceptional hardness of the wood allows it to be used in the construction of bridges, tool handles, and even telephone poles, which is why it is known in English as "Persian Ironwood" and in German as "Eisenholz".

Figure 1 - Ironwood Parrotia Persica

Gleditsia caspica (Caspian locust) is an endemic and relict tree species of the Hyrcanian forests, found only along the southwestern coast of the Caspian Sea, in southeastern Azerbaijan (Lankaran, Astara) and northern Iran [11]. Phylogenetic analyses indicate that *G. caspica* originated from *Gleditsia japonica*, which is widespread in East Asia [12]. The range much of its habitat has been lost due to anthropogenic impacts, and the species currently exists mainly as isolated individuals or small groups.

Figure 2 - Gleditsia caspica *(Caspian Locust)*

In recent years, the conservation and sustainable management of biodiversity in the Hyrcanian forests have gained international attention [13]. However, scientific information on the relationship between the distribution of *P. persica* and *G. caspica* and the morphogenetic and physicochemical properties of soils remains very limited [14]. Existing research has primarily focused on the general characteristics of the soil cover in the Lankaran-Astara region and the study of macroelement composition in soils.

Therefore, a detailed investigation of the soils under both species is of significant scientific and practical importance for both the conservation of the Hyrcanian forests and the assessment of the region's agricultural potential.

The aim of this study is to investigate the relationship between the distribution patterns of *P. persica* and *G. caspica* and soil conditions in the mountain forest ecosystems of the Lankaran-Astara region, as well as to evaluate the agrochemical properties of these soils and determine their fertility potential for agricultural use.

The objectives of this study are:

1. To determine the distribution density of *P. persica* and *G. caspica* across elevation gradients and slope exposures.
2. To analyze the morphological, physicochemical properties, and trace element composition of soils formed under both species.
3. To determine the correlation between soil parameters and species distribution density.
4. To evaluate the agrochemical potential and agricultural use potential of the studied soils.

MATERIALS AND METHODS

The research was conducted between 2022 and 2025 in the Lankaran-Astara economic region, on the southeastern slopes of the Talysh Mountains (38°30'–39°00' N, 48°30'–49°00' E). The area features low-mountain (0–600 m), mid-mountain (600–1200 m), and high-mountain (1200–2400 m) zones, with slope steepness of 5–30° and various exposures [2]. The humid subtropical climate has annual precipitation of 1200–1750 mm (maximum in autumn) and mean annual temperature of 12–14°C, with a growing season of 230–250 days [15].

A transect method was used to study 28 soil profiles, selected based on vegetation: *P. persica*-dominated (8 profiles), *G. caspica*-dominated (8), mixed forest (6), and control areas without either species (6). Genetic horizons (A0, A1, B, C) were identified according to WRB [16]. Horizon thickness was measured, and color was recorded using the Munsell chart. From each horizon, three composite samples (each from 5 subsamples within 10×10 m) were collected using a stainless steel auger. A total of 112 samples were air-dried (20–25°C, 7–10 days), crushed, and sieved (<2 mm) for analysis.

All analyses were conducted at the Institute of Soil Science and Agrochemistry (ANAS).

Total organic carbon (TOC) was determined by dry combustion (Vario EL III, Elementar). Carbonates were removed with 1 M HCl; samples were combusted at 900°C. TOC was calculated as total carbon minus inorganic carbon [17]. Organic matter was calculated as TOC × 1.724 [18].

FTIR spectroscopy (Bruker Alpha II, ATR unit) was used to assess organic matter quality. Spectra were recorded at 4000–400 cm^{-1} (4 cm^{-1} resolution, 32 scans). The aliphatic/aromatic ratio was calculated from peaks at 2920 cm^{-1} (C–H) and 1620 cm^{-1} (C=C) [19].

Soil pH was measured in a 1:2.5 soil-water suspension (Mettler Toledo SevenCompact S210) after shaking for 30 minutes and standing for 1 hour [20].

Particle size distribution was determined by laser diffraction (Mastersizer 3000, Malvern Panalytical). Organic matter and carbonates were removed with H_2O_2

and HCl, respectively. Fractions were classified according to USDA [21].

Trace elements (Fe, Mn, Zn, Cu, Cd, Pb, Ni, Co, Cr) were analyzed by ICP-MS (Agilent 7900). Samples (0.5 g) were digested in aqua regia using microwave digestion (Mars 6). Quality control was ensured using certified reference material NIST 2709a (recovery 92–106%) [22].

Clay mineral composition was determined by X-ray diffraction (D8 Advance, Bruker). The clay fraction (<0.002 mm) was separated by sedimentation. Oriented mounts were analyzed under three treatments: air-dried, ethylene glycol-solvated, and heated (550°C). Minerals were identified using EVA software [23].

Tree density was assessed in 10×10 m plots [24]. Ten plots were established per species, counting individuals with DBH≥5 cm. Density was expressed as trees/ha. Elevation and slope exposure were recorded using GPS (Garmin GPSMAP 64s) and compass.

GIS analyses were performed using ArcGIS Pro 3.0 with SRTM DEM (30 m resolution) [25]. Topographic variables (elevation, slope, aspect, topographic wetness index) were derived.

Species distribution modeling was conducted using MaxEnt 3.4.4 [26]. Occurrence data (50 points per species) and environmental variables (topographic, climatic, and soil parameters) were used. Model settings included 10 cross-validation replicates and 5000 iterations. Model accuracy was evaluated using AUC [27].

Statistical analyses were performed in R 4.2.3 [28]. Normality was tested using Shapiro–Wilk. Differences between soil types were assessed using t-test or Mann–Whitney U test. Pearson correlation was used to evaluate relationships between species density and environmental variables.

Random Forest analysis (`randomForest` package) was applied to identify factors influencing species distribution [29]. The model used 500 trees with mtry = p/3. Variable importance was assessed by mean decrease in accuracy (MDA) and mean decrease in Gini (MDG). Statistical significance was set at α = 0.05.

RESULTS AND DISCUSSION

Our study, using GIS analyses and MaxEnt modeling, determined that *P. persica* reaches its maximum density (410 trees/ha) on northern slopes, while *G. caspica* is more common on southeastern slopes (265 trees/ha). This difference is related to the water regime requirements of the two species. Northern slopes receive less solar radiation throughout the day, leading to longer soil moisture retention. *P. persica,* as a mesophytic plant, thrives under these conditions. Southeastern slopes receive more solar energy, resulting in faster soil drying, whereas *G. caspica*, as a xeromesophyte, is adapted to these conditions. Soil moisture was found to range between 25–30% on northern slopes and 15–20% on southern slopes, explaining the observed differences in species distribution.

Differences in distribution were also observed along the elevation gradient. *P. persica* occurs at elevations of 200–1600 m, with an optimal zone at 600–800 m. Within this elevation range, air humidity is optimal (annual precipitation 1400–1600 mm), and temperature fluctuations are minimal (mean annual temperature 12–13°C). Above 800 m, the density of *P. persica* gradually decreases, with only scattered individuals found above 1600 m. *G. caspica* occurs at elevations of 200–1200 m, with an optimal zone at 400–600 m. Above 1200 m, the density of *G. caspica* sharply decreases, which can be explained by its sensitivity to low temperatures. In the 400–600 m interval, the mean annual temperature is 14–15°C and precipitation is 1200–1400 mm, which is optimal for the species.

Random Forest analysis showed that the most influential factors for *P. persica* distribution were slope exposure (34.2%), elevation (28.7%), and humus content (18.3%). This result indicates that topographic factors play the primary role for *P. persica*, while soil humus content is of secondary importance. The high influence of slope exposure reflects the species' sensitivity to light and moisture regimes, while the significant effect of elevation indicates its adaptation to temperature and precipitation gradients. For *G. caspica*, the most important factors were iron content (31.5%), pH (24.8%), and slope exposure (19.4%). This result shows that *G. caspica* is more sensitive to soil chemical properties, particularly iron content and acidity level. The high influence of iron is related to the specific iron requirements of the *Gleditsia genus*.

The accuracy of MaxEnt modeling was AUC = 0.892 for *P. persica* and AUC = 0.874 for *G. caspica*. These values, close to 0.9, indicate that the models fall into the "very good" accuracy category. Based on these models, projections were made according to climate change scenarios (RCP 4.5 and RCP 8.5).

The results indicate that by 2050, the range of *P. persica* will shift to elevations of 400–1200 m, while the range of *G. caspica* will shift to 200–600 m. Range contraction will be more severe under the RCP 8.5 scenario. These projections highlight the need to create new protected areas for both species.

Table 1 - Ecological characteristics of ironwood and Caspian locust

Characteristic	*P. persica* (ironwood)	*G. caspica* (Caspian locust)
Ecological type	Mesophyte	Xeromesophyte
Optimal elevation (m)	600–800	400–600
Elevation range (m)	200–1600	200–1200
Preferred slope exposure	North, northwest	South, southeast
Maximum density (trees/ha)	410	265
MaxEnt AUC value	0.892	0.874
Random Forest main factor 1	Slope exposure (34.2%)	Iron content (31.5%)
Random Forest main factor 2	Elevation (28.7%)	pH (24.8%)
Random Forest main factor 3	Humus content (18.3%)	Slope exposure (19.4%)

Our results show high consistency with studies conducted in the Iranian Hyrcanian forests. Sagheb-Talebi et al. [30] reported that *P. persica* in the Iranian Hyrcanian forests is mainly concentrated on northern slopes at 400–1200 m elevation, with AUC values ranging from 0.85 to 0.91, which aligns well with our result of 0.892 Pourmajidian et al. [31] stated that *G. caspica* prefers warmer and sunnier slopes in the Mazandaran province of Iran, with AUC values ranging from 0.82 to 0.89. Kooch et al. [32]identified slope exposure, elevation, and organic matter as the main factors affecting *P. persica* distribution, which fully agrees with our Random Forest analysis results.

Physicochemical Properties of Soils: Soils formed under *P. persica* belong to the mountain forest brown soil type. These soils have a humus layer (A+AB horizons) with an average thickness of 55 cm, average humus content of 6.2%, TOC of 4.2%, pH of 6.0, and physical clay content of 52.5%. The high humus content and thick profile of these soils indicate their high fertility potential. The slightly acidic reaction (pH 6.0) is optimal for most forest plants. The heavy mechanical composition (clayey) ensures water retention in the soil but simultaneously complicates drainage. Profile analysis showed that humus thickness is inversely proportional to slope steepness: on steep slopes (>15°), humus layer thickness is 40–45 cm, while on gentle slopes (5–15°), it is 55–65 cm.

Soils formed under *G. caspica* belong to the mountain forest yellow and brown soil types. These soils have a humus layer with an average thickness of 30 cm, average humus content of 3.5%, TOC of 2.4%, pH of 6.5, and physical clay content of 38.5%. Compared to soils under *P. persica*, these soils have a thinner humus layer, lower humus content, and lighter mechanical composition. The neutral pH (6.5) is favorable for most plants. Mountain forest yellow soils have a yellowish color throughout the profile, indicating the predominance of hydrated forms of iron compounds. Iron-manganese concretions are frequently encountered in the illuvial horizon of these soils.

FTIR spectroscopy results showed that soils under *P. persica* exhibit intense peaks in the aliphatic C–H (2920 cm^{-1}) and aromatic C=C (1620 cm^{-1}) regions, indicating the predominance of stable forms of humus [19]. This stable organic matter remains in the soil for a long time and significantly contributes to carbon sequestration. The aliphatic/aromatic ratio was 1.2 in soils under *P. persica* and 0.8 in soils under *G. caspica*, indicating that organic matter in soils under *P. persica* is more decomposed and in a more stable form. Soils under *G. caspica* showed more intense carboxyl C=O (1720 cm^{-1}) and hydroxyl O–H (3400 cm^{-1}) regions, reflecting the less stable, readily decomposable nature of the organic matter [19].

Table 2 - Physicochemical properties of soils under ironwood and Caspian locust

Parameter	Soils under *P. persica*	Soils under *G. caspica*
Soil type	Mountain forest brown	Mountain forest yellow and brown
Humus layer thickness (A+AB), cm	55	30
Humus content (A1), %	6.2	3.5
TOC (total organic carbon), %	4.2	2.4
pH (H_2O)	6.0	6.5
Physical clay (<0.01 mm), %	52.5	38.5
Texture	Clayey, heavy clayey	Clayey, medium clayey
Aliphatic/aromatic ratio (FTIR)	1.2	0.8

The high humus content (6.2%) and thick humus layer (55 cm) observed in soils under *P. persica* are consistent with findings by Kooch et al. [32] in the Iranian Hyrcanian forests (humus 5.5–7.5%, thickness 45–65 cm). Khormali et al. [33]. reported TOC values of 3.8–5.2% in soils under *P. persica* in Iran's Gilan province, which aligns with our results (3.5–4.8%). The humus content (3.5%) and TOC values (2.4%) found in soils under *G. caspica* correspond to values reported by Pourmajidian et al. (humus - 2.8–4.2%, TOC 1.8–3.0%) [31]. Our FTIR spectroscopy results are also consistent with those reported by Ellerbrock and Gerke [19].

Trace Element Content and Vertical Distribution: ICP-MS analysis determined the content of nine trace elements (Fe, Mn, Zn, Cu, Cd, Pb, Ni, Co, Cr). Concentrations of heavy metals (Cd, Pb, Ni, Co, Cr) were below background levels in all samples, indicating that the soils are free from anthropogenic contamination. Cd concentrations ranged from 0.1–0.3 mg/kg, Pb from 8–15 mg/kg, Ni from 20–35 mg/kg, Co from 5–10 mg/kg, and Cr from 40–60 mg/kg, all below the maximum permissible concentrations (MPC).

In mountain forest brown soils formed under *P. persica*, Zn and Cu reach maximum concentrations in the upper horizon (A1) and decrease with depth. Zinc was 54 mg/kg in the A1 horizon and 45 mg/kg in the B horizon. Copper was 14.5 mg/kg and 11.5 mg/kg, respectively. This distribution pattern indicates biogenic accumulation: Zn and Cu absorbed by plants from deeper layers are returned to the upper soil layer through leaf litter. Zn concentration in leaf litter was found to be 80–100 mg/kg, and Cu concentration 20–25 mg/kg, explaining the enrichment of these elements in the upper horizon. Fe and Mn were relatively evenly distributed throughout the profile (Fe - 4550–4680 mg/kg, Mn - 335–365 mg/kg). The relatively even distribution of these elements indicates their derivation from parent material and the absence of intensive migration within the profile.

In mountain forest yellow soils formed under *G. caspica*, Fe and Mn concentrations increase with depth, reaching maximum values in the B horizon. Iron was 5150 mg/kg in the A1 horizon and 5400 mg/kg in the B horizon; manganese was 380 mg/kg and 400 mg/kg, respectively. This distribution pattern indicates a leaching (lessivage) process: iron and manganese compounds are washed from the upper horizons and accumulate in the illuvial horizon. This process contributes to the yellowish coloration in the profile of mountain forest yellow soils. Zn and Cu were relatively higher in the A1 horizon (42 mg/kg and 11.0 mg/kg, respectively).

Table 3 - Distribution of trace elements across soil profile (mg/kg)

Horizon	*P. persica* (mountain forest brown soils)				*G. caspica* (mountain forest yellow soils)			
	Fe	Mn	Zn	Cu	Fe	Mn	Zn	Cu
A1	4550	365	54	14.5	5150	380	42	11.0
B	4620	350	50	13.0	5400	400	38	9.5
C	4680	335	45	11.5	5300	390	35	8.5

XRD analysis determined the composition of clay minerals. Soils under *P. persica* are dominated by illite (45–50%), kaolinite (25–30%), and smectite (10–15%). The predominance of illite indicates that these soils are relatively less leached and that physical weathering processes prevail. Illite is rich in potassium and serves as an important potassium source for plants. Soils under *G. caspica* are dominated by kaolinite (40–45%), illite (30–35%), and vermiculite (10–12%). The predominance of kaolinite indicates that these soils are more intensively leached and subjected to higher degrees of weathering [23].

Zinc (54 mg/kg) and copper (14.5 mg/kg) concentrations in soils under *P. persica* correspond to values reported by Kooch et al. [32], (Zn 45–60 mg/kg, Cu 10–18 mg/kg). Iron (5400 mg/kg) and manganese (400 mg/kg) concentrations in soils under *G. caspica* correspond to values reported by Pourmajidian et al. (Fe 4800–5800 mg/kg, Mn 340–450 mg/kg) [31]. The differences observed in the vertical distribution of trace elements also align with international studies. Khormali et al. showed that Fe and Mn compounds accumulate in the illuvial horizon of yellow soils, while in brown soils, trace elements are concentrated in the upper horizon [33]. Our clay mineral composition results also agree with those reported by Moore and Reynolds [23].

Agrochemical Potential and Agricultural Use Potential: Mountain forest brown soils formed under *P. persica* are characterized by high humus content (6.2%), high TOC (4.2%), and rich trace element content (Zn - 51.5 mg/kg, Cu - 13.5 mg/kg). If these soils are used for cultivation, the need for organic fertilizers would be significantly reduced. The slightly acidic pH (6.0) is suitable for many crops (e.g., legumes and vegetables). The high cation exchange capacity of these soils (25–30 cmol/kg) enhances their ability to retain fertilizer elements and release them gradually to plants. The high organic matter content improves soil water-holding capacity (field water capacity 35–40%) and structure.

Soils formed under *G. caspica*, particularly mountain forest yellow soils, have neutral pH (6.5), which is optimal for most agricultural crops, including cereals, vegetables, and industrial crops. These soils also contain high amounts ofFe (5300 mg/kg) and Mn (390 mg/kg). While iron is essential for chlorophyll synthesis, excessive concentrations can be toxic to some plants. Irrigation management requires careful attention in these soils, as under water-logging conditions, toxic forms of iron can develop.

The concentrations of trace elements in both soil types fall within the "normal" range established by Kabata-Pendias [34]. This range is Zn 50–70 mg/kg, Cu 10–20 mg/kg, Fe 5000–10000 mg/kg, and Mn 300–600 mg/kg. All trace elements in our study fall within this range, indicating that the soils are safe in terms of heavy metal contamination [34].

Table 4 - Agrochemical potential of the studied soils

Indicator	Soils under *P. persica*	Soils under *G. caspica*	Agronomic significance
Humus, %	6.2	3.5	Reduces need for organic fertilizers
TOC, %	4.2	2.4	Carbon sequestration potential
pH	6.0	6.5	Favorable for most crops
Cation exchange capacity, cmol/kg	25–30	18–22	Retains fertilizer elements
Field water capacity, %	35–40	28–32	Regulates water regime
Zn, mg/kg	51.5	40.0	Essential for plant growth
Cu, mg/kg	13.5	10.0	Essential for photosynthesis
Fe, mg/kg	4600	5300	Requires careful irrigation
Mn, mg/kg	350	390	Essential for plant growth
Agricultural potential	High for organic farming	Suitable for most crops	—

Our findings regarding the high fertility potential of soils under *P. persica* align with those reported by Kooch et al. [32], who classified soils under *P. persica* as "highly fertile" and noted their high potential for organic farming. Pourmajidian et al. highlighted the neutral pH and high iron content of soils under *G. caspica,* emphasizing the importance of proper drainage system installation in these soils [31]. The international standards presented by Kabata-Pendias serve as a primary source for assessing heavy metal content in soils [34].

CONCLUSION

This study has demonstrated a close relationship between the distribution of Parrotia persica(ironwood) and Gleditsia caspica *(Caspian locust)* and soil conditions in the mountain forest ecosystems of the Lankaran-Astara region.

The two species occupy different ecological niches within the same geographic area. *P. persica* develops optimally on humid northern slopes at 600–800 m elevation, with a maximum density of 410 trees/ha. *G. caspica* predominates on dry southeastern slopes at 400–600 m elevation, with a maximum density of 265 trees/ha. Random Forest analysis showed that the most influential factors for *P. persica* distribution were slope exposure (34.2%), elevation (28.7%), and humus content (18.3%), while for *G. caspica,* they were iron content (31.5%), and slope exposure (19.4%).

Soil properties also showed significant differences between the species. Mountain forest brown soils form under *P. persica*, characterized by a thick humus layer (55 cm), high humus content (6.2%), slightly acidic reaction (pH 6.0), and heavy texture. Mountain forest yellow and brown soils form under *G. caspica*, with a thinner humus layer (30 cm), moderate humus content (3.5%), neutral reaction (pH 6.5), and medium texture.

Trace element distribution also exhibited different patterns. Soils under P*. persica* are rich in Zn (54 mg/kg) and Cu (14.5 mg/kg), with these elements reaching maximum concentrations in the upper horizon and decreasing with depth, indicating biogenic accumulation. Soils under *G. caspica* are rich in Fe (5400 mg/kg) and Mn (400 mg/kg), with these elements increasing with depth and reaching maximum values in the B horizon, indicating leaching (lessivage) processes. Clay mineral composition also differed: illite predominates in soils under *P. persica*, while kaolinite predominates in soils under *G. caspica.*

In terms of agrochemical potential, soils under *P. persica* have high potential for organic farming due to their high humus and trace element content. Soils under *G. caspica*, with their neutral pH and high iron-manganese content, are suitable for most agricultural crops. Trace element concentrations in both soil types fall within the "normal" range according to international standards, indicating that the soils are safe from heavy metal contamination.

Practical recommendations include limiting anthropogenic impacts on northern slopes for *P. persica* and on southern slopes for *G. caspica*, maintaining forest floor cover, and creating new protected areas for both species based on climate change projections. In agriculture, promoting organic farming on soils under *P. persica* and ensuring proper drainage and irrigation systems on soils under *G. caspica* are recommended.

The results provide a scientific basis for both the conservation and restoration of the Hyrcanian forests, which are inscribed on the UNESCO World Heritage List, and for the sustainable agricultural use of soils in the region.

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ТҮЙІН

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ТЕМІР АҒАШЫН *(PARROTIA PERSICA)* ЖӘНЕ КАСПИЙ КАРОБЫН *(GLEDITSIA CASPICA)* ҚОЛДАЙТЫН ЛЯНКАРАН-АСТАРА ТАУ ОРМАНДЫ ТОПЫРАҚТАРЫНЫҢ АГРОХИМИЯЛЫҚ ҚАСИЕТТЕРІ МЕН ҚҰНАРЛЫ ӘЛЕУЕТІ

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Бұл зерттеу реликті ағаштардың екі түрінің - Парротия персиялық *(Parrotia persica)* және Каспий гледичия *(Gleditsia caspica)* таралу заңдылықтары мен Ланкаран - Астара экономикалық аймағының таулы орман экожүйелеріндегі топырақ жағдайлары арасындағы байланысты зерттейді. Зерттеу 2022 және 2025 жылдар аралығында жүргізілді. 28 топырақ профилінен барлығы 112 топырақ үлгісі жиналып, жалпы органикалық көміртегі (ЖОК), FTIR спектроскопиясы, pH, бөлшектердің мөлшерінің таралуы (лазерлік дифракция), микроэлементтердің құрамы (ICP-MS) және саздың минералды құрамы (XRD) талданды. Нәтижелер *P. persica* өзінің максималды тығыздығына (410 ағаш/га) солтүстік беткейлерде 600-800 м биіктікте жетеді, ал *G. caspica* оңтүстік-шығыс беткейлерде 400-600 м биіктікте жоғары тығыздыққа (265 ағаш/га) жетеді. *P. persica* астында пайда болған таулы орман қоңыр топырақтарында қарашірік мөлшері жоғары (6,2%), ЖОК (4,2%) және аздап қышқыл pH (6,0), ал *G. caspica* астындағы тау орманының сары және қоңыр топырақтары сипатталады. Қарашіріктің орташа мөлшері (3,5%), ЖОК (2,4%) және бейтарап pH (6,5) бойынша. *P. persica* астындағы топырақтар Zn (54 мг/кг) және Cu (14,5 мг/кг), Ал *G. caspica* астындағы топырақтар байытылған. Құрамында Fe (5400 мг/кг) және Mn (400 мг/кг) жоғары концентрациясы бар. *P. persica* астындағы топырақтар органикалық егіншіліктің жоғары әлеуетін көрсетеді, ал *G. caspica* астындағы топырақтар бейтарап Рн-ға ие, бұл оларды дақылдардың кең ауқымына қолайлы етеді.

Түйінді сөздер: темір ағашы, Каспий гледичиясы, топырақ жағдайлары, агрохимия, топырақ құнарлылығы, микроэлементтер.

РЕЗЮМЕ

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АГРОХИМИЧЕСКИЕ СВОЙСТВА И ПОТЕНЦИАЛ ПЛОДОРОДНИЯ ГОРНО-ЛЕСНЫХ ПОЧВ ЛЯНКЯРАН-АСТАРА, ПОДДЕРЖИВАЮЩИХ ЖЕЛЕЗНОЕ ДЕРЕВО *(PARROTIA PERSICA)* И КАСПИЙСКОЕ РОЖКОВОЕ ДЕРЕВО *(GLEDITSIA CASPICA)*

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В этом исследовании изучается взаимосвязь между особенностями распространения двух реликтовых видов деревьев – Парротия персидская *(Parrotia persica)* и Каспийской гледичия *(Gleditsia caspica)* и почвенными условиями в горных лесных экосистемах Ленкоранско-Астаринского экономического региона. Исследование проводилось в период с 2022 по 2025 год. В общей сложности из 28 почвенных профилей было отобрано 112 образцов почвы, которые были проанализированы на содержание общего органического углерода (ООУ), ИК-спектроскопию, pH, распределение частиц по размерам (лазерная дифракция), состав микроэлементов (ICP-MS) и глинисто-минеральный состав (XRD). Результаты показывают, что *P. persica* достигает своей максимальной плотности (410 деревьев/га) на северных склонах на высоте 600-800 м, в то время как *G. caspica* достигает более высокой плотности (265 деревьев/га) на юго-восточных склонах на высоте 400-600 м. Бурые почвы горных лесов, сформировавшиеся под *P. persica*, характеризуются более высоким содержанием гумуса (6,2%), ООУ (4,2%) и слабокислым pH (6,0), в то время как жёлтые и бурые почвы горных лесов под *G. caspica* характеризуются умеренным содержанием гумуса (3,5%), ООУ (2,4%) и нейтральными pH (6,5). Почвы под *P. persica* обогащены Zn (54 мг/кг) и Cu (14,5 мг/кг), в то время как почвы под *G. caspica* содержит более высокие концентрации Fe (5400 мг/кг) и Mn (400 мг/кг). Почвы под *P. persica* обладают высоким потенциалом для органического земледелия, в то время как почвы под *G. caspica* имеют нейтральный pH, что делает их пригодными для выращивания широкого спектра культур.

Ключевые слова: железное дерево, гледичия каспийская, почвенные условия, агрохимия, плодородие почв, микроэлементы.

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