Vol 1, № 1, 2025

e-ISSN 3106 1095
P-ISSN 3106-1087

WESTERN caspian UNIVERSITY

Journal of Forest and Ecosystem Sciences

Baku - 2025

WESTERN caspian UNIVERSITY

E-ISSN: 3106-1095
P- ISSN:3106-1087

Western Caspian University

Journal of Forest and Ecosystem Sciences
Vol 1, No 1, 2025

DOI:10.54414/ULLT3898

www. forestjournal@wcu.edu.az

CONTENTS

Content DOI: 10.54414/IJTY3714

Spread of Forest Ecosystems in Azerbaijan, Structure, Usage Changes and Learning

Aydin Yakhyayev [1], **Adilaqa Melikov**,

[1]Western Caspian University, Baku, Azerbaijan

[2]Forest Development Service, Baku, Azerbaijan

Received:20.10.2025 **Accepted:28.10.2025** **Published:30.10.2025**

https://doi.org/10.54414/YLUS1025

Abstract:

This article provides an analysis of the distribution and structure of forest ecosystems, changes in use, and the work carried out in the last 10-15 years in the direction of their study. For this, the report materials of the Forest Development Service of the MENR for the relevant years were used. Here, the dynamics of changes in the spread of trees and forest covers in the Republic, their distribution by area and species, are given. Here, at the same time, a distribution scheme for land use categories was developed. Hansen's global changes in forest lands during 2000-2018 are presented. The article shows the biodiversity characteristics of the forest ecosystems of the Republic, the distribution directions of the main forest-forming species in the altitudinal zones of mountainous areas, which were analyzed. The work also highlights the main functions of forest ecosystems and their role. Finally, issues such as the protection of forest ecosystems and their sustainable development and expansion of their areas are analyzed, and promising directions are identified.

Keywords: Forest ecosystems, Land use change, Biodiversity in Azerbaijan, Sustainable Forest management,

1. Introduction

1.1. Forest ecosystems and their distribution and structure.

In 2021-2023, forest-related land use and land use change, fire, etc., were studied using Collect Earth at the country level with the Remote Sensing method in Azerbaijan. The report was prepared by collecting and analyzing national data. This report assesses both current forest cover and land-use change from 2000 to 2024. As a result of the evaluation, it was found that the area covered by forest in Azerbaijan is 1.301, 088 thousand have, or of the general area 15.1% constitutes. Comparing the land uses of 2000 and 2016, the results show that relatively small land use changes occurred in all types of land use in Azerbaijan. Very slight increases were observed in forests (annual increase of 0,007%) and grasslands (annual increase of 0,018%). However, an increase of 37,962 ha or 7,9% was observed in settlements over sixteen years. The results of the Global Forest Survey also confirm very little land use change between forest and non-forest land use classes (Forest Code of the Azerbaijan Republic, 1997. art.8).

Forest management on 1.213,7 thousand hectares of the republic's forests is carried out by the Ministry of Ecology and Natural Resources according to the Forest Code of the Republic of Azerbaijan and the Law on Environmental Protection. Other forest areas are located on lands owned by other owners (FAO Collect Earth, 2019).

1.213,7 thousand belonging to the Ministry of Ecology and Natural Resources. Hectare of forest land of the forest fund – 1.035 thousand hectares, and areas covered with forest 1.021 thousand hectares, which is unevenly distributed throughout the territory of the Republic. Thus, 49 % of the total forest areas belong to the Greater Caucasus, 34 % to the Lesser Caucasus, 15% to the Southern zone, and 2 % to the lowland zone (Fig. 1).

Of the total area in Azerbaijan, 31,8 percent has tree cover, which is 2.751,2 thousand hectare. The tree cover is approximately 52,7%-i is available in other types of land use. All types of land use in Azerbaijan have different levels of fire risk (Ahrends A., et al., 2010).

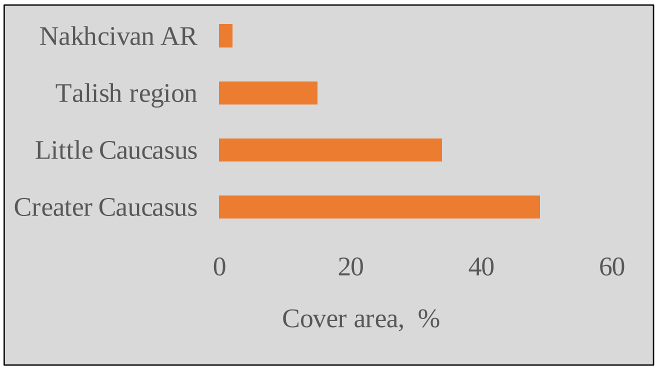


Figure 1. Tree cover of the regions

During the last inventory, it was determined that the total area of the state forest fund is 1.213,7 thousand hectares, and 1.043,8 thousand hectares of this area are covered with forest. During the inventory conducted in 2018-2021, it was calculated that there is a total of 1.301,2 thousand ha of forested area in the temporary forest fund and in the territories belonging to other owners. In the 2015 Forest Resources Assessment (FRA), it was determined that the forest area in Azerbaijan is 1.139,4 thousand ha (Fig. 2).

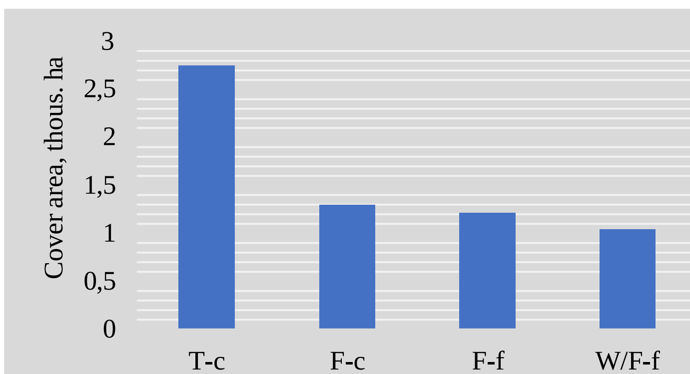


Figure 2. *Comparison of forest area statistics by assessment/survey:*

T-c - Tree-coveredarea AzR; F-c – Area covered with forest; F-f –

Including the forest fund; W/F-f – Woded area in the forest fund

Among the six types of land use in Azerbaijan (forests, arable lands, other lands, pastures, wetlands, and residential areas), land use change and area growth were mainly observed in residential areas. This is followed by grasslands and woodlands. On the other hand, the area of farmland, other lands and wetlands has decreased (Tab. 1).

Table 1. *Land use change trends in forest ecosystems*

Soil use categories	Primary areas (ha)	Current areas (ha)	Change in area (ha)	Change in areas (%)
Forest	1 299 729, 29	1 301 188,32	1 459,03	0,11
Sown areas	3 305 138,59	3 270 192,26	-34 946,33	-1,06
Othes areas	1 019 834,86	1 011 951,91	-7 882,95	-0,80

Pasture areas	2 298 562,71	2 305 186,62	6 623,91	0,29
Swamps	256 429,12	253 213,71	-3 215,41	-1,25
Residential areas	480 305,43	518 267,18	37 961,75	7,90
Total	8 860 000,00	8 860 000,00	0,00	0,00

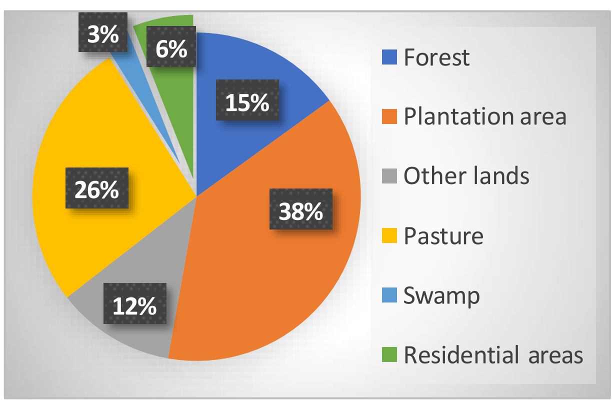
Cropland, other land, and wetlands decreased by 1.06%, 0.80%, and 1.25%, respectively, while forests, grasslands, and settlements increased by about 0.11%, 0.29%, and 7.90%, respectively. The Collect Earth estimate shows a total net forest increase of 1,459 ha (0.11%) over the sixteen years of interest. In contrast, Hansen et al. (2013) report a forest loss of 8,611 hectares between 2000 and 2017 (FAO Forest Resources Assessment, 2015).

It should be noted that between 2000 and 2016, no forest area was converted to agricultural land or other land use categories. It is considered a good thing that the forest areas are not turned into farmland for agricultural purposes. The figures show that very little forest loss has occurred in the country over the past period. The reason for this is natural regeneration in the forests destroyed during the occupation (more than 54,000 hectares), abandoned settlements and farmlands, afforestation related to forest protection, and reforestation works are carried out rapidly.

On the other hand, due to the increase in infrastructure needs of the population in the country, some of the land use categories, such as farmland, other lands and pastures, have been transformed into the residential use category (Fig.3).

The land use change matrix shows that the areas of land use categories have not changed much over time, except for settlements. Hansen's global forest change shows a similar trend (Fig. 4).

Figure 3. *Soil use categories, ha*



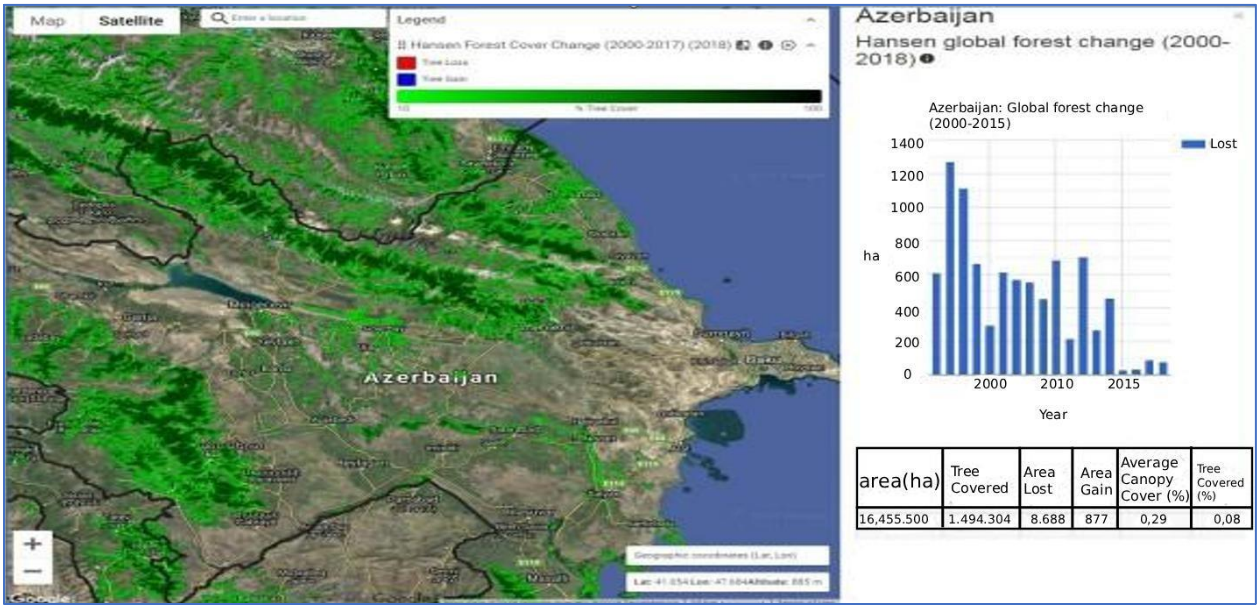


Figure 4. *Hansen global forest change (2000-2018)*

Based on satellite images of tree-covered areas, land use changes caused by various natural events such as cutting of trees, fire and flood, etc. have been determined with high accuracy. In addition, the changes caused by the fire were determined graphically based on the NDVI program. According to the results of the analysis, during the research period, fires occurred at different levels in all categories of land use in Azerbaijan. Based on the same program, there are also changes in the category of pasture use areas that have been discovered (IPCC, 2003: Good Practice Guidance for Land Use, Land-Use Change and Forestry).

Table 2. *Change directions of land use categories, ha*

Compared to other land use categories, most of the changes in use occurred in croplands (50.8%),

Land resignation category.	Opening	Fire	Pasture	Flood	Fishing	Other	None of them	Total
Forest	99,5	120 776,4				1 628,8	1 178 683,7	122 504,6
Plantation area	100,0	554 893,1	99,5			1 665,3	2 714 998,5	556 757,8
Other lands		35 354,3		1 623,1		1 683,8	981 173,7	38 661,2
Pasture	2 030,5	278 618,6	698,5				2 023 839,0	281 347,6
Swamp	1,614.6	23,988.9		1 723,2	1 580,9		222 741,9	28 907,7
Residential areas		64 881,5				3,399.9	449,985.8	68,281.4
Total	3 844,5	1 078 512,8	797,9	3 346,3	1 580,9	8 377,8	7 571 422,6	1 096 460,3

pastures (25.7%) and forests (11.2%). As it turns out, fire is a major threat in all land use categories, and sustainable measures must be taken on farms to prevent it (IPCC, 2006. Guidelines for National Greenhouse Gas Inventories).

The conducted analyses are the total for the Republic for all land use categories. 1.078.512,85 ha area was determined to be burnt. According to the data of the Hansen global organization, between 2000 and 2018, a total of 3,090,864 hectares of land were burned in the country. Changes in logging, fire and other use categories in the country 122.504,65 ha affected the forest area, which is 9.4% of the total forest area.

One of the factors that significantly affects the change of land use categories is the erosion processes occurring in forested and other land use areas. In wooded areas in the country total area prone to erosion is 161,073.48 hectares (Table 3).

Table 3. Erosion trends of land use categories, ha

Soil heat-fade category.	Type of erosion	Very low	Down	Medium	High	Very high	Total
Forests	Sliding			99,45	1 636,89		1 736,34
	Precipitation Surface flows	1 768,28	100,03	100,03	99,45	1 738,72	3 806,51
	River erosion	1 594,74	1 631,67	99,45			3 325,86
Cultivated fields	River erosion	1 673,66		100,03			1 773.69
Other lands	Sliding		7 965,94			1 585,34	9 551,28
	Precipitation Surface flows		8 036,96	14 503,67	1 575,95	6 764,67	30 881,24
	River erosion		1 545,66				1 545,66
	Coastal erosion		1 594,74			1 580,94	3 175,68
	Wind erosion	11 183,75	14 797,02	3 304,23		1 672,56	30 957,56
Grasslands	Sliding	1 575,95	3 101,54	198,90	1 919,12		6 795,50
	Precipitation Surface flows	5 493,98	5 110,80	11 323,97	3 497,55	1 729,20	27 155,51
	River erosion	198,90		1 549,08	1 599,58		3 347,56
	Wind erosion	1 705,91	3 321,45				5 027,37
Swamps	Precipitation Surface flows			1 606,55			1 606,55
	River erosion	1 527,81	199,48	4 717,79	6 401,76	1 714,64	14 561,49
	Coastal erosion	1 557,22	3 201,63	4 715,65	4 744,73	1 606,47	15 825,69
Total		28 280,19	50 606,9	42 318,8	21 475,03	18 392,53	161 073,48

As can be seen from the obtained figures, small and medium-sized planting areas are the least prone to erosion (1773.69 ha - 1.1%), and forested areas (8868.69 ha - 5.5%) are attributed. In other categories of use, it was determined that the tendency to erosion is higher (IPCC, 2019. Intergovernmental Panel on Climate Change Web Page). \

According to the analysis, the tree cover is 31.77% of the total area, which is 2,751,167 thousand. ha constitutes. As can be seen from the table, the existing forest areas make up 47.29% of the area covered with trees, of which 1830.87 hectares are sparse. 52.7% of the tree cover belongs to other land types outside the forest stock. Most of this area is cultivated land (638,190 thousand ha - 23.2%) and pastures (430,413.77

thousand ha - 15.65%). Residential areas also have groves, and the tree cover is more than 12.67%. In comparison to cropland, settlements and pastures, tree stands are relatively less common in other lands and wetlands and are found in 13,013.85 ha and 19,941.95 ha, respectively (NFP, 2013. National Forest Program 2015- 2030 (Final Draft), Republic of Azerbaijan, Baku).

Tree stands are mostly distributed in forested areas. Since the trees in residential areas cover an area of 348,519.53 ha, this area constitutes 67.3 percent of the total residential area (FAO. (2010. Global forest resources assessment and baseline report).

2. Biodiversity characteristics of forest ecosystems.

As a whole, the forests of the Republic of Azerbaijan are classified as group I and are of great importance in the prevention of climate change, the expansion of desertification processes, the reduction of biological diversity, and the disruption of the gas balance in the atmosphere, which are considered global environmental problems. Plays an important role in the development of the fields. The changeable and complex topography of the areas, as well as the growth of forest trees and shrubs up to 2000-2200 meters above sea level, also led to the formation of a rich and colorful species diversity. From this point of view, 435 types of trees and shrubs, including 107 trees and 328 shrubs, are spread over wide areas in the forests of our Republic. The Republic of Azerbaijan is among the countries with the least forest cover. The country's forest fund, belonging to the state, performs irrigation, soil protection and climate regulation functions. The forests of Azerbaijan belong to the first group and are given to forest enterprises for the purposeful development of forestry. Since the forests belong to group I, there is no industrially significant scraping. Forests in our country are unevenly distributed; 85% of them are located in mountainous areas, and 15% are located in plains (Burgi M. and Hersberger A., 2009).

Azerbaijan forests have unique forest formations. These formations are:

Coniferous forest formations consisting of hook pine;

Juniper sparse forest formations;

Beech forest formations consisting of eastern beech;

Oak forest formations

Chestnut oak forest formations;

Forest formations consisting of Caucasian oak;

Forest formations consisting of eastern oak;

Forest formations consisting of long-stemmed oak;

Forest formations consisting of Araz oak;

Velas forest formations;

Relic forest formations consisting of ironwood;

Birch forest formation

Forest formations of velvet birch;

Forest formations consisting of Tranttoveter birch;

Palm forest formations;

Elm forest formations;

Forest formations consisting of common walnut;

Forest formations consisting of common chestnut;

Forest formations consisting of azad wood;

Forest formations consisting of silk acacia;

Forest formations consisting of sedge;

Pollen forest formations;

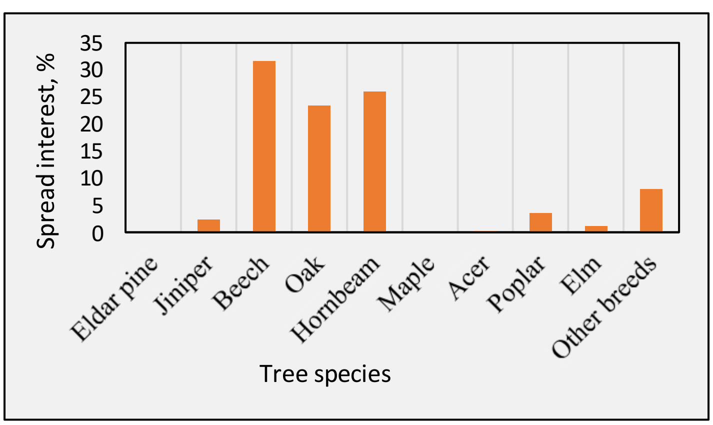
Tugay forest formations formed along the Kura-Araz coasts;

Poplar forest formations.

There are 435 types of trees and shrubs in the forests and green areas of Azerbaijan, 70 of which belong to endemic species. Broad-leaved forests are typical of the entire Republic. 95% of the forests are in the highlands, and the remaining 5% are mainly located around watercourses and in the plains. Most of the forests are located on steep mountain slopes, and they have irreplaceable soil protection, water purification and climate purification importance. This type of forest is more common in the low and medium mountainous areas of the Greater Caucasus, the Lesser Caucasus, Talysh Mountains (especially at 600-1600 m absolute altitudes).

Forests consist of three main tree species - beech, hickory and oak. They make up 81.09 percent of the entire forest cover. Besides these, birch, elm, linden, alder, poplar, linden, willow, etc., broad-leaved trees are also common throughout the area. 7 out of 107 tree species growing naturally in Azerbaijan are conifers. They include European sycamore, Eldar pine, hook pine, multi-fruited, heavy-smelling, red and long-stemmed junipers.

The Republic of Azerbaijan is considered the homeland of many rare species of shrubs. As a relic plant of the Tertiary period, blackthorn is a rare gem of forests. This tree is distributed in the South (Ismayilli, Gabala regions), Southeast (Pirgulu, Shamakhi regions) of the Greater Caucasus. Late-growing but long-lived blackthorn has never covered large areas. The homeland of the Eldar pine is Azerbaijan, and its distribution area is the Eldar hollow area of the Jeyranchol mountain range. Among the relict and rare trees of the third period growing in the Talysh mountains are ironwood, Lankaran acacia, chestnut-leaved oak, azat, Caucasian palm, boxwood, walnut, Hirkan maple, etc. are rare pearls of (Fig.5).



nes

Belts	The main plant formations	of the Greater Caucasus	
		south slope	North, East part
Semi-desert and desert	Yovshanli-shorangali semi-desert	100-200m	up to 150 m
Semi-desert and semi-steppe	Semi-desert with wormwood, Steppe, frigana groups and complex of arid forests	120-200 m	400-600m
Semi-steppes, arid forests and scrubs	Fragments of stony semi-steppe and arid forests, thickets	200-700m	-
Arid forests	Saqqizli - juniper forests, stone-standing, semi-steppe, frigana groups, sables	200-600m	-
Plain forests	Mixed broadleaf ivy forest, marshy meadows	200-800 m	0-600 m
Low mountain forest	Iberian oak, holm oak, oak-black forests	350-900m	-
Middle mountain forest	Beech, beech-beech forests	1600-2300m	600-2300m
Upper mountain forest	Subalpine forests, thickets and meadows	1600-3000 m	1500-3000m
Alp		3000 (3300) m	3000m and above

3. Forest ecosystems and their functions.

Forest ecosystems represent complex natural-historical systems spread throughout the forest stock and covering the fauna and flora of the area. The benefits of ecosystems to human society are called "ecosystem services". In other words, ecosystem services are a set of products and services that ecosystems provide in accordance with the needs and demands of people. In turn, these services have an important role in ensuring the continuity of life on Earth. The following are the main directions of "ecosystem services":

- Conservation of biodiversity; - Regulation of the atmosphere; - Watershed services;
- Soil protection services; - Recreational services (Dudley N., et al, 2005).

Conservation of biodiversity. There are various relationships between forest formations and biodiversity. Forests are areas where many types of trees and plants are spread. In addition, forests provide habitat for numerous species, some of which are endemic to the area and of special economic importance. The use of these types of endemic trees and shrubs for various purposes leads to their destruction. Therefore, the protection of this type of tree and shrub plants by the farm is considered one of the important measures in the protection of biodiversity. Biodiversity is essential to the sustainability of ecosystems and supports all other ecosystem services (Millennium Ecosystem Assessment, 2005). Forest ecosystems with high biodiversity are considered more attractive for recreational activities, as well as providing more carbon sequestration. However, in addition to wood, forest ecosystems contain various non-wood products, including wild fruits, vegetables, nuts, mushrooms, medicinal plants, etc. can provide forest products supply services (Gibson L. et al, 2011).

It is considered important to take the following measures to protect biodiversity in forest ecosystems: - restoration of natural forest cover; - protection of intact forest landscapes; - main-taining a network of ecologically protected areas; - preservation or restoration of natural forest features; - conservation or restoration of species diversity.

Recreational services. In Azerbaijan, the use of forests for recreational and tourism activities (sports excursions, watching wildlife) continues to spread widely. When people use these services in the forest, they restore their health, including reducing stress, providing psychological and physiological recovery. In this direction, the infrastructure created in the forest ecosystems of the Republic and their quality (for example, roads, camps), and the intensity of management of these networks increase their attractiveness for recreation (Gurevitch J. and Padilla D., 2004).

Invasive plant species. At the same time, ***a***n analysis of the results of the inventory of the invasive flora of the Azerbaijani part of the Greater Caucasus (BC) was carried out. Researches were carried out in the natural (desert, psammophyte-littoral, desert, bush, forest, meadow) ecosystems of the Azerbaijan part of the BK, as well as ecosystems disturbed by anthropogenic activity. Here, 39 plant species of foreign origin (60.9% of the total flora of Azerbaijan, including 64 species) are mentioned, of which 12 (30.7% of the region's foreign flora) are invasive species. *Asteraceae Dumort* (11 types, 28%), *Poaceae Barnhurt* (13 species; 33.3%), *Amaranthaceae Juss* (5 species, 12.8%) are the main groups of invasive flora of the region. The results obtained analysis showed that annual plants are dominated by 25 species (64.1%), and perennials by 12 species (30.8%). The participation of tree forms is 2 types (5.1%). According to the system of life forms, therophytes with 27 species (69.23%) are dominant, the rest are hemicryptophytes with 10 species (25.64%), chamephytes - 2 species (5.13%). The distribution of invasive plants is subject to vertical zonation. It was determined that the most optimal height level of invasive plants is spread at heights of 100-600 (700) m.

It should be noted that in the middle of the 20th century, the highest point of vertical distribution of species was 600 (700) m above sea level. Currently, the spread of invasive plants from sea level up to 1100 m is observed; that is, the distribution range of these plants is also observed in the middle and upper mountain belts of the mountains, which can be associated with global warming (Larsen F. et al, 2012).

In the Azerbaijani part of the Greater Caucasus, most of the invasive species are distributed in the regions bordering Russia and Georgia. In particular, 12 species enter the local flora more rapidly and have a high reproductive potential, and these include: Australia akalifi (*Acaliph of the south*), Refolding Blackbird (*Amaranthus retroflexus*), Wormwood ragweed (*Ambrosia artemisiifolia*), high rotation (*Ailanthus altissima*), Canadian bluebell (*Erygeron canadensis*), curly crumb (*Erigeron Bonariensis*), small-flowered onion (*Galinsoga parviflora*), Amerika çiçəbaharı (*American Phytolacca*), annual creeper (*Phalacroloma annual*), False white acacia (*Robinia pseudoacacia*), common plover (*Xanthium strumarium*), Thorny xanthium (*Xanthium spinosum*). The analysis of the situation of invasive plants in the areas where invasive plants are spread has shown that the representatives of foreign flora species are starting to intensify in the region, and regular monitoring should be considered as the first measure to control them (Mason N. et al, 2005).

4. Protection of forest ecosystems and increase of forested areas.

In 2003, the "National Program for the restoration and increase of Azerbaijan's forests" was adopted. The national program covered the years 2003-2008 and reduced the problems of the forest sector to some extent. Thus, during these years, reforestation measures were carried out in 71634 hectares, out of which 28030.0 hectares were planted in open areas.

In the last decade, there has been a trend of decreasing forest areas around the world. According to the information provided by the UN FAO organization, 5 million ha of forest areas are lost (destroyed) on our planet every year. This manifests itself mostly in the Amazon and African forests. This intensifies the process of desertification, leading to land degradation, food shortages and, ultimately, population starvation. The most forested regions in the world are Russia, Brazil, Canada, and Finland. Forestry and the forest industry make up 15% of the economy in Russia, 18% in Brazil, 12% in Canada, 22% in Finland. It is the development of the forest industry that increases the export potential of these countries' forest products. In recent years, the reduction of forest areas has increased the attention of international organizations to this issue. Taking into account the reduction of forest areas, the "Bonn Call" document was prepared, and the restoration of the forest landscape in 130 million ha by 2030 was envisaged by the countries. Since this challenge is voluntary, each country, taking into account its potential, informed about the contribution it will make and joined that challenge. Currently, 96 countries have joined the call. Since the main priority direction of our country is the increase and restoration of forest areas, as well as the increase of the percentage of forests, the Republic of Azerbaijan joined this call in 2018 and undertook to carry out forest restoration measures in 170 thousand ha by 2030. Targeted measures are being implemented in this direction (McCarthy J. and Prudham S., 2004).

In 2011-2020, reforestation measures were carried out on 106,299.0 ha in the territory of the republic, of which 25,634 ha were planted and seeded. During these years, 27,876.0 thousand pieces of planting material were grown, 35,878.94 thousand trees were planted, and the forested areas increased by 30,739 ha.

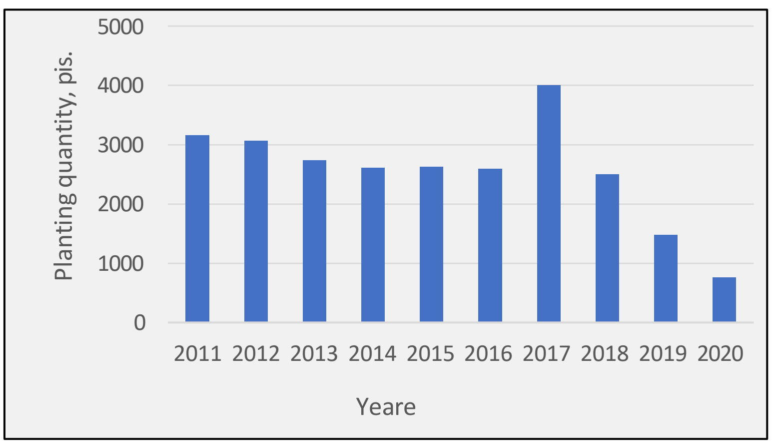


Figure 6. Cultivated areas by year

On the other hand, as a result of continuous and decisive measures taken in the field of forest protection, the cases of illegal logging have decreased by 2.5 times in the last ten years. At the same time, during these years, the volume of wood materials and products imported to the Republic increased 10 times and reached 180 million US dollars. 12.1 thousand tons of grass, 1.3 thousand tons of grain, 792 tons of garden fruits, 1.4 thousand tons of garden pomegranates, 1.2 thousand tons of nuts, 214 tons of citrus fruits and 32,065 tons of honey were supplied in connection with the implementation of the "State Program on the reliable provision of food products to the population in the Republic of Azerbaijan" (2003-2008 and 2008-2015) done (Tab. 6).

5. Effects on forest ecosystems.

As in many parts of the world, there is strong pressure on biodiversity in Azerbaijan on three levels. The main threats are the conversion of natural ecosystems to productive systems (agriculture or livestock), pollution, climate change, overexploitation of populations and the introduction of exotic species.

Threats affecting the forests of Azerbaijan affect not only trees, but also fungi, microorganisms, fauna, etc., which are the main components of the forest disappear with them. Threats to forests are mainly divided into two groups: direct and indirect. Direct threats include deforestation, which has the following causes: Use of firewood - fuel and scraps for industrial purposes; Urbanization - destruction of forest areas due to urban development; Cutting down trees for the purpose of creating pasture for livestock or burning; Forests for the creation or expansion of additional use areas such as roads; Deforestation to build infrastructure (Mittermeier R., et. al, 2004).

One of the problems that hinders the natural regeneration of forest resources is the existence of nomadic livestock, which is the overloading of pastures and the overgrazing of livestock by farmers. This situation causes the retreat of the upper border of the forests and the destruction of subalpine plant formations. All this makes it even more necessary to review the management of forest resources of the Republic of Azerbaijan. For centuries, forests have been considered the main source of human economic activity. As in other countries, forests in Azerbaijan, especially those spreading near settlements, performed two main economic and cultural-spiritual functions. Even now, there are forest areas that are considered sacred and no economic activities are carried out there. Below is the dynamics of illegal cutting in the forests of the Republic in 2010-2020 (Tab. 5).

Table 5. Defined in the Republic in 2010-2020

dynamics of illegal scraps

Years	Number of trees cut (number)	Volume, m^3	Value (manats)
2010	61637	34483	245813
2011	38587	24300	172922
2012	52563	24066	157437
2013	56958	32623	222348
2014	47389	22051	152032
2015	42152	21362	147687
2016	43365	22253	154619
2017	81420	55437	470138
2018	49816	26355	289941
2019	38956	19107	337290
2020	21583	11041	453836
Total	**534426**	**293078**	**2804063**

During the 9 months of 2021, 12,834 trees were cut down illegally. Illegally cut trees were valued at 277,495 manats, with a volume of 6,050 m^3.

At the same time, preliminary calculations conducted in the Karabakh region show that the forest areas were intensively changed during the occupation. Deforestation of these forests from 1992-2020 was initially determined to be more than 54 thousand hectares.

6. Degradation of forests.

Deforestation and degradation are global problems. Thus, according to the forecasts of leading international organizations, by 2030, approximately 47% of the world's forests will face the risk of intensive fragmentation or degradation. Both cases have a negative impact on the sustainable development of forests.

There is an approach to the degradation of forests as a change in the diagnostic indicators of the land under the forest by cutting down trees. In this direction, there is a high risk of forest destruction in the area of about 6.5 million km² in the next 10 years. Another major driver of forest degradation is climate change: higher temperatures and unpredictable weather patterns increase the risk and severity of wildfires, pests and diseases. However, the main cause of forest degradation is unsustainable and illegal logging (Pereira H., et. al, 2010).

7. Tugai forests can be cited as an example.

In the last 20-30 years, the lack of fuel and the resettlement of refugee families in the surrounding regions of Kura increased the pressure on the trees of Tugai forests, which led to the thinning of the existing forests, the deterioration of their condition, and the reduction of their area. Another factor affecting forest degradation is the presence of settlements nearby. This has gradually enabled the spread of cases such as the occupation of forest areas by local residents and the carrying out of various purposeful activities. Also, cattle damage to forests has completely stopped the development of natural regeneration in forests. The thinning of forest massifs and problems arising from the normal development of forest plantations planted in open areas create serious obstacles to the development of forests, which increases the negative effects on the environment.

8. Problems arising in forest ecosystems and directions for their solution.

The role of the forest sector in the national economy is underestimated, and the paradigm of sustainable forest management is poorly applied in practical forest management. The most important forest management issues were identified in several scientific discussions held in 2018-2020. During the discussions, it was shown that the main problem of forestry in the country is the replacement of the extensive operational nature of forest management with a continuous intensive forest management model. This, in turn, will allow for achieving a higher economic efficiency of the forest sector by increasing the productivity of forests and the volume of firewood supply in areas with developed social and transport infrastructure by protecting protective forests, especially protected and untouched natural areas.

The need to address important issues, such as replacing primary data-based and comprehensive forestry projects with a sound methodological base, adequately funded forestry activities, and forest management regulations that provide quality control tools for forest management, is justified. Forecast indicators for the development of the Forest Sector until 2030 require the importance of a new forest policy and significant investments in the forest sector.

The forested area of the country is 11.8%, 85% of which is spread in the mountainous part and has great potential in terms of ecological services. In these areas, erosion and degradation problems are very serious.

To ensure the implementation of the "Strategic Action Plan prepared for the effective solution of socio-economic, humanitarian, organizational and other urgent issues in the liberated territories" of the Coordination Headquarters established by the Order of the President of the Republic of Azerbaijan No. 2303 dated November 24, 2020, the "State Program for the Restoration and Sustainable Development of the Liberated Territories of the Republic of Azerbaijan for 2022-2026" was prepared. According to the mentioned State Program, the Ministry of Ecology and Natural Resources prepared the "Forest Fund Restoration Program" covering the years 2022-2026 in the occupied territories of the Republic of Azerbaijan. These lands intended for reforestation will open up great social, economic and ecological opportunities for the country.

9. Study of forest ecosystems.

Within the framework of the "Assessment and Monitoring of Forest Resources" - GCP/AZE/007/GFF project in the Republic, the issues of determining the borders of forest fund lands, carrying out geodesy-topographic works, drawing up plan-cartographic materials, inventorying forests by determining the distribution of forests, their species composition, age groups, firewfood stock, afforestation, reclamation, conservation, protection and other economic measures were studied. Forest structure works were carried out for the purpose of determining the rules and methods of conducting these measures, determining the functions of forests, determining the directions and volumes of forest use, studying recreation, tourism and logistics issues, conducting forest-biological, forest-pathological observations, evaluating the activities of forestry, and forming and developing the optimal organization of the farm.

The rules, research and studies applied in forest management are carried out in accordance with the principles of the Forest Legislation of the Republic of Azerbaijan, the FAO (Food and Agriculture Organization) guidelines of the United Nations, and the "Methods and Principles" of the Republic of Turkey for the preparation of Ecosystem-Based Functional Forest Structure Planning.

Ecosystem-based Functional Forestry works enable the identification of "Ecosystem Services" (water and soil conservation and carbon sequestration), digitization and integration of the landscape planning process.

Assessed forest "Ecosystem services" are mapped according to mathematical models, terrain, data and developed methods. The distribution area of trees and shrubs and the analysis of forest functions are carried out on the maps. The purpose of these analyses includes the services provided by the forest ecosystem.

Within the framework of the "Assessment and Monitoring of Forest Resources to Strengthen the Forestry Knowledge Framework in Azerbaijan" - GCP/AZE/007/GFF project, research was conducted in the service areas of Barda, Zagatala, Sheki, Gabala, Shamakhi, Lankaran and Masalli Regional Forestry Centers in 2018-2021.

Research on forest ecosystems was carried out in Lankaran and Masalli Regional Forestry Centers. The research was carried out by the Forestry Development Service under the Ministry of Ecology and Natural Resources. At this time, forest ecosystem services have been evaluated economically, ecologically, and socio-culturally.

With this approach, which was applied for the first time in Azerbaijan, it played an important role in the development of effective decisions, taking into account the impact of plans and projects in the forest ecosystem on all services provided by the forest ecosystem.

In addition, between 2018 and 2021, forest-related land use and land use change, fire, etc., were carried out based on the "Collect Earth" method at the country level by the Remote Sensing method in Azerbaijan within the framework of the "Assessment and Monitoring of Forest Resources to Strengthen the Forest Knowledge Framework in Azerbaijan" - GCP/AZE/007/GFF project. A comprehensive report was prepared through the collection and analysis of national data. This report assesses both the current forest area and land-use change from 2000 to 2016 and provides appropriate recommendations.

The results of the assessment show that the total forest area in Azerbaijan is approximately 1,301,188 ha or 15.1% of the total area. Comparing the land uses of 2000 and 2016, the results show that relatively small land use changes occurred in all land use categories in Azerbaijan. Very slight increases were observed in forests (annual increase of 0.007%) and grasslands (annual increase of 0.018%). However, residential areas accounted for the largest change with an increase of 37,962 ha or 7.9% over 16 years. The results of the Global Forest Survey also confirm that very little land-use change occurs between forest and non-forest land use categories.

1,213.7 thousand of the total forest area belongs to the forest fund. ha (Ref: NFP, 2013; ProDoc) and previous studies show that this land area is 1,021 thousand. ha (NFP, 2013) or 1,036.27 thousand. ha (Ref: ProDoc), i.e., 11.8%. And 12% of the total country area is covered with forests. According to the FAO Forest Resources Assessment Report (FRA-2015), the total forest area of Azerbaijan is 1,139.4 thousand. ha or 13% of the country's territory.

10. Conclusion

As a result of the work carried out, the following conclusions can be drawn:

1. There have been no significant changes in the area of trees and forest cover in the territory of the Republic over the past 20 years, but a further 7.9% increase in the use of forest lands as a place of residence has been recorded.
2. The trends in biodiversity change in forest ecosystems in recent years and the shifts of the main forest formations against the background of climate change have been analyzed, and the migration of the main forest-forming species to relatively humid (to the upper mountain belts) afforestation conditions has been identified.
3. It has been established that the forest ecosystems of the Republic mainly carry out functions such as biodiversity protection, atmospheric regulation, protection of water and soil resources, and recreational activities.

References

1. Ahrends, A., Burgess, N. D., Milledge, S. A., Bulling, M. T., Fisher, B., Smart, J. C. R., & Clarke, G. P. (2010). Predictable waves of sequential forest degradation and biodiversity loss spreading from an African city. *Proceedings of the National Academy of Sciences, 107*(33), 14556–14561.

2. Azerbaijan. (1997). *Forest Code of the Azerbaijan Republic* (Article 6).

3. Bürgi, M., & Hersperger, A. M. (2009). The driving forces of the landscape are changing: Current and new directions. *Landscape Ecology, 24*(8), 1083–1085.

4. FAO. (2019). *FAO Collect Earth.* Retrieved from http://www.openforis.org/tools/collectearth.html

5. FRA. (2015). *FAO Forest Resources Assessment.* Retrieved from http://www.fao.org/forestresources-assessment/en/

6. Hansen, M. C., et al. (2013). High-resolution global maps of 21st-century forest cover change. *Science, 342*(15 November), 850–853. Retrieved from http://earthenginepartners.appspot.com/science-2013-global-forest

7. IPCC. (2003). *Good practice guidance for land use, land-use change and forestry.* Retrieved from http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.html

8. IPCC. (2006). *2006 IPCC guidelines for national greenhouse gas inventories.* Retrieved from http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html

9. IPCC. (2019). *Intergovernmental Panel on Climate Change web page.* Retrieved from http://www.ipcc.ch/

10. NFP. (2013). *National Forest Program (Forest Policy Statement and the Action Plan) 2015–2030 (Final Draft).* Republic of Azerbaijan, Baku.

11. Dudley, N., Baldock, D., Nasi, R., & Stolton, S. (2005). *Measuring forest biodiversity: Guidelines for managers of protected areas.* International Union for Conservation of Nature and Natural Resources.

12. FAO. (2010). *Global forest resources assessment and baseline report.* Food and Agriculture Organization of the United Nations.

13. Gibson, L., Lee, T. M., Koh, L. P., Brook, B. W., Gardner, T. A., Barlow, J., ... & Sodhi, N. S. (2011). Primary forests are indispensable for the conservation of tropical biodiversity. *Nature, 478*(7369), 378–381.

14. Gurevitch, J., & Padilla, D. K. (2004). Are invasive species the main cause of extinction? *Trends in Ecology and Evolution, 19*(9), 470–474.

15. Holmes, T. P., Blate, G. M., Zweede, J. C., Pereira, R., Barreto, P., Boltz, F., ... & Bauch, S. (2002). Financial and environmental indicators of mitigation in the eastern Amazon. *Forest Ecology and Management, 163*(1–3), 93–110.

16. Larsen, F. W., Bladt, J., Becher, P. K., Svenning, J. C., & Rahbek, C. (2012). Informed identification of potential sites for restoration of historic landscape connectivity. *Ecography, 35*(11), 1048–1058.

17. Mason, N. W., Mouillot, D., Lee, W. G., & Wilson, J. B. (2005). Functional richness, functional similarity and functional divergence: The main components of functional diversity. *Oikos, 111*(1), 112–118.

18. McCarthy, J. F., & Prudham, S. (2004). The nature of neoliberalism and the nature of neoliberalism. *Geoforum, 35*(3), 275–283.

19. Mittermeier, R. A., Gil, P. R., Hoffmann, M., Pilgrim, J., Brooks, T., Mittermeier, C. G., ... & Fonseca, G. A. (2004). *Hotspots revisited: Earth's most biologically rich and endangered terrestrial ecoregions.* Conservation International.

20. Pereira, H. M., Leadley, P. W., Proença, V., Alkemade, R., Scharlemann, J. P., Fernandez-Manjarrés, J. F., ... & Araújo, M. B. (2010). Scenarios for global biodiversity in the 21st century. *Science, 330*(6010), 1496–1501.

Regional Generalized Nonlinear Height-Diameter Model for Two Age Stands of Small-Leaved Linden

Aydar Gabdelkhakov[1], Ilyas Fazlutdinov[2], Maria Martynova[3], Alina Musabirova[4] and Zagir Rakhmatullin[5]

[1] Bashkir State Agrarian University,

[2] Ministry of Forestry of the Republic of Bashkortostan,

[3] Bashkir State Agrarian University,

[4] Bashkir State Agrarian University,

[5] Bashkir State Agrarian University,

Received:20.10.2025 Accepted:24.10.2025 Published:30.10.2025

https://doi.org/10.54414/OJCO2155

Abstract

Tree height and diameter at breast height (*dbh*) are essential for assessing quantitative stand characteristics, developing models of stand structure and productivity. The relationships between them (HD) represent a natural indicator of forest growth and serve as a measure of forest management practices. Measuring tree height is more challenging in uneven-aged forests compared to measuring diameters. To overcome these difficulties, the development of HD models is crucial. This study aimed to develop a reliable HD model for two-aged stands of *Tilia cordata* Mill. by incorporating stand-level variables. To effectively model the HD relationship, ten widely recognized nonlinear functions were evaluated. The selection of the best-performing model, which accurately describes the relationship between tree height and diameter, was based on the lowest root mean square error (*RMSE*), mean absolute percentage error (*MAPE*), and Akaike's information criterion (*AIC*), as well as the highest adjusted coefficient of determination (R^2-adj.), with statistically significant regression coefficients ($p < 0.05$). Performance statistics indicated that the three-parameter F.J. Richards function was the most suitable and is recommended for predicting HD relationships in small-leaved linden trees within the environmental region under study. This function was further modified by incorporating stand-level variables, such as mean height and quadratic mean diameter for each layer, as additional integrated predictors. The functions were fitted using nonlinear least squares. The fitted generalized HD model and its validation explained variability of 85–95% of the observed tree heights in small-leaved linden stands. This model enables the prediction of individual height curves for each layer within a given stand.

Keywords: small-leaved linden, two-aged stands, height-diameter model, nonlinear generalized model, validation, Richards function.

1. Introduction

Tree height and diameter are key parameters used to determine stem volume, estimate forest aboveground biomass, and assess overall forest condition and structure (Sharma et al., 2016; Ciceu et al., 2023; Tanovski et al., 2023). The relationship between them (HD) serves as a natural indicator of forest growth and a measure of forest management practices. Consequently, research on the height-diameter relationship holds significant scientific and practical importance, prompting numerous studies aimed at identifying mathematical models that most accurately describe this dependence (Ahmadi & Alavi, 2016; Dubenok et al., 2021).

A wide range of two- and three-parameter HD equations has been developed for various tree species across different regions (Seki, 2022). In these models, diameter serves as the predictor variable for estimating tree height. However, due to the structural heterogeneity of forest ecosystems, describing HD relationships using a single model is highly challenging (Sağlam & Sakici, 2024). In order to reduce variability in HD relationships and improve prediction accuracy, generalized models have been developed (Ismail et al., 2025). Generalized HD models incorporate not only diameter at breast height (DBH) but also individual tree- and stand-level variables. Literature reports such variables as age, site index, stand basal area, stem density, basal area of larger trees, dominant or mean height and diameter, among others (Sharma et al., 2016; Ahmadi & Alavi, 2016; Ciceu et al., 2020).

To our knowledge, no studies have been published on generalized height-diameter models for uneven-aged small-leaved linden (*Tilia cordata* Mill.) stands. Therefore, this research addresses a relevant gap by developing a generalized model for predicting tree height from DBH in two-aged linden stands. The study objectives were as follows: (1) selecting the most suitable model from a set of ten base models, (2) integrating stand-level variables that may influence the HD relationship to construct a generalized model, and (3) evaluating the predictive accuracy of the generalized model.

2. Material and Methods

The area under study, Arkhangelsk Forestry District, is situated in the central-eastern part of the Republic of Bashkortostan, the Russian Federation, along the western slope of the Southern Urals on the right bank of the Belaya River. The area is located between 54.21799–54.78734°N and 56.46937–57.43891°E, with elevations ranging from 150 to 900 m above sea level, classifying it as mountainous forest terrain. The climate is strongly continental, with an average annual precipitation of approximately 600 mm, more than half of which occurs during the growing season from May to September. Mean annual temperatures range from 2 to 6°C, and the frost-free period lasts 115 days. The predominant soils are gray forest soils.

Natural stands of small-leaved linden (*Tilia cordata* Mill.) in the study area cover approximately 95,000 ha with a growing stock exceeding 18 million m^3. Mixed linden stands dominate, often including oak (*Quercus robur L.*), maple (*Acer platanoides L.*), elm (*Ulmus glabra Huds*. and *Ulmus laevis Pall*.), birch (*Betula pendula Roth*.), and aspen (*Populus tremula L*.), with occasional presence of spruce (*Picea obovata Ledeb*.), fir (*Abies sibirica Ledeb.*), and pine (*Pinus sylvestris L.*). Pure linden stands also occur. Uneven-aged linden stands account for about 18% of the total, most of which are two-aged, while three-aged stands are less common. The majority of uneven-aged linden stands are over 60 years old, with an age difference between generations (layers) ranging from 10 to 70 years.

Temporary sample plots (TSPs) ranging from 0.5 to 1.0 ha in size were used for the study: ten for modeling and three for testing. On each TSP, a complete inventory of tree diameters was conducted by layers, and heights of sample trees (randomly selected, 1-10 specimens per 1-cm diameter class) were measured. Diameter at breast height (*dbh*, 1.3 m) was measured using calipers, while tree height (*h*) was measured with a Blume-Leiss mechanical hypsometer with 0.5 m precision.

For each layer of the TSPs, three average-sized trees (60 stems total) were felled as sample trees. These trees were sectioned into 2-m segments, from which discs were obtained for complete growth analysis. The results of this growth analysis were subsequently used for mathematical modeling of the h-dbh relationship.

Based on the sample trees, stand age was determined to range from 70-95 years for the first layer and 50-75 years for the second layer. Some stand characteristics were reported earlier (Gabdelkhakov et al., 2025).

The training dataset comprised 2 842 tree measurements (first layer: n=1 435; second layer: n=1 407). For testing, h and *dbh* values from 391 trees were used (first layer: n=210; second layer: n=181).

Based on literature review, ten widely used equations (base models) for height-diameter relationships were initially selected and tested (Ismail et al., 2025; Tanovski et al., 2023). In the second stage, the selected base model was enhanced by integrating stand-level variables to develop a generalized model. Additional integrated stand variables included mean height (*H*) and quadratic mean diameter (*Dq*) for each layer. In the third stage, after fitting the generalized model to the training dataset, its predictive performance was evaluated using the test dataset.

Model fitting was performed using nonlinear least squares regression. The selection of the best model describing the height-diameter relationship was based on classical statistical metrics used in forest biometrics research. The model with the lowest root mean square error (*RMSE*), mean absolute percentage error (*MAPE*), and Akaike's information criterion (*AIC*), along with the highest adjusted coefficient of determination (R^2-adj.), was considered optimal (Ahmadi & Alavi, 2016). To visualize the magnitude and distribution of errors relative to DBH, relative error (RE) graph was developed (Tanovski et al., 2023). Additionally, the significance of model parameters was examined. Heteroscedasticity was assessed through graphical analysis of residual patterns and application of the Breusch-Pagan test (Breusch & Pagan 1979). All data analyses were conducted using StatSoft Statistica and Microsoft Excel.

3. Results and Discussion

Figure 1 presents scatter plots of diameter and height by stand layer based on growth analysis data from sample trees. The diagrams demonstrate significant correlations of r = 0.957 and r = 0.931 for the first and second layers, respectively. This relationship exhibits complex nonlinear behavior (Lebedev, 2020a), with the height curve increasing more rapidly during early growth stages than in later phases (Sharma et al., 2016). Notably, the height growth rate was higher in the supressed layer compared to the dominant layer.

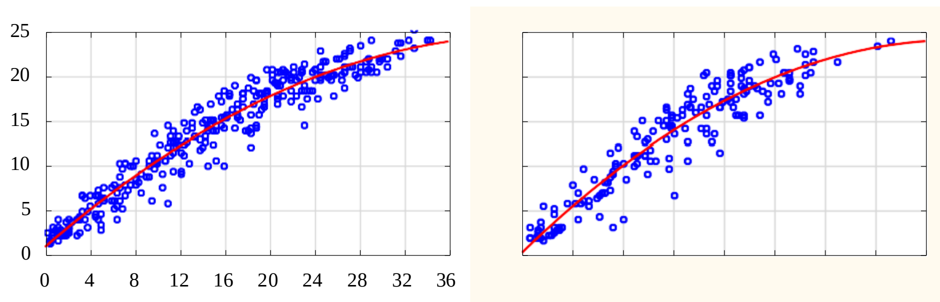


Figure 1. Scatter diagram of h (vertically, m) depending on dbh (horizontally, cm) for sampled trees in small-leaved linden stands (a – dominant layer, b – suppressed layer)

Analysis of the presented HD relationships reveals that models relying solely on DBH for height prediction in uneven-aged linden stands are insufficient for explaining tree height variation and fail to meet effective forest management requirements. Consequently, incorporating additional stand-level variables is necessary to improve height prediction accuracy.

Height-diameter functions must satisfy specific criteria. First, the equation's intercept must equal 1.3 m (Sharma & Parton, 2007; Ismail et al., 2025; Tanovski et al., 2023). Second, the curve must be monotonically increasing with a horizontal asymptote (Lebedev & Kuzmichev, 2020b; Tanovski et al., 2023). Regression analysis determined parameters for each of ten candidate models (not shown) in small-leaved linden stands. The multitude of growth-influencing factors results in substantial height variation among trees of equal DBH, significantly affecting model performance. Evaluation of ten equations identified the three-parameter F.J. Richards function (Richards, 1959) as demonstrating superior accuracy:

$$h = 1.3 + b_1(1 - \exp(-b_2 dbh))^{b_3} \quad (1)$$

where b_1, b_2, b_3 – model parameters.

This equation has been effectively used in nonlinear HD models by numerous researchers (Sharma & Parton, 2007; Ahmadi et al., 2013; Özçelik et al., 2018; Ciceu et al., 2020, 2023; Sağlam & Sakici, 2024), demonstrating high predictive performance. The generalized Richards model incorporating additional stand-level variables (mean height (H) and quadratic mean diameter (D_q) for each canopy layer) takes the following form (Lebedev, 2020a):

$$h = 1.3 + \frac{(H - 1.3)(1 - \exp(-(a_1 + a_2 D_q)^{(\frac{dbh}{D_q})})^{a_3 + a_4 D_q}}{(1 - \exp(-(a_1 + a_2 D_q)))^{a_3 + a_4 D_q}} \qquad (2)$$

where a_1, a_2, a_3, a_4 – model parameters.

Table. Model estimates

Parameter	Estimate	*RMSE*	*MAPE*	R^2-adj	*AIC*
Base function (dominant canopy layer)					
b_1	22,15356	1,433	7,483	0,913	522
b_2	0,12712				
b_3	2,57598				
Base function (supressed canopy layer)					
b_1	18,11063	1,652	8,209	0,744	712
b_2	0,17306				
b_3	2,19962				
Generalized function (training data)					
a_1	3,28804	1,086	3,992	0,941	244
a_2	-0,00994				
a_3	3,27137				
a_4	-0,07211				
Generalized function (validation data)					
a_1	3,28804	1,067	4,175	0,857	33
a_2	-0,00994				
a_3	3,27137				
a_4	-0,07211				

The final statistical indicators for the base model (1) of both layers and the generalized model (2) are presented in the table. The quality metrics (*RMSE*, *MAPE*, R^2-adj., and *AIC*) demonstrate strong predictive capability of the selected model for both layers. The generalized model, incorporating additional stand variables of the mean height H and quadratic mean diameter Dq of each layer, exhibited excellent fit, explaining over 94% of observed variability (R^2-adj.) with *RMSE* < 1.1 m, *MAPE* < 4.0%, and low *AIC* values. The generalized model showed minimal deviations between predicted and measured heights. Model parameters $a_{1\text{-}4}$ had low standard errors (0.418, 0.003, 0.204, and 0.007, respectively), with statistically significant estimates of p-value < 0.001. The model's high predictive accuracy partly stems from including data from average sample trees, though we assumed these trees remained representative of their layers throughout their lifespan (an idealization that may not always hold).

Nonlinear models used in forestry for height prediction often exhibit heteroscedasticity, where error variance is non-constant across observations. Visual residual analysis and Breusch-Pagan tests confirmed the absence of heteroscedasticity. Residual graphs (not shown) supported assumptions of normality, homoscedasticity, and independence — residuals were randomly distributed without discernible patterns. These findings align with prior studies (Sharma & Parton, 2007; Siipilehto et al., 2023; Ismail et al., 2025), where the asymptotic Richards model performed well in its original form and improved further after modification.

Application to test data yielded consistent results. Minor differences in performance metrics between training and testing phases arose from inherent dataset variations. Figure 2 shows that relative errors (RE) for data were generally small, though slight overestimation occurred for both thinner and larger trees. The three-parameter base model, when generalized, provided greater flexibility for HD curves, corroborating other research (Lebedev, 2020a; Siipilehto et al., 2023; Ismail et al., 2025).

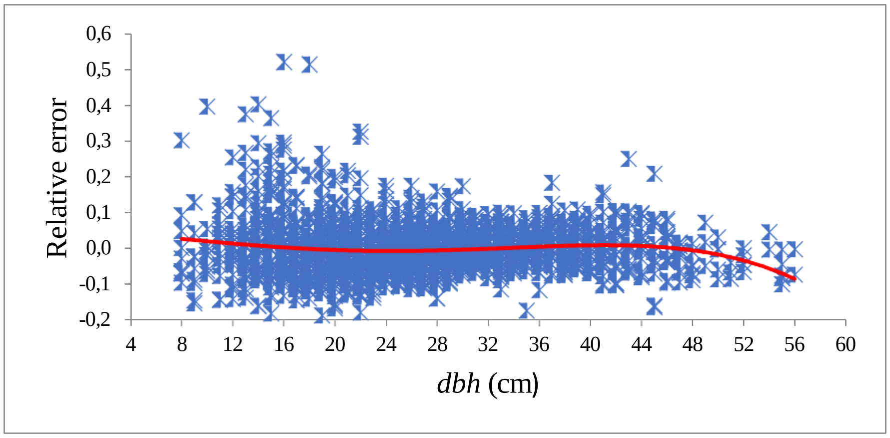


Figure 2. Relative error

4. Conclusions

This study evaluated several base HD models to develop an optimal height-diameter relationship model for two-aged small-leaved linden (*Tilia cordata* Mill.) stands. The three-parameter Richards model, grounded in growth theory, demonstrated superior performance by accurately capturing accelerated early-stage height growth followed by slower maturation rates, while also accounting for the greater growth velocity of the supressed canopy layer. The fitted generalized HD model and its validation explained the variability of 85–94% of the observed height in small-leaved linden stands across the area under study.

The model enables stand-specific height curve predictions for individual canopy strata using three readily obtainable variables: diameter at breast height (DBH), quadratic mean diameter, and mean stand height. The quadratic mean diameter serves as a proxy for stand density and competition intensity, exhibiting strong correlations with stems per hectare, while mean height complements this by accounting for height variability. These variables are routinely collected in forest inventories and can be projected forward using growth equations. The developed equation can be used for forest inventories and as primary input data for growth and yield models when formulating forest management plans.

References

1. Ahmadi, K., & Alavi, S. J. (2016). Generalized height-diameter models for Fagus orientalis Lipsky in Hyrcanian forest, Iran.https://doi.org/10.17221/51/2016-JFS

2. Ahmadi, K., Jalil Alavi, S., Kouchaksaraei, M. T., & Aertsen, W. (2013). Non-linear height-diameter models for oriental beech (Fagus orientalis Lipsky) in the Hyrcanian forests, Iran. *Biotechnology, Agronomy, Society and Environment*, *17*(3), 431-440.

3. Breusch, T.S. & Pagan, A.R. (1979). A Simple Test for Heteroscedasticity and Random Coefficient Variation. *Econometrica*, 47(5): 1287-1294. https://doi.org/10.2307/1911963

4. Ciceu, A., Chakraborty, D. & Ledermann, T. (2023). Examining the transferability of height–diameter model calibration strategies across studies. *Forestry: An International Journal of Forest Research*, cpad063, https://doi.org/10.1093/forestry/cpad063
5. Ciceu, A., García-Duro, J., Seceleanu, I. & Badea, O. (2020). A generalized nonlinear mixed-effects height–diameter model for Norway spruce in mixed-uneven aged stands. *Forest Ecology and Management*, 477, 118507. https://doi.org/10.1016/j.foreco.2020.118507
6. Dubenok, N.N., Kuzmichev, V.V. & Lebedev, A.V. (2021). Two- and Three-Parameter Models of the Relationship of the Height of Trees with a Diameter at a Height of 1.3 m in Oak Stands. *Forestry information*, 3, 45–58. https://doi.org/10.24419/LHI.2304-3083.2021.3.04
7. Gabdelkhakov, A., Konovalov, V., Rakhmatullin, Z., Martynova, M. & Fazlutdinov, I. (2025). Variability of Tree Diameters in Small-Leaved Linden Stands. *Lesnoy Zhurnal (Forestry Journal)*, 1: 42-57, https://doi.org/10.37482/0536-1036-2025-1-42-57
8. Ismail, M.J., Poudel, T.R., Ali, A. & Dong, L. (2025). Incorporating stand parameters in nonlinear height-diameter mixed-effects model for uneven-aged *Larix gmelinii* forests. *Front. For. Glob. Change*, 7, 1491648. https://doi.org/10.3389/ffgc.2024.1491648
9. Lebedev, A.V. (2020a). New generalised height-diameter models for the birch stands in European Russia. *Baltic Forestry*, 26(2): 265–271. https://doi.org/10.46490/BF499
10. Lebedev, A. & Kuzmichev, V. (2020b). Verification of two- and three-parameter simple height-diameter models for birch in the European part of Russia. *Journal of Forest Science*, 66(9): 375-382. https://doi.org/10.17221/76/2020-JFS
11. Özçelik, R., Cao, Q., Trincado, G. & Göçer, N. (2018). Predicting tree height from tree diameter and dominant height using mixed-effects and quantile regression models for two species in Turkey. *Forest Ecology and Management*, *419-420*: 240-248. https://doi.org/10.1016/j.foreco.2018.03.051
12. Richards, F.J. (1959). A Flexible Growth Function for Empirical Use. *Journal of Experimental Botany*, 10(2): 290–301. https://doi.org/10.1093/jxb/10.2.290
13. Sağlam, F. & Sakici, O.E. (2024). Ecoregional height–diameter models for Scots pine in Turkiye. *J. For. Res*., 35, 103. https://doi.org/10.1007/s11676-024-01757-z
14. Seki, M. (2022). Height–diameter allometry of two commercial pine species located in low productive forest stands of northwestern Türkiye. *Austrian Journal of Forest Science*, 139(4): 265-288.
15. Sharma, M. & Parton, J. (2007). Height–diameter equations for boreal tree species in Ontario using a mixed-effects modeling approach. *Forest Ecology and Management*, 249(3): 187-198. https://doi.org/10.1016/j.foreco.2007.05.006
16. Sharma, R.P., Vacek, Z., & Vacek, S. (2016). Nonlinear mixed effect height-diameter model for mixed species forests in the central part of the Czech Republic. *Journal of Forest Science*, 62(10): 470-484. https://doi.org/10.17221/41/2016-JFS
17. Siipilehto, J., Sarkkola, S., Nuutinen, Y. & Mehtätalo, L. (2023). Predicting height-diameter relationship in uneven-aged stands in Finland. *Forest Ecology and Management*, 549, 121486. https://doi.org/10.1016/j.foreco.2023.121486
18. Tanovski, V., Matović, B., Risteski, M. & Trajkov, P. (2023). Modelling the tree height-diameter relationship of Macedonian pine (*Pinus peuce* Gris.) forests in North Macedonia. *J. For. Sci*., 69: 497–513. https://doi.org/10.17221/68/2023-JFS

The Role of Technological Infrastructure in Forest Engineering and Ecosystem Management: Current Trends and Future Perspectives

Selcuk Gumus[1]

[1]Karadeniz Technical University, Türkiye

Received:19.10.2025 Accepted:27.10.2025 Published:30.10.2025

https://doi.org/10.54414/VASL7073

Abstract

Forest ecosystems are critically important for biodiversity, carbon storage, climate regulation, and socio-economic services. This review examines the transformative role of technological infrastructure in sustainable forest management. Focusing on innovation and methodology, it evaluates the applications of technologies such as remote sensing, GIS, UAVs, IoT, artificial intelligence, and digital twins in forest engineerng applications, forest inventory, fire management, biodiversity monitoring, and decision support systems through a systematic literature review. The results reveal that these technologies enable a transition to a data-driven, proactive, and effective management paradigm. However, significant challenges such as cost, the digital divide, human resources, and ethical limitations persist. The article provides strategic recommendations for policymakers, researchers, and forest managers and discusses the contributions of technology-integrated forest engineering and management to socio-economic and ecological sustainability.

Keywords: Forest management, remote sensing, Geographic Information Systems (GIS), UAV, IoT, artificial intelligence, digital twin, sustainable management, ecosystem services, forest policy.

1. Introduction

Forest ecosystems are critical for biodiversity, carbon storage, climate regulation (Bonan, 2008), soil and water cycles, and provide economic and cultural benefits (Lal, 2008). Sustainable forest management requires moving beyond classical timber production-focused approaches to balance ecosystem services and preserve ecological integrity (FAO, 2020). Increasing population, climate change, rapid urbanization, and natural disasters are making the challenges faced by forest engineering and management even more complex (Seidl et al., 2017).

Rapid developments in information technologies have enabled data-driven and real-time decision-making processes in forest ecosystem management. This technological innovation not only increases operational efficiency but also profoundly affects socio-economic dimensions such as the assessment of ecosystem services, rural development, and shaping forest policies. Satellite imagery, UAVs, LiDAR systems, Geographic Information Systems (GIS), sensor networks, Internet of Things (IoT), big data analytics, artificial intelligence and digital twin applications offer revolutionary solutions for monitoring, assessing, and managing forests (Asner, 2013; Pettorelli et al., 2018; Reichstein et al., 2019; Abad-Segura et al.,2020). These technologies enable the collection of high-resolution data over large areas, rapid detection of ecosystem changes, and development of early warning systems for natural disasters (Paneque-Gálvez et al., 2014; Linares & Ni-Meister, 2024).

However, the implementation of technological infrastructure faces challenges such as cost, data standardization, lack of human resources, and legal/ethical limitations (Maxwell et al., 2018; Stone et al., 2016). Therefore, addressing the opportunities and limitations offered by technological infastructure with a holistic approach is crucial for shaping future strategies.

The aim of this review is to comprehensively present the current status, application areas, benefits, and limitations of technological infrastructure in forest engineering and ecosystem management; and to provide a guiding assessment of the intersection points of technological progress with forest management policies and sustainable development goals in the context of future trends and policy/application recommendations. This article aims to systematically classify these technological components and detail the synergies and emerging paradigms arising from their integration into forest management practice.

2. Technological Infrastructure Components

Technological infrastructure plays a critical role in monitoring ecosystem dynamics, analyzing, and making sustainable management decisions in forest engineering aplications and ecosystem management. This infrastructure has a multidimensional structure encompassing hardware, software, network communication technologies, and information management systems.

2.1. Remote Sensing Technologies

Remote sensing (RS) systems are widely used to monitor large-scale and temporal changes in forest ecosystems. Satellite time series analyses play a critical role in detecting, mapping, and understanding the geographical distribution of forest degradation (logging, fire) (Asner, 2013). High-resolution satellite imagery and LiDAR data provide critical data for estimating forest structure, biomass, and carbon stocks (Pettorelli et al., 2018). Unmanned aerial vehicles (UAVs) enable obtaining detailed data on a smaller scale and are used particularly in assessing young forests, tree diseases, and post-fire areas (Paneque-Gálvez et al., 2014).

2.2. Geographic Information Systems (GIS)

GIS is a fundamental software infrastructure for spatial data management, analysis, and visualization. Numerous applications such as forest road planning, habitat integrity analysis, and erosion risk assessment are GIS-based. Thanks to GIS's powerful data integration capacity, data from different sources (satellite data, meteorological stations, field measurements) can be combined on a single platform and used effectively in decision-making processes in many areas of forest ecosystem management (Kerr & Ostrovsky, 2003).

2.3. Sensors, Monitoring Systems and Internet of Things (IoT)

Ground-based sensors are particularly important for monitoring microclimate, soil moisture, flow dynamics, and biotic-abiotic stress factors, providing foundational data for integrated forest monitoring systems. Long-term ecological research networks in forest ecosystems, such as FLUXNET, supply critical data on carbon cycling and energy flows. These datasets support advanced modeling of forest ecosystem processes (Baldocchi et al., 2001). Sensor-based infrastructures, when integrated with IoT, enable real-time and predictive detection of fire events, pest outbreaks, and drought effects, offering critical applications for forest management (Linares & Ni-Meister, 2024; Ali et al., 2025).

2.4. Big Data and Artificial Intelligence Applications

The increasing volume and complexity of forest-related data in recent years have rendered traditional analysis methods insufficient. Big data analytics and AI-based algorithms have become essential tools for understanding forest dynamics, modeling biodiversity, and predicting complex processes such as fire risk (Reichstein et al., 2019). Machine learning algorithms—such as Random Forest, Support Vector Machines, and Deep Learning—have proven highly successful in land cover classification, fire risk prediction, and habitat modeling (Maxwell et al., 2018).

2.5. Technology Integration and Digital Twins

The real power of technological components comes from their integrated operation. For example, remote sensing data obtained from UAVs and satellites are processed on GIS platforms and analyzed with AI algorithms to transform into meaningful information. The most advanced level of this integration is the 'digital twin' concept. A digital twin is a dynamic virtual model of a physical forest ecosystem, fed with real-time data (Fuller et al., 2020). This model enables managers to predict potential outcomes of events such as fire, disease outbreaks, or different harvesting scenarios and take proactive interventions (Buonocore et al., 2022). The concept of the digital twin, still emerging in forestry, is being explored as a way to replicate and simulate dynamic forest systems. Through big data analytics and AI integration, digital twins can enhance scenario modeling for sustainable forest management.

3. METHODOLOGY

This study is a review based on systematic literature review and thematic analysis approaches (Moher et al., 2009). The study was conducted in three main stages:

3.1. Literature Review

• Databases: Web of Science, Scopus, ScienceDirect, SpringerLink, and Google Scholar were used (Gurevitch et al., 2018).

• Keywords: “forest engineering”, "forest management", "forest ecosystem management", "technological infrastructure", "remote sensing", "GIS", "UAV", "IoT", "artificial intelligence", "big data", "digital twin".

• Time range: Studies published between 2000-2025 were primarily evaluated.

• Language: Peer-reviewed articles, reports, and conference proceedings published in English and Turkish were included in the review (FAO, 2020).

3.2. Selection Criteria

• Inclusion criteria: Being directly related to forest ecosystem management; being technological infrastructure-focused; providing empirical, conceptual, or methodological contribution (Gurevitch et al., 2018).

• Exclusion criteria: Studies not directly related to the topic; those with insufficient methodological description; duplicate content.

3.3. Analysis Process

• The screening process was conducted within the framework of the PRISMA approach (Moher et al., 2009).

• Preliminary screening: 350 studies were identified, reduced to 120 studies through title and abstract review, and after full-text review, 48 studies were analyzed in detail.

• Studies were divided into five main categories using thematic coding method:

Data collection and monitoring technologies (Asner, 2013; Paneque-Gálvez et al., 2014; Ecke et al., 2022)

Data processing and analysis methods (Reichstein et al., 2019; Maxwell et al., 2018)

Application areas (forest inventory, fire risk, biodiversity) (Pettorelli et al., 2018; Kilic et al. 2006; Akçay et al., 2023)

Benefits and contributions (Abad-Segura et al., 2022; Gumus et al. (2008))

Challenges and limitations (Maxwell et al., 2018; Stone et al., 2016; Diktaş-Bulut et al., 2025)

4. CURRENT TRENDS AND APPLICATION AREAS

The use of technological infrastructure in forest ecosystems is increasingly diversifying and intensifying.

4.1. Forest Inventory and Biomass Estimation

Remote sensing and LiDAR data have become cornerstone technologies for forest inventory and the estimation of biomass and carbon stocks (Pettorelli et al., 2018). The deployment of Unmanned Aerial Vehicles (UAVs) and high-resolution satellite imagery has further enhanced the accuracy of monitoring young forest stands and calculating timber volume (Paneque-Gálvez et al., 2014; Ecke et al., 2022). These data integrated with GIS play a critical role in many areas of forest ecosystem management, including spatial distribution analyses. The efficacy of these methodologies is substantiated by a growing body of research in Türkiye, where their application has advanced significantly since the early 2000s. For instance, pioneering work by Kilic et al. (2006) utilized Landsat data to establish a foundation for temporal change detection in Turkish forest ecosystems, a trajectory continued by contemporary studies. Akçay et al. (2023) effectively leveraged multi-temporal Sentinel-2 imagery for precise biomass estimation in Northern Anatolia, demonstrating the enhanced capabilities of recent satellite platforms. Similarly, Vatandaşlar & Zeybek (2020) applied handheld laser scanning technology for detailed inventory purposes in northeastern Turkey. Collectively, these studies underscore the effective integration and evolution of remote sensing, UAV, and GIS technologies for comprehensive forest structural assessment, inventory, and carbon stock modeling.

4.2. Fire and Risk Management

The real-time monitoring of critical environmental variables such as humidity, temperature, soil moisture, wind speed, and precipitation is now enabled by Internet of Things (IoT) networks and sensor systems, forming the backbone of modern fire early warning systems. These measurements are vital for the early detection of fire risk, with their effectiveness well-documented in global research (Jin & Goulden, 2014). The integration of IoT-based sensor networks and real-time data acquisition systems into forest management practices has become increasingly widespread in Türkiye, providing the foundational data for developing sophisticated predictive models (Ali et al., 2025).

The data from these systems feed into big data analytics and artificial intelligence-based algorithms, which are becoming increasingly important for modeling complex processes such as fire risk, propagation, and the preparation of sophisticated risk maps (Reichstein et al., 2019). The considerable potential of AI-based models for early fire detection is well-corroborated. Machine learning and deep learning approaches are now being effectively applied across a spectrum of forestry applications, including forest fire risk mapping and early fire prediction (Yıldırım et al., 2023; Fidanboy et al., 2023). In Türkiye, research in this area is particularly advanced and multidisciplinary. A pertinent example is the work of Baybaş et al. (2024), who applied machine learning algorithms to environmental, terrain, and land cover data to predict forest fire risk in the Mediterranean region, finding that the Random Forest algorithm yielded the most accurate predictions.

This focus on predictive modeling is complemented by post-fire analysis using satellite imagery, as seen in the work of Çolak & Sunar (2018), who monitored fire-affected areas in İzmir using Sentinel-2 and Landsat data. Further contributing to this field, İban & Şekertekin (2022) applied machine learning for wildfire susceptibility mapping in Adana and Mersin.

4.3. Biodiversity and Habitat Monitoring

The precision with which species diversity, tree health, and habitat structure can be monitored has been fundamentally transformed by remote sensing, Unmanned Aerial Vehicles (UAVs), and hyperspectral or multispectral sensors (Turner et al., 2015; Maxwell et al., 2018). The synergy created by combining these technological approaches with artificial intelligence (AI) and Geographic Information Systems (GIS) has proven particularly powerful, significantly enhancing predictive habitat modeling and thereby providing robust support for conservation initiatives and biodiversity protection.

A key development in this domain has been the adoption of UAV-based photogrammetry, which provides a cost-effective and high-resolution alternative to traditional field surveys. The deployment of UAVs equipped with multispectral and thermal sensors has led to their successful application in critical areas such as tree health assessment and detailed habitat mapping (Ecke et al., 2022).

Beyond health and habitat assessments, remote sensing data are extensively used for classification tasks. Machine learning algorithms such as support vector machines and random forest are effectively employed to classify land cover and distinguish between tree species with high accuracy (Kaya & Dengiz, 2024). This capability is crucial for tracking changes in species composition, monitoring ecosystem health, and informing targeted conservation strategies.

4.4. Sustainable Management and Decision Support Systems

Geographic Information Systems (GIS)-based decision support systems are pivotal for sustainable forest management, as they facilitate decision-making by simulating different management scenarios and integrating multi-source data (Diaz-Balteiro & Romero, 2008; Kerr & Ostrovsky, 2003). Furthermore, big data analytics and artificial intelligence (AI) help balance ecosystem services with economic outputs, thereby increasing the accuracy and effectiveness of forest management plans (Reichstein et al., 2019).

In Türkiye, GIS and remote sensing applications in forest engineering have been effectively applied to critical areas such as forest road planning, terrain stability, and environmental impact assessment. The work of Gumus et al. (2008), Hacisalihoğlu et al. (2019) and Gümüş (2021) exemplifies this, integrating GIS with digital terrain models to assess forest road locations, examine the effects of road construction on soil erosion and hydro-physical properties, and highlight the role of spatial analysis in minimizing environmental risks. Complementing this, Akay and colleagues (2008, 2016) utilized LiDAR and GIS for forest structure assessment, fire behavior modeling, and access zone analysis. Collectively, these studies demonstrate the successful integration of spatial modeling and remote sensing into sustainable forest road design and terrain-based risk assessment.

Beyond these applications, recent research is further advancing the digitalization of forest engineering. Studies now emphasize the use of geophysical sensors, such as seismic refraction and electrical resistivity methods, to enhance the precision of subsurface terrain analysis. The integration of this sensor-based data into planning and design processes represents a significant step forward in creating comprehensive, data-driven decision support systems for sustainable forest management (Diktaş-Bulut et al., 2025).

4.5. Ecosystem Services Assessment and Decision Support Systems

Technological advancements are increasingly being harnessed to support the quantitative assessment of ecosystem services, including carbon sequestration, water provision, and recreational value. The use of big data, AI, and GIS facilitates predictive scenario modeling that integrates complex socio-economic and ecological data (Diaz-Balteiro & Romero, 2008). A cutting-edge development in this sphere is the concept of digital twins, which utilize real-time data streams from sensors, UAVs, and satellites to create dynamic virtual replicas of forest ecosystems. These digital twins enable the simulation of management interventions, climate impacts, or fire scenarios, thereby enhancing proactive and evidence-based decision-making (Fuller et al., 2020; Buonocore et al., 2022). Complementing traditional GIS and remote sensing approaches, these studies highlight how big data and AI technologies enhance forest monitoring, inventory, and risk prediction.

4.6. Summary of Current Trends and Application Areas

Technological infrastructure enables proactive, data-driven forest management. Remote sensing and UAVs improve inventory and monitoring; IoT networks allow early detection of threats; GIS and AI enable predictive modeling and scenario analysis; digital twins integrate multiple data streams for strategic decision-making. Challenges include cost, human resources, standardization, and algorithmic transparency (Table 1).

Table 1. Current Trends and Application Areas of Technological Infrastructure in Forest Management

Technology	Application Area	Benefits	Challenges
Remote Sensing (Satellite, LiDAR)	Forest inventory, biomass/carbon estimation	High-resolution, large-scale data; improved accuracy; monitoring of structural changes	Cost; cloud coverage; data processing requirements
UAV / Drones	Young forests, post-fire assessment, species monitoring	Detailed small-scale mapping; rapid deployment; flexible monitoring	Limited flight time; regulatory restrictions; weather dependency
GIS	Spatial planning, erosion risk, habitat analysis, decision support	Integration of multi-source data; spatial analysis; scenario modeling	Data standardization; software training needed
IoT / Sensor Networks	Microclimate, soil moisture, fire/pest detection	Real-time monitoring; early warning systems; ecosystem process tracking	Installation cost; maintenance; network connectivity
Big Data & AI (Machine Learning, Deep Learning)	Fire risk prediction, habitat modeling, vegetation classification	Predictive analytics; pattern recognition; improved decision-making	Algorithm transparency; data quality; model bias
Digital Twin	Simulating scenarios for management, climate, risk	Proactive decision-making; integrated ecosystem modeling; strategic planning	High complexity; real-time data requirement; computational demand

Source: Compiled by the author based on literature review (2024).

5. DİSCUSSİON

This review demonstrates that technological infrastructure has transformed forest management from a reactive discipline into a proactive, data-driven, and predictive science. The findings are consistent with the existing literature indicating that the integration of remote sensing and AI, in particular, exponentially increases the scale, speed, and accuracy of data collection compared to traditional field studies (Christin et al., 2019; Reichstein et al., 2019; Zulfiqar et al., 2021). Recent research from Türkiye further supports these findings, showing successful applications of UAV-based monitoring (Eker et al., 2021), GIS-integrated risk assessment (Gumus et al. (2008), and IoT-based real-time data acquisition systems (Tagarakis et al., 2024) in forest management contexts.

However, this digitalization process also brings with it a significant paradigm shift. Forest management now requires not only ecological knowledge but also the ability to process big data, understand algorithms, and manage cyber-physical systems. This situation urgently necessitates the revision of forest engineering education curricula (Burleigh & Jönsson 2025).

Furthermore, as dependence on technology increases, 'data quality' and 'algorithmic transparency' become critically important. A machine learning model trained with low-quality data can lead to erroneous management decisions. Similarly, the inability to understand the logic behind decisions made by deep learning models operating as 'black boxes' can undermine managers' trust in these systems (Rudin, 2019). Therefore, explainability in AI applications (explainable AI - XAI) should be one of the focal points of future research (Chinnaraju 2025).

6. CHALLENGES AND LIMITATIONS

Although technological infrastructure transforms forest management, some limitations and challenges exist:

6.1. Cost and Resource Constraints

UAVs, LiDAR, satellite imagery, and sensor networks can require high costs. The applicability of these technologies is limited in small-scale and low-budget projects (Maxwell et al., 2018).

6.2. Data Management and Standardization

Standardizing and harmonizing data from different sources poses a technical challenge; however, planetary-scale platforms like Google Earth Engine largely alleviate this problem (Gorelick et al., 2017).

6.3. Human Resources and Training

Qualified human resources are needed for the effective use of new technologies. Lack of training in GIS, remote sensing, and artificial intelligence applications may limit the use of technological infrastructure (Abad-Segura et al., 2022; Burleigh & Jönsson 2025).

6.4. Legal and Ethical Limitations

The use of drones, data sharing, and personal/environmental privacy are subject to legal regulations. Additionally, ethical standards must be established for the use of technologies (Stone et al., 2016).

6.5. Digital Divide and Algorithmic Bias

Although technological progress is global, access is not equal. Forest management institutions in developing countries risk falling behind these technologies due to high costs and lack of infrastructure. This 'digital divide' could deepen global forest management inequalities. Furthermore, AI models may reflect biases in the data they are trained on. For example, a model trained only on forest types from a specific geography may fail to analyze a different ecosystem (Causevic et al., 2024).

6.6. Policy and Governance Deficiencies

The effective adoption and use of technological infrastructure requires clear policy frameworks and governance mechanisms. There are legislative gaps in areas such as data sharing protocols, privacy regulations, standards for UAV use, and cybersecurity measures. Additionally, collaborative governance models that encourage data and technology sharing among different institutions (forest directorates, environment ministries, research institutes) are needed. Without addressing these deficiencies, the potential return on technological investments cannot be fully realized.

7. CONCLUSION AND FUTURE PERSPECTIVES

Technological infrastructure in forest ecosystem management offers revolutionary opportunities in data collection, analysis, and decision support processes. Remote sensing, UAVs, LiDAR, GIS, sensor networks, IoT, big data analytics, artificial intelligence, and digital twin applications play critical roles in monitoring ecosystem changes, risk management, biodiversity tracking, and sustainable planning.

The review results demonstrate that:

Technological infrastructure enables the collection and analysis of high-resolution data over large areas, increasing the accuracy of management decisions.

GIS and AI-supported decision support systems help balance ecosystem services with economic outputs.

Drone and sensor-based monitoring systems allow early detection of risks such as fire, pest organisms, and climate change.

However, factors such as cost, data standardization, lack of human resources, digital divide, algorithmic bias, and legal/ethical limitations restrict the effective and equitable use of technological infrastructure.

Future Perspectives

• Digital Twin and Simulation Models: Digital twin systems fed with real-time data will enable simulation of different management and climate scenarios and strengthen strategic planning (Buonocore et al., 2022; Tagarakis et al., 2024).

• Integrated Sensor Networks and IoT: Establishing more widespread sensor networks in forest areas will increase the effectiveness of early warning and automatic monitoring systems (Ali et al., 2025).

• Big Data, AI and Explainable Artificial Intelligence (XAI): Big data analytics and deep learning algorithms will help develop more sensitive models of forest dynamics. XAI studies will increase trust by providing transparency in decision-making processes (Chinnaraju, 2025).

• Policy, Governance and International Cooperation: For effective implementation of technologies, comprehensive policy frameworks including open data policies, harmonization of standards, and ethical guiding principles should be developed in addition to trained human resources. International cooperation focused on technology transfer and capacity building will play a key role in reducing the digital divide and supporting sustainable forest management at the global scale (FAO, 2020).

• Citizen Science and Stakeholder Participation: Data collected by the public through smartphone applications (e.g., tree disease reports) can support professional monitoring networks and democratize data collection processes (Fraisl et al., 2022). This has the potential to strengthen the social acceptability of forest management decisions by increasing public participation in management.

In conclusion, technological infrastructure not only increases operational efficiency in forest management but also contributes to the creation of sustainable and resilient ecosystems. Future research should focus on the integration of existing technologies, cost-effective strategies, XAI applications, policy-governance models, and optimizing decision support processes.

8. ACKNOWLEDGMENTS

The author acknowledges the use of AI assistants in the preparation of this review article, in accordance with ethical AI usage principles. ChatGPT (OpenAI) was employed to support the literature synthesis, conceptual structuring, and initial drafting phases of the manuscript. DeepSeek AI (deepseek.com) was utilized for language refinement, formatting suggestions, DOI verification, and consistency editing. The author retains full responsibility for the final content, interpretations, and conclusions presented in this work.

References

1. Abad-Segura, E., González-Zamar, M. D., Vázquez-Cano, E., & López-Meneses, E. (2020). Remote sensing applied in forest management to optimize ecosystem services: advances in research. *Forests*, *11*(9), 969. https://doi.org/10.3390/f11090969

2. Akay, A. E., Oğuz, H., Karas, I. R., & Aruga, K. (2009). Using LiDAR technology in forestry activities. *Environmental monitoring and assessment*, *151*(1), 117-125.https://doi.org/10.1007/s10661-008-0254-1

3. Akay, A. E., Wing, M. G., Zengin, M., & Köse, O. (2016). Determination of fire-access zones along road networks in fire-sensitive forests. *Journal of Forestry Research, 28*(3), 557–564. https://doi.org/10.1007/s11676-016-0283-5

4. Akçay, H., Aksoy, S., Kaya, S., & Dash, J. (2023). Evaluating the potential of multi-temporal Sentinel-1 and Sentinel-2 data for regional mapping of olive trees. *International Journal of Remote Sensing, 44*(23), 7338–7364. https://doi.org/10.1080/01431161.2023.2282404

5. Ali, G., Mijwil, M. M., & Ayad, J. (2025). Leveraging the Internet of Things, remote sensing, and artificial intelligence for sustainable forest management. *Babylonian Journal of Internet of Things*, 1–65. https://doi.org/10.58496/BJIoT/2025/001

6. Asner, G. P. (2013). Geography of forest disturbance. *Proceedings of the National Academy of Sciences, 110*(20), 8350–8355. https://doi.org/10.1073/pnas.1301601110

7. Baldocchi, D., Falge, E., Gu, L., Olson, R., Hollinger, D., Running, S., ... & Wofsy, S. (2001). FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. *Bulletin of the American Meteorological Society, 82*(11), 2415–2434. https://doi.org/10.1175/1520-0477(2001)082<2415:FANTTS>2.3.CO;2

8. Baybaş, S., Akgün, Ö., Adıgüzel, E. D. C., & Gökpınar, E. (2024). A machine learning approach for forest fire prediction: A case study from Türkiye. *Veri Bilimi, 7*(2), 1–10.

9. Bonan, G. B. (2008). Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science, 320*(5882), 1444–1449. https://doi.org/10.1126/science.1155121

10. Buonocore, L., Yates, J., & Valentini, R. (2022). A proposal for a forest digital twin framework and its perspectives. *Forests, 13*(4), 498. https://doi.org/10.3390/f13040498

11. Burleigh, S., & Jönsson, H. (2025). European agrifood and forestry education for a sustainable future: Gap analysis from an informatics approach. *Open Research Europe, 4*, 93. https://doi.org/10.12688/openreseurope.17205.3

12. Causevic, A., Causevic, S., Fielding, M., & Barrott, J. (2024). Artificial intelligence for sustainability: Opportunities and risks of utilizing Earth observation technologies to protect forests. *Discover Conservation, 1*(1), 2. https://doi.org/10.1007/s44353-024-00002-2

13. Chinnaraju, A. (2025). Explainable AI (XAI) for trustworthy and transparent decision-making: A theoretical framework for AI interpretability. *World Journal of Advanced Engineering Technology and Sciences, 14*(3), 170–207. https://doi.org/10.30574/wjaets.2025.14.3.0106

14. Christin, S., Hervet, É., & Lecomte, N. (2019). Applications for deep learning in ecology. *Methods in Ecology and Evolution, 10*(10), 1632–1644. https://doi.org/10.1111/2041-210X.13256

15. Colchester, M., Apte, T., Laforge, M., Mandondo, A., & Pathak, N. (2003). *Bridging the gap: Communities, forests and international networks.* Center for International Forestry Research.

16. Çolak, E., & Sunar, A. F. (2018). Remote sensing and GIS integration for monitoring the areas affected by forest fires: A case study in İzmir, Turkey. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLII-3/W4,* 165–170. https://doi.org/10.5194/isprs-archives-XLII-3-W4-165-2018

17. Diaz-Balteiro, L., & Romero, C. (2008). Making forestry decisions with multiple criteria: A review and an assessment. *Forest Ecology and Management, 255*(8–9), 3222–3241. https://doi.org/10.1016/j.foreco.2008.01.038

18. Diktaş-Bulut, N., Gümüş, S., Karslı, F., & Acar, H. H. (2025). Determination of rippability classes through classical and geophysical methods in new forest road excavations, and their evaluation in terms of cost and progress payments. *Croatian Journal of Forest Engineering, 44*(1), 77–90. https://doi.org/10.5552/crojfe.2023.2532

19. Ecke, S., Dempewolf, J., Frey, J., Schwaller, A., Endres, E., Klemmt, H.-J., ... & Seifert, T. (2022). UAV-based forest health monitoring: A systematic review. *Remote Sensing, 14*(13), 3205. https://doi.org/10.3390/rs14133205

20. Eker, R., Alkan, E., & Aydın, A. (2021). A comparative analysis of UAV-RTK and UAV-PPK methods in mapping different surface types. *European Journal of Forest Engineering, 7*(1), 12–25. https://doi.org/10.33904/ejfe.938067

21. Fidanboy, M., Adar, N., & Okyay, S. (2022). Development of a forest fire prediction model based on deep learning and forecast fire risk map of Turkey. *Turkish Journal of Forestry Research*, *9*(2), 206–218. https://doi.org/10.17568/ogmoad.1066557

22. Food and Agriculture Organization of the United Nations. (2020). *Global forest resources assessment 2020.* FAO. https://doi.org/10.4060/ca9825en

23. Fraisl, D., Hager, G., Bedessem, B., Gold, M., Hsing, P. Y., Danielsen, F., ... & Haklay, M. (2022). Citizen science in environmental and ecological sciences. *Nature Reviews Methods Primers, 2*(1), 64. https://doi.org/10.1038/s43586-022-00144-4

24. Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). Digital twin: Enabling technologies, challenges and open research. *IEEE Access, 8*, 108952–108971. https://doi.org/10.1109/ACCESS.2020.2998358

25. Gorelick, N., Hancher, M., & Moore, R. (2017). Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment*, *202*, 18–27. https://doi.org/10.1016/j.rse.2017.06.031

26. Gümüş, S., Acar, H. H., & Toksoy, D. (2008). Functional forest road network planning by consideration of environmental impact assessment for wood harvesting. *Environmental Monitoring and Assessment, 142,* 109–116. https://doi.org/10.1007/s10661-007-9912-y

27. Gurevitch, J., Koricheva, J., Nakagawa, S., & Stewart, G. (2018). Meta-analysis and the science of research synthesis. *Nature, 555*(7695), 175–182. https://doi.org/10.1038/nature25753

28. Gümüş, S. (2021). Stream-crossing approaches on forest roads networks: A critical review on practices in Türkiye. *European Journal of Forest Engineering, 7*(2), 92–97. https://doi.org/10.33904/ejfe.1036104

29. Hacisalihoğlu, S., Gümüş, S., Kezik, U., & Karadağ, H. (2019). Impact of forest road construction on topsoil erosion and hydro-physical soil properties in a semi-arid mountainous ecosystem in Turkey. *Polish Journal of Environmental Studies, 28*(1), 113–121. https://doi.org/10.15244/pjoes/81615

30. İban, M. C., & Şekertekin, A. (2022). Machine learning-based wildfire susceptibility mapping using remotely sensed fire data and GIS: A case study of Adana and Mersin provinces, Turkey. *Ecological Informatics, 69,* Article 101647. https://doi.org/10.1016/j.ecoinf.2022.101647

31. Kaya, N. S., & Dengiz, O. (2024). Investigation of the effects of pixel-based supervised classification using support vector machine, random forest and maximum likelihood algorithms based on Sentinel-2A MSI data. *Turkish Journal of Remote Sensing and GIS*, *5*(2), 138–157. https://doi.org/10.48123/rsgis.1410250

32. Kerr, J. T., & Ostrovsky, M. (2003). From space to species: Ecological applications for remote sensing. *Trends in Ecology & Evolution, 18*(6), 299–305. https://doi.org/10.1016/S0169-5347(03)00071-5

33. Kilic, S., Evrendilek, F., & Demirkesen, A. C. (2006). Environmental monitoring of land-use and land-cover changes in a Mediterranean region of Turkey. *Environmental Monitoring and Assessment*, *114,* 157–168. https://doi.org/10.1007/s10661-006-2525-z

34. Lal, R. (2008). Carbon sequestration. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1492), 815–830. https://doi.org/10.1098/rstb.2007.2185

35. Linares, M., & Ni-Meister, W. (2024). Impact of wildfires on land surface cold season climate in the Northern high-latitudes: A study on changes in vegetation, snow dynamics, albedo, and radiative forcing. *Remote Sensing*, *16*(8), 1461. https://doi.org/10.3390/rs16081461

36. Maxwell, A. E., Warner, T. A., & Fang, F. (2018). Implementation of machine-learning classification in remote sensing: An applied review. *International Journal of Remote Sensing, 39*(9), 2784–2817. https://doi.org/10.1080/01431161.2018.1433343

37. Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & PRISMA Group. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *PLoS Medicine, 6*(7), e1000097. https://doi.org/10.1371/journal.pmed.1000097

38. Paneque-Gálvez, J., McCall, M. K., Napoletano, B. M., Wich, S. A., & Koh, L. P. (2014). Small drones for community-based forest monitoring: An assessment of their feasibility and potential in tropical areas. *Forests, 5*(6), 1481–1507. https://doi.org/10.3390/f5061481

39. Pettorelli, N., Schulte to Bühne, H., Tulloch, A., Dubois, G., Macinnis-Ng, C., Queirós, A. M., & Nicholson, E. (2018). Satellite remote sensing of ecosystem functions: Opportunities, challenges and way forward. *Remote Sensing in Ecology and Conservation, 4*(2), 71–93. https://doi.org/10.1002/rse2.59

40. Reichstein, M., Camps-Valls, G., Stevens, B., Jung, M., Denzler, J., Carvalhais, N., & Prabhat. (2019). Deep learning and process understanding for data-driven Earth system science. *Nature, 566*(7743), 195–204. https://doi.org/10.1038/s41586-019-0912-1

41. Rudin, C. (2019). Stop explaining black box machine learning models for high-stakes decisions and use interpretable models instead. *Nature Machine Intelligence, 1*(5), 206–215. https://doi.org/10.1038/s42256-019-0048-x

42. Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., & Reyer, C. P. O. (2017). Forest disturbances under climate change. *Nature Climate Change, 7*, 395–402. https://doi.org/10.1038/nclimate3303

43. Stone, P., Brooks, R., Brynjolfsson, E., Calo, R., Etzioni, O., Hager, G., Hirschberg, J., & Teller, A. (2016). *Artificial intelligence and life in 2030* (Report of the 2015 Study Panel). One Hundred Year Study on Artificial Intelligence (AI100), Stanford University. https://ai100.stanford.edu/2016-report

44. Tagarakis, A. C., Benos, L., Kyriakarakos, G., & Bochtis, D. (2024). Digital twins in agriculture and forestry: A review. *Sensors, 24*(10), 3117. https://doi.org/10.3390/s24103117

45. Turner, W., Rondinini, C., Pettorelli, N., Mora, B., Leidner, A. K., Szantoi, Z., ... & Woodcock, C. (2015). Free and open-access satellite data are key to biodiversity conservation. *Biological Conservation, 182*, 173–176. https://doi.org/10.1016/j.biocon.2014.11.048

46. Vatandaşlar, C., & Zeybek, M. (2020). Application of handheld laser scanning technology for forest inventory purposes in NE Turkey. *Turkish Journal of Agriculture and Forestry, 44*(3), 229–242. https://doi.org/10.3906/tar-1903-40

47. Yıldırım, O., Günay, F. B., & Yağanoğlu, M. (2023). Forest fire prediction using machine learning methods. *Journal of the Institute of Science and Technology, 13*(3), 1468–1481. https://doi.org/10.21597/jist.1249908

48. Zulfiqar, A., Ghaffar, M. M., Shahzad, M., Weis, C., Malik, M. I., Shafait, F., & Wehn, N. (2021). AI-ForestWatch: Semantic segmentation-based end-to-end framework for forest estimation and change detection using multi-spectral remote sensing imagery. *Journal of Applied Remote Sensing, 15*(2), 024518. https://doi.org/10.1117/1.JRS.15.024518

Temperature Trends and Ecosystem Resilience in Iran: A Climate-Based Framework for Sustainable Management

Hüseyin Toros[1], Aydin Ulubey (Gulubayov)[2], Mikhail Remizov[3], Mohsen Abbasnia[4]*

[1] Department of Climate Science and Meteorological Engineering, Istanbul Technical University, Maslak Istanbul, Turkey.

[2] Professor of Meteorology, Department of Mechanics and Mathematics, School of Advanced Technologies and Natural Sciences, Western Caspian University, Baku, Azerbaijan,

[3] Professor of Meteorology, Department of Mechanics and Mathematics, School of Advanced Technologies and Natural Sciences, Western Caspian University, Baku, Azerbaijan,

[4] Corresponding Author*: Researcher of Climate Change, Department of Climate Science and Meteorological Engineering, Adana Alparslan Türkeş Science and Technology University, Adana, Turkey.

Received :01.10.2025 Accepted: 03.10.2025 Published:30.10.2025

https://doi.org/10.54414/YIVW2215

Abstract

This study applies the Mann–Kendall trend test to evaluate long-term changes in annual maximum, minimum, and mean temperatures across Iran from 1980 to 2017. Results reveal a consistent upward trend in all temperature parameters nationwide, with spatial variability linked to geographic and topographic factors. Stations in southern regions, such as Bandar-Abbas and Ahvaz, exhibited the lowest positive trends, whereas Kermanshah and Tabriz located in the northeastern mountainous zones, recorded the highest increases in maximum temperature, approximately 2.7 °C and 2.5 °C, respectively. Interestingly, these high-altitude stations showed the smallest rise in minimum temperatures, contrasting with cities like Mashhad, Ahvaz, and Tehran, where minimum temperatures increased more rapidly than maximum values. Among all stations, Mashhad demonstrated the most pronounced warming across all temperature metrics. From a sustainability standpoint, these findings underscore the urgency of region-specific climate adaptation strategies. The accelerated warming in urban and high-latitude areas may intensify energy demands, disrupt agricultural cycles, and strain water resources, particularly in already vulnerable ecosystems.

Keywords: Temperature Trends, Climate Change, Iran, Mann–Kendall Test, Environmental Sustainability, Spatial Analysis

1. Introduction

Climate change has emerged as a defining challenge for environmental sustainability, with rising temperatures threatening the integrity of ecosystems, water resources, and agricultural productivity. In arid and semi-arid regions such as the Middle East, understanding long-term temperature trends is critical for developing adaptive strategies that promote sustainable ecosystem management and climate resilience. Numerous studies have documented significant warming trends across Iran which is located in arid and semi-arid regions. Masoodian (2004) and Ghasemi (2015) identified consistent increases in maximum, minimum, and mean temperatures, while Sabohi and Soltani (2009) highlighted urban vulnerability to climatic shifts in major cities. Abbasnia et al. (2016) projected future temperature changes using HADCM3 and CGCM3 models, reinforcing the urgency of climate-informed planning. Tabari et al. (2012) emphasized the role of autocorrelation in detecting monotonic trends, and Ghasemi and Khalili (2008) explored the influence of large-scale circulation patterns such as the North Sea–Caspian Pattern (NCP) on Iran's winter temperatures.

Recent international assessments further underscore the regional climate risks. The IPCC (2023) reports that the Middle East, including Iran, is warming faster than the global average, with increased heatwaves, reduced snowpack, and heightened threats to water security and agriculture. Daneshvar et al. (2019) project a 2.6 °C rise in mean temperature and a 35% decline in precipitation, noting Iran's high ranking in global greenhouse gas emissions. Ranjbar-Saadatabadi (2025) found that 79% of synoptic stations recorded temperature anomalies during autumn and winter 2024–2025, with November peaking at +2.05 °C above the long-term average and 90% of stations showing reduced precipitation. Nasirian and Naddafi (2025) highlighted the ecological consequences of glacier melt in the Alborz and Zagros ranges, emphasizing the need for community-based adaptation and renewable energy investment. These findings align with global comparative studies, such as Kruger and Shongwe (2004) on South Africa, which demonstrate spatial heterogeneity in warming trends across mid-latitude regions. The statistical foundation for such analyses is grounded in robust methodologies like the Mann–Kendall trend test (Kendall et al., 1983), enabling detection of non-parametric trends in climatological time series.

Given Iran's topographic complexity, from low-lying coastal zones to mountainous highlands, temperature trends vary significantly by elevation and latitude. This spatial variability has direct consequences for ecosystem resilience, agricultural planning, and water resource management. Integrating climate trend analysis into national and regional sustainability frameworks can help prioritize adaptation measures tailored to local vulnerabilities. Such measures include adjusting crop calendars, enhancing urban green infrastructure, and protecting biodiversity hotspots. This study contributes to the growing body of climate research by analyzing observed temperature trends across Iran from 1980 to 2017. The results offer actionable insights for ecosystem-based climate adaptation, supporting Iran's transition toward resilient and sustainable environmental governance.

2. Materials and Methods

Iran is geographically located in the mid-latitudes (25°N to 40°N), encompassing a wide range of climatic zones shaped by its complex topography, elevation gradients, and continental positioning. The country spans arid, semi-arid, Mediterranean, and mountainous climates, influenced by the Zagros and Alborz Mountain ranges, interior basins, and salt deserts. These features act as climatic barriers and contribute to significant spatial variability in temperature and precipitation patterns across the country (Raziei, 2022; Roshan et al., 2024; Motavalli-Anbaran et al., 2011).

To represent this diversity, eight synoptic meteorological stations were selected: Bandar-Abbas, Ahvaz, Tehran, Mashhad, Kermanshah, Tabriz, Isfahan, and Shiraz. These stations span coastal lowlands, central plateaus, urban basins, and mountainous regions. For example, Bandar-Abbas experiences a subtropical arid climate, while Ahvaz is characterized by hot desert conditions. Tehran and Shiraz exhibit semi-arid climates, Mashhad and Tabriz reflect cold semi-arid conditions, and Kermanshah shows Mediterranean influences. Isfahan, centrally located, represents an arid steppe climate. This classification aligns with the Köppen-Geiger, Feddema, and UNEP climate frameworks, which confirm that over 98% of Iran's territory falls under arid or semi-arid categories (Raziei, 2022). Next, Monthly maximum, minimum, and mean temperature data from 1980 to 2017 were obtained from the Iranian Meteorological Organization (IRIMO). The dataset was subjected to quality control and homogenization procedures to ensure consistency and reliability across stations and time periods.

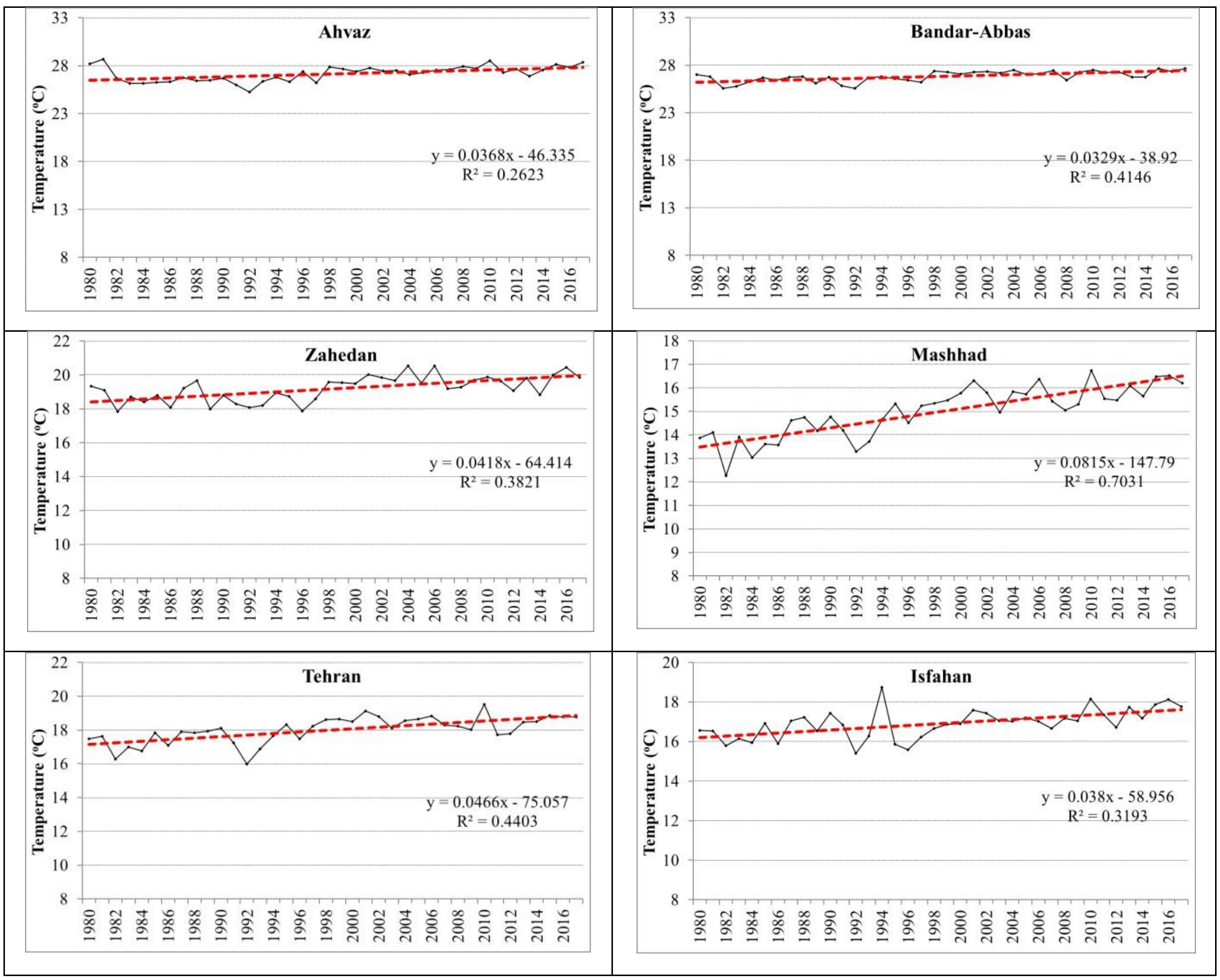
To detect long-term temperature trends, the study applied the Mann–Kendall non-parametric trend test (Kendall, Stuart, & Ord, 1983), a widely accepted method in climatological research for identifying monotonic trends in time series data without assuming a specific distribution. The test was conducted on annual averages of each temperature parameter for all stations.

3. Results and Discussion

To evaluate long-term temperature behavior across the selected stations, the nonparametric Mann–Kendall trend test was employed to analyze mean annual temperature data. The following results present the identified trends for each station, categorized by maximum, minimum, and mean temperature parameters.

3.1. Mean temperature trends

Over the analyzed period, there is a general increase in annual mean temperature throughout the study area. However, the increase in mean temperature is not observed at the same rate for all stations (Figure 1). Geographic locations of the stations with highest positive trends lie from south to north parts of Iran. There are several reasons for temperature increases at some stations. Pollutions arising from industries have been increased in Mashhad, Kermanshah, and Tabriz, and thereby causing local warming. Population growth and urban development in these cities will made this region warmer, by increasing the local consumption of energy and changing the nature of the land surface (Saboohi and Soltani, 2009). In addition, the mountainous regions located in the higher latitudes are more faced with the risk of rising temperatures compared to the lowland regions of southern parts of Iran (Abbasnia et al., 2016). Therefore, the lowest positive trends have occurred for southern stations such as, Bandar-Abbas, Ahvaz, and Zahedan.



\

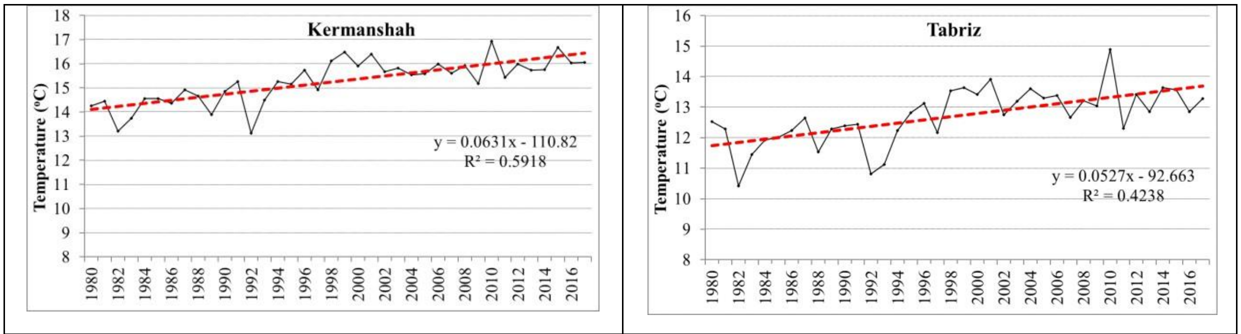
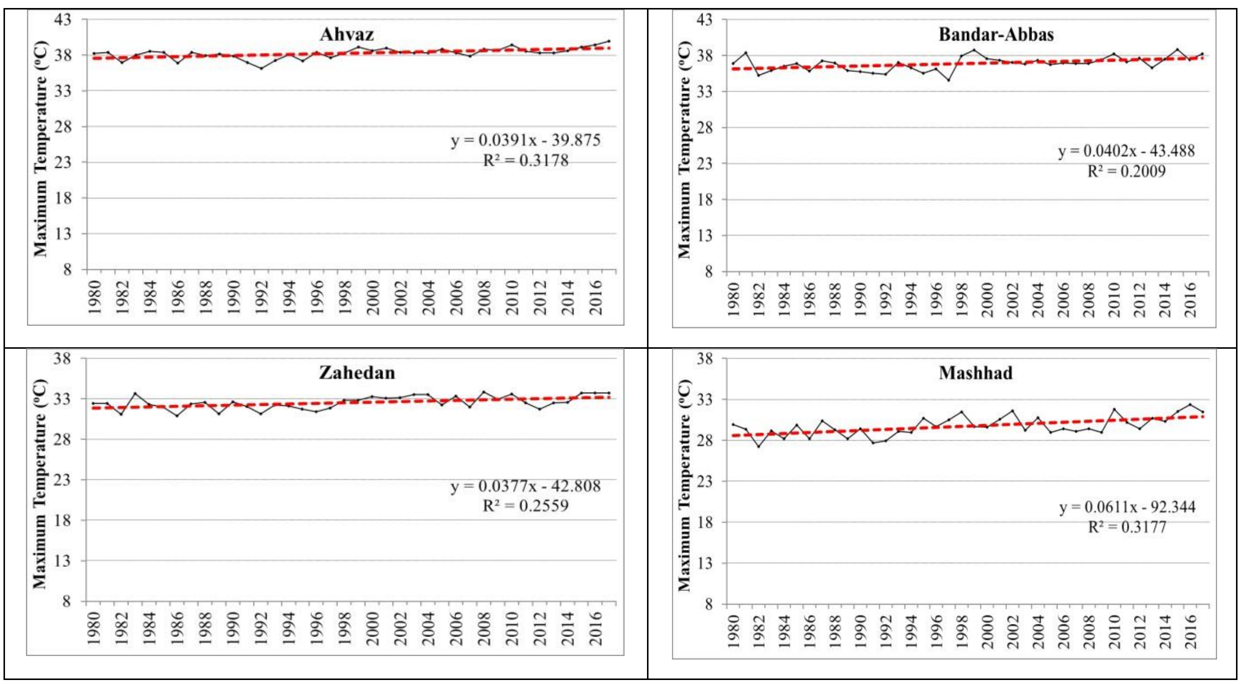


Figure 1- Annual mean temperature trends over selected stations

3.2. Maximum temperature trends

The maximum temperatures in all studied stations have revealed the positive trends during the observational period (Figure 2). In this case, a previously study conducted by Masoodian (2004) indicated that maximum temperature has been increased by about 1.4°C per century in Iran from 1951 to 2000. The highest rising trends in maximum temperatures have obtained for the stations located in mountainous and northern parts of Iran. In this regards, two stations of Kermanshah and Tabriz have had the highest rising trends by about 2.7 and 2.5 °C during the studied period, respectively. In contrast, the lowest rising trends in maximum temperatures have occurred for the southern stations of Zahedan, Ahvaz, and Bandar-Abbas by about 1.36, 1.4, and 1.48 °C during the studied period, respectively. Most of the studied stations have revealed the higher increasing rate for maximum temperatures compared to the mean temperatures.



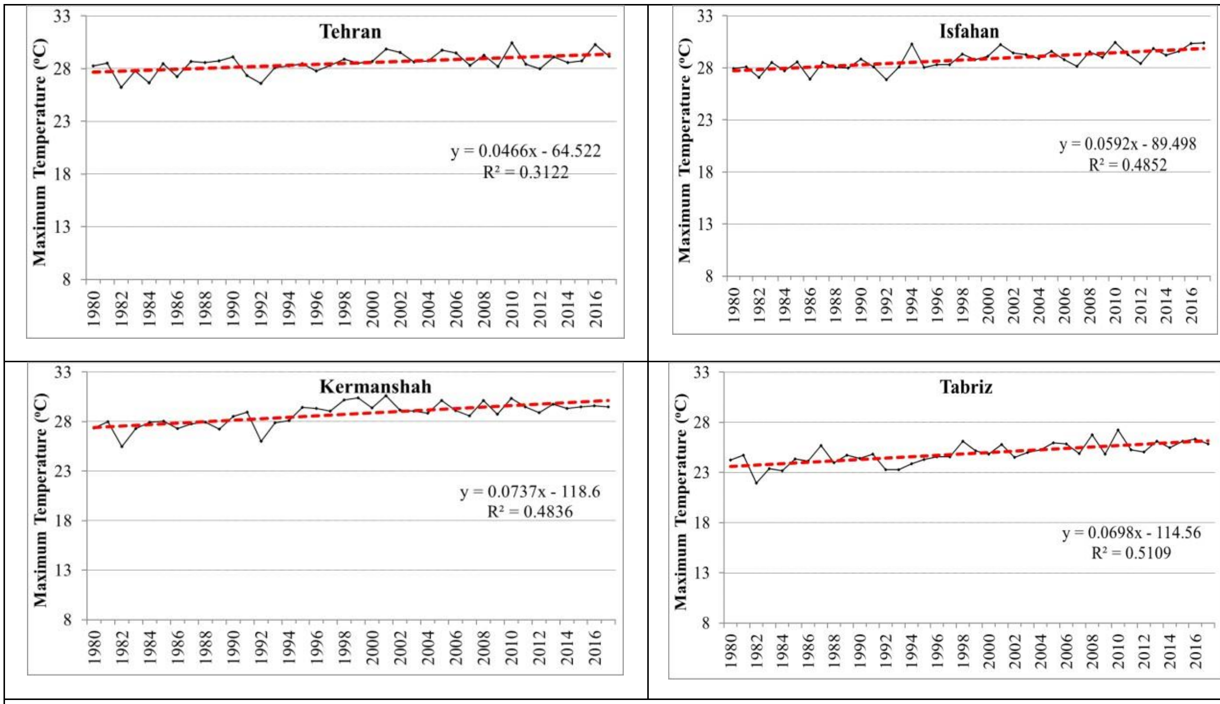


Figure 2- Annual maximum temperature trends over selected stations

3.3. Minimum temperature trends

There were positive trends in the minimum temperatures throughout Iran area (Figure 3). The highest rising trends in minimum temperatures have not showed consistent patterns over Iran. In this case, Mashhad, and Ahvaz have respectively revealed the highest rising trends during the observational period. While, the lowest increasing trends have happened in station scales of Isfahan and Tabriz. What can obtain from surveying the results of minimum temperatures is that two stations of Tabriz and Kermanshah among all studied stations have revealed the lowest positive trends in all of the three parameters of mean, maximum, and minimum temperatures during the studied period. While, the highest positive trends for mountainous and higher latitude stations of Tabriz and Kermanshah have happened in maximum temperature among all parameters of temperature. In addition, the rising trends at station scales of Mashhad, Ahvaz, and Tehran have only had higher rate in minimum temperature than maximum temperature. Moreover, the highest upward trends in all of three temperature parameters have occurred at the station scale of Mashhad among all of studied stations. In the final analysis, the results of warming trends in all of the three parameters of temperature are consistent with previous studies, which showed the last decade of the previous century was substantially warmer than previous decades in global scale (Kruger and Shongwe, 2004).

\

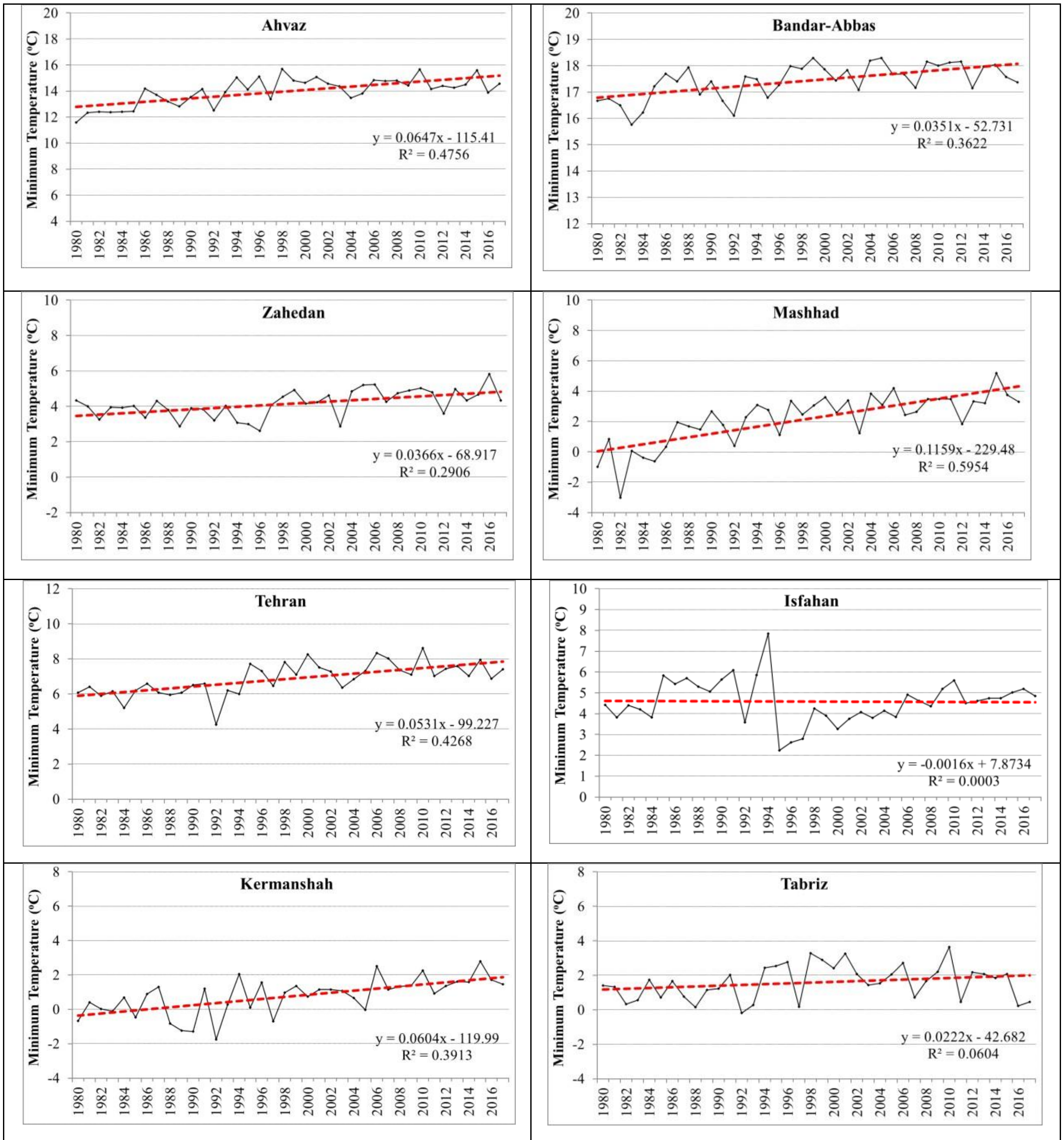


Figure 3- Annual minimum temperature trends over selected stations

4. Conclusion

This study has demonstrated that Iran's temperature regime between 1980 and 2017 has undergone statistically significant warming, with spatial and temporal variability shaped by topography, latitude, and urbanization. While all stations revealed upward trends in maximum, minimum, and mean annual temperatures, the magnitude and consistency of these changes varied across regions. Mountainous and northern stations such as Kermanshah and Tabriz exhibited the most pronounced increases in maximum temperatures, whereas southern lowland stations like Bandar-Abbas and Ahvaz showed more moderate warming. These findings align with broader climatological evidence that the final decades of the 20th century marked a turning point in regional and global temperature acceleration. Importantly, the divergence in warming rates across Iran underscores the need for localized climate adaptation strategies. Urban expansion, energy consumption, and land surface modification have amplified warming in cities such as Mashhad and Tabriz, suggesting that sustainable urban planning, incorporating green infrastructure, energy-efficient design, and pollution mitigation, will be critical in managing future climate risks. Moreover, the vulnerability of high-altitude and semi-arid zones to temperature extremes calls for targeted ecosystem conservation and water resource management.

Given the climatic parallels between Iran and other arid and semi-arid regions of the Middle East, North Africa, and Central Asia, these insights offer transferable value. Policymakers and researchers in similarly exposed regions should prioritize elevation-sensitive climate modeling, integrate temperature trend analysis into long-term planning, and foster regional collaboration to address shared vulnerabilities. Ultimately, the observed warming trends reinforce the urgency of embedding climate resilience into environmental governance, infrastructure development, and transboundary sustainability frameworks.

5. Acknowledgments

The authors gratefully acknowledge the Iranian Meteorological Organization (IRIMO) for providing access to the national temperature dataset used in this study. We also extend our sincere appreciation to the international collaboration between Istanbul Technical University (ITU), Western Carolina University (WCU), and Alparslan Türkeş Science and Technology University (ATU), whose joint efforts in climate research and academic exchange have enriched the scope and impact of this work.

References

1. Abbasnia, M., Tavousi, T., & Khosravi, M. (2016). Assessment of future changes in the maximum temperature at selected stations in Iran based on HADCM3 and CGCM3 models. *Asia-Pacific Journal of Atmospheric Sciences*, *52*(4), 371–377. https://doi.org/10.1007/s13143-016-0023-4

2. Daneshvar, M. R. M., Ebrahimi, M., & Nejadsoleymani, H. (2019). An overview of climate change in Iran: Facts and statistics. *Environmental Systems Research*, *8*(7). https://doi.org/10.1186/s40068-019-0135-3

3. Ghasemi, A. R. (2015). Changes and trends in maximum, minimum and mean temperature series in Iran. *Atmospheric Science Letters*, *16*(3), 366–372. https://doi.org/10.1002/asl.574

4. Ghasemi, A. R., & Khalili, D. (2008). The effect of the North Sea–Caspian pattern (NCP) on winter temperatures in Iran. *Theoretical and Applied Climatology*, *92*, 59–74. https://doi.org/10.1007/s00704-007-0302-3

5. Intergovernmental Panel on Climate Change (IPCC). (2007). *Climate change 2007: The AR4 synthesis report*. https://www.ipcc.ch/report/ar4/syr/

6. Intergovernmental Panel on Climate Change (IPCC). (2013). *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/report/ar5/wg1/

7. Intergovernmental Panel on Climate Change (IPCC). (2023). *Climate change 2023: Synthesis report. Contribution of Working Groups I, II, and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_LongerReport.pdf

8. Kendall, M. G., Stuart, A., & Ord, J. K. (1983). *The advanced theory of statistics: Design and analysis, and time-series* (Vol. 3, 4th ed., pp. 780–790). Griffin.

\

9. Kruger, A. C., & Shongwe, S. (2004). Temperature trends in South Africa: 1960–2003. *International Journal of Climatology, 24*(15), 1929–1945. https://doi.org/10.1002/joc.1096

10. Masoodian, S. A. (2004). Temperature trends in Iran during the last half century. *Geographical Research Quarterly, 54,* 29–45.

11. Motavalli-Anbaran, S.-H., Zeyen, H., Brunet, M.-F., & Ardestani, V. E. (2011). Crustal and lithospheric structure of the Alborz Mountains, Iran, and surrounding areas from integrated geophysical modeling. *Tectonics, 30*(5), TC5012. https://doi.org/10.1029/2011TC002934

12. Nasirian, H., & Naddafi, K. (2025). A new perspective on climate change in the geography of Iran: Current and potential future implications. *Journal of Environmental Health Science and Engineering, 23*(25). https://doi.org/10.1007/s40201-025-00948-y

13. Ranjbar-Saadatabadi, A. (2025). Analysis of monthly precipitation and temperature anomalies in Iran and their association with atmospheric circulations during autumn and winter 2024–2025. *Journal of Environmental and Spatial Physics*. https://jesphys.ut.ac.ir/article_102931.html?lang=en

14. Raziei, T. (2022). Climate of Iran according to Köppen–Geiger, Feddema, and UNEP climate classifications. *Theoretical and Applied Climatology, 148,* 1395–1416. https://doi.org/10.1007/s00704-022-03992-y

15. Roshan, G., Sarli, R., Grab, S. W., Nasiri, V., & Socha, J. (2024). Elevational trends of land surface temperature in the Alborz Mountains within the context of global warming. *Stochastic Environmental Research and Risk Assessment, 38,* 1721–1739. https://doi.org/10.1007/s00477-023-02651-6

16. Sabohi, R., & Soltani, S. (2009). Trend analysis of climatic factors in great cities of Iran. *Journal of Water and Soil Science (JWSS) – Isfahan University of Technology, 12*(46), 303–321.

17. Tabari, H., Hosseinzadeh Talaee, P., Ezani, A., & Shifteh, B. (2012). Shift changes and monotonic trends in autocorrelated temperature series over Iran. *Theoretical and Applied Climatology, 109,* 95–108. https://doi.org/10.1007/s00704-011-0566-2

Ecological Assessment of Anthropogenic Impacts on the Soil Cover in the Absheron Peninsula

Aruz Mikayilov[1], **Lala Karimova**
[1]Western Caspian University, Baku, Azerbaijan
[2]Western Caspian University, Baku, Azerbaijan

Received: Accepted:26.10.2025 Published:30.10.2025
https://doi.org/10.54414/SGRY2927

Abstract

Soil ecosystems serve as crucial carriers of ecological functions, ensuring the sustainability of biocenoses, nutrient cycling, and agricultural productivity. However, intensive anthropogenic impacts—including industrialization, urbanization, and agricultural expansion—lead to the transformation of the morphogenetic characteristics of the soil cover, structural degradation, and disruption of chemical balance. Therefore, the conducted studies comprehensively assessed the ecological and geochemical status of soils on the Absheron Peninsula under the influence of anthropogenic pressure. In these studies, soil samples collected from the districts of Garadag, Surakhani, and Sabunchu were analyzed for pH, electrical conductivity, nitrogen-phosphorus-potassium balance, particle size distribution, as well as by X-ray spectral and X-ray diffractometric methods. The results indicate that the soils are predominantly characterized by weakly to strongly alkaline conditions, with certain areas exhibiting nutrient deficiencies and elevated ion concentrations. Samples obtained from oil fields in the Sabunchu district showed evidence of organic contamination, high carbonate content, and enrichment with heavy metals, indicative of ecotoxicological effects. Additionally, using GIS technologies and satellite imagery, the degradation status of the land cover, the degree of disruption in soil-vegetation integrity (expressed in percentages), and existing materials were assessed, allowing for the classification of soils into four ecological status groups: satisfactory (5%), conflicted (48%), critical (5%), and catastrophic (42%). This categorization confirms that the soil resources of the peninsula are under severe ecological risk.

Keywords: ecosystem, anthropogenic impacts, degradation, chemical balance, ecological, electrical conductivity, ion concentration, ecological risk

1. Introduction

Soil ecosystems, as an integral component of the environment, play a vital role in vegetation development, the cycling of water and nutrients, and human life activities (İmanova S. H., 2014, Geography of the Republic of Azerbaijan, Vol. 1).

Soils are not limited to serving as resources for agriculture and industry; they are also essential components for the conservation of biodiversity and the sustainable development of the environment. However, anthropogenic activities have increasingly impacted soils in recent years, negatively affecting their structural, functional, and chemical properties (Alizadeh E. K., Rustamov Q. I., Karimova E. J., 2015; Hasanov X. E., 1998).

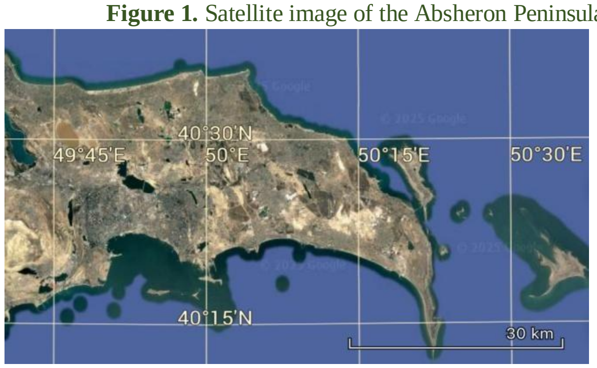
A number of researchers have conducted various scientific studies to assess the degradation, pollution levels, and ecological-geochemical characteristics of the soil cover on the peninsula (Alizadeh, E. K., Rustamov, Q. I., Karimova, E. J., 2015; Ismayilov, A. I., Yashar, Ə. Y., Feyziyev, F. M., 2021; Mammadov, Q. Sh., Həkimova, N. F., 2003; Mirzayev, A. B., Shikhaliyev, F. B., 2012; Suleymanov, T. I., Yashar, Ə., 2016; Budagov, B. A., Mamedov, R. M., Ismatova, Kh. R., Mikayilov, A. A., 2002; Bayramova, L. A., 2024; Guliyev, A., Islamzade, R., Suleymanova, P., Babayeva, T., Aliyeva, A., Hajiyeva, Kh., 2024; Hajiyeva, G. N., Ibrahimova, L. P., 2024).

However, the analysis of existing studies indicates that over the past decade, intensive anthropogenic pressures on the soil cover of the area have exacerbated ecological problems. Therefore, there is a need for a comprehensive assessment of the physical-chemical properties, biological productivity, natural resilience, balance against anthropogenic pollution, and overall ecological status of the soils of the Absheron Peninsula under contemporary conditions, as well as for identifying future development trends. In this context, the ecological assessment of anthropogenic impacts on the soil cover of the Absheron Peninsula remains highly relevant.

2. Materials and Methods.

The Absheron Peninsula, selected as the study area, is located in the southeastern part of the Republic of Azerbaijan and covers an area of 2,110 km². To the north, the peninsula is bounded by the city of Sumgait and the surrounding territory of the Absheron District (Fig. 1).

Figure 1. Satellite image of the Absheron Peninsula



The eastern boundary of the Absheron Peninsula is limited by the Caspian Sea. This part of the peninsula includes sea-related ports, oil platforms, and industrial facilities. The eastern boundary encompasses the peninsula's most remote coastal points. The southern boundary is also bordered by the Caspian Sea, covering the southern coastal areas of Baku, including Bibiheybet, Bayil, and Shikov. The southern shores of the Absheron Peninsula are also known for oil platforms and industrial zones. To the west, the peninsula is bordered by the low-mountainous areas of Gobustan, with a length of approximately 60 km and a maximum width of 30–35 km (Mammadov, Ə. Y., Suleymanov, (2011); Shirinov, N. Sh., Valiyev, X. A., Aliyev, (1998); Geography of the Republic of Azerbaijan, Vol. 1, 2014).

The peninsula includes the cities of Baku, Sumgait, and Khirdalan, where approximately 40% of the country's population resides (Environmental Status in Azerbaijan, 2025., Regions of Azerbaijan, 2024).

A comprehensive approach was applied to study the impact of anthropogenic factors on the soil cover of the Absheron Peninsula, utilizing the following methods:

Route Observation. Visual observations were conducted at pre-designated sites within the study area to assess the impact of anthropogenic factors on the soil-vegetation cover. Structural changes occurring on the soil surface were recorded. In addition, the effects of industrial enterprises, settlements, and agricultural fields on the soil cover were evaluated through direct observation.

Laboratory Analysis. Physical and chemical analyses were conducted on soil samples collected from the selected study sites. Parameters such as pH, humus content, pollutant concentrations, and other key characteristics were determined. These analyses provided a substantial database for assessing the impact of anthropogenic factors on soil quality.

Geographic Information Systems (GIS) Analysis. To achieve the main objectives of the study, observations were conducted across various areas of the peninsula using modern Geographic Information Systems (GIS) and satellite imagery. Visual changes in the soil cover and anthropogenic impacts were mapped. Analyses of satellite images were performed to determine changes in soil cover and levels of degradation. GIS technologies were used to assess the spatial distribution dynamics of anthropogenic effects and to identify the factors and directions of landscape transformation.

Statistical Analysis. Systematic statistical analyses were conducted on the collected data to determine the relationships between various anthropogenic impacts and soil properties. The results of soil analyses were comparatively evaluated using statistical methods to assess the degree of anthropogenic influence.

Comparative Analysis. Based on observations and analyses conducted in areas with different ecological conditions and levels of anthropization, comparisons were made. Soil sites located near and far from industrial facilities were compared to determine the extent of anthropogenic effects on the soil cover.

3. Analysis and Discussion

Based on the applied methods, a scientific analysis of the impact of anthropogenic factors on the soil cover in the studied area was conducted, and several essential recommendations were proposed for the conservation and restoration of soil resources in the region.

For the study, areas of the Absheron Peninsula with varying degrees of anthropization were selected. Industrial zones, residential areas, and regions with livestock farms were the main criteria for selection. Soil samples were collected from these areas and analyzed under laboratory conditions. The sampling sites covered the industrial zones of Garadag, Surakhani, and Sabunchu (Fig. 2).

Figure 2. Observation pilots

The physical-geographical conditions of the sampling sites were initially analyzed in a laboratory setting. At each sampling plot, the soil surface was cleared of vegetation, and a profile was excavated to collect soil samples from specified depths. Samples were taken using the envelope method from depths of up to 30 cm, where the root system of the vegetation and the majority of organic matter are concentrated. The envelope method involved dividing the plot into five points—four corners and one center. From each point, soil samples were collected at depths of 0–10 cm, 10–20 cm, and 20–30 cm, then mixed separately by depth to produce a composite sample for each site (Fig. 3).

Figure 3. Soil sampling procedure

Figure 4. Packaging of soil samples

After collection, the soil samples were sent to the Soil Science and Agrochemistry Institute of ANAS (Azerbaijan National Academy of Sciences) for laboratory analyses.

In the laboratory, both physical and chemical analyses were conducted on the soil samples. The physical analysis determined the particle-size distribution of the soil, providing information about its physical properties, while the chemical analyses allowed evaluation of the main agrochemical parameters of the soil solution.

To examine the chemical characteristics and structural composition of the soil, X-ray spectral and X-ray diffractometric methods were applied.

- pH value: The electrometric method was used to assess the acidity-alkalinity balance of the soil. This parameter directly affects soil biological activity and the uptake of nutrients by plants.
- Total nitrogen (N): Determined using the Kjeldahl method, this parameter was used to evaluate the nitrogen reserves and productivity potential of the soil.
- Available phosphorus (P): The content of available phosphorus was determined using the Olsen method. This analysis assessed the soil's phosphorus supply level and fertilization requirements.
- Available potassium (K): Measured using the ammonium acetate extraction method, this parameter evaluated the soil's potassium richness. Potassium is a macronutrient crucial for the soil-plant system, and its content is a key indicator of soil fertility.
- Electrical conductivity: Measured to determine soil salinity and ion concentration, this analysis helps identify processes of salinization and sodification in the soil.
- Soil texture: The particle-size distribution (sand, silt, clay) was determined using the hydrometer method. This analysis provided information on soil structure, water retention capacity, aeration, and resistance to erosion.

Thus, within the study methodology, soil samples were collected from selected sites and analyzed for their physical and chemical properties using modern laboratory techniques. The applied methods allowed assessment of changes in the soil cover and the identification of anthropogenic impacts. The obtained results provide a basis for developing effective measures to prevent soil degradation in the next phase of the study.

The data obtained from mechanical and chemical analyses of soil samples collected from observation plots, along with GIS analysis of satellite imagery, clearly demonstrate the varied impacts of anthropogenic factors on soil properties in the Absheron Peninsula.

Sample 1. Collected from the Garadag district (40°27'35" N, 49°39'38" E), the soil had a pH of 7.8, indicating a mildly alkaline condition. Mildly alkaline soils, with pH values between 7 and 8.5, significantly influence plant growth and soil productivity. In these soils, the mineral and chemical composition plays a crucial role in plant development and agricultural suitability.

Mildly alkaline soils are generally considered fertile due to high organic matter and mineral content, which enhances productivity. However, under highly alkaline conditions, the mobility of certain micronutrients, particularly iron and phosphorus, may decrease, negatively affecting nutrient uptake by plants. Water retention and circulation are also important; these soils usually have good drainage, preventing prolonged water retention and providing favorable conditions for crops. Additionally, high carbonate content strengthens soil structure and can influence root system development. Therefore, although mildly alkaline soils possess positive productivity potential, appropriate agrotechnical management can further enhance their fertility.

Sample 2. Collected from the Surakhani district (40°28'39" N, 49°56'23" E), the soil also exhibited a pH of 7.8, indicating mildly alkaline conditions. Its characteristics are similar to Sample 1; however, the proportions of nitrogen, phosphorus, and potassium differ from the first sample.

Sample 3. Collected from an oil-extracting area in the Sabunchu district (40°26'48" N, 49°55'41" E), the soil had a pH of 8.8, indicating strongly alkaline conditions. Strongly alkaline soils have a pH above 8.5, creating a more challenging environment for plant growth. High alkalinity in these soils can limit the uptake of certain minerals by plants, reducing soil fertility.

The mineral composition of strongly alkaline soils, particularly calcium and magnesium, is high, which can alter soil structure, leading to compaction and disruption of water circulation. Water retention is shorter in these soils, aiding drought resistance; however, excessive water can damage soil structure and plant root systems. High alkalinity also reduces the mobility of certain micronutrients, especially phosphorus and iron, limiting their absorption by plants. Consequently, plant nutrition is weakened, and growth is slowed.

Table 1. Results of chemical analyses of the study sites

Sample No	Sample name	pH	**Degree of soil nutrient supply (based on gradation)**			EC (ds/m) – Electrical Conductivity
			Nitrogen 40-120 Mg/kg	Phosphorus 15-60 Mg/kg	Potassium 300-600 Mg/kg	
			Sample nutrient supply indicator			
			Nitrogen N/Nh_4 Mg/kg	Phosphorus P_2O_5 Mg/kg	Potassium K_2O Mg/kg	
1	Garadag (40°27′35″ N, 49°39′38″ E)	7.8	7,76	22,22	177,13	2,87
2	Surakhani (40°28′39″ N, 49°56′23″ E)	7.8	5,17	18,89	134,96	2,12
3	Sabunchu Oil Area (40°26′48″ N, 49°55′41″ E)	8.8	6,9	23,33	169,90	1,97

As shown in the table, the soil samples were found to have very low availability of nitrogen in the ammonium form, moderate availability of available phosphorus, and very low availability of exchangeable potassium—all of which are essential nutrients for plant uptake.

The presence of key nutrients such as nitrogen, phosphorus, and potassium in the soil is crucial for healthy plant growth and high productivity. The availability of these three primary elements directly affects nutrient uptake by plants and their overall development.

Nitrogen is one of the most important nutrients for plants. It plays a fundamental role in the production of proteins and other organic compounds. Adequate nitrogen in the soil promotes vegetative growth, stimulates leaf and stem development, and participates in photosynthesis, providing energy for plants. However, excessive nitrogen can weaken root development and disrupt the balanced uptake of nutrients.

Phosphorus is a microelement essential for energy metabolism, root development, and flowering. Its presence in the soil supports healthy root system growth and contributes to photosynthesis and other biochemical processes. Phosphorus deficiency can lead to weak plant development and reduced productivity.

Potassium regulates water circulation in plants, strengthens cell walls, and enhances resistance to diseases. Adequate potassium in the soil improves nutrient uptake, facilitates water-related processes, and increases stress tolerance, contributing to overall plant health. Potassium deficiency can result in poor plant growth and lower yields.

The electrical conductivity (EC) indicated in the table reflects the soil's ability to conduct electric current and is primarily related to the concentration of ions in the soil. High electrical conductivity signifies a high content of salts and minerals, which can hinder plant growth. Low electrical conductivity indicates low levels of minerals and ions, which may reduce soil fertility. In summary, soil electrical conductivity is a key indicator of soil salinity and productivity.

In the analyzed soil samples, low salinity was observed. Notably, Sample 3, contaminated with oil, showed lower salinity compared to the other samples.

Soil texture represents the proportion of mineral particles (sand, gravel, clay, etc.) in the soil. This composition significantly affects soil structure and properties. For example, sandy soils have good drainage but low water retention, whereas clay soils retain water well but have poor aeration. Soil texture is crucial for water retention, air circulation, and root development.

The analyzed soil samples were found to be loamy-clay in texture. Loamy-clay soils occupy an intermediate position between sandy and clay soils in terms of structure. They allow good water and air permeability while retaining adequate moisture. The mechanical composition of light loamy soils facilitates cultivation and is favorable for agriculture. However, to maintain fertility, these soils should be enriched with organic matter and managed with proper irrigation practices.

Table 2. Results of mechanical analyses of soils in the study area (percentage of each fraction relative to total soil mass)

Sample No	Section No	1-0,25	0,25-0,05	0,05-0,01	0,01-0,005	0,005-0,001	<0,001
1	Garadag (40°27′35″N, 49°39′38″ E)	1,70	14,70	12,00	9,60	24,00	38,00
2	Surakhani (40°28′48″N, 49°56′23″ E)	4,66	71,74	12,00	2,80	4,00	4,80
3	Sabunchu Oil Area (40°26′48″ N, 49°55′41″ E)	11,10	64,90	11,20	1,60	6,00	5,20

As shown in the table, the soil at the observation site in Garadag is primarily loamy-clay in texture. The high proportion of clay and silt particles indicates strong water retention and a dense soil structure. This soil type can lead to slow water infiltration and increased susceptibility to erosion.

The soils at the observation site in Surakhani mainly consist of coarse silt particles. Such soils retain a moderate amount of water but are prone to wind erosion.

At the Sabunchu Oil observation site, coarse silt particles predominate, but the relatively higher sand content indicates a lighter soil structure. This soil type allows better water permeability but increases water loss and sensitivity to drought.

Furthermore, results from X-ray spectral analysis of the soil sample from the Sabunchu Oil site revealed significant changes in the chemical composition. The analysis indicates that several soil properties reflect anthropogenic impacts, particularly contamination from oil and petroleum products.

Table 3. Results of X-ray spectral analysis (chemical composition) of the oil-contaminated soil sample

Name of chemical substance	Percentage (%)
Na_2O	1,60
MgO	1,55
Al_2O_3	9,26
SiO_2	50,31
P_2O_5	0,16
SO_3	0,45
K_2O	2,33
CaO	14,02
TiO_2	0,74
MnO	0,13
Fe_2O_3	6,02
BaO	0,09
SrO	0,07
ZrO_2	0,07
ZnO	0,05
Cr_2O_3	0,02
NiO	0,01
CuO	0,01
Rb_2O	0,0095
CT	0,59
LOİ (Loss on Ignition at 950 °C)	12,51

As shown in the table, the oil-contaminated soil sample is predominantly composed of silicon dioxide (SiO_2) – 50.3%. Additionally, aluminum oxide (Al_2O_3) – 9.26%, iron oxide (Fe_2O_3) – 6.02%, magnesium oxide (MgO) – 1.55%, potassium oxide (K_2O) – 2.33%, and sodium oxide (Na_2O) – 1.60% were observed. The high content of calcium oxide (CaO) – 14.02% indicates the presence of carbonate deposits or technogenic impacts in the soil.

The presence of phosphorus pentoxide (P_2O_5) – 0.16% and sulfur trioxide (SO_3) – 0.45% can be considered as factors increasing soil acidity, likely resulting from industrial and petroleum activities. Furthermore, the loss on ignition (LOI) at 950 °C was 12.51%, indicating a high amount of carbonates, oil residues, hydrocarbons, and other volatile substances in the soil.

The analysis also revealed that the total organic matter content is 9.23%, highlighting a high level of organic contamination, directly associated with organic compounds introduced into the soil through oil extraction activities

4. Conclusion.

The results of our study on the soils of the Absheron Peninsula indicate that anthropogenic impacts in the investigated area have affected both the physical and chemical properties of the soil, weakened its natural structure, reduced fertility, and increased its sensitivity to exogenic processes. The influence of anthropogenic factors has caused significant changes in the physical and chemical characteristics of the soil cover. In areas contaminated with industrial and petroleum waste, soil structure degradation, depletion of the fertile layer, and increased salinity were observed.

The analysis of the mechanical composition of soil samples showed that in some areas the proportion of clay and silt fractions had increased, leading to disturbances in water and air regimes, higher soil compaction, and increased susceptibility to erosion. Chemical analyses demonstrated variability in the content of essential nutrients, with some areas showing deficiencies in nitrogen, phosphorus, and potassium, while others exhibited increased salinity. Additionally, X-ray spectral and X-ray diffraction analyses revealed that soils were heavily exposed to petroleum-derived contamination, with high contents of carbonates, clays, and metal-bearing oxides (Fig. 5

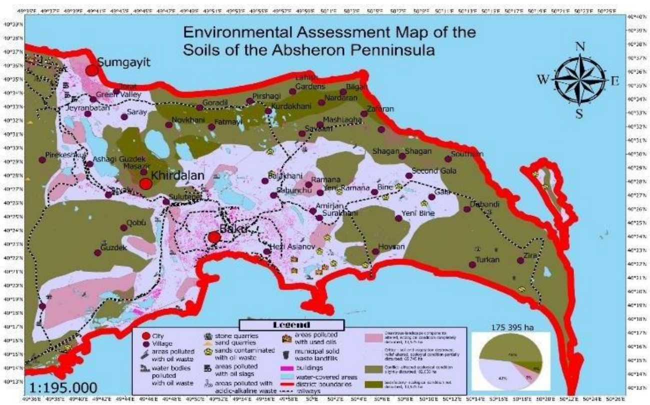


Figure.5. Ecological assessment of soils in the Absheron Peninsula

In the final stage of the study, based on a systematic analysis of the existing materials and satellite imagery, the soils of the peninsula were classified into four categories according to their ecological status: satisfactory (5%), conflicted (48%), critical (5%), and catastrophic (42%).

The results indicate that 95% of the peninsula's area has lost its natural balance, experiencing varying degrees of ecological transformation. Comparative analyses show that in all analyzed soil samples, the permissible limits of heavy metals (MPC indicators) have been exceeded. In particular, Fe, Cu, Ni, Zn, and Cr present a very high risk of contamination, which is primarily of technogenic origin.

The main sources of contamination include oil and industrial waste, sludge, acidic and alkaline substances, as well as waste from stone and sand quarries and municipal waste.

Comparison of the soil's mineralogical composition with normal reference le-vels indicates a high content of calcite, anorthite, and hematite, reflecting strong anthropogenic influence. Although clay minerals (montmorillonite, illite, and kaolinite) are present at sufficient levels, the low proportion of montmorillonite suggests limited swelling capacity and restricted water retention. The low SiO_3 content indicates a soil with a heavy fraction and structurally weak charac-teristics (Fig.6).

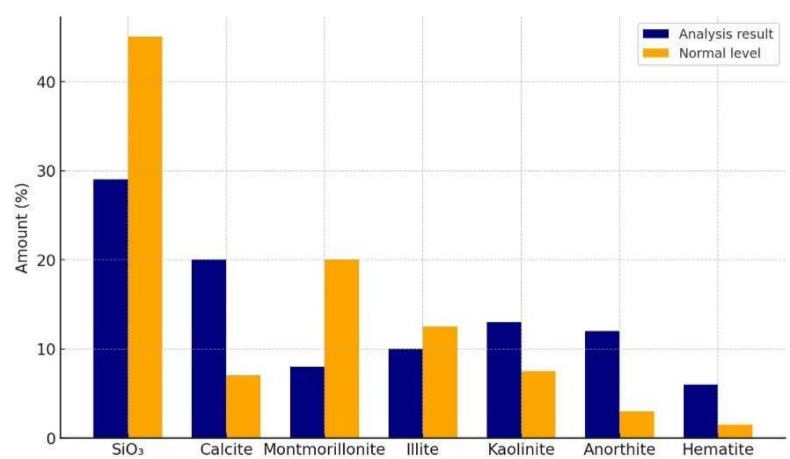


Figure 6. Comparison of soil mineral composition

The obtained results indicate that restoring the ecological balance of the soil cover in the Absheron Peninsula requires the implementation of proper soil management strategies. Implementing comprehensive measures aimed at preserving fertility, preventing erosion, and rehabilitating contaminated soils is crucial for environmental sustainability.

Currently, there is no single standardized reclamation model for restoring oil-contaminated soils worldwide. This is mainly due to the diverse physical-geographical conditions of oil- and gas-producing areas.

The choice of the method to be applied depends on several factors, including the intensity of contamination, oil composition, duration of contamination, soil physicochemical properties, landscape, and climatic conditions (Agayev, Sh. B., Afkerov, Q. X. (2007); Aslanov, H. Q., Safarli, S. A. (2008); Hasanov, X. A. (1998); Ibadova, S., Aliyeva, N., Abdullaeva, K., Bagirova, N. (2025).

The financial costs required for carrying out soil reclamation and phytoremediation measures on the Absheron Peninsula have been estimated based on an approximate economic evaluation. The total area of the peninsula is 211,000 hectares. Based on general analyses of the area, it was determined that 82,000 hectares are slightly degraded, 65,745 hectares are partially degraded, and 13,925 hectares are completely degraded. The economic evaluation of reclamation and phytoremediation measures to restore the soil cover of the area is presented in Table 4.

Table 4. Approximate Economic Evaluation of the Absheron Peninsula Soils

(Calculations are based on projects implemented by SOCAR)

Type of Measure	Area (ha)	Average cost (AZN)	Total cost (AZN)
Phytoremediation (weakly degraded areas)	82,000	600	49200000
Reclamation(partially degraded areas)	65745	1200	78894000
Reclamation+Phytoremediation (fully degraded areas)	13925	1600	22280000
Total	-	-	150374000

Thus, based on our economic assessment, it has been determined that the total investment required for the restoration of the soil cover and the maintenance of ecological balance is approximately 260–270 million AZN.

The results indicate that the implementation of reclamation and phytoremediation measures is essential for restoring the ecological stability of the soil cover in the Absheron Peninsula. According to the economic analysis, the total investment needed for this process is estimated at 260–270 million AZN.

The analyses and results presented in this article provide a basis for identifying practical measures to protect soil resources and ensure the sustainability of the natural environment.

References

1. Agayev, Sh. B., & Afkerov, Q. X. (2007). *Absheron Peninsula's degraded and polluted soils, their distribution and reclamation issues* (p. 31). MBM..

2. Aslanov, H. Q., & Safarli, S. A. (2008). *Oil-contaminated soils of Azerbaijan: Their reclamation and utilization* (p. 190). Baku: Elm..

3. *Geography of the Republic of Azerbaijan* (Vol. 1). (2014). Baku: Elm. (494 p.)

4. *Environment in Azerbaijan*. (2025). Baku: ARDSK. (140 p.)

5. *Regions of Azerbaijan*. (2024). Baku: ARDSK. (849 p.)

6. Budaqov, B. A., Mammadov, R. M., Mikayılov, A. A., & Ismetova, X. R. (2003). *Desertification degree and types in Absheron Peninsula and countermeasures*. In *Problems of Desertification in Azerbaijan: Proceedings of the Scientific-Practical Conference Dedicated to the 75th Anniversary of Academician B. A. Budaqov* (pp. 40–53). Baku: Elm.

7. Elizade, E. K., Rustamov, Q. I., & Karimova, E. C. (2015). *Ecogeochemical characteristics of modern landscapes of Absheron Peninsula* [Monograph]. European Publishing. (245 p.)

8. Hasanov, X. A. (1998). *Justification of reclamation methods for degraded soils in Absheron Peninsula* [Author's abstract]. Baku. (159 p.)

9. Imanova, C. (2022). *Optimizing the use of water resources of mountain rivers of the Greater Caucasus (case study on the Gudyalchay River)* (Master's thesis, Khazar University, Azerbaijan).

10. Ismayilov, A. I., Yashar, A. Y., & Feyziyev, F. M. (2021). Study of oil-contaminated soils based on satellite imagery and geoinformation technologies. *Geography and Natural Resources*, (1), 78–86.

11. Mammadov, A. Y., & Suleymanov, T. İ. (2011). Assessment of the ecological state of Absheron Peninsula lakes based on Geographic Information Systems and satellite imagery. *Reports of the Azerbaijan National Aerospace Agency, 14*(1), 9–14.

12. Mammadov, Q., & Hakimova, N. F. (2003). *Ecological fertility model of oil-contaminated soils* (52 p.). Baku: Elm..

13. Mirzayev, A. B., & Shikhaliyev, F. B. (2012). *Ecological problems of oil field areas in Absheron Peninsula and the Azerbaijani sector of the Caspian Sea and ways of their remediation* (368 p.). Baku: Elm.

14. Suleymanov, T. İ., & Yashar, Ə. (2016). Mapping of construction and vacant lands of Absheron Peninsula based on multispectral satellite imagery. *Reports of the Azerbaijan National Aerospace Agency, 19*(4), 27–32.

15. Shirinov, N. Sh., Valiyev, X. Ə., & Aliyev, Y. Q. (1998). *Nature and ecology of the Caspian Sea and its coasts* (199 p.). Baku.

16. Budagov, B. A., Mamedov, R. M., Ismatova, Kh. R., & Mikayilov, A. A. (2002). Dynamics of desertification processes in the eastern part of the Republic of Azerbaijan. *Reports of the Azerbaijan National Academy of Sciences, Earth Sciences Series*, (2), 7–16..

17. Bayramova, L. A. (2024). Sustainable development and environmental protection in the Absheron peninsula: a geo-ecological perspective. *Journal of Geology, Geography and Geoecology*, *33*(3), 430-439.

18. Guliyev, A., Islamzade, R., Suleymanova, P., Babayeva, T., Aliyeva, A., & Haciyeva, X. (2024). Impact of petroleum contamination on soil properties in Absheron Peninsula, Azerbaijan. *Eurasian Journal of Soil Science*, *13*(4), 358-365.

19. \Hajiyeva, G. N., & Ibrahimova, L. P. (2024). Ecological problems of technogenically disturbed lands on the Absheron Peninsula. *Journal of Geology, Geography and Geoecology*, *33*(1), 70-76.

20. Ibadova, S., Aliyeva, N., Mamedova, R., Abdullaeva, K., & Bagirova, N. (2025). Soil monitoring of the Absheron Peninsula (Republic of Azerbaijan). In *E3S Web of Conferences* (Vol. 623, p. 01009). EDP Sciences.