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Effects of Climate Change on Warming and Rainfall Patterns; Iran Case Study

Hüseyin Toros[1], Aydin Gulubayov (Ulubey)[2], Naime Filiz Tümen Özdil[3], Sibel Özdaş[4], Mikhail Remizov[5], Mohsen Abbasnia[6*]

[1]Professor of Meteorology, Department of Climate Science and Meteorological Engineering, Istanbul Technical University, Maslak Istanbul 34469, Türkiye.
[2] Professor of Physics, Department of Mechanics and Mathematics, School of Advanced Technologies and Natural Sciences, Western Caspian University, Baku, AZ1072, Azerbaijan.
[3]Professor of Mechanics, Faculty of Aeronautics and Astronautics, Department of Mechanical Engineering, Adana Alparslan Turkes Science and Technology University, Adana, Türkiye.
[4]Associate professor of Biology, Faculty of Engineering, Department of Bioengineering, Adana Alparslan Türkeş Science and Technology University, Adana, Türkiye.
[5]Professor of Mathematics, Department of Mechanics and Mathematics, School of Advanced Technologies and Natural Sciences, Western Caspian University, Baku, AZ1072, Azerbaijan.
[6*]Corresponding Author: Researcher in Climate Change, Department of Climate Science and Meteorological Engineering, Istanbul Technical University, Maslak Istanbul 34469, Türkiye.

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Abstract

The analysis investigates lasting climate trends underlying the importance of territorial coincidence of trend changes among temperature fluctuations, (minimum, average, and maximum) and precipitation observed in the past four decades at eight major meteorological stations in Iran. Applying the Mann–Kendall trend test indicated a steady increase in annual temperatures, while a general decline in annual precipitation in all territories of Iran. These dual trends vary across the study stations, strongly affected by altitude, latitude, and regional climate zones. In this case, high-altitude northern stations reached the highest rising trends in maximum temperature, as well as significant decrease in precipitation was observed. In contrast, lowland southern stations showed a weaker warming trend and also observed smaller changes in their precipitation. Only two stations, Tehran and Mashhad, with the highest urban density, showed sharper nighttime warming trend through an increase in minimum temperatures, which could highlight the role of local dynamics influenced by urbanization growth. Overall, the combined results of temperature and precipitation trends highlight that the mountainous regions located in the higher latitudes tend to be riskier concerning the increase in daily maximum temperature and decrease in precipitation amount. In general, these local differences in changes in temperature and precipitation are influenced by two main factors: altitude and latitude, which therefore emphasizes the need for climate adaptation strategies tailored to the geography and topography in each diverse ecosystem.

Keywords: Climate change, Precipitation, Temperature, Ecosystem Resilience, Adaptation Strategies, Iran.

1.Introduction

Climate change has emerged as a critical global challenge. Rising levels of carbon dioxide in atmosphere have been recorded for over five decades. Strong scientific evidence indicates that this issue has resulted increased global average surface temperature, along with with significant changes in precipitation patterns (IPCC, 2023). The latest report of IPCC indicates that the global warming trend will likely exceed 1.5°C during the 21st century. This milestone underscores that the 1.5°C target is no longer a distant risk to be avoided, but a threshold already temporarily surpassed and at risk of becoming permanent (IPCC, 2023). The trends in temperature and precipitation as two of the most important indicators of climate change have become hot topics. Many studies carried out in different parts of the world for detecting possible climate trends and changes. The temperature variations especially for arid and humid climates have been observed in most regions of the planet. Arid and semi-arid regions such as Iran are particularly vulnerable, where climatic variability directly threatens water security, agricultural productivity, and ecological resilience (Daneshvar et al., 2019; Nasirian & Naddafi, 2025). Concerning the climate of Iran, several studies have been performed (Azizi and Roushani 2008). These studies pointed out significant variations in climate of Iran. Recent studies have consistently recorded warming trends throughout Iran country (Ghasemi, 2015; Tabari et al., 2012; Ranjbar-Saadatabadi, 2025). Temperature rises over Iran are most characteristic in high-altitude northern territories, with urban basins demonstrating an intensified nighttime warming trend (Sabohi & Soltani, 2009). Besides, climate change has also influenced rainfall in Iran, exacerbating hydrological stress and increasing ecological sensitivity in regional scales (Modarres & da Silva, 2007; Zohrabi et al., 2014). Recent analyses confirm that precipitation anomalies during 2024–2025 were strongly associated with atmospheric circulation changes, and have exacerbated ecological stress in northern parts of Iran (Ranjbar-Saadatabadi, 2025). In addition, climate projections of Iran using SDSM modeling indicate that future increases in maximum temperatures will disproportionately affect the arid climatic regions of Iran (Abbasnia & Toros, 2016). Moreover, new perspectives show that climate change in Iran not only alters hydrological cycles but also ecological vulnerability (Nasirian & Naddafi, 2025). In this regard, Shamsipour and Azizi (2024) have emphasized the importance of linking climate trends with ecosystem resilience in Iran to combat the adverse effects of climate change.

Despite numerous previous studies conducted at the local scale, a comprehensive research view that consider both analysis of temperature and precipitation trends have so far been limited in the study area especially in relation to changes in topographic, spatial, climatic factors. Therefore, this study has attempted to address this gap in scientific opinion by applying the Mann-Kendall trend test to long-term observational data collected from several major synoptic stations across Iran. By comprehensively examining the spatial overlap of changes in the trends of warming and precipitation patterns, this research highlights critical ecological vulnerabilities and provides practical insights for planning and adaptation strategies tailored to local climate, taking into account the diverse topographic and ecological characteristics of the main regions of Iran.

2.Materials and Methods

Iran is geographically located in the middle latitudes and is widely rugged. Temperatures across Iran generally increase from north to south and from west to east (Abbasnia and Toros 2016), which is due to the characteristics of the mountains that are mainly located in the north and west of the country (Figure 1).

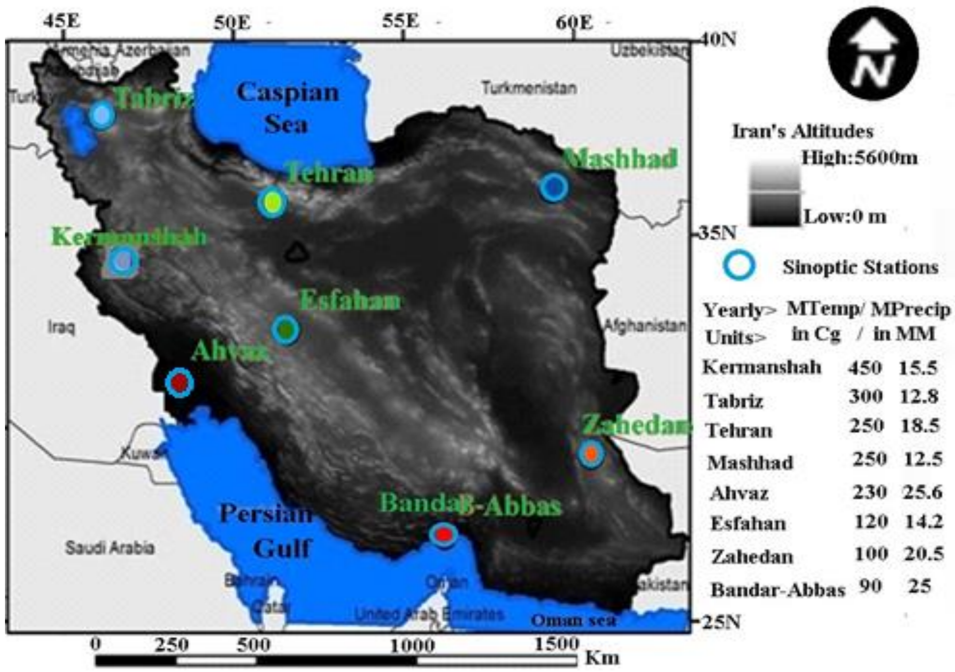

Figure 1- *Distribution of geographical areas in the study area*

In this study, monthly data on minimum, maximum, average of temperature and total average of precipitation parameters for eight synoptic stations during the period 1980 to 2017 were prepared from the Iranian Meteorological Organization. The study stations were selected from three main regions including mountainous areas, central interior plateau, and lowland areas, which can reflect all the characteristics of the topographic regions and geographical distribution within the vast country of Iran. After preparing the dataset, quality control was performed on all times series to ensure data validity. Next, long-term annual trends in these key climate variables were calculated using the Mann-Kendall trend test. This non-parametric trend test is widely known for detecting trends in long-term timeseries (see Mann, 1945; Kendall, 1975). In addition, the magnitude of trends was quantified using the Sen's slope estimator, which determines the rate of change in each time series. All statistical analyses were performed at the 95% confidence level ($p<0.05$) to ensure reliability in distinguishing true trend from its random. Finally, observational trends of the precipitation and temperature parameters are assessed at each station, regionally. This approach to selecting stations based on altitude and distance from water sources allows for the identification of spatially overlapping warming and precipitation trends, and thus, the climatic diversity of regions and their ecological vulnerability can be examined regionally throughout Iran.

3.Results and Discussion

The diverse topography and climatic zones across Iran lead to distinct responses to climate change. In this regard, long-term analysis of temperature and precipitation at eight synoptic stations highlights their altitude- and latitude-dependent patterns. Located in the northeast of Iran, the city of Mashhad represents the semi-arid region. The city, influenced by the effects of urbanization, experienced the highest increase in annual mean temperature among all stations. Kermanshah and Tabriz, situated in the mountainous territories of the northwest, also demonstrated a significant warming trend in daily mean temperature. While the average temperature increase in the cities was slightly less than Mashhad, the recorded maximum temperature was among the highest among all the stations examined. All these mentioned above indicate that reduced snow cover, increased solar energy absorption, and changes in atmospheric circulation intensify the daily warming in mountainous areas. On the contrary, Ahvaz, Bandar Abbas, and Zahedan, located in the low-land, and arid southern regions, with the weakest trends in mean daily temperatures, have stable temperature regime due to their climate type, low vegetation cover, and minimal seasonal variation. However, warming trends remain statistically significant even in these regions, indicating that no region is protected against long-term temperature rises. In general, all stations experienced an increase in the annual mean temperature (Figure 2, first row). Kermanshah (+2.7°C) and Tabriz (+2.5°C) saw the most severe increases (Figure 2, second row) in maximum temperature, while Bandar Abbas experienced a more moderate temperature rise (+1.36°C). A statistically significant upward trend was observed in Aal studied stations. In this regard, Mashhad and Tehran showed the most severe increase in minimum temperatures compared to maximum temperatures, which exacerbates the nighttime warming. In contrast, Tabriz and Kermanshah recorded weaker increases in minimum temperatures despite intense daily maximum temperature. This result indicates a broadening of the daily temperature range in mountainous regions (Figure 2, third row). In this context, the findings of the temperature trends of the present study are confirmed by previous research conducted by Abbasnia et al. (2025) in identifying temperature anomaly trends across Iran. However, in the present study, all these temperature patterns are examined in a complementary and broader manner by simultaneously examining and matching them with precipitation trend patterns to assess spatial overlap.

Conversely, annual precipitation results analysis exhibited mainly declining trend across all study stations, pointing to a general a general progression towards drought and reduced precipitation across different Iranian regions over time. These reductions in magnitude varied significantly according to their spatial distribution and were affected by regional climates, altitude, and closeness to water sources. Under these circumstances, most severe annual precipitation decreases were recorded in Kermanshah and Ahvaz, with a value of -10.5 mm and -9.5 mm respectively, over the whole studied period (Figure 2, fourth row).

Situated in a mountainous region, Kermanshah, is becoming more sensitive to drought conditions because of greater decreasing trend in precipitation. Secondly, Ahvaz, located in the southwestern lowland region, had a significant decreasing trend, which may be followed by exacerbate water scarcity and water stress. A gradual increase in annual precipitation was only recorded in Isfahan station, which may be governed by local climate variability or convective precipitation anomalies in the central plateau of Iran. Nevertheless, this increase was slight and does not substitute a larger regional drought. The cities of Zahedan and Bandar Abbas representing arid regions exhibited a slightly stable precipitation trend, persistent with low baseline precipitation and restricted interannual variability in rainfall events. Oppositely, stations in the northern highlands, historically exposed to more precipitation because of closeness to humidity sources and ornithological elevation, are anticipated to be more prone to drought conditions.

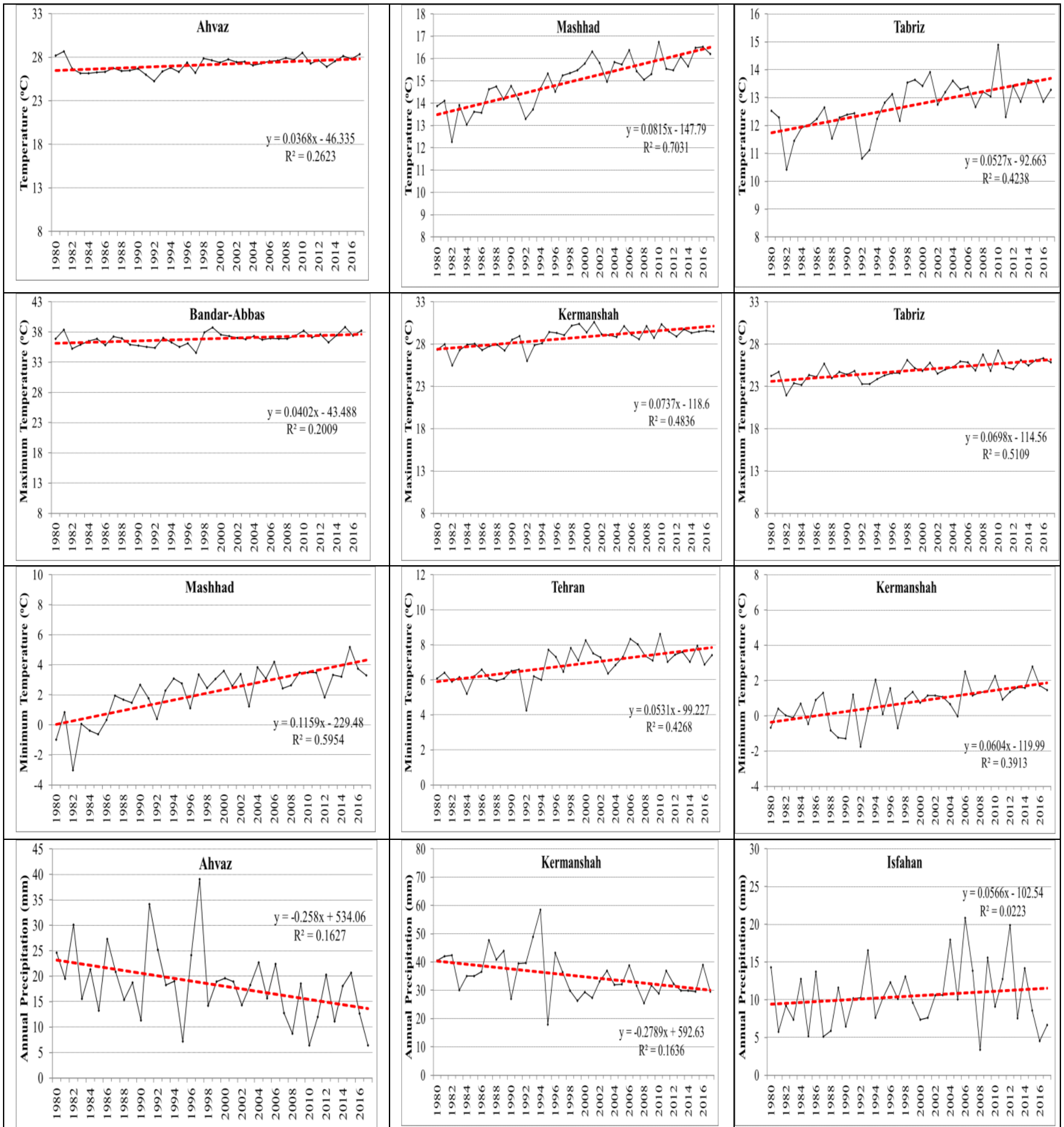

Figure 2- *Selected annual climatic trends at representative synoptic stations in Iran;*
Row 1: Average temperature trend in Ahvaz, Mashhad, and Tabriz
Row 2: Maximum temperature trend in Bandar-Abbas, Kermanshah, and Tabriz
Row 3: Minimum temperature trend in Mashhad, Tehran, and Kermanshah
Row 4: Average Total Precipitation trend in Ahvaz, Kermanshah, and Isfahan

An extensive and comparative analysis with spatial coincidence of rising temperature and precipitation trends in the explored area reveals critical environmental sensitivity. From this standpoint, mountainous regions such as Kermanshah and Tabriz have encountered severe daily warming besides reduced precipitation. This duality and variability observed in the precipitation and temperature fluctuations threatens the stability of mountain snowpack, groundwater recharge, and the resilience of regional vegetation. In addition, Tehran and Mashhad cities, which are densely populated areas with further urban expansion, have exposed to more severe nighttime warming trends. Local climate dynamics has exacerbated the issue. Arid regions such as Ahvaz and Bandar Abbas, demonstrating less precipitation variability over the entire study period, can be exposed to water scarcities. Ultimately, Isfahan city recording a small increase in total precipitation among all regions, would not compensate for the broader drought trend.

The observed results suggest that environmental ecosystems in Iran are become increasingly vulnerable to climate change-induced stressors. Decreased precipitation combined with rising temperatures is likely to accelerate evapotranspiration, reduce groundwater recharge, and aggravate vegetation stress at local and regional scales. These processes endanger regional biodiversity, change hydrological cycles, and undermine ecosystem services for human well-being. Critically, the dual stressors of warming and drying show differences in magnitude or intensity, but also strongly dependent on altitude, latitude, and climate type. In term of management, mountainous areas need special strategies to handle lower snowfall, while densely populated urban areas require long-term actions to mitigate heat island effects and preserve ecological integrity of the environment. Arid regions, although showing less variability in rainfall, are vulnerable to groundwater depletion under the influence of global warming.

4. Conclusion

The results of Mann–Kendall trend test for temperature and precipitation parameters have revealed statistically significant warming and drying trends across Iran during an analyzed period of 1980 to 2017. In this regard, all studied stations have showed increasing trends in mean, maximum, and minimum temperatures, although the magnitude and spatial distribution of change varied regionally. The results of warming trends have showed the last decade of the previous century was substantially warmer than previous decades. Northern high-altitude stations such as Kermanshah and Tabriz have recorded the strongest increases in maximum temperature. This indicates intense daytime warming in mountainous areas compared to other regions. In contrast, southern low-altitude stations including Bandar-Abbas, Ahvaz, and Zahedan have showed more moderate warming in arid and hot climatic regions.

In other hand, precipitation trends were mostly negative during the whole studied period. The highest decreasing trend in precipitation has observed in Kermanshah which is located at higher latitudes and altitudes. Only Isfahan station among all studied stations has exhibited a slight positive trend in precipitation. In mountainous regions such as Tabriz and Kermanshah, increasing diurnal temperature range may accelerate snowmelt, reduce soil moisture, and disrupt temperature-sensitive biological cycles. This variation between day and night heating patterns will lead to the vital environmental consequences. Decreasing DTR range driven by increasing nighttime temperatures in more densely populated cities such as Tehran and Mashhad, may exacerbate heat stress, increase energy demand, and aggravate ecological vulnerability.

Combining data on warming and drying trends confirms that arid regions, particularly Iran, are exposed to a severe, dual-threat climate crisis. These findings emphasize that local ecosystems call for tailored, location-specific action plans, such as smarter water management, ecosystem-based conservation, and sustainable urban planning to adapt to these changes.

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Biological and Ecological Characteristics of *Ailanthus Altissima (Mill)*

Aydin Yahyayev[1] and **Turan Huseynov**[1]

[1]School of Advanced Technologies and Innovation Engineering, Department of Ecology and Environmental Sciences, Western Caspian University, Baku, AZ1072, Azerbaijan.

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Abstract

In a lot of western countries *Ailanthus Altissima* is considered an invasive tree species. *Ailanthus* has gained this reputation due to its rapid growth and ability to crowd out native trees. It produces a large amount of seeds and these seeds spread easily and develop deep, strong root system after germination. This type of root system makes it difficult to remove the plant during mechanical control methods. *Ailanthus* is also known for its abilty to produce special allelopathic substances. They slow down the growth rate of other tree species and make the minerals less accessible for them. This species is common in most urban places. They can be found on roadsides, near walls, old buildings, gardens and its roots can damage paving, walls and other infrastructure. Numerous studies have investigated its biology, dispersal mechanisms, control methods including mechanical, chemical and biological. The purpose of this article is to provide overview of some of the studies summarising resear methods, laboratory analyses, field trials highlighting key findings regarding growth patterns, environmental impacts and control effectiveness. This review highlights the ecological, infrastructural, and other challenges associated with *Ailanthus* as well as ongoing research aimed at reducing its spread and understanding its behaviour under different environmental conditions.

Keywords: *Ailanthus Altissima*, seed dispersal, invasive species, impact in urban environment, management strategies, control methods, ecological research

1.Introduction

The tree of heaven (*Ailanthus altissima, Mill*) is a tree that originates from northern and central China and is found on every continent except Antarctica. Its rapid growth and ability to thrive in difficult conditions with minimal care have made it a relatively popular garden plant in the East. Its natural habitat is mainly mountainous and hilly regions, but also it can be found in coastal plains. The *ailanthus* tree produces several hundred thousand seeds per year (Thomson, 2011), and these light, winged seeds can be transported over long distances from the parent plant (Planchuelo et al., 2016). It grows vigorously and forms dense clonal stands that can displace native vegetation (Hunter, 2000). The *ailanthus* tree's ability to tolerate poor soils and air pollution makes it a frequent coloniser of urban areas (Ferret, 1974; Mergen, 1959). Roadsides and footpaths are excellent migration routes for this tree.

Ecology – *Ailanthus altissima* is an extremely competitive and fast-growing tree, whose young shoots can reach a height of 3 to 4.5 m. Once established, it can displace native vegetation and form dense clonal stands. It has been cultivated throughout Absheron since ancient times and is found in the Kur-Araz, Samur-Shabran, Lankaran, Alazano-Ayracha regions, as well as in the plains of Kura, Nakhchivan, Ismayilli and on the coast of the Caspian Sea. Main areas of distribution: Baku, Shamakhi, Agsu, Kurdamir, Goychay, Agdash, Ganja, Yevlakh, Mingechevar, Barda, Agdam, Salyan, Sabirabad, Beylagan, Nakhchivan (Mamedov et al., 2014).

Although the tree of heaven is more common in urban areas, it is invasive in agricultural land and natural areas and poses an ecological threat. The tree of heaven is a prolific seed producer, and its seeds can be spread by wind, water, birds, agricultural equipment and road vehicles. However, most new plants in a given area usually develop from root suckers. When the trunk is felled, new shoots can form on the lateral roots at a distance of 15 to 27 metres from the parent tree. After germination, the seedlings can form deep roots within three months, allowing the plant to grow rapidly and compete with native species for light and space. *Ailanthus* grows in full sun but also tolerates shade. In addition, this plant produces an allelopathic substance that inhibits the growth of other plants in its vicinity.

Biology – *Ailanthus* can be characterised by the following features:

• It is a small to medium-sized tree that can reach a height of over 25 m. Generally, its height reaches 20-25 m.

• The leaves are lanceolate and have 1-3 teeth on each side of the leaf. When crushed, the leaves give off an unpleasant odour.

• The bark is smooth, grey and cracks with age.

• The young branches are green then turn into light brown with age. Aged branches turn into gray

• It flowers in July and August. The greenish-yellow flower has 5 sepals and 5 petals.

• The seeds are surrounded by a papery, wing-like shell.

• The fruits are slightly twisted, curved. It has a reddish color.

• Diseases do not cause serious problems, with the exception of *Verticillium wilt*.

• *Ailanthus* is generally characterised as a shade-intolerant tree and does not respond well to reduced light intensity, but there is evidence that *Ailanthus* is characterized as a shade-tolerant species in various regions of the world.

• Studies have also shown that an extract made from the leaves of *ailanthus* (ailonthon) has a negative effect on 35 species of gymnosperms and 11 species of angiosperms.

2.Key findings of studies published between 2000 and 2025

Ailanthus altissima's rapid spread, great adaptability, and ecological effects have attracted more scientific attention over the past few decades. Its biological characteristics, reproductive strategies, and ability to compete in both natural and man-made environments have been studied by researchers from various geographical areas. Special attention has been given to its invasive behaviour aswell as to its management and control. The results of these investigations serve as the foundation for comprehending the ecological significance of the species and for creating efficient management plans. This section summarizes key scientific studies and highlights the most important findings related to *Ailanthus altissima*:

Hunter, J. (2000) His results researching Ailanthus.

Location: California, USA.

Method: Starting with past studies, Hunter (2000) pieced together insights about Ailanthus altissima through narrative analysis. Rather than running new tests, he examined published papers, on-the-ground notes, official records, and judgments from specialists. One by one, these materials helped shape a layered understanding of the plant. From ecology work to trials measuring control success, each reference contributed meaningfully. What stood out was how features like growth patterns, seed spread methods, and intervention results varied by environment. Through careful linking of findings, differences across ecosystems came into view.

Result: One finding stood out clearly: mechanical removal alone fails often, due to the plant's tendency to grow new shoots from underground roots. Though it seems logical, doing cuts again and again sometimes boosted the number of stems instead of reducing them. On the other hand, using chemicals - particularly applying herbicides right after cutting stumps or near the lower stem - reduced sprouting far better. Success improved sharply once physical removal was paired with chemical treatment. What mattered just as much was spotting infestations early and acting fast. Depending only on chopping proved unwise throughout the trials.

Research on Ailanthus altissima seedling growth in gaps under the forest canopy.

Location: Hudson Valley, New York, USA.

Method: The authors conducted an observational field study in a centuries-old coniferous and deciduous forest, focusing on *Ailanthus altissima* seedlings that had emerged in naturally occurring gaps in the canopy. They measured the height of the seedlings, stem diameter and radial growth rates over time and quantified light availability in the gaps and under the canopy. For comparison purposes, the same measurement protocols were used for native tree species growing in the same gaps.

Result: *Ailanthus* seedlings grew significantly faster than the competing native species in the gaps in the canopy. Growth rates in height and radius were significantly higher with greater light exposure. The species showed rapid growth after the clearing was created, enabling it to quickly reach the forest canopy. The recruitment of new seedlings was closely related to the disturbances caused by the clearings. These characteristics confirm the classification of the species as invasive and clearing-dependent. Even old forests are vulnerable after disturbances. (Knapp, L. B., & Canham, C. D. 2000).

DiTomasso and Kaiser (2001) investigated the use of herbicides on *Ailanthus* trunk.

Location: Yolo County, California, USA

***Method*:** The authors conducted a field trial with herbicides in which three systemic herbicides (imazapyr, triclopyr and glyphosate) were applied to the trunk using different application methods: trunk cut, stump injection, treatment at the base of the trunk and the "hack-and-squirt" method on trees of different sizes. The effects of the treatment were monitored by regular assessments of survival, regrowth and the condition of the tree crowns during the growing seasons.

Result: Treatments at the base of the trunk and trunk pruning with imazapyr or triclopyr achieved the best control, often exceeding 90-95% mortality. Injections into the trunk with imazapyr and glyphosate also resulted in high control with minimal regrowth. At the same time, injection into the tree stump and manual pruning alone did not suppress growth. The untreated trees quickly sprouted again. The study confirmed that the choice of herbicide and the method of application significantly influence the effectiveness of control. Chemical treatment of the trunks is recommended for long-term control.

Birch and Zedaker, (2003) evaluated herbicide treatments on *Ailanthus* trees of varying sizes.

Location: Virginia, USA.

Method: The researchers conducted a field trial on established ailanthus plantations, applying eight treatments of low-dose herbicides to the base of the trunks. The treatments were compared with manual pruning of the trees as a control. The applications were carried out on trees of varying sizes, and mortality, regrowth intensity and vegetation recovery over time were recorded during follow-up observations.

Result: Herbicide treatments led to high mortality in *Ailanthus altissima*, with very little regrowth observed. The combined use of Garlon 4 and Tordon K was especially effective, as it not only killed the treated trees but also limited regrowth from the root system. By contrast, manual pruning on its own triggered strong regrowth from both stumps and roots. In sites where pruning was carried out only once, stem density increased over time, which ultimately accelerated the spread of the species. Overall, the findings indicated that mechanical removal without herbicide application can be counterproductive, while integrated chemical control remains the most dependable management approach.

Trifilo et al. (2004) tested drought resistance of *Ailanthus* tree.

Location: Italy.

Method: Over 13 weeks, potted *Ailanthus altissima* seedlings experienced four distinct irrigation levels to generate varying soil moisture states. Leaf water status and stomatal function were tracked regularly during this time, while root and shoot hydraulic performance was assessed via high-pressure flow measurements. Instead of relying solely on physiological data, researchers also analyzed cross-sections of root xylem under magnification to detect structural shifts due to limited water availability. When drought-exposed specimens showed altered traits, these findings stood in contrast to individuals receiving consistent hydration. Patterns in transport efficiency often trailed behind visible tissue modifications, suggesting delayed functional consequences. Though some adjustments appeared early, others emerged only after prolonged exposure to dry conditions. Such differences highlighted how internal structure and whole-plant physiology respond at separate rates.

Result: Even when drought was intense, the young plants kept their leaf moisture fairly steady. Because stomata shut early, less water escaped through evaporation. While that happened, roots carried far less water due to falling conductivity, slowing supply inward. As a result, vital tissues avoided breakdown from dehydration. These combined adjustments reveal a method of saving water effectively - this likely supports why the plant thrives and survives where rainfall is low.

Kota (2005) investigated seed germination of *Ailanthus* and its differences from Liriodendron tulipifera.

Location: USA.

Method: Out in the eastern U.S., Kota looked at how *Ailanthus altissima* stacks up against the local Liriodendron tulipifera near woods borders and open spots. Instead of just observing nature, a mix of on-site checks and hands-on tests shaped the core of the work. Samaras, those winged seeds that ride the wind, got gathered farther and farther from adult trees - this helped sketch out how far they typically travel. From there, patterns in seed spread began to take shape using the collected data points. When young plants took root, their start in life was tracked carefully after deliberate planting across zones marked by varying disruption levels. Germination outcomes appeared alongside survival numbers, both recorded repeatedly as weeks passed. Over months, increases in plant mass also entered the picture as part of growth tracking. Because both species faced identical surroundings during testing, contrasts emerged more clearly. One thing became visible - the invasive type often behaved differently than its native counterpart when placed side by side.

Result: When it dried out, *Ailanthus altissima* kept its leaves hydrated by shutting stomata fast. Because of stress, roots lost most of their ability to move water - this slowed loss. Instead of growing tall, the plant put energy into staying alive. Unlike local trees, Ailanthus changed how it functioned depending on surroundings. With these traits, young plants lasted longer when rain varied - and showed why they thrive where ecosystems are broken.

Another study aimed to investigate control methods of *Ailanthus* trees produced following results

Location: Rondo Provincial Park, Ontario, Canada.

Method: The authors evaluated various methods of controlling ailanthus in the park using a range of treatments, including manual removal with mulching, cutting the stem with glyphosate treatment, cutting the stem only, and the EZJect Capsule injection system with glyphosate. The treatments were carried out on both young and mature specimens in different areas of the park. After treatment, monitoring was carried out over several seasons to record tree mortality and regrowth responses. The feasibility of management in a protected area was also assessed.

Result: Treatment by cutting the stem with glyphosate resulted in maximum control of young shoots. The EZJect system effectively destroyed mature fruit trees. Manual digging and mulching was moderately successful for small plants. Only cutting the stumps led to increased regrowth and infestation. Chemical treatments were necessary for long-term control. The study emphasised the importance of adapting methods to plant size and site conditions. (Meloche, C., & Murphy, S. D. 2006).

Ding et al. (2006) researched biological control of *Ailanthus*

Location: China, Europe and North America.

Method: The authors reviewed the literature on the natural enemies of *Ailanthus altissima* in its native and introduced ranges and collected data on phytophagous insects, pathogens and other antagonists of the species. The review catalogued phytophagous insects, fungi and potyviruses recorded in China, Europe and North America. The authors assessed host specificity and the potential effectiveness of biological control by comparing documented interactions and the degree of damage. Potential risks to non-target species were also considered when assessing suitability for classical biological control programmes.

Results: Several insects, including *Eucryptorrhynchus brandti* and *E. chinensis*, showed high host specificity. Fungal diseases and vascular pathogens also showed significant damage potential. Some organisms were excluded due to the risks to non-target species. The review identified promising candidates for further testing. Biological control was considered a complementary strategy with mandatory risk assessment.

Another research on chemical control of *Ailanthus* trees and their results

Location: USA.

Method: The authors conducted a field trial with herbicides on stems of *Ailanthus altissima* in California, using three systemic herbicides – imazapyr, triclopyr and glyphosate – with four methods of stem application: stem cutting, injection into the stump, injection into the stem and treatment at the base of the stem. These methods were applied to both individual stems and groups of individuals to evaluate their effectiveness. Manual pruning and untreated plants served as controls. After treatment, mortality and regrowth were monitored to compare the effectiveness of the different combinations of herbicides and methods.

Result: Cutting through the main stem and its base using imazapyr or triclopyr led to strong suppression - more than 90% success across trials. Trunk injections with either imazapyr or glyphosate brought similar outcomes, killing most trees while limiting sprouting afterward. When treatment shifted solely to injecting stumps, results fell sharply. Removing growth by hand, absent any chemical follow-up, triggered rapid rebounding shoots instead. The findings showed how key both the specific herbicide used and its delivery approach really are. For lasting effectiveness, applying chemicals directly to the trunk tends to work best. (DiTomaso, J. M., & Kyser, G. B. 2007).

Landenberger, et al. (2007) studied *Ailanthus altissima* seed movement.

Location: America, West Virginia

Method: Out into the open, a field investigation tracked how *Ailanthus altissima* seeds move through landscapes in West Virginia - places like farmland, untouched woods, and spots where trees had been partly cut. Along straight lines stretching 100 meters from parent trees, researchers gathered falling seeds at fixed points throughout the release season to map their spread. Instead of focusing only on distance, they paid attention to things like plant density, wind paths, and traits of the seeds themselves. Rather than treating each factor alone, interactions between them emerged when analyzed via three-way ANOVA and fitted regression equations. From edge to core, variation in seed deposition revealed strong ties to both proximity and setting.

Results: Wind carried seeds across every kind of landscape, often beyond one hundred meters. Where they landed depended heavily on which way the air moved and how plants were arranged on the ground. Even though some seeds were bigger than others, both kinds covered roughly the same ground. Movement happened mostly during the first part of the growing period. Where tree lines meet open ground, seeds move farther into nearby ecosystems. These results, taken together, clarify how quickly *Ailanthus altissima* expands across broken-up terrain.

Another study investigating the effectiveness of herbicide treatments on *Ailanthus* yielded these results.

Location: America

Method: Starting with tree injections, Lewis and McCarthy used imazapyr to target *Ailanthus altissima* in Ohio woodlands. Close inspection followed around each treated trunk, focusing on plants within three meters for signs of off-target damage. Death among injected trees and nearby stems was logged weekly across more than a year. Trunk size mattered; it shaped how far harm spread beyond the main target. Distance from the treated stem helped clarify where unintended losses occurred. Alongside physical measurements, hidden connections - like linked roots or soilborne chemical flows - were weighed as possible transmission routes. Observations ran continuously, capturing delayed responses just as clearly as immediate ones. (Lewis, K., & McCarthy, B. 2007).

Result: Every *Ailanthus* that received treatment ended up dead. Still, nearby trunks suffered too - about 17.5% perished, even some from different species. As separation grew from the treated trees, chance of harm dropped noticeably. Tiny stems showed higher sensitivity compared to bulky ones; where plants crowded together or plots stretched wide, chemical movement reached farther. Taken together, these outcomes suggest careful planning matters when applying injected herbicides among diverse woodlands.

Rebbek, et al. (2013) studied effect of *Verticillium nonalfalfae* on *Ailanthus Altissima*.

Location: USA

Method: Stem specimens came from sick *Ailanthus altissima* trees spotted across southern Ohio during joint field and lab work. Instead of skipping steps, researchers cleaned sample surfaces before placing them on plum extract agar to grow fungi. Colonies thought to be relevant emerged under scrutiny involving spore-bearing structures plus genetic methods. Rather than relying only on appearance, scientists pulled out DNA and sequenced three gene regions - EF 1α, GPD, TS - for deeper analysis. Once processed, those results entered BLAST queries matching them against known entries in databases. When testing harmful potential, young plants received doses of spore mixtures followed by close watch for illness signs or death. What began as visible decline in forests ended in controlled proof linking fungus to disease.

Result: Every isolate turned out to be *Verticillium nonalfalfae*. Seedlings that received the inoculation began showing serious wilting before death followed, pointing clearly to intense pathogenic strength alongside narrow host range. Notably, this work marked the initial verified case of V. nonalfalfae within Ohio's borders, joining two other American states with recorded instances. Taken together, evidence suggests this microbe could serve effectively in managing Ailanthus altissima populations through natural means.

Another research showing effect and damage of *Verticillium nonalfalfae* on *Ailanthus Altissima* and its results.

Location: Virginia, North Carolina, South Carolina, United States.

Method: The researchers conducted a large-scale regional field survey of ailanthus sites in the southeastern United States (Virginia, North Carolina, and South Carolina), covering approximately 26,500 km of roads and forests. They visually examined the trees for symptoms of *Verticillium* wilt and took samples from the trunk and xylem of symptomatic trees to isolate the pathogen and cultivate it on selective media. In greenhouse trials, healthy seedlings were inoculated with isolates to assess the virulence and severity of the disease. Incidence data were recorded and compared between study years to assess changes in distribution and frequency.

Result: Areas infected with *Ailanthus* were identified at six sites in the mountains of Virginia. All isolates resulted in 100 per cent mortality of infected seedlings. The incidence of the disease increased between 2011 and 2012. The pathogen showed high virulence and stability between isolates. The results indicate natural spread in the region. The study confirmed the potential of the pathogen as a biological control agent. (Snayder et al. 2012/2014).

Cabra-Rivas et al. (2014) studied *Ailanthus altissima* seedling distribution along a river.

Location: Spain.

Method: Through a field study, researchers examined how water carries seeds of Ailanthus altissima by introducing samaras into two distinct 100-meter stretches of river - one nearly natural, the other altered in form. Instead of simultaneous measurements, they monitored fruit motion and settling across 90 minutes via sight checks paired with periodic collection. While tracking progress downstream, they also measured physical features like aquatic plants and dead wood at both locations. Rather than assuming uniform behavior, they assessed differences in travel range and trapping frequency between sites. Because structural variation affected outcomes, comparisons focused on how habitat layout shapes floating seed movement. Although brief in duration, the observation window captured meaningful shifts in distribution patterns.

Results: Fewer fruits stayed in place where the river showed signs of damage - about one-fifth compared to healthier stretches. Because plants were sparser, drifting fruits moved greater distances before stopping. Instead of flowing freely, many seeds got caught when water plants slowed their path. With fewer obstacles present, floating fruit traveled longer routes more easily. As a result, broken habitats made it likelier for seeds to reach faraway spots by water. In these areas, plant life once acted like nets; now that protection is weaker. Dispersal patterns shifted noticeably wherever human impact altered natural conditions.

Knusel et al. (2017) came into following conclusions studying shade tolerance of *Ailanthus.*

Location: Switzerland.

Method: Using hemispheric photos, researchers measured how much light reached 204 young tree-of-heaven saplings, aged one to seven, growing beneath chestnut trees at six Swiss locations. Rather than relying on estimates, they directly linked each plant's growth and survival to actual canopy gaps above it. Though some originated from seeds, others sprouted from roots - both types tracked over time. Instead of assuming uniform behavior, scientists compared performance across brightness levels found in real woodland settings. Following several seasons, individual output patterns helped redefine assumptions about how well this species copes in dim environments. Because field conditions varied naturally, conclusions reflect realistic understory scenarios. Notably, results challenge earlier lab-based generalizations about its low-light limits.

Results: Survival among young *Ailanthus* specimens occurred even when light was limited - something earlier estimates did not expect. Not only seed-originated individuals but also those from vegetative propagation handled shaded conditions fairly well. Even though thick overhead foliage slowed development, the plants persisted without dying off. This evidence questions long-held views about the plant needing abundant sunlight. Where tree cover forms a tight roof above ground and parent trees are nearby, forests might face higher risks of infestation because shade adaptability strengthens how aggressively the species spreads.

Petruzzellis et al. (2019) studied differences between *Ailanthus altissima* and *Fraxinus ornus*

Location: Italy.

Method: The study conducted a comparative analysis of functional traits between *Ailanthus altissima* and *Fraxinus ornus,* which is native to Italy. Leaf and wood properties related to water transport (hydraulics) and carbon investment were measured, including vessel anatomy, leaf area, and wood density. Hydraulic efficiency and responses to drought were assessed under different light conditions using standardised physiological measurements. Phenotypic plasticity was assessed under different conditions, and carbon investment indices were evaluated to understand the differences in structural investment between species.

Results: *Ailanthus* showed higher hydraulic efficiency than *Fraxinus ornus.* The species showed higher phenotypic plasticity in response to light changes but had lower drought tolerance and lower structural investment. Rapid resource utilisation favoured rapid growth. These traits favour invasion under productive conditions. The results show a trade-off between efficiency and resilience.

Bubichi, et al. (2020) researched effect of *Aleurocanthus spiniferus* on *Ailanthus Altissima*

Location: Bari, Italy.

Method: A field study was conducted in Bari, southern Italy, to assess the infestation of *Ailanthus altissima* by *Aleurocanthus spiniferus*. The insects (adults and larvae) were collected from various trees and morphologically identified under a stereomicroscope. Microbiome and microtranscriptome analyses were performed using deep sequencing of small RNAs (sRNA Seq), and bioanalytical tools were used to analyse RNA profiles, including bacterial endosymbionts and microRNAs. Damage to the host, infection frequency and spatial distribution were recorded to assess insect-host interactions.

Result: *Ailanthus altissima* was regularly infested by *A. spiniferus*. The infections did not pose a threat to the survival of the host. The insect harboured several bacterial endosymbionts. Several known and new microRNAs were identified. The species has been shown to adapt to the host. Although the insect is not lethal, it can affect the physiology of the plant.

Pepe et al. (2022) came to these conclusions while researching the water resistance of *Ailanthus altissima*.

Location: Italy (Mediterranean region)

Method: The authors conducted a controlled water stress experiment on seedlings of *Ailanthus altissima, Phytolacca americana* and *Robinia pseudoacacia* under Mediterranean conditions to compare the responses of the species. The plants were exposed to predetermined drought conditions, and measurements were taken throughout the stress period. The physiological characteristics of the leaves (gas exchange, water status of the leaves), morphological characteristics (leaf mass per unit area – LMA, leaf area) and indicators of water use strategy were recorded. The data were analysed using a two-way ANOVA and correlation analysis to assess the influence of species and duration of stress on physiological and morphological responses.

Result: *Ailanthus* showed greater resistance to water stress compared to other species. Leaf mass per unit area increased under stress conditions. Tolerance was maintained despite the water use strategy. Physiological plasticity favoured survival. These characteristics improve competitiveness in the Mediterranean climate and demonstrate adaptation to fluctuations in water availability.

Results of Research on the Occurrence and Molecular Characterization of *Aculus mosoniensis* associated with *Ailanthus altissima*

Location: France

Method: Field surveys mapped *Ailanthus altissima* stands throughout several French regions, targeting possible eriophyid mite associations. From every location, researchers gathered leaves from numerous host trees following a structured sampling approach. Specimens were extracted carefully before being inspected using optical microscopy. Key physical traits - especially those useful for classification - received particular attention during analysis. Instead of relying solely on appearance, scientists turned to DNA methods for verification. Individual mites had their mitochondrial COI region analyzed through sequencing techniques. Genetic data helped pin down exact species while also revealing variation within sampled populations. From these sequences, scientists looked at variation within species and differences among haplotypes, while mapping where *Aculus mosoniensis* occurs across the landscape to understand how widely it has spread. Host preferences formed another part of the investigation, along with an assessment of whether this mite might serve a role in managing plant pests naturally.

Results: Found only *Aculus mosoniensis* among the collected mites. For the first time ever, presence in France gets solid confirmation. Variation within the species shows up clearly through DNA testing. Movement across European regions appears ongoing, driven by active spread. Favoring certain hosts may make this organism useful for managing pests naturally. Research into its environmental interactions should continue. (Kashefi, et al. 2022).

3.Result

A look at earlier research highlights Ailanthus altissima (Mill.), a tree originally from Across northern and central regions of China, this tree species now ranks among the toughest non-native plants to manage in numerous areas. Though initially developed for uses like medicine, its role has since spread across the globe. Now found well outside where it first grew, ornamental planting carried this species across new territories. The reason behind its widespread invasion largely ties to its thriving quickly under tough conditions marks its life cycle, while abundant seeds ensure wide spread. Harsh climates rarely slow it down thanks to built-in resilience traits. Success in extreme settings comes not just from speed but also from reproductive strength. Survival hinges on endurance paired with prolific output across difficult landscapes. A tree's ability to thrive often depends on how it reproduces. What makes *A. altissima* particularly successful lies in the way it multiplies. Spreading quickly becomes possible when new growth emerges frequently. Its method of reproduction gives it an edge over others. Because offspring develop rapidly, colonies expand without delay. This pattern allows dense stands to form across varied environments. Meanwhile, this plant moves quickly by sending out roots that travel along the ground, Besides forming thick clusters originating from a single source, this type of growth tends to overshadow local flora. Competition gradually reduces the presence of indigenous plants. Shrinking species variety while shifting how nearby environments are built and operate. Because of studies on how organisms function and their environments, scientists understand better what allows this species to settle successfully. Thriving across diverse environments has been possible due to adaptability. Research into dry conditions reveals that *A. altissima* relies on multiple strategies to conserve water, such as precise control of when stomata open, movement of water through roots faces constraints. Survival during dry spells becomes possible because of these adjustments. Severe water scarcity could threaten numerous indigenous species, possibly leading to their decline. Besides this, studies shows *A. altissima* can adapt easily. Though thriving in open areas, where conditions are disrupted, survival remains possible even when light levels drop below full sun exposure. This flexibility allows the species to invade both open environments and more closed forest ecosystems. Studies on seed dispersal confirm the species' ability to effectively colonise fragmented landscapes, river corridors and human-altered environments such as roadsides and urban areas.

Management-oriented studies clearly show that mechanical control methods alone are largely ineffective and often counterproductive, as cutting stimulates active regrowth and increases population density. In contrast, chemical methods – in particular the treatment of stumps, application to the bark and injection of chemicals such as imazapyr and triclopyr into the trunk – have repeatedly shown high mortality rates and long-term growth suppression. However, several studies also point out that the use of herbicides is not without risks. In particular, they warn about possible negative effects on non-target species during herbicide transport and stress the importance of careful, well-controlled application, especially in mixed stands. Case studies from protected and conservation areas further indicate that successful management of *Ailanthus altissima* cannot rely on a single method. Instead, effective control usually depends on integrated approaches that are adapted to local ecological conditions.

In recent years, biological control has received increasing attention as a potential long-term solution. Scientists are now studying a fungus called *Verticillium nonalfalfae,* with attention also given to finding success in targeted insect and mite hosts has emerged from recent studies. Cases of naturally occurring infestations agents showing strong pathogenic effects might help limit *A. altissima* populations. Their impact appears significant under certain conditions. This potential arises naturally during infection cycles. Effectiveness varies across environments. Still, results point toward meaningful suppression in some cases. Continued observation may clarify long-term outcomes over time, shifts in population patterns emerge. The spread of Ailanthus altissima emerges clearly when patterns are examined across different regions. It stems from multiple elements, such as strong breeding rates, flexible body functions allow survival under shifting conditions. Despite narrow limits in some species, these organisms handle wide changes well. What sets them apart is how easily they adjust internal processes when surroundings shift. Their capacity to thrive amid disruption stands out clearly advantage of ecosystem disturbances. Effective control therefore requires an integrated approach combining chemical, mechanical and possibly biological methods, as well as early detection and prevention at the landscape level. Without continuous and scientifically sound measures, *A. altissima* will continue to expand its range and have a significant impact on the ecology and management of both natural and urban ecosystems.

Several studies have investigated methods for controlling Ailanthus altissima. DiTomasso (2001) and Kaiser (2007) tested herbicides, including imazapyr, triclopyr and glyphosate, which were applied through cuts in the trunk, injections into the trunk, injections into the stump and treatments at the base of the trunk, while manual pruning and untreated plants served as controls. Burch and Zedaker (2003) applied low-volume herbicide treatments at the base of the trunk and compared them with manual cutting to evaluate their effectiveness in terms of mortality, regrowth and stand recovery. Melosh and Murphy (2006) tested trunk cutting with glyphosate, manual removal with mulching, and the EZJect Capsule injection system, observing both young and mature trees. Across the reviewed studies, herbicide treatments were consistently found to be more effective than pruning alone, particularly when they were combined with mechanical removal. In contrast, pruning by itself often resulted in regrowth, which in some cases continued over several growing seasons. What emerges here points to a need - more often than not - for combined strategies when aiming at lasting management outcomes.

Ailanthus altissima has drawn scientific attention due to its bodily reactions under stress, yet findings remain scattered across different experiments because methods differ too widely to allow clear comparisons between results seen so far focus on how well it withstands dry conditions. Studies by Trifilò in 2004 and later by Pepe in 2022 tested ailanthus under such stress. Fresh young plants faced limited moisture, their responses measured through indicators like pressure within leaves and tiny openings on surfaces. Leaf tension dropped when supply tightened, showing how each specimen managed available resources differently. Some held steady longer, others reacted quickly as conditions shifted. Observations tracked shifts over time, noting differences in behavior under strain. Each data point reflected a moment of adjustment during exposure. Hydraulic traits, alongside measures like conductance, shape how leaves manage water. Leaf mass per unit area emerges as a key factor when examining gas exchange dynamics. Another investigation explores similar patterns across species. Petruzzelli (2019) examined how plants function by analyzing water movement through leaves alongside wood structure. Under varying light, traits shift alongside carbon allocation while flexibility in form adjusts accordingly. Later work on shade tolerance came from Knyzel and team in 2017, examining how trees manage light through crown structure, by capturing images across the hemisphere, researchers tracked how seedlings developed and stayed alive. In combination, these studies demonstrate that *Ailanthus altissima* exhibits a high degree of physiological flexibility helps sustain moisture levels when stressed, also supporting survival where light is limited. This fuels quick development while improving chances of survival.Focusing on how species spread, some studies explore movement and settlement processes. Take Knapp, whose work illustrates this approach, Kenham (2000), meanwhile, monitored how young plants developed and established themselves within naturally occurring openings in the tree cover through systematic observation. Height shifts, along with diameter changes, occurred alongside fluctuating radial growth speeds due to shifting light conditions through the years. Findings showed what stands out is how swiftly the species takes advantage of improved light levels when gaps form in the canopy. Seed spread varies across regions. According to Landenberger and colleagues in 2007, movement patterns differ based on environmental factors. Through transect-based seed collection, researchers examine how surroundings shape plant distribution patterns using regression alongside three-factor ANOVA to assess influences. Cabra-Rivas and team reported findings in 2014 a team ran a test outdoors, placing seeds into stretches of a stream while tracking what happened afterward. Some segments received seed deposits; others did not - patterns emerged over time through close watching floating seeds move differently depending on how water flows, while the amount that stay trapped changes with current patterns.

Though several studies explored pathogens alongside possible biocontrol methods, each approached the topic differently. From infected trees, Rebek and team in 2013 gathered samples, growing fungi on specialized media before identifying them through physical traits and DNA analysis, then testing disease potential under glasshouse conditions. Rather than lab work alone, Snyder and colleagues across 2012 and 2014 expanded into open fields, observing how aggressively Verticillium nonalfalfae spreads using controlled plant infections. Instead of original data, Ding et al., back in 2006, pulled together prior research, weighing insect and fungal agents based on how precisely they target hosts and whether that makes them strong candidates for biological suppression strategies. Recently, work by Bubici and colleagues in 2020 examined Ailanthus altissima linked to Aleurocanthus spiniferus through field observations, blending physical traits analysis with sRNA-Seq alongside computational methods. In parallel, research led by Kashefi in 2022 explored Aculus mosoniensis presence across natural sites, relying on visual classification together with COI gene data to assess genetic differences and spatial trends.

One reason method differed among studies was the kind of question each team aimed to answer. When looking at weedkillers and ways to manage plants, scientists often applied treatments outdoors then watched changes over time. Instead of outdoor work, those exploring plant reactions under pressure ran tests in stable conditions to track how systems responded. To understand movement patterns, researchers paired real-world observations with number-based tools that revealed trends. For organisms meant to limit growth, investigators turned to lab cultures, gene-level checks, and sheltered growing spaces - each helping show how attackers linked with hosts and whether they might help control spread.

Work continues on Ailanthus altissima in Azerbaijan's Absheron area, studying how it spreads and alters ecosystems locally. Because environmental changes matter, scientists look closely at shifts in plant communities, ground composition, and biological variety. Some investigations turn toward practical roles - such as wood supply or energy feedstock - as one path forward emerges. Although eradication proves difficult, teams test physical clearing methods alongside targeted herbicide use and watch how seeds move across spaces. These combined actions support sharper insights into regional patterns of growth while shaping realistic ways to manage unwanted expansion. When results accumulate, clearer options appear for handling the species without worsening disruption elsewhere.

4.Conclusions

From what has been studied so far, a few main points stand out clearly:

1. Looking at current studies shows *Ailanthus altissima (Mill.)* - originally from northern and central China - has turned into a highly disruptive invader across global ecosystems. Though first introduced outside its range for ornamental purposes, it now outcompetes local flora in diverse climates. Its rapid growth allows dense stands to form quickly, especially in disturbed areas like roadsides or abandoned lots. Because it releases chemicals that hinder nearby plant development, few species can survive near mature individuals. While some regions attempt mechanical removal, resprouting after cutting makes long-term control difficult. In contrast to slower-growing natives, this species adapts fast to urban pollution and poor soils. Over time, persistent colonization alters soil composition and reduces biodiversity in invaded zones.

2. Despite dry conditions, *Ailanthus altissima* manages its water well through specific adaptations. Stomatal regulation plays a role, while reduced root hydraulic conductivity helps limit excessive loss. Together, these traits support survival when moisture is scarce. The tree maintains function even as soil water declines sharply. Evidence shows it prioritizes conservation over rapid uptake. Rather than deep foraging, it adjusts internally to stretch available supplies. Under stress, growth slows but physiological balance holds. This resilience emerges from coordination between leaf and root behaviors. Water savings accumulate not by one method alone, yet through linked strategies. Prolonged droughts become tolerable due to such integrated responses.

3. When it comes to handling *Ailanthus altissima*, studies show relying only on physical removal tends to fail - sometimes backfiring when cut stems respond with vigorous sprouting, increasing overall numbers. Though straightforward, chopping down these trees often leads to denser stands rather than reduction, making the issue harder to manage over time.

4. In Azerbaijan, work is underway to develop management strategies, including mechanical removal, chemical control and seed dispersal monitoring, to prevent further spread in urban and natural areas.

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Relationship Between Total Soluble Salts (TSS) and Ion Composition in Sodic Soils of the Karabakh Steppe: Implications for Ecosystem Services

Amrakh Mamedov[1] and Turkan Aghazadah[1]

[1]School of Advanced Technologies and Innovation Engineering, Department of Ecology and Environmental Sciences, Western Caspian University, Baku, AZ 1072, Azerbaijan.

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Abstract

Salinity, and particularly sodicity, represents one of the key constraints on agricultural productivity and the functioning of soil ecosystem services in the semi-arid regions of Azerbaijan, including the Karabakh Steppe of Azerbaijan. A reliable assessment of salinity conditions, together with ecosystem restoration and the design of effective reclamation strategies, requires a clear understanding of the relationships between total soluble salts (TSS), electrical conductivity (EC), and the concentrations of individual ions. In this study, the interactions between TSS and major ions were examined in sodic soils characterized by HCO_3^-–SO_4^{2-} and SO_4^{2-}–HCO_3^- salinity types. The analysis was based on detailed ion composition measurements and integrated soil profile investigations, covering both the plant root zone and the deeper vadose zone. The results indicate consistently strong correlations between TSS and EC throughout the soil profiles ($R > 0.8$). In contrast, the relationships between TSS and individual base ions showed greater variability, with correlation coefficients generally remaining below 0.90. This pattern suggests that ionic composition, rather than total salt concentration alone, plays a dominant role in regulating EC values. The salinity regime was defined by a cation dominance sequence of $Na^+ > Ca^{2+} > Mg^{2+}$, while the anion composition in both the root zone and vadose zone followed the order $HCO_3^- > SO_4^{2-} > Cl^-$. This distribution is typical of long-term irrigated sodic soils in semi-arid environments. Surface horizons exhibited moderately low selective EC; however, EC became increasingly variable with depth and reached maximum values below the root zone, particularly at depths of 100–150 cm. This vertical pattern reflects the downward leaching of salts from upper horizons driven by irrigation and precipitation, followed by their accumulation in deeper vadose layers under conditions of restricted drainage and upward capillary flux from shallow sodic groundwater. These results demonstrate that EC alone is insufficient to characterize sodicity hazards. Integrated evaluation of EC, TSS, ion composition, and depth-dependent processes provides a robust framework for salinity monitoring, soil reclamation, sustainable soil health, and ecosystem management in semi-arid irrigated systems.

Keywords: salinity, sodicity, soil solution, major ions ecosystem services, sustainable management

1. Introduction

1.1. Soil ecosystem services and salinity effects

Soil ecosystem services represent the fundamental functions through which soils sustain environmental quality, agricultural productivity, and human well-being. These services include regulating (water filtration, nutrient cycling, carbon sequestration, erosion control), supporting (soil formation, root anchorage, habitat provision), provisioning (food, fiber, biomass, clean water), and cultural services linked to landscapes and heritage (Figure 1). Together, they are commonly framed within the concepts of soil health and soil multi-functionality, which describe the ability of soils to deliver multiple services simultaneously (Keesstra et al., 2022). The One Health framework, soil ecosystem services link ecosystem integrity with animal and human health. Degradation under saline and sodic conditions thus constitutes not only an environmental constraint but also a wider public and animal health concern. Numerous studies show that soil salinity–solidity status, structure, organic matter content, and climatic stress strongly regulate ecosystem service delivery across agroecosystems (Adhikari & Bouma, 2021; Greiner et al., 2021; Lal, 2021; Schulte et al., 2021). Salinity-induced declines in aggregation, infiltration, microbial activity, and biogeochemical functioning reduce soil productivity and resilience, with indirect impacts on food security and livestock health (Dominati et al., 2010; Bünemann et al., 2018).

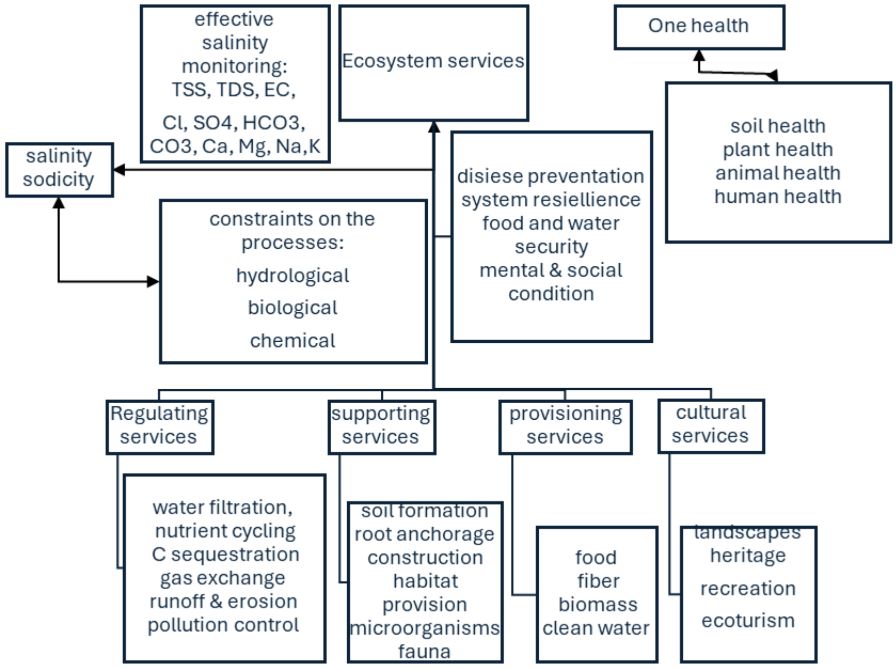


Figure 1. *Soil ecosystem services and One Health interactions as affected by soil salinity-sodicity.*

In semi-arid regions, soil health indicators also act as early-warning signals of sodicity-related One Health risks and are closely linked to key salinity metrics, including total soluble salts (TSS), total dissolved salts (TDS), electrical conductivity (EC), sodium adsorption ratio (SAR), and soluble ion composition (Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-). Because interactions among TSS, EC, and ion composition control ion mobility, mineral equilibria, soil structure, and water flow, correct interpretation of TSS as a function of EC and ionic chemistry is essential for diagnosing salinity hazards and designing sustainable soil and ecosystem management strategies (Rengasamy, 2021; Corwin & Lesch, 2021; Qadir et al., 2021).

1.2. Main salt components of the soil solution

The behavior of soluble ions in soil solution is controlled by three complementary properties: ionic strength, ion-specific toxicity, and contribution to electrical conductivity (EC). Although often used interchangeably, these properties represent distinct chemical and biological processes with different implications for soil functioning and ecosystem services (Sposito, 2008).

Ionic strength is defined as $I=0.5\sum CiZi^2$. and depends on both ion concentration (C_i) and charge (Z_i). Thus, divalent ions (Ca^{2+}, Mg^{2+}, SO_4^{2-}, CO_3^{2-}) contribute four times more to ionic strength than monovalent ions, exert an unreasonable influence on mineral equilibria, EC– SAR–ESP relationships, and clay coagulation-flocculation–dispersion behavior (Sposito, 2008; Sparks, 2020). Accordingly, the ionic-strength hierarchy generally follows: $CO_3^{2-} \approx$, $SO_4^{2-} \approx Ca^{2+} \approx$, $Mg^{2+} > Na^+ \approx K^+ \approx Cl^- \approx HCO_3^-$.

Ion toxicity, in contrast, reflects plant physiological and soil structural effects and typically follows the order: $Na^+ > Cl^- > HCO_3^- > CO_3^{2-} > Mg^{2+} > SO_4^{2-} > Ca^{2+} > K$ (Ayers & Westcot, 1985; Rengasamy, 2010). Sodium is particularly destructive due to its strong distributive effect on clay particles and disruption of plant nutrient balance, while Ca^{2+} reduces sodicity, also increasing soil structural stability (Qadir & Schubert, 2002).

Electrical conductivity (EC) is primarily dependent on mobility and dissociation, following the order of: $Cl^- > Na^+ > K^+ > Ca^{2+} > Mg^{2+} > SO_4^{2-} > HCO_3^- > CO_3^{2-}$ (Suarez, 1981; Rhoades et al., 1999). These contrasting hierarchies prove that sodicity hazards cannot be reliably diagnosed by EC or TSS alone, as similar EC values may correspond to considerable various structural and biological outcomes depending on ionic composition. Effective salinity–sodicity assessment, therefore, requires interpreting EC as a function of both TSS and ion-specific behavior, rather than relying on bulk salinity indicators alone (Rengasamy, 2010).

1.3. Factors affecting relationships among soil salinity components

Electrical conductivity (EC) reflects the combined effects of ionic strength and ion mobility and is commonly expressed as EC = f(TSS), because total soluble salts (TSS), together with major anions (Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-}) and cations (Na^+, Ca^{2+}, Mg^{2+}, K^+), determine soil solution conductivity (Rengasamy, 2021). However, this relationship is not constant and varies with soil texture, chemistry, mineralogy, hydrological conditions, and management. (Figure 2) These factors regulate dissolution–precipitation reactions, ion exchange, permeability, leaching, and evaporation, making EC a system-dependent and often non-linear indicator rather than a simple proxy for TSS (Pereira et al., 2022; Wang et al., 2022).

EC–TSS–ion relationships are strongly impacted by management practices by changing salt redistribution and evaporative concentration (Figure 2). Practices such as, residue retention, mulching, and cover cropping help limit surface evaporation and stabilize EC, whereas poor drainage, soil compaction, and bare soil surfaces promote salt accumulation and elevate EC values. Introduction of gypsum or other Ca^{2+}-rich facilitates the replacement of exchangeable displaces Na^+, reduce ESP, enhances hydraulic conductivity, and makes EC–TDS relationships more predictable (Levy et al., 2005; Greiner et al., 2021).

Soil salt dynamics and the relations between electrical conductivity (EC), total soluble salts (TSS), and ion composition are also affected by tillage practices, irrigation water quality, and drainage conditions. Soil aggregates are destroyed by conventional tillage, which also increases surface evaporation, and creates favorable conditions for salt accumulation near the soil surface, as well as weakening the correspondence between EC and subsurface salinity (Richards, 1954; Levy et al., 2003; Mamedov & Levy, 2013). However, reduced or conservation tillage preserves soil structure, improving water filtration and percolation, as well as facilitates downward salt leaching, which leads to more consistent EC–TSS relationships and improved salinity regulation (Greiner et al., 2021; Zhang et al., 2022; FAO, 2015).

Soil salinity chemistry is adapted through the usage of saline or bicarbonate-rich irrigation water by applying Na^+, Cl^-, and SO_4^{2-} and carbonate precipitation reactions that reduce Ca^{2+} activity, which affect EC independently of bulk salt concentration (Ayers & Westcot, 1985; Suarez, 1981; Qadir & Schubert, 2002; Peker et al.,2024). This chemical dissociation unveils that soils with similar EC values may demonstrate completely different sodicity hazards and structural behavior (Levy et al., 2005; Rengasamy, 2010; Corwin & Yemoto, 2019).

Upward capillary flux in landscapes with shallow saline or sodic groundwater, further stimulates salt recycling into the root zone, which fosters Na dominance and increases salinity–sodicity risks under irrigated agriculture (Oster et al., 1999; Van der Zee et al., 2014; Cui et al., 2019; Oster et al., 2021; Li et al., 2023). These interacting management and hydrological controls confirm that EC–TSS–ion relationships are system-specific (Figure 2) and should be interpreted in the context of tillage intensity, irrigation water chemistry, drainage efficiency, and groundwater depth and chemistry (Corwin & Scudiero, 2017; Qadir et al., 2021; Rengasamy, 2021).

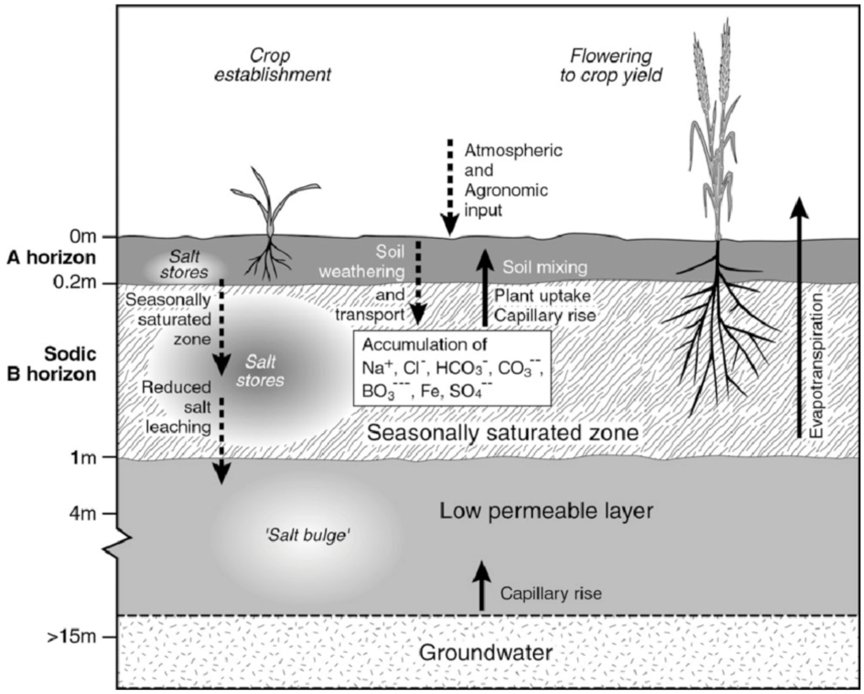


***Figure 2**. Accumulation of salts and ions in the root (vadose) zone driven by leaching–evaporation processes under shallow groundwater conditions*

Ion retention and mobility are also managed by soil texture and mineralogy. Fine-textured soils with high cation exchange capacity (CEC) retain cations on exchange sites, weakening EC–TSS proportionality, whereas coarse-textured soils favor dissolved salts and make EC a more reliable indicator. Carbonate and sulfate minerals regulate Ca^{2+} and Mg^{2+} availability and sodicity development, while smectitic clays amplify Na^{+}-induced dispersion and surface EC accumulation (Rengasamy, 2021; Mamedov & Levy, 2013).

The Objective. Together, these interacting physical, chemical, hydrological, and management factors demonstrate that EC–TSS relationships are site-specific rather than universal. Accordingly, the objective of this study is to quantify the relationships between TSS, EC, and individual ion concentrations in sodic soils of the Karabakh Steppe to improve salinity diagnosis and support sustainable soil management and ecosystem service delivery.

2. Materials and Methods

2.1. Study area and sampling

Soil samples were collected in spring from 60 locations within an irrigated collector–drainage system at the regional experimental station of the Research Institute of Water and Melioration in the Barda District, central Karabakh Plain, Azerbaijan (47°11′16.29″ E, 40°23′45.86″ N). Samples were taken from eight depth intervals (0–25 to 250–300 cm), and groundwater samples were collected from 40 sites at depths of 3.0–3.2 m.

The investigated area (30ha=300m x 600m +200 x 600m=18ha+12ha)) is equipped with the equipments for water balance measurement and with open drainage channels spaced 200 or 300 m apart (600 m lenght), with an average depth of ~3.0 m. Soils are long-term irrigated gray-meadow and meadow-gray soils (FAO Calcisols or LuvisolS) with clayey texture, low organic matter, and sodic groundwater chemistry (Ismayilov et al., 2021). Salinity levels are generally low to moderate (TSS < 0.10–0.2 g kg^{-1}), with dominant $Na–HCO_3–SO_4$ salinity types.

2.2. Soil and water analyses

Air-dried soil samples were ground and passed through a 2-mm sieve. Particle-size distribution was determined using the hydrometer method (Gee & Bauder, 1986). Cation exchange capacity (CEC), exchangeable sodium, calcium carbonate content, and soil organic matter were measured following standard procedures (e.g., ASA–SSSA, 1986; Nelson et al., 1982; Rhoades, 1986; Thomas, 1986). Within the crop layer (0–30 cm), soils exhibited considerable temporal variation in their key physicochemical properties. Beyond these temporal changes, significant differences were also apparent in soil composition, carbonate content, exchangeable sodium percentage (ESP), infiltration rates, aggregate stability, and levels of soil organic carbon (SOC). Although the surface soil was characterized by a clay texture, relatively low salinity levels, lower organic matter content, reduced aggregate stability, and lower infiltration rates, it was simultaneously distinguished by low saturated hydraulic conductivity, an alkaline reaction, elevated ESP, and high calcium carbonate content and higher field water retention (FC) and wilting point(WP)(Table 1).

Table 1. *Soil properties in the cultivated layer (0-30 cm)*

Soil	Particles, %		CEC[a]	pH	EC	OM	WSA	FC	WP	$CaCO_3$	ESP	Ks
	vlay	– sand	mmol/kg				------------------ % ---------------------					mm/h
Clay	54	18	42	8.4	1.7	1.4	50.4	28.2	19.1	16	14	1.2

CEC=cation exchange capacity; EC=electrical conductivity; OM=organic matter; FC=field capacity; wp=wilting point; ESP=exchange able sodium percentage; Ks=saturated hydraulic conductivity.

Soil salinity was assessed using 1:5 soil–water extracts, equilibrated for 4 h. EC and soluble ions were measured following standard methods (ASA–SSSA, 1986), and TSS was determined gravimetrically. Additional analyses included pH, saturation extract EC (ECe), soluble cations, carbonate and bicarbonate by titration, chloride by $AgNO_3$ titration, and SAR calculation. Also published EC–TSS relationships for sodic soils were used for comparison and salinity type evaluation (Ismayilov et al., 2021).

2.3. Statistical analysis

Statistical analyses were performed using SAS (PROC GLM, JMP). Mean comparisons were conducted using the Tukey–Kramer HSD test ($p < 0.05$). Pairwise correlations and least-squares regression and correlation analysis were applied to quantify relationships among EC, TSS, and individual ion concentrations (SAS Institute, 2018).

3. Results

3.1. Vertical distribution of salts in the soil profile

The vertical distribution of salts within the 0–300 cm soil profile shows clear depth-dependent patterns controlled by irrigation, drainage spacing, and shallow groundwater (~3 m). Under long-term management, salinity demonstrate heterogeneity, with distinct leaching and accumulation zones rather than a uniform vertical gradient. Electrical conductivity (EC) and total soluble salts (TSS) are generally lower in the upper layers but show increasing variability with depth, reaching maximum values occurring below the root zone (Figures3-4). This pattern designates downward salt transport from irrigation and rainfall, followed by partial accumulation in deeper vadose horizons because of restricted drainage and capillary rise (Figures 5-6).

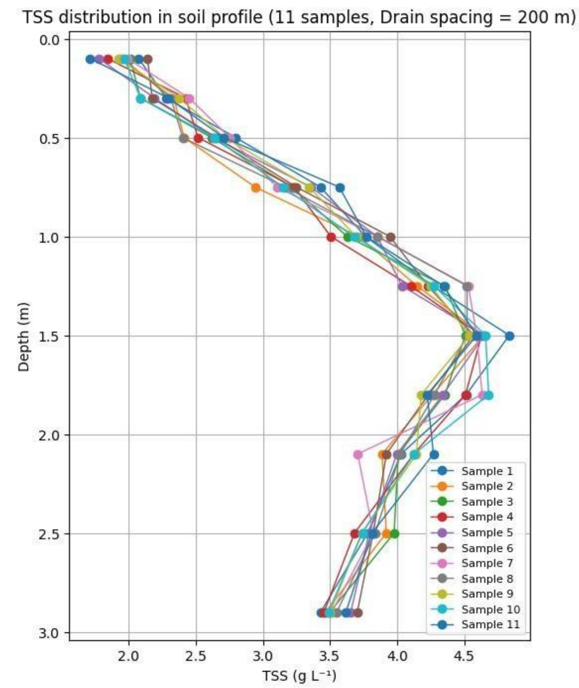


***Figure 3**. Vertical distribution of total soluble salts (TSS) in a 0–3 m soil profile based on 11 sampling points under open drainage with 200 m spacing. Individual profiles consistently show low TSS in the root zone, a distinct accumulation zone at 1.5–2.0 m depth, and stabilization toward the rain/groundwater level, indicating effective salt leaching and controlled salinity under closer drain spacing.*

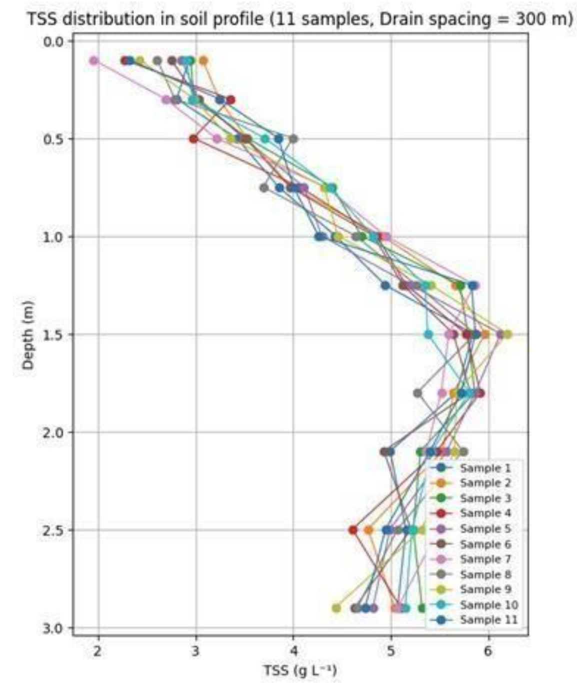


***Figure 4.** Vertical distribution of total soluble salts (TSS) in a 0–3 m soil profile based on 11 sampling points under open drainage with 300 m spacing. Profiles show consistently higher TSS and a shallower accumulation zone (≈1.2–1.8 m) compared with closer drain spacing (200 m), indicating reduced leaching efficiency and enhanced salt storage in the vadose zone.*

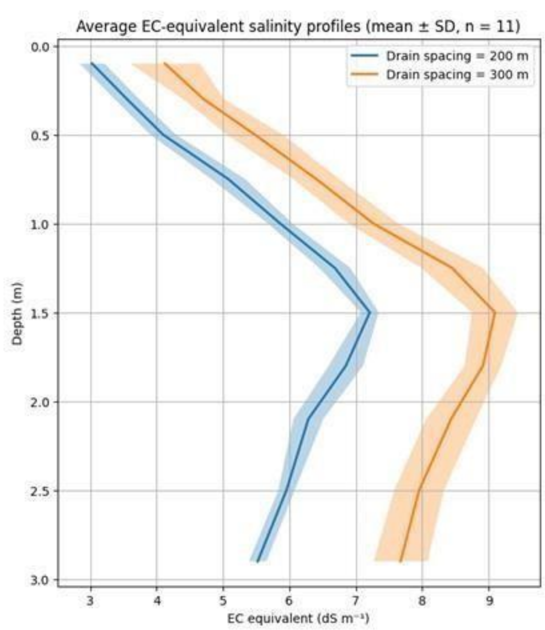


***Figure 5**. Average EC-equivalent salinity profiles (mean ± standard deviation, n = 11) in a 0–3 m soil profile under open drainage with 200 m and 300 m spacing. EC values were derived from total soluble salts (TSS) using EC ≈ TSS/0.64. Narrower drain spacing (200 m) resulted in lower root-zone salinity and a deeper salinity maximum, whereas wider spacing (300 m) caused higher EC throughout the profile and a shallower accumulation zone with greater EC*

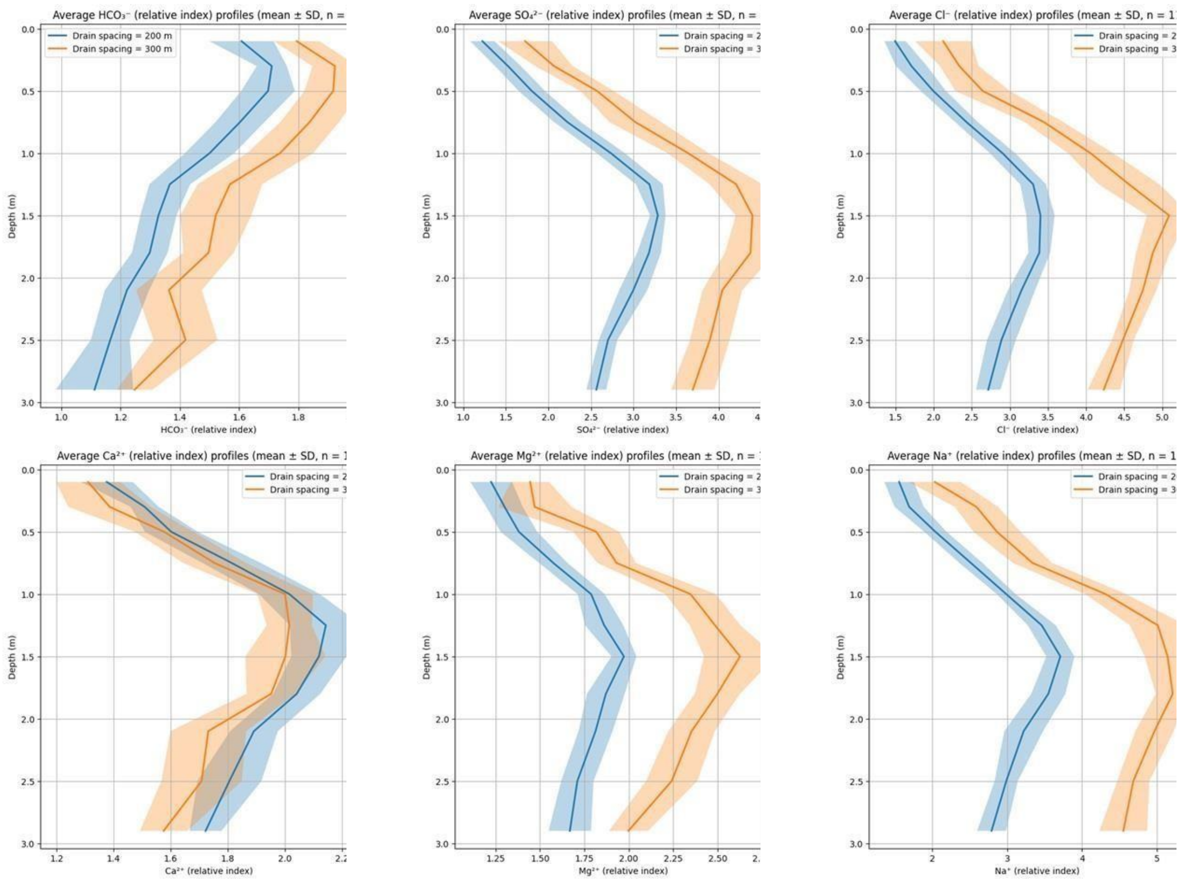


***Figure 6**. Average depth profiles (mean ± SD, n = 11) of ions in a 0–3 m soil profile under open drainage with 200 m and 300 m spacing. Shaded bands represent ±1 SD across sampling points, indicating spatial variability. Wider drain spacing results in higher ion accumulation and shallower maxima, which correspond to reduced leaching efficiency*.

HCO_3^- and SO_4^{2-} manage ionic composition throughout the profile, reaffirming an HCO_3–SO_4 salinity type. Bicarbonate demonstrates high variability and positive skewness, which indicate carbonate dissolution and alkalinity development. In contrast, sulfate exhibits the simultaneous influence during leaching and precipitation–dissolution processes within the soil profile. Chloride, as a relatively conservative ion, shows the clearest tendency toward deep accumulation, indicating zones of long-term salt storage. Sodium is present throughout the entire profile with moderate average concentrations but marked variability, suggesting that sodicity-related processes are not confined to the root zone and instead extend downward through cation exchange and vertical redistribution. By comparison, Ca^{2+} and Mg^{2+} maintain relatively stable distributions with depth. Overall, the soil profile can be described as dynamically restructured, with active salt redistribution in surface horizons, partial leaching across the root zone, and the accumulation of soluble salts in deeper layers. This vertical differentiation highlights the importance of assessing the full soil profile, rather than only surface horizons, when evaluating salinity status and drainage efficiency.

3.2. Descriptive statistics of salinity components

The descriptive statistics show clear depth-dependent changes in hydrochemical properties, with the 0–300 cm profile consistently exhibiting higher variability and slightly elevated concentrations compared to the shallow 0–100 cm zone (Table 2). EC increased with depth, from a mean of 0.386 dS m^{-1} (0–100 cm) to 0.462 dS m^{-1} (0–300 cm). The maximum value also rose markedly, indicating progressive salt accumulation in deeper layers. Higher standard deviation in the deeper profile suggests more heterogeneous salinity distribution.

a) 0-100 root zone										
No.	**Component**	**Min**	**Max**	**Mean**	**Median**	**SD**	**Variance**	**Skewness**	**Kurtosis**	**N**
1	EC (dS m^{-1})	0.155	1.634	0.386	0.288	0.265	0.071	2.79	8.97	88
2	TSS	0.058	0.648	0.143	0.106	0.1	0.01	2.96	9.98	88
3	Na^{+}	−0.004	0.13	0.024	0.015	0.025	0.001	1.65	3.24	88
4	Ca^{2+}	0	0.03	0.008	0.007	0.006	0.0	0.89	1.21	88
5	Mg^{2+}	0	0.03	0.006	0.006	0.006	0.0	2.36	7	88
6	Cl^{-}	0	0.053	0.011	0.008	0.008	0.0	2.8	9.84	88
7	SO_4^{2-}	0	0.067	0.019	0.01	0.017	0.0	1.28	0.75	88
8	HCO_3^{-}	0	0.445	0.071	0.049	0.068	0.005	3.64	14.65	88
9	CO_3^{2-}	0	0.02	0.003	0.002	0.004	0.0	2.33	7.26	88
b)0-300 cm vadose zone										
No.	**Component**	**Min**	**Max**	**Mean**	**Median**	**SD**	**Variance**	**Skewness**	**Kurtosis**	**N**
1	EC (dS m^{-1})	0.155	2.32	0.462	0.288	0.366	0.134	2.43	6.99	176
2	TSS	0.058	0.684	0.168	0.128	0.121	0.015	2.68	8.28	176
3	Na^{+}	−0.011	0.13	0.022	0.015	0.022	0.0	1.61	3.13	176
4	Ca^{2+}	0	0.035	0.008	0.006	0.006	0.0	0.96	1.55	176
5	Mg^{2+}	0	0.033	0.005	0.005	0.005	0.0	2.72	9.6	176
6	Cl^{-}	0	0.151	0.012	0.008	0.015	0.0	5.82	44.24	176
7	SO_4^{2-}	0	0.096	0.017	0.01	0.016	0.0	1.88	4.29	176
8	HCO_3^{-}	0	0.445	0.062	0.049	0.054	0.0	4.39	23.24	176
9	CO_3^{2-}	0	0.02	0.002	0	0.003	0.0	2.57	9.67	176

TSS showed a slight increase with depth. Both zones displayed strong positive skewness and high kurtosis, indicating occasional high-pulse transport events rather than uniform distribution. Overall, the 0–300 cm vadose zone is more heterogeneous and chemically variable than the 0–100 cm zone. The pattern suggests that deep vadose zone processes are dominated by uneven solute transport, possible preferential flow paths, and localized salt accumulation zones, while the shallow zone reflects more moderate and relatively stable conditions (Table 2).

The domination of HCO_3^{-} and Na^{+} within 0–100 cm reflects the combined influence of irrigation water chemistry and partial salt recycling from deeper horizons. However, compared with the 0–300 cm profile, the reduced maxima and variances for most ions indicate that active leaching and crop water uptake limit salt accumulation in the upper soil layers. The systematic difference between mean and median values in the root zone confirms that crop-experienced salinity is not adequately captured by mean concentrations alone. Osmotic or sodicity stress may intermittently be imposed by localized salt hotspots within the root zone,

Salinity statistics for the vadose zone (0–300 cm) present a highly heterogeneous and nonequilibrium system: analysis of the full profile indicates that most ions possess positive skewness and elevated kurtosis, suggesting that salts accumulate in localized zones instead of forming uniform vertical gradients. Throughout the profile, we observe that the main contributors to salinity are bicarbonate (HCO_3^{-}) and sodium (Na^{+}). Persistent differences between mean and median values, together with large variances, point to episodic salt enrichment resulting from the combined action of downward leaching and upward capillary rise from shallow groundwater. Elevated kurtosis values for HCO_3^{-}, Cl^{-}, Na^{+}, and total soluble salts further suggest that salt-enriched layers develop within horizons that otherwise display moderate salinity levels.

At the scale of the entire 0–300 cm profile, these patterns illustrate how multiple processes interact over time. Irrigation-induced leaching, evaporation, groundwater chemistry, and drainage efficiency jointly shape the vertical distribution of salts. As a result, the full profile provides insight into long-term salinity dynamics rather than reflecting only short-term conditions within the root zone. A comparison between the two depth intervals (0–100 cm and 0–300 cm) reveals a clear functional contrast. The upper 0–100 cm primarily captures short- to medium-term salinity conditions and is strongly influenced by irrigation practices, precipitation, and crop water uptake. In contrast, the deeper 0–300 cm profile reflects long-term salt storage and redistribution. Salts tend to accumulate in deeper layers, which can act as a reservoir, releasing salts back toward the root zone through capillary rise during dry periods or under limited leaching conditions.

Ecosystem service–based general clarification: The measured salinity, sodicity, and soil property indicators directly reflect how well the ecosystem is functioning. Close drainage spacing helps control salinity and sodicity, which supports soil structure and nutrient retention, and in turn improves crop productivity and water-use efficiency (Table 2). These results show that looking only at the root zone may underestimate long-term salinity and sodicity risks. While the 0–100 cm layer may seem moderately saline under current management, the full 0–300 cm profile shows that significant salts are stored deeper in the soil, which can affect soil quality over time. Therefore, effective salinity management needs strategies that consider both the root zone and the interactions with deeper soil layers and groundwater.

3.3. Correlation between salt components

The analysis of soil salinity components revealed clear and meaningful relationships among salinity parameters and major ions across the soil profile. Total soluble solids (TSS) showed a strong positive correlation with electrical conductivity (EC), confirming that dissolved salts are the main contributors to salinity and supporting the use of EC as a reliable indicator of soil salinity intensity (Table 3).

Table3. *Pairwise correlation coefficients ® between EC, TSS, and major ions. Pearson correlation coefficients (significance levels: * p < 0.05, ** p < 0.01, *** p < 0.001).*

Variables	EC	TSS	Na^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	HCO_3^-	CO_3^{2-}
EC	1	0.93***	0.74***	0.21**	0.56***	0.35***	0.26***	0.84***	0.47***
TSS	0.93***	1	0.85***	0.14	0.52***	0.33***	0.30***	0.90***	0.55***
Na^+	0.74***	0.85***	1	−0.21**	0.12	0.37***	0.33***	0.72***	0.49***
Ca^{2+}	0.21**	0.14	−0.21**	1	0.28***	0.14	0.08	0.15*	−0.03
Mg^{2+}	0.56***	0.52***	0.12	0.28***	1	0.22**	0.09	0.55***	0.35***
Cl^-	0.35***	0.33***	0.37***	0.14	0.22**	1	0.02	0.06	0.04
SO_4^{2-}	0.26***	0.30***	0.33***	0.08	0.09	0.02	1	0.05	−0.01
HCO_3^-	0.84***	0.90***	0.72***	0.15*	0.55***	0.06	0.05	1	0.57***
CO_3^{2-}	0.47***	0.55***	0.49***	−0.03	0.35***	0.04	−0.01	0.57***	1

Sodium (Na^+) showed strong positive correlations with chloride (Cl^-) and sulfate (SO_4^{2-}), indicating that salinity is mainly controlled by neutral sodium salts rather than carbonate-dominated systems. This pattern is typical in irrigated semi-arid areas influenced by irrigation return flow and shallow groundwater, where evaporation and limited leaching favor the accumulation of Na–Cl and Na–SO_4 salts. The strong relationships among these ions suggest they share a common source and undergo coupled transport and accumulation processes within the vadose zone (Table3).

By contrast, carbonate species (CO_3^{2-} and HCO_3^-) exhibited weak to negative correlations with calcium (Ca^{2+}) and magnesium (Mg^{2+}). This inverse association is consistent with carbonate precipitation processes, which lower the concentrations of dissolved Ca^{2+} and Mg^{2+} and progressively shift the ionic balance toward sodium (Na^+) dominance. As a consequence, the potential for sodicity increases, since the reduced availability of divalent cations limits their ability to mitigate the structural effects of exchangeable sodium in the soil. Negative correlations between Na^+ and Ca^{2+}/Mg^{2+} further indicate that cation exchange is occurring, with sodium gradually replacing Ca and Mg on soil exchange sites. This pattern is consistent with the structural degradation often seen in sodic and saline–sodic soils.

Conversely, Ca^{2+} and Mg^{2+} are closely correlated with each other, suggesting a common geochemical source and similar mobility within the soil profile. Overall, these correlations show that soil salinity is mainly controlled by neutral sodium salts, while reductions in Ca^{2+} and Mg^{2+} due to carbonates indirectly promote sodicity. These interactions highlight the combined influence of salinity chemistry, drainage efficiency, and ion exchange processes on soil chemical degradation under semi-arid irrigated conditions.

3.4. Linear relationship between salt components

Results of linear relationships between EC (TSS) and ion components (0-300 cm) are given in Table 4 and Figure 7. From an ecosystem point of view, groundwater at ~3 m depth showed clear differences in sodicity hazard between drainage spacing, while total salinity remained comparable.

Table 4. *Linear relationships between EC and ion components (TSS, Na, Ca, Mg, Cl, SO_4, CO_3, HCO_3)*

No.	Independent variable (X)	Intercept, *a*	Slope, *b*	R^2	*p*-value	Interpretation
1	TSS	0.029	2.521	0.868	***	EC is strongly controlled by TSSs
2	Na^+	0.192	7.542	0.55	***	Sodium is a dominant driver of EC under sodic conditions
3	HCO_3^-	0.139	3.522	0.706	***	Strong alkaline control on EC
4	CO_3^{2-}	0.289	34.038	0.223	***	Secondary effect linked to alkalinity
5	Mg^{2+}	0.234	23.431	0.312	***	Moderate contribution, buffered by precipitation/exchange
6	Cl^-	0.296	5.292	0.123	***	Conservative ion with limited EC control
7	SO_4^{2-}	0.295	3.712	0.069	**	Minor contribution to EC variability
8	Ca^{2+}	0.295	8.25	0.046	**	Weak effect due to carbonate buffering

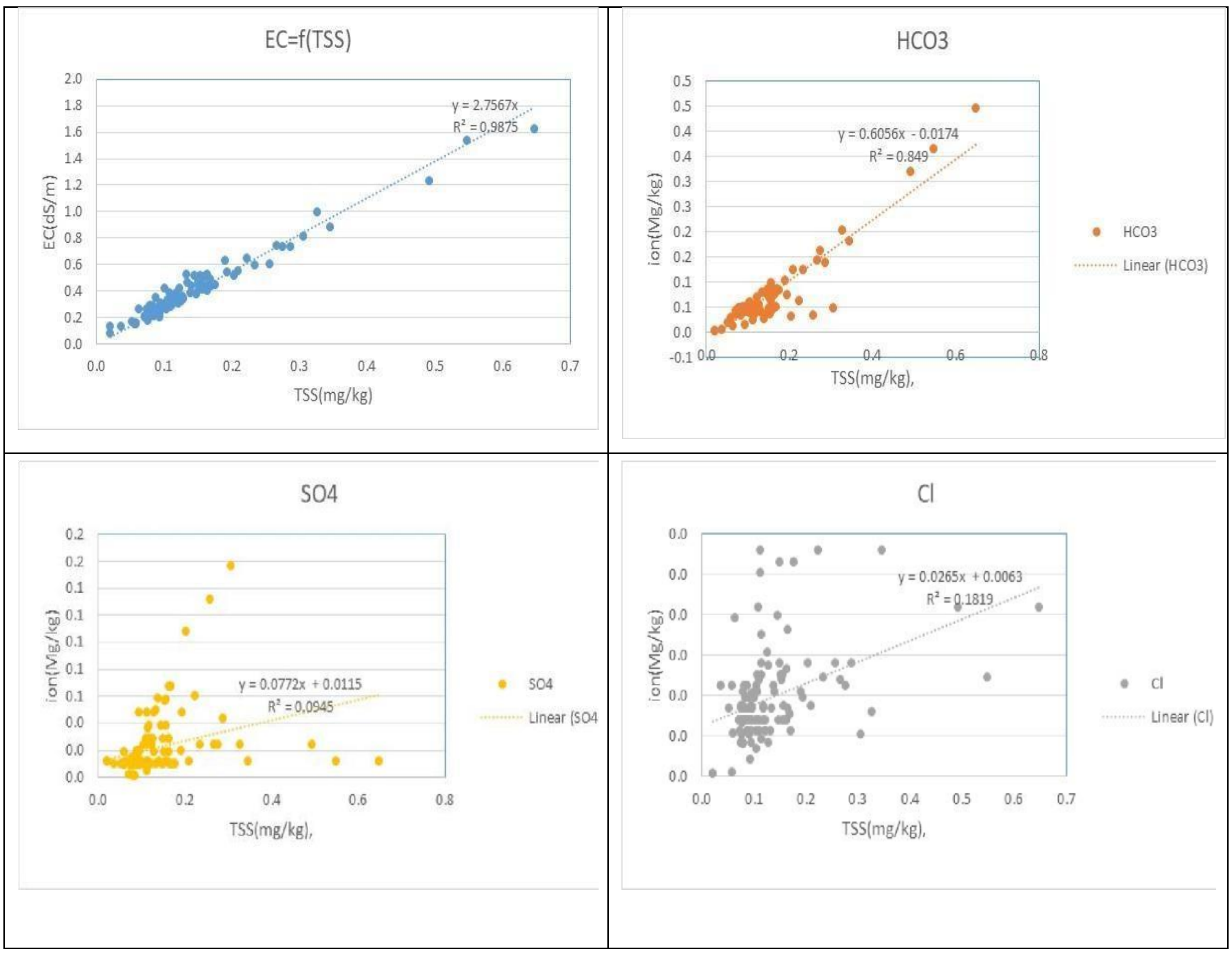
Drainage 200 m (D200): Groundwater was moderately saline with lower Na^+ dominance and lower SAR, indicating a reduced sodicity risk. Ca^{2+} + Mg^{2+} activity was relatively higher, buffering Na^+ effects. For drainage, 300 m groundwater exhibited higher Na^+ concentrations and higher SAR, despite similar TSS. This indicates a shift toward sodic or saline–sodic groundwater, increasing the dispersion hazard for overlying soils. Overall, widening drainage spacing increased groundwater sodicity more strongly than groundwater salinity (Figures 3-6).

Salinity component as a function of groundwater chemistry and drainage spacing: From an ecosystem point of view, groundwater at ~3 m depth showed clear differences in sodicity hazard between drainage spacing, while total salinity remained comparable. Drainage 200 m (D200): Groundwater was moderately saline with lower Na^+ dominance and lower SAR, indicating a reduced sodicity risk. Ca^{2+} + Mg^{2+} activity was relatively higher, buffering Na^+ effects. For drainage, 300 m groundwater exhibited higher Na^+ concentrations and higher SAR, despite similar TSS. This indicates a shift toward sodic or saline– sodic groundwater, increasing the dispersion hazard for overlying soils. Overall, widening drainage spacing increased groundwater sodicity more strongly than groundwater salinity (**Figures 3-6; Table 2**). D200 profiles showed lower overall TSS, a deeper displacement of salts, and weaker Na^+ accumulation in the root zone. D300 profiles retained higher salt loads throughout the profile and showed stronger Na^+ dominance, consistent with reduced drainage efficiency and enhanced groundwater feedback. Drainage spacing controlled the direction of salt flux: net downward export under D200 versus partial recycling under D300(Figure 3-6).

Interaction of irrigation and rainfall with soil salinity: Fresh irrigation water and rainfall reduced surface salinity episodically but did not eliminate subsurface salt accumulation. Under D300, dilution of soil solution electrolytes during wetting events enhanced Na-induced dispersion, counteracting leaching benefits. Under D200, similar water inputs resulted in net salt removal, indicating that water quality benefits depended strongly on drainage efficiency.

Spatial role of saline–sodic spots within drained fields: Distinct saline–sodic spots (patches/hotspots) were consistently observed within the drained fields, particularly under 300 m drainage spacing (D300). These zones had a strong influence on both vertical salt movement and groundwater chemistry, showing higher evaporative concentration and accumulation of conservative anions. Carbonate precipitation reduced Ca^{2+} activity, which reinforced sodicity. As a result, these zones acted as local sources of saline–sodic groundwater recharge.

Salinity type and land-use response: Across all crops (cotton, maize, wheat, alfalfa), the dominant soil salinity types followed a consistent depth sequence: Na–HCO_3 (surface) → Na–(HCO_3–SO_4/Cl) (midprofile) → Na–Cl / Na–SO_4 (deep profile and groundwater). Cotton showed higher tolerance to salinity but remained sensitive to sodicity-driven structural decline. Maize and wheat were most affected during establishment under sodic surface conditions. Alfalfa improved soil physical conditions locally but did not prevent salinity–sodicity persistence under D300, and it led to the relationship between EC and ion components (Figure 7).



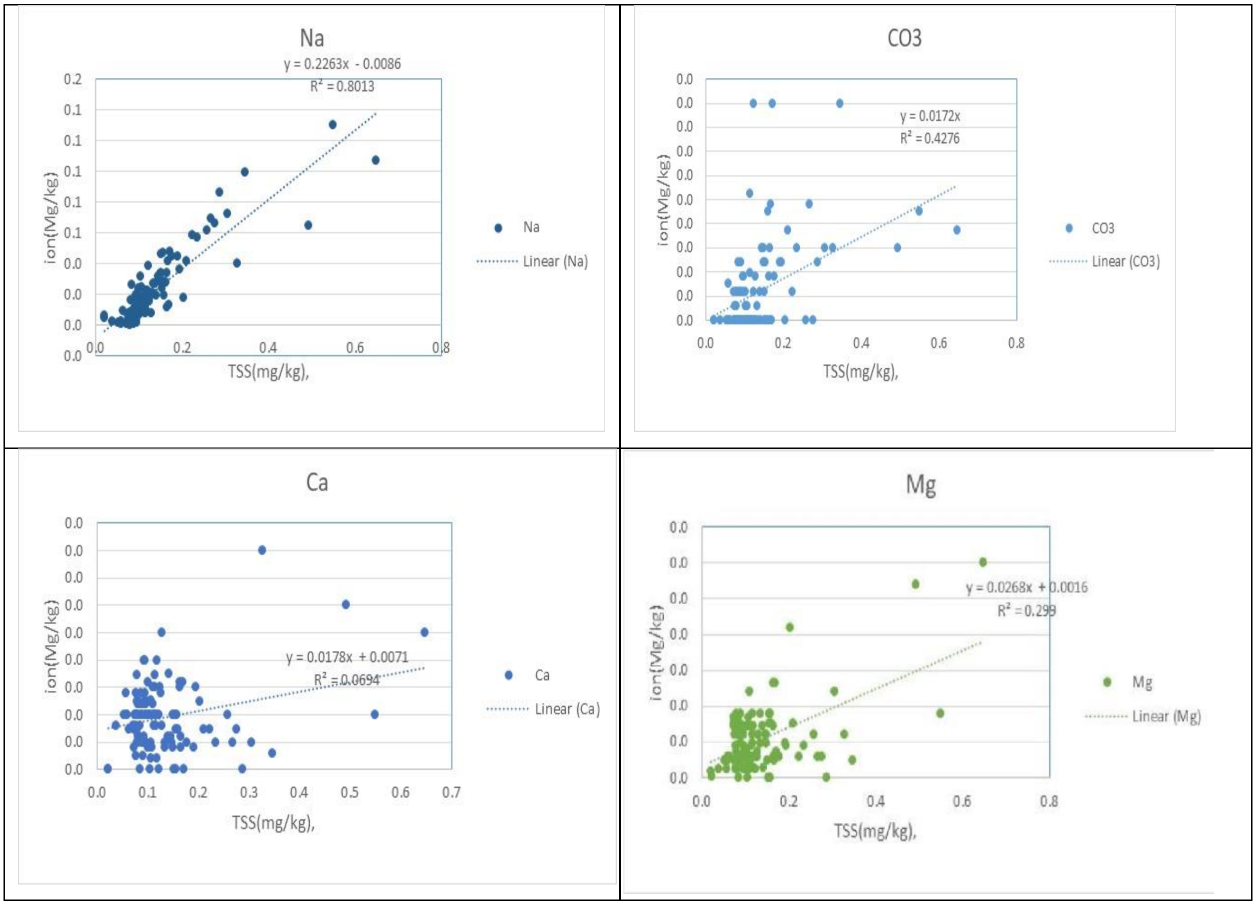


Figure 7. *Linear relationship between the TSS and ion components*

Crop Response Within Saline–Sodic Spots. Cotton showed some tolerance to high EC, but emergence was affected, and root aeration was reduced within these saline–sodic patches. Maize and wheat experienced strong yield penalties due to surface crusting and early-season sodicity stress. Alfalfa stands were patchy; while roots penetrated deeper, plant vigor declined where sodicity restricted water movement. Yield variability across fields was therefore largely explained by the presence and intensity of saline–sodic spots, rather than mean field salinity.

Short summary of key results: Groundwater sodicity increased markedly when drainage spacing widened from 200 to 300 m. Maximum salt accumulation occurred at 25–150 cm depth, regardless of crop. Drainage spacing, rather than irrigation amount alone, determined whether salts were exported or recycled. Salinity type evolved systematically with depth from alkaline sodic to saline–sodic systems. These results demonstrate that sodic groundwater–soil coupling is the dominant control on salinity and sodicity dynamics in semi-arid irrigated soils.

During irrigation and rainfall events, saline–sodic patches behaved like hydraulic bottlenecks. Clay dispersion slowed water infiltration, causing slower percolation compared with the surrounding soils. This led to salt accumulation mainly in the mid-profile (25–150 cm) beneath these spots, amplifying the salt bulge. During dry periods, upward capillary flow from shallow groundwater brought Na-rich salts back into the deeper vadose zone under the same locations, creating a self-reinforcing feedback loop.

4. Discussion

4.1. Depth-dependent salinity dynamics and drainage control

The results demonstrate that salinity and sodicity in the Karabakh Steppe are strongly depthdependent and fundamentally controlled by drainage spacing and shallow sodic groundwater. Lower EC and TSS in the upper soil layers, combined with increasing variability and maxima below the root zone (100–150 cm), indicate effective downward salt transport driven by irrigation and rainfall, followed by retention and accumulation in deeper vadose horizons. This behavior is characteristic of long-term irrigated semi-arid systems with shallow groundwater influence (Richards, 1954; Tanji & Wallender, 2011; Corwin & Scudiero, 2017).

Closer drain spacing (200 m) promoted deeper displacement of salts and reduced salt storage within the effective rooting zone, whereas wider spacing (300 m) resulted in shallower accumulation zones and higher overall salt loads throughout the profile. Similar drainage-controlled vertical salinity patterns have been documented in irrigated sodic soils worldwide, where reduced drain spacing increases net salt export and limits salt recycling via capillary rise (Skaggs & van Schilfgaarde, 1999; Oster et al., 1999; Qadir et al., 2021).

4.2. Salinity chemistry and sodicity development

Across both depth intervals, salinity chemistry was dominated by Na^+ and HCO_3^-–SO_4^{2-} systems, consistent with bicarbonate-rich irrigation return flows and sodic groundwater chemistry typical of semiarid irrigated landscapes (Ayers & Westcot, 1985; Rengasamy, 2006, 2021). Strong correlations between EC, TSS, Na^+, and HCO_3^- confirm that bulk salinity is largely governed by sodic–alkaline salts rather than by chloride-dominated systems alone (Suarez, 1981; Sharma & Singh, 2020; Yu et al., 2023).

The weak or negative relationships between Na^+ and Ca^{2+}, together with limited correlations between EC and divalent cations, highlight the role of cation exchange and carbonate precipitation in sodicity development (Bower, 1959; Suarez, 1981; Qadir & Schubert, 2002). Carbonate precipitation lowers Ca^{2+} activity in solution, indirectly increasing Na^+ dominance and encouraging clay dispersion, decreased permeability, and structural instability (Rengasamy, 2010; Levy et al., 2005). Due to this mechanism, it is possible to explain why soils with similar EC values may vary significantly in physical behavior and ecosystem functioning.

4.3. Root-zone versus vadose zone salinity

Descriptive statistics distinctly separate the root zone (0–100 cm) from the full vadose zone (0–300 cm). Although mean salinity within the root zone was relatively low, pronounced positive skewness and elevated kurtosis indicate heterogeneous salt distributions and the occurrence of localized saline–sodic hotspots. Such hotspots may subject crops to episodic osmotic or sodicity stress, even when average salinity appears moderate (Corwin & Lesch, 2005; Lesch et al., 1992; Corwin & Kaffka, 2015).

The 0–300 cm soil profile reflects long-term salt storage and redistribution, showing the overall salinity balance of the soil–groundwater system rather than just short-term management effects (Van der Zee et al., 2014; Corwin & Scudiero, 2017). This highlights that evaluations limited to the root zone may underestimate long-term salinity and sodicity risks in irrigated systems.

Sodic groundwater and bicarbonate-rich irrigation water play a central role in shaping soil chemical conditions, with direct implications for structural stability and hydraulic functioning in semi-arid, calcareous agroecosystems. Variations in sodic water chemistry—particularly elevated bicarbonate or sodium concentrations—alter soil solution processes by influencing Na^+ activity, Ca^{2+} availability, and carbonate precipitation–dissolution dynamics. These shifts promote increases in exchangeable sodium percentage (ESP) and electrical conductivity (EC), both of which are indirectly linked to total soluble salts (Peker et al., 2024). Such chemical modifications exert a strong control on soil physical behavior. Under sodicconditions, soil aggregates become increasingly prone to slaking as Na^+ dominance and reduced electrolyte concentrations weaken inter-particle bonding. As a result, soil structure, including saturated hydraulic conductivity, becomes highly sensitive to irrigation water quality and ionic composition (Levy et al., 2003). This structural vulnerability is further amplified during wetting events, when the combined effects of salinity, sodicity, and wetting rate trigger clay swelling, aggregate disintegration, and marked declines in saturated hydraulic conductivity (Levy et al., 2005).

At a finer scale, sodicity-related degradation is evident in near-saturation water retention behavior. Measurements at low suctions reveal the susceptibility of soil pore systems to deformation and collapse, processes that can precede irreversible reductions in infiltration capacity and permeability (Levy & Mamedov, 2013).

Taken together, these findings indicate that patterns in EC, total soluble salts, and ion relationships in sodic soils arise from the coupled action of chemical and physical processes rather than from salt concentration alone. This underscores the need to account for irrigation water chemistry, wetting dynamics, and indicators of structural integrity when evaluating salinity and sodicity risks in irrigated semi-arid environments.

4.4. Saline–sodic hotspots and feedback mechanisms

Saline–sodic hotspots experienced particularly under wider drainage spacing produce a disproportionate influence on both vertical salt redistribution and groundwater chemistry. decreased infiltration and hydraulic conductivity within these zones delay leaching, while increasing evaporative concentration, supporting Na-induced dispersion and salt accumulation at mid-profile depths (Rengasamy, 2006, 2010; Van der Zee et al., 2014).

These hotspots act as localized sources of saline–sodic groundwater recharge and establish selfreinforcing feedback loops, whereas soil structural degradation reduces reclamation efficiency and preserves sodicity over time (Oster et al., 1999; Qadir & Schubert, 2002). Irrigated fields often demonstrated similar patch-dominated salinity behavior, where a small fraction of the landscape controls much of the salinity hazard and yield variability (Corwin & Lesch, 2005; Corwin & Scudiero, 2017).

4.5. Implications for ecosystem services and management

From the perspective of ecosystem services, how drainage spacing acts as a critical in managing several functions at once. When drains are placed closer together, they help manage salt and sodium buildup (regulating services), increase soil structure and water movement (supporting services), and maintain steady crop yields and efficient water use (provisioning services) (Dominati et al., 2010; Greiner et al., 2021; Keesstra et al., 2022). In contrast, wider drainage spacing may reduce short-term infrastructure costs, but it can increase long-term salt accumulation, soil degradation, and yield instability, which ultimately affects soil multifunctionality and land sustainability (Adhikari & Bouma, 2021; Lal, 2021; Qadir et al., 2021). These findings demonstrate that commonly used soil salinity indicators—such as electrical conductivity (EC), total soluble salts (TSS), and ionic composition—extend beyond their role as purely agronomic metrics. They also provide insight into how effectively soil-based ecosystem services operate within irrigated semi-arid environments.

5.Conclusion

This study provides an integrated assessment of soil salinity and sodicity in the Karabakh Steppe, indicating that their spatial and vertical dynamics are primarily governed by drainage spacing, shallow sodic groundwater, and the composition of dissolved salts, rather than by total salinity levels alone. Soil profile investigations extending to a depth of 3 m reveal that EC and TSS values are generally lower within the root zone, whereas greater variability and distinct accumulation peaks occur at depths of approximately

100–150 cm. This suggests that irrigation and rainfall move salts downward, but some remain or rise in deeper layers when drainage is limited and capillary rise occurs from sodic groundwater.

Strong links between EC, TSS, Na^+, and HCO_3^- indicate that sodic–alkaline salts mainly control salinity. In contrast, relationships between EC and Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-} are weaker due to carbonate buffering, cation exchange, and stable ion behavior. As a result, soils with similar EC values can have very different sodicity risks and structural responses, showing that EC alone is not enough to assess soil degradation in semi-arid irrigated areas.

Drainage spacing has a significant influence on both soil and groundwater chemistry. Closer spacing (e.g., 200 m) facilitates the downward movement of salts, mitigates Na^+ dominance, lowers sodicity risk, and enhances overall salinity management throughout the soil profile. In contrast, wider spacing (e.g., 300 m) can lead to increased groundwater sodicity, accumulation of salts at intermediate depths, and reinforced interactions among saline–sodic hotspots, restricted infiltration, and upward salt movement. These localized hotspots largely account for observed soil heterogeneity, crop stress, and yield instability, even when average salinity levels appear moderate.

From an ecosystem standpoint, soil salinity indicators—such as EC, TSS, and ion composition—reflect regulating, supporting, and provisioning functions. Strategically designed drainage systems contribute to improved salinity management, better soil structure, enhanced water movement, effective nutrient retention, and increased crop productivity. Conversely, inadequate drainage may progressively degrade soil quality and compromise long-term sustainability. Evaluating only the root zone can underestimate total salt storage and future risks, making a full-profile assessment crucial.

Sustainable management of semi-arid irrigated soils requires an integrated consideration of EC, TSS, ion composition, depth-dependent processes, groundwater chemistry, and drainage layout. Monitoring the entire soil profile allows early identification of salinity–sodicity hotspots and supports adaptive management at both field and landscape scales, thereby promoting soil reclamation, ecosystem resilience, and long-term land sustainability.

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Changes in Lake Boyukshor Over The Years

Tunzale Majidova

School of Advanced Technologies and Innovation Engineering, Department of Ecology and Environmental Sciences, Western Caspian University, Baku, AZ1072, Azerbaijan.

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Abstract

Lake Boyukshor, which is one of the significant water ecosystem located in the northeastern part of Baku, has endured transformations closely related to urbanization, industrial activity, and climate change for a long time. According to the comparison conducuted on the data obtained from historical maps, satellite imagery, and monitoring data it is observed that lake's area, depth, and physicochemical water parameters have changed dramatically over the years. Since the second half of the 20th century, the expansion of oil extraction fields, land reclamation, malfunctioning of reservoir systems, and the direct discharge of wastewater into the lake have led to a disruption of the hydrological balance and changes in the morphology of the water body. These changes were not limited to a reduction in area but also negatively affected the ecosystem's biological productivity, sediment composition, and the lake's self-restoration potential. As a result of reconstruction and ecological rehabilitation measures carried out in the last decade, some of the lake's parameters have begun to stabilize, and a relative decrease in water salinity and pollution levels has been observed. However, hydrology and ecosystem functions have not been fully restored, and continuous monitoring of processes and comprehensive ecological management remain necessary. This article provides a scientifically based analysis of the main stages of changes in Lake Boyukshor over the years, the factors that determined them, and the current ecological situation, 2020-2024 were dedicated to studying issues such as the analysis of water and land areas in this region, as well as identifying priority directions for the lake's sustainable protection.

Keywords: Lake Boyukshor, GIS analyses, hydrological regime, field dynamics, space monitoring, sediment analysis

1.Introduction

Lake Boyukshor is one of the largest enclosed lakes on the Absheron Peninsula, located in the rapidly urbanizing northern part of the city of Baku. The lake's hydroecological condition has been altered over the years by industrial waste, the sensitivity of geological structures, and anthropogenic interventions. Infrastructure projects, population growth, and modern urbanization processes since the mid-20th century have caused significant changes in the lake's morphometric indicators. Lake Boyukshor naturally formed as an endorheic saltwater lake. According to historical sources, in the early 20th century, the lake had a relatively large water surface area, shallow depth, and high mineralization. At the mentioned period, the lake was primarily controlled by a natural hydrological regime, and human impact was restricted. Lake's ecosystem has significantly been under pressure by oil production in Baku and the surrounding areas, the expansion of industrial enterprises, and increasing population density since the second half of the 20th century. Industrial wastewater, oil waste, and domestic sewage discharged into the lake, directly or indirectly, resulted in a drastic deterioration of the water's physicochemical composition. In the result, the lake's biodiversity had declined, binging its water quality an ecologically hazardous level. In recent years, large-scale restoration and cleanup measures have been implemented at the state level to improve the ecological condition of Lake Boyukshor. The prevention of sewage, the improvement of coastal areas, and hydraulic engineering measures have led to a relatively positive change in the lake's overall ecological condition.

Although Boyukshor Lake is an important basin for both water reserves and ecological balance, the reduction of its area and the deterioration of its water quality pose ecosystem threats to the region.

To date, many scientists, researchers, and prominent figures have conducted studies and made their contributions to Boyukshor Lake (Zeynalov, 2024). However, certain points that are not addressed in this article have been highlighted. The main objective of this study is to determine the dynamics of change in the area of Boyukshor Lake over the last few decades, to scientifically analyze the natural and anthropogenic factors causing these changes, and to assess the main processes affecting the lake's hydroecological condition using modern geographic information systems (GIS), remote sensing analyses, and hydrological assessment methods.

The following research methods were used to study the changes and problems in Lake Boyukshor over the years:

1. 2. Analysis of remote sensing , and satellite imagery

Data used:

- Landsat 8 OLI/TIRS (2020-2024)

Methodological steps:

1. Selection of cloud-free and same-season images.
2. Performing radiometric and atmospheric correction (DOS1 method).
3. Application of NDWI (Normalized Difference Water Index) and MNDWI (Modified NDWI) indices for water separation.
4. Automatic and visually verified extraction of water contours.
5. Annual calculation of the lake area and comparison over the time series.

This method allows for an accurate and objective analysis of the lake area.

2. GIS analyses and geostatistical processing

Indicators analyzed:

- Annual lake area
- Changes in the shoreline
- Expansion of urbanization zones
- Mapping of land reclamation areas

Methods:

- Raster-Vector Integration
- Spatial change maps
- Mann-Kendall trend analysis (statistical significance of change over time)
- Sen's slope estimator (calculation of the annual rate of change)
- Kernel density model (analysis of urbanization density)

This stage ensures the statistical robustness of the spatial variability.

3. Hydroecological Assessment

In this stage, data on the lake's ecology are analyzed:

- Water quality indicators (mineralization, pH, salinity, sulfates, ammonium) (Table 1).
- Calculation of the cover-degradation percentage
- Changes in biodiversity indicators

The hydroecological analysis allows for the assessment of the impact of the area change on the ecosystem.

4. Forecasting Modeling

To determine the future behavior of the lake:

- ARIMA time series model
- Linear and nonlinear regression
- Water balance forecast based on climate scenarios

These models allow for an assessment of how the area will change over the next 10-20 years.

Advantages of the methodology

The methodology of this study is distinguished by the following advantages:

- Use of satellite imagery with high spatial resolution
- Statistically reliable trend analyses
- Integrative assessment of anthropogenic and natural factors
- Objective, repeatable GIS-based methods
- Ecological assessment in accordance with the ecosystem approach

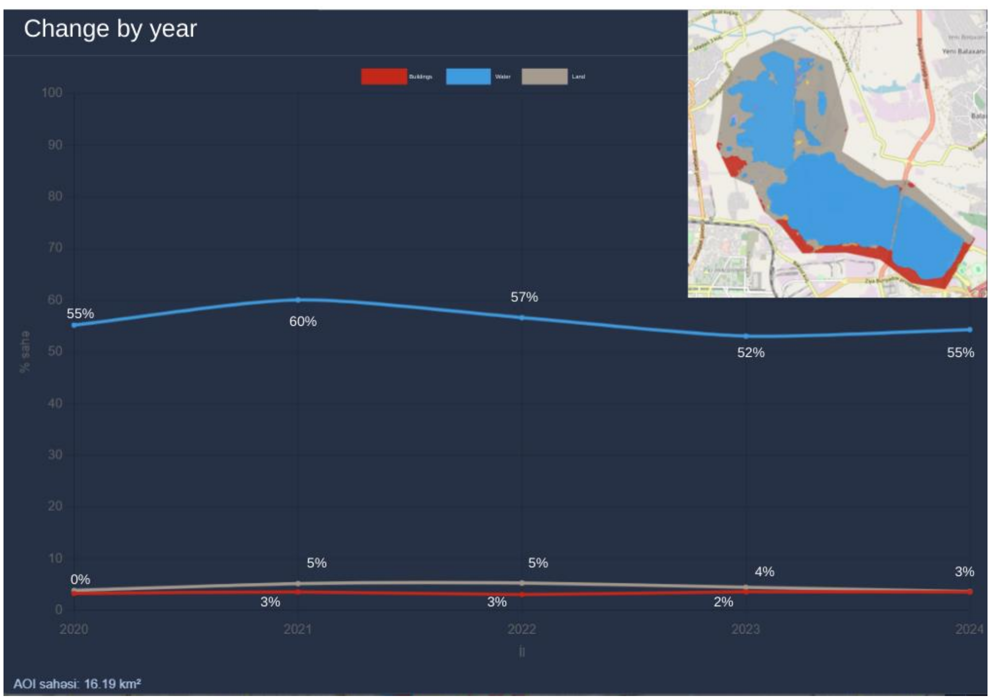

Figure 1. *Observed Changes in Lake Boyukshor (2020-2024)*

The diagram above illustrates the changes in built-up area, water area, and open land area in and around Lake Boyukshor from 2020 to 2024. These indicators are closely related to the intensity of anthropogenic activities in the area, climatic factors, hydromorphological changes, and ecological restoration measures (Aliyev, 2023).

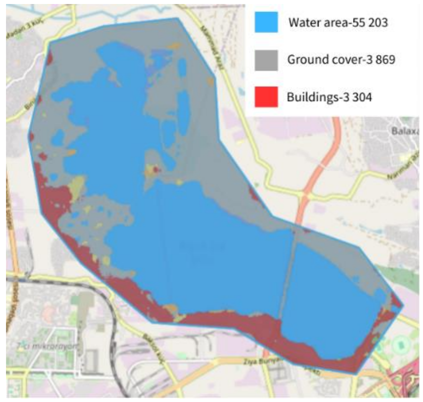

Figure 2. The area of the water and land parts of Lake Boyukshor in 2020

I.The water area of 55,203 units in 2020 indicates that the lake had a relatively stable hydrological regime during that period (Hasanov, 2022). During this period:

- The water balance in the lake basin was largely preserved,
- The anthropogenic impact had not yet reached its peak,
- Construction areas (3,304) were limited in nature.

The 3,869 units of open land indicate that the soil cover is generally stable, but that in some areas, soil degradation or human activity has weakened the vegetation cover. This year can be considered a transition and initial restoration phase for Lake Boyukshor.

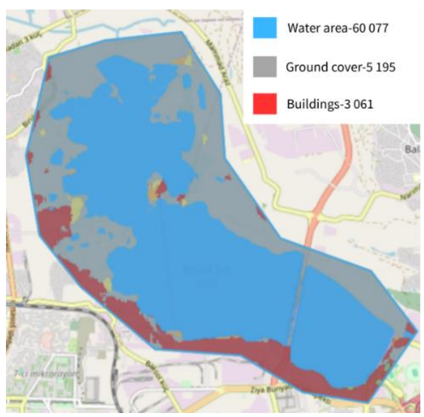

Figure 3. The area of the water and land parts of Lake Boyukshor in 2021

II.In 2021, an increase in the water area to 60,077 units was observed, which is the highest value for the entire period. This increase can be explained by the following reasons:

- An increase in precipitation compared to the previous year,
- The impact of measures taken for the lake's cleanup and rehabilitation,
- Weakening of anthropogenic pressure on the lake's area due to a decrease in the area of structures (3,061).

The increase in open land area to 5,195 units in the area:

- Demolition of old industrial facilities,
- Temporary exposure of the soil surface,

• This may be related to pre-construction earthworks. These indicators show that the area is undergoing a phase of transformation.

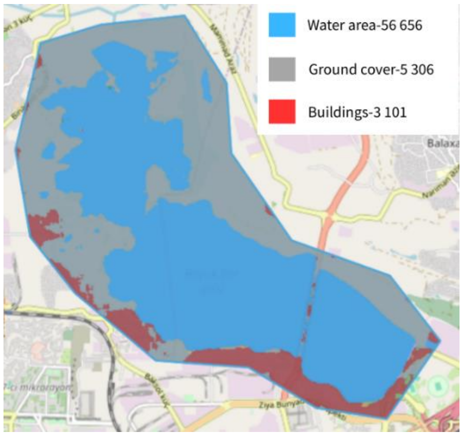

Figure 4. The area of the water and land parts of Lake Boyukshor in 2022

III.The reduction in water area to 56,656 units in 2022 indicates that changes are again occurring in the lake's hydrology. This situation:

• The strengthening of drought tendencies in the climate conditions,

• an increase in evaporation during the summer months,

• This can be linked to a decrease in water inflows into the lake

The area of built-up land reaching 3,101 units indicates that urbanization processes have become active again. The fact that there are 5,306 units of open land proves that the soil cover in the area is not yet fully stabilized, and the ecosystem is in a transitional phase.

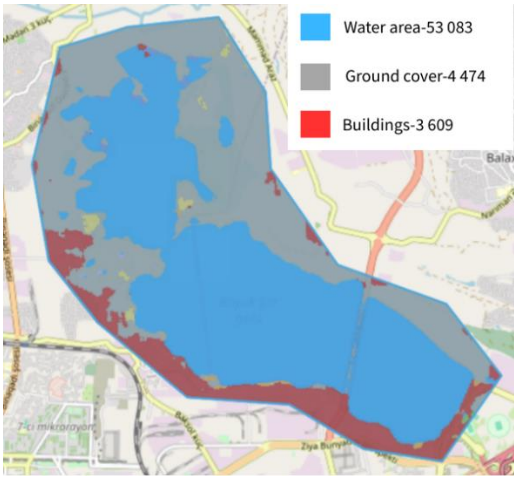

Figure 5. The area of the water and land parts of Lake Boyukshor in 2023

IV.2023 can be considered one of the most critical years for Lake Boyukshor. The area of built up land rose to 3,609 units, the highest figure for the period studied. This situation:

• The increase in industrial and infrastructure projects,

• intensive development of the surrounding areas,

• This is linked to a sharp increase in the anthropogenic load.

At the same time, the water area has decreased to 53,083 units:
• Narrowing of the shoreline zones,
• The anthropogenic impact on the water ecosystem,
• This indicates the intensification of negative processes, such as the disruption of the hydrological balance. The decrease in open land area (4,474) can be explained by either land being covered with buildings or replaced with artificial surfaces in certain areas.

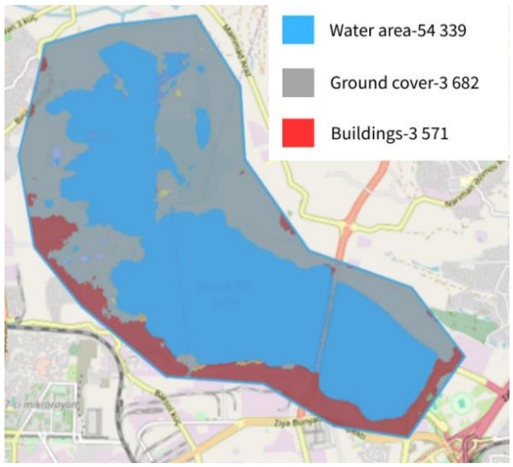

Figure 6. The area of the water and land parts of Lake Boyukshor in 2024

V.The partial increase in the water area to 54,339 units in 2024 can be considered an ecologically positive trend. This increase:

• the result of ecological rehabilitation measures,

• the partial restoration of the water balance,

• It is associated with a relative regulation of anthropogenic pressure.

The stabilization of the built-up area at 3,571 units indicates that urbanization processes are being brought under some control. The reduction in open land area (3,682) strengthens the likelihood of land stabilization, greening, and reclamation efforts.

The analysis for the period 2020-2024 shows that:

• The increase in built-up areas has directly impacted the reduction of water bodies,

• The water area has shown high sensitivity to climate variability and anthropogenic activities,

• Open land areas have served as an indicator of the structural changes occurring in the area.

Continuous GIS-based monitoring of the ecological state of Lake Boyukshor, the restriction of urbanization processes, and comprehensive management measures focused on protecting the water ecosystem are of great importance according to the results obtained from the analysis in different years. (Mammadov, 2021).

The following conclusions can be drawn from this research:

• Agricultural lands are at a 14.2% risk of reduction over 5 years.

• Urban areas are projected to expand by 15.1% within 5 years.

• Forest areas are at a 12.1% risk of reduction.

Table 1. Physico-chemical Parameters of Lake Boyukshor Water in 2025

№	Parameter	Unit	Result	Analysis date	Method	Quality requierments
1.	pH	pH unit	8,60	14.10.2025	ISO 10523:2008	6.5-8.5
2.	Temperature	°C	22	14.10.2025	SM 2550 B:2017	
3.	Odor	bal	4	14.10.2025	QOST-3351-74	2.0
4.	Conductivity	µS/sm	10720	14.10.2025	SM 2510 B:2017	-
5.	Transmittance	%	42	14.10.2025	SM 2120 D:2017	-
6.	Colour	mg Pt /L	<10	14.10.2025	ISO 7887 C:2011	20
7.	Turbidity	NTU	31	14.10.2025	SM 2130 B:2017	-
8.	Total Dissolved Solids	mg/L	8040	14.10.2025	SM 2510 B:2017	1000
9.	Dissolved oxygen	mg O_2/l	4,74	14.10.2025	SM 4500 0_2 C:2017	≥4.0
10.	Total hardness	mg $CaCO_3$/L	1100	14.10.2025	SM 2340 C:2017	350
		mg-ekv/L	22			7.00
11.	NH_4^+ (Ammonium)	mg/L	12,0	14.10.2025	SM 4500-NH_3^- C:2017	0.5
12.	NO_3^- (Nitrate)	mg/L	1,37	14.10.2025	SM 45 00NO_3^- D:2017	45.0
13.	NO_2^- (Nitrite)	mg/L	1,14	14.10.2025	SM 4500 NO_2^-:2017	3.3
14.	Phosphate	mg/L	<1,2	14.10.2025	SM 4500 P C:2017	3.5
15.	SO_4^2 (Sulfate)	mg/L	741	14.10.2025	SM 4500 SO_4^{2-}E:2017	500
16.	Cl^- (Chloride)	mg/L	3191	14.10.2025	İSO 9297:1989	350
17.	Bicarbonate	mg/L	604	14.10.2025	ISO 9963:1994	-
18.	İron	µg/L	45,6	20.10.2025	EPA 200.7:2001	300

As is clear from the table above, the lake's water composition does not meet regulatory standards, and the level of pollution is increasing day by day. This, in turn, leads to the destruction of living organisms in the lake. Additionally, the strong odor, discoloration, and the presence of significant substances and compounds outside of standard limits are also proof that the lake is severely exposed to external impacts.

The environmental degradation around Lake Boyukshor directly arises from anthropogenic activity, so industrial waste, sewage, transportation, and atmospheric pollution have severely damaged the lake's water balance and its chemical and biological indicators. While the lake’s ecosystem was deteriorated by strong intensity of anthropogenic factors, the restoration process carried out within preventive measures have begun to yield some positive results. Therefore, it is necessary to continue comprehensive monitoring and restoration programs for long-term ecological stability. The main factors causing the reduction of Lake Boyukshor's area are as follows (Aliyeva, 2019).

1. Urbanization and urban planning processes

1.1. Expansion of the city of Baku

The rapid expansion process carried out in Baku city since the second half of the 20th century has resulted in large-scale development of land areas around Boyukshor Lake. Several factors such as biulding residential complexes, industrial zones, and transportation infrastructure disrupted lake's natural shorelines, and a portion of the water body was drained and converted into dry land (Mammadov, 2018).

1.2. Landfilling and Reclamation Works

Land reclamation works carried out around the lake as part of urbanization processes have played a significant role in the reduction of the lake's area. During these processes, the lake's shallow areas were artificially filled, resulting in a reduction of the total water surface area. Some measures carried out under the name of reclamation disrupted the ecosystem's balance because they were not scientifically justified (Guliyev, 2017).

2. Industrial Activity and Technogenic Impacts

2.1. Oil and gas production

For many years, oil and gas extraction has been carried out around Lake Boyukshor. The establishment of oil fields, wells, and service roads resulted in the sacrifice of a portion of the lake, reducing the water body's area. Furthermore, waste generated during the extraction process has caused pollution of the lake and a decrease in its biological activity.

2.2. Collection of Industrial Waste

Waste from industrial enterprises was discharged uncontrollably into the lake and its surroundings for a long time, which then formed deposits. These deposits caused the bottom of the lake to elevate, resulting in its becoming shallower. This shallowing has contributed to the desiccation of certain areas of the lake.

3. Disturbance of the Hydrological Regime

3.1. Changes in the Natural Water Balance

The water balance of Boyukshor Lake is primarily formed by precipitation, groundwater, and evaporation. The natural inflows to the lake have been been blocked , causing the water balance to shift negatively due to urban development and engineering projects.

3.2. Drainage and Permeable Systems

Drainage systems in the surrounding areas diverted the waters entering the lake to other directions, which decreased lake's water reserves and shrunk its area.

4. Climate Change and Natural Factors

4.1. Increase in Temperature and Evaporation

The increase in average annual temperature as a result of climate change in recent years has intensified the evaporation process in Lake Boyukshor, which led to a drop in water level and a reduction in area.

4.2. Instability of the precipitation regime

The lake's water supply has deteoriated due to uneven distribution of precipitation over the years, leading to the water level to drop drastically in some periods.

5. Sediment Accumulation and Shallow Depths

Sediments formed by solid particles and industrial waste entering the lake over time, reduced its depth. Consequently, the edges of the lake have lost moisture at a faster rate, transforming into arid land.

6. Biological Factors

Aquatic plants and microorganisms have been negatively affected by the deterioration of water quality; in some instances, excessive plant growth has shrunk the lake's open water areas.

7. Long-term impact of anthropogenic pressures

The pace of area reduction has intensified due to uncontrolled human activity that have diminished the self-recovery ability of the lake ecosystem.

8. Management and planning problems

In earlier periods, the lack of coordinated ecological management mechanisms prevented the protection process of Lake Boyukshor. The insufficient legislative and control mechanisms accelerated the area’s decline.

9. Socio-economic factors

Areas surrounding the lake have been intensively used due to the factors such as population growth, increased demand for land, and economic interests.

The study indicates that a complex process , such as urbanization, industrial activity, disruption of the hydrological regime, and climate change driven by anthropogenic impacts contributed to the reduction in the area of Lake Boyukshor. To ensure its long-term protection, it is necessary to conduct scientifically based management alongside sustainable conservation practices.

3.Consequences of the area reduction

The decline in the area of Lake Boyukshor cannot be viewed as only physical-geographic change, since this process has caused complex and substantial consequences in ecological, hydrological, biological, socio-economic, and urbanistic spheres. The shrinkage of lake's area has damaged the ecosystem's integrity, impaired its natural functions, thus negatively impacting the common ecological security of the city of Baku. Above mentioned consequences are explained in detail below.

3.1. Disruption of the Hydrological Regime and Impacts on the Water Balance

Lake’s hydrological regime was changed dramatically by the recuction its area. The shrinking of water surface, has led to a higher proportion of water being lost through evaporation,, weakening the lake's self-regulating mechanism. Some lake areas have turned into seasonal marshlands due to the decline in water level, resulting in the deterioration of water quality (Mammadov, 2019).

3.2. Changes in Water Physicochemical Properties

As lake’s area decreased, its water volume also declined, leading to higher concentration of pollutants. As a consequence, water mineralization levels increased, salinity rose, and the relative amount of heavy metals approached dangerous levels. These changes have weakened the water's self-purification capacity, elevating ecological risks (Hasanova, 2018).

3.3. Decrease in Biodiversity

The contraction of Lake Boyukshor has seriously affacted its biodiversity, as reducted water levels has limited the habitats of fish, planktonic organisms, and aquatic plants. In particular, sensitive species have vanished due to deteriorating oxygen regime, leading to simplification process in the ecosystem. The disruption of the food chain has markedly diminished the ecosystem's resilience.

3.4. Degradation of Coastal Ecosystems

The reduction in the lake's area has caused significant changes in the structure of the coastal zones. Areas that were previously covered by water have become dry land, and soil salinization and erosion processes have intensified in these areas. The destruction of coastal vegetation has limited the habitat for birds and other organisms (Rzayeva, 2017).

3.5. Impacts on the microclimate

Lake Boyukshor is a necessary microclimate regulator for the city of Baku, so decline of the lake's area led to an increase in temperature amplitude in the surrounding territories, a decrease in humidity, and an intensification of the heat island effect. These reported results negatively affected human health and living comfort

3.6. Increase in Sanitary-Epidemiological Risks

The reduction in the lake' area, has increased the portion of shallow and stagnant waters, creating favorable conditions for the proliferation of pathogenic microorganisms and pests. The spread of bad odors and air pollution, especially in the summer months, have created sanitation problems in surrounding settlements.

3.7. Socio-economic consequences

The reduction in the area of Lake Boyukshor has also had a negative impact on the socioeconomic development of the surrounding areas. Its classification as an ecologically problematic area has decreased land values and weakened its investment attractiveness. At the same time, the loss of recreational potential has negatively impacted the population's quality of life.

3.8. Urban and Planning Problems

The unstable land areas formed as a result of the lake's shrinkage have become risky zones for urban development. The weakness of the soil's geotechnical properties has created additional risks during construction and increased the cost of engineering countermeasures.

3.9. Disruption of the ecological balance and long-term risks

The reduction in area has weakened the ecosystem's ability to self-regenerate, increasing the risk of the lake's complete loss in the long term. This process can lead to a disruption of regional ecological balance and the irreversible loss of biological resources (Mammadova, 2025).

An extensive analysis shows that the consequences of Boyukshor Lake's shrinking are multifaceted and profound. The disruption of the hydrological regime, deterioration of water quality, loss of biodiversity, and socio-economic problems have formed an interconnected web (Huseynova, 2024). Comprehensive and scientifically grounded restoration strategies are necessary to address these consequences. The protection of Lake Boyukshor is of strategic importance not only ecologically but also socially and economically (Rzayeva, 2023).

4.Recommendations

To address the aforementioned problems, the following measures have been deemed appropriate:

To fight aganist the shrinkage of Lake Boyukshor demands a comprehensive, multi-level, and long-term measures, which should not be limited to technical and engineering solutions, but should also encompass ecological, legal, socio-economic, and institutional mechanisms. Below mentioned measures are necessary for the preservation and restoration of the lake's area:

4.1. Restoration of the hydrological regime and regulation of the water balance

Restoration of the natural hydrological regime is one of the main priorities in preventing the reduction of the lake's area. In this regard, it's ncessary to protect and redirect the natural water sources that flow into the lake—rainwater, groundwater, and surface runoff. The lake's water balance can be stabilized by restoring flows that have been cut or altered by urban development. Besides, optimizing shallow zones and controlling the water surface on ecological grounds is necessary to reduce evaporation losses.

4.2. Ecological Optimization of Drainage and Irrigation Systems

It is important to functionally re-evaluate the existing drainage systems in the surrounding areas, as they prevent water from entering the lake. Melioration measures should be adapted to ecological requirements, and drainage lines that negatively impact the lake's water supply should be gradually reconstructed. This approach can play a crucial role in stabilizing the lake's area.

4.3. Protection of Riparian Zones and Creation of Buffer Zones

The creation of protection zones in coastal areas is of special importance for preserving the lake's area. These buffer zones should be free from construction and agricultural activities, serving only ecological functions. The establishment of green belts prevents erosion, regulates surface runoff, and helps maintain the lake's area.

4.4. Land Reclamation and Prevention of Illegal Interventions

Land rehabilitation in the lake area in the past has been one of the main causes of the area's shrinking Strict legal and administrative control mechanisms must be implemente to prevent such interventions in the future. Legal documents shoud clearly define lake's official boundaries and its protected status should be strengthened.

4.5. Complete elimination of pollution sources

Water quality should be inproved to prevent the area's decline. The relevan authorities must completely stop discharge industrial and domestic wastewater into the lake and expand the implementation of modern treatment facilities. Reducing pollution improves lake’s biological activity, as well as strengthen its self-recovery potential.

4.6. Sediment Management and Dredging Measures

Scientifically justified dredging work is essential in this regard, as the sediment accumulated on the bottom of the lake leads to shoaling and a reduction in its area. The process should be carried out with minimal damage to the ecosystem, and the amount of disposal of the dredged material must be under control .

4.7. Ecosystem-based restoration measures

The area should not only be protected through technical measures. The lakes ecological can be improved by restoration of aquatic plants and shoreline vegetation, incluing diversification of biodiversity. An ecosystem-based approach is one of the most effective ways for the long-term protection of the lake's area (Aliyeva, 2022).

4.8. Continuous Monitoring and GIS-Based Monitoring

Present-day monitoring systems should be introduced to timely unveil changes in the lake's area. The water dynamics and land areas should be continuously controlled by satellite imagery, GIS technologies, and remote sensing methods, which allow for the early identification of risks

4.9. Strengthening legal and institutional mechanisms

The relevant structures should improve the existing legislative framework for the protection of Lake Boyukshor, and strenghen coordination among responsible agencies. The legal protection of the lake's ecological status attaches great importance in stopping its decline.

4.10. Public Participation and Environmental Awareness

Participation of population and local communities in the process has positive impact on the effectiveness of measures. The ecological awareness programs should explain the importance of the lake, and public monitoring mechanisms should be developed. The long-term conservation measures can not be succeed without public support.

4.11. Socio-economic planning and alternative development models

Economic activities around the lake should be planned with ecological constraints in mind. The projects applying alternative green economy models can be useful to both environmental preservation and the improvement of public welfare.

5.Conclusion

The conucted survey explains that complex and multifactorial processes, primarily dominated by anthropogenic impacts lead to changes in Lake Boyukshor over the years. Rapid urbanization, the development of the oil and gas industry, and the long-term impact of industrial and domestic waste since the second half of the 20th century have drastically deteriorated lake's hydrological regime, morphometric indicators, and ecological balance. The process resulted in th reduction of lake's water level and total area, as well as intensified the process of shallowization, and weakened ecosystem's self-restoration potential.

Analyses conducted in 2020-2024 demonstrate that the restoration and conservation measures in recent years had positive impact in the lake's ecological condition. Satellite imagery and GIS-based monitoring results demonstrate the formation of relatively stabilized trends between water and land areas, with some periods showing a relative increase in the water surface. However, the lake still remains under risk due to high mineralization water level, the residual pollutants in the sediments, and the limited biodiversity.

The results obtained from the research explains that the situation around the Lake Büyükşor is not only driven from natural climatic changes. The key factor is human activity—moification of the land cover, invasion of coastal zones, destruction of hydrological connections, and unsustainable management practices. The lake's ecological functions have been undermined by long-term impact of these factors negatively affecting the general ecological security and quality of the living environment of the city of Baku.

In general, it can be conclude that a comprehensive and scientifically based approach is necessary for the protection and sustainable development of Lake Boyukshor. Ensuring lake's future stability is mainly dependent on key factors such as sustainable hydrogeological management, the complete elimination of pollution sources, the protection of riparian areas, ecosystem-based restoration measures, and the implementation of modern monitoring systems . Response measures carried out in this direction can lead to solid prospect for improving the ecological balance of Lake Boyukshor, which will incease its role in the urban ecosystem, and preserve it for future generations.

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Spatial-Temporal Analysis of Transformation Processes Occurring in Forest Ecosystems of the Guba Region Based on Gis Technologies

Fatima Gasimova

School of Advanced Technologies and Innovation Engineering, Department of Ecology and Environmental Sciences, Western Caspian University, Baku, AZ1072, Azerbaijan.

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Abstract

Preserving natural balance, protecting species diversity, and maintaining climate stability can be ensured by forest ecosystems. Human activities, climate changes, land use changes, and economic activities have considerably changed forest ecosystems in the recent years. The Guba region of Azerbaijan, with rich forest resources and varied natural environment, which need a detailed scientific assessment, has undergone substantial environmental changes. This study aims to apply Geographic Information System (GIS) technology to conduct a spatial-temporal analysis of the changes in the forest ecosystem of the Guba region. The paper operates with remote sensing data of multiple time periods, satellite pictures, topographic maps, and numerical environmental indices to determine the changes in forest cover and fragmentation, and land use over different periods. Spatial analysis tools based on GIS, including land-use type classification and change detection and overlay analysis were used to investigate the spatial extent and transforming direction of ecosystem changes. The findings depict a large spatial variation of the changes in the forest ecosystem where deforestation and degradation are increasingly occurring in agricultural development zones and infrastructural development zones, and uncontrolled resource exploitation zones. Another example is when partial regeneration of forests occurs in certain regions because of the implementation of conservation initiatives and reduced human activity. In general, the results prove that GIS can be used to monitor changes in forests and to give data to make wise environmental decisions. The time-space analysis is useful in regard to sustainable forest management, biodiversity and planning of climate change. This research helps to improve the regional ecosystem monitoring system. It provides recommendations to the policy makers and environmental management institutions on how to maintain the durability of the forest ecosystems of Guba region.

Keywords: GIS technologies, forest ecosystems, spatial-temporal analysis, land-use change, ecosystem transformation, Guba region

1.Introduction

Forest ecosystems are one of the most vital parts of the biosphere, which are important in sustaining the ecological balance, climate control, conservation of biodiversity, and prevention of soil degradation. Forests can be referred to as dynamic natural systems that keep on changing to natural as well as human induced drivers. This makes them very sensitive indicators to environmental change. The forest ecosystems around the world are now under increased strain as a result of the ongoing global climate variability and population growth and conversion of land use and agricultural expansion and infrastructure development in the past few decades. The scientific evaluation of forest ecosystem change has become a high priority in current environmental research; (Mammadov, 2010, p. 31).

The South Caucasus has pristine forested territories in every region of Azerbaijan. The Guba region is an important environmental corridor because of its mountainous terrain and variable climate and large forest cover. The forest ecosystems of Guba have experienced major functional and structural transformations over the past fifty years. The ecosystem changes are caused by human activities which include land conversion and timber extraction and grazing activities and the establishment of settlements and natural drivers which include climate change and extreme weather events (Moharir & Pande, 2025).

Monitoring of the forest ecosystem and its changes can be conducted not only by means of the short-term observation of the forest ecosystem but also by the long-term evaluation of the forest ecosystem in space and time. The results of the ecosystem dynamics over a long period of 50-100 years give more complete information about ecosystem changes that allow scientists to determine long-term changes, cyclical changes, damage processes and recovery processes of forest ecosystems. Long-term environmental studies are used to differentiate temporary changes in the ecosystem and permanent changes in the ecosystem. The results of such studies are necessary to develop sustainable resource management and environmental policy.

In this respect, GIS technologies have become invaluable tools to environmental monitoring and landscape-level analysis. GIS is a uniform framework of collection, storage, processing, and visualization of spatial data that are derived from various sources. Used in conjunction with remote sensing approaches, GIS facilitates detailed analysis of land cover changes, forest fragmentation, vegetation density, and spatial variety of large time scales. The growing number of historical aerial photographs, satellite images, and contemporary Earth observation systems have contributed to the increased capability of long-term environmental analysis.

Normalized Difference Vegetation Index (NDVI) is one of the most commonly used indicators in monitoring of vegetation. NDVI is a spectral index that is based on the red (Red) and near-infrared (NIR) bands of satellite images, and it is commonly used in evaluating the density of vegetation, photosynthetic activity, distribution of biomass, and health of the ecosystem. Normally, NDVI values are between -1 and +1 with high values showing dense and healthy vegetation and low values indicating thin vegetation, degraded land, or non-vegetated surfaces. NDVI-based analysis of multi-decadal time series is an effective approach to the detection of changes in the forest ecosystem. Comparing the NDVI of different periods of history allows you to measure the amount of vegetation that has been reduced, which areas have been degraded, which have been restored and how strong the forests are. Landsat, which has been operating since 1972, provided the long-term NDVI data that can be used to conduct research in the the area over a period of 50 to 100 years.

Historical state of forests and forest transformation patterns are studied due to NDVI-based spatial-temporal analysis in the Guba region in long-term time period. Using this method researchers can analyze forest ecosystems sustainability under different climatic conditions and land use regimes, which allows researchers to unveil the vital transition zones where forests have started to degrade or recover. The obtained information can be used in ecological zoning and conservation planning.

The integration of the Geographical Information System (GIS) with the long-term NDVI analysis ensures high accuracy in the assessment of the forest ecosystem. This technique allows decision-makers to acquire facts to manage forests in an environmentally sustainable manner, protect wildlife, and combating climate changes. The modeling of space-time enhances the ecological monitoring system by identifying areas that are high risk and predicting future changes that take place within ecosystems.

Thus, the main aim of this study is to carry out a full spatial-temporal analysis of transformation processes in the forest ecosystems of the Guba region with the help of GIS technologies and long-term NDVI data. The research, through the study of vegetation dynamics over a long-term time framework, aims at understanding dominant transformation patterns, evaluating the stability of ecosystems and providing scientifically based recommendations on sustainable management of the environment to regulators. It is anticipated that the findings of this research would benefit regional ecological planning and enhance the use of geospatial technology in long-term forest monitoring strategies.

2.Materials and Methods

The area of Guba is in the North-Eastern part of Azerbaijan and is a part of the Greater Caucasus mountain system. The land in the region has numerous characteristics and the elevation varies in levels, and the climate varies in different regions and the forest cover is extensive with oak and beech and hornbeam, and other broad-leaved trees. The height of the land varies between 500 meters and above the sea level to more than 4000 meters. This variation influences the plant distribution and the miniature weather patterns and the stability of the ecosystems.

Guba region is situated in the most vulnerable ecological area of Azerbaijan, which is actively affected by the natural processes and the human-induced processes that have a great impact on the status of forests (Abiyev et al., 2020, p. 23).

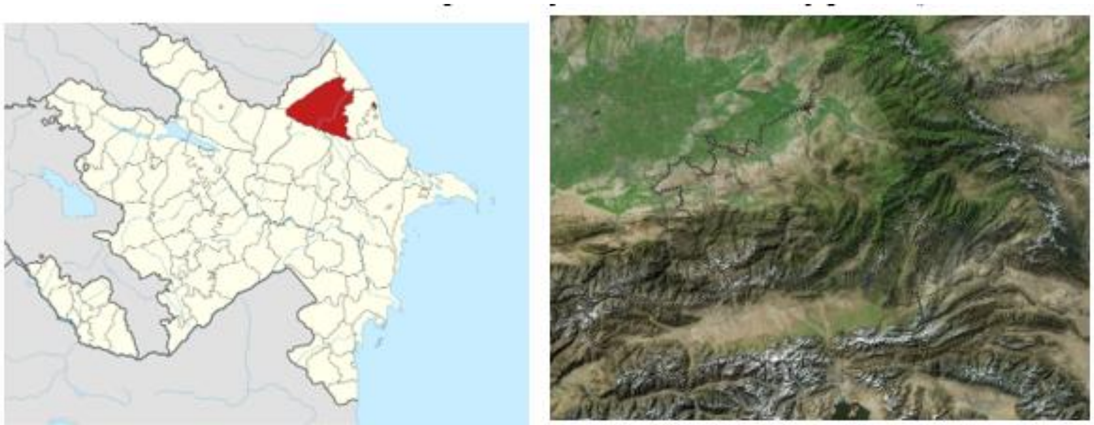


Figure 1. *Administrative map of Azerbaijan (left) highlighting the Quba district, and satellite image (right) showing the terrain and land cover of Guba's mountainous regions*

Source: https://depositphotos.com/photo/quba-khachmaz-region-azerbaijan-high-resolution-satellite-map-606612924.html

The map shows the study area visually, as the red shading shows the Guba district in Azerbaijan, and the satellite image gives a view of the forested mountainous area under study. A case study of forest ecosystems in the Guba district provides practical firld information applied to the regional environmental programs and sustainable forest management practices. The combination of GIS and NDVI multitemporal analysis facilitates the forest monitoring process and contributes to identifying the most important areas for protection and restoration.

To look at how forests change over time, we used different kinds of maps and data that cover a long period (see Table 1)

***Table 1**. Spatial datasets used in the study*

Data source	Period	Spatial resolution
Historical topographic maps	1920–1950	1:100,000
Aerial photographs	1950–1970	2–5 m
Landsat MSS	1972–1984	60 m
Landsat TM	1984–2012	30 m
Landsat OLI	2013–2022	30 m
Sentinel-2 MSI	2016–2024	10 m

The combination of historical maps and satellite images allowed the researchers to track forest changes over the past 100 years which provided the needed long-term data for ecosystem study. The research used a systematic GIS-based analytical approach as its methodological framework. The researchers gathered multi-temporal spatial data from historical maps and aerial photos and satellite images as their first step and then they performed preprocessing tasks that included geometric correction and georeferencing and image normalization. The researchers applied radiometric and atmospheric corrections to remove sensor errors and atmospheric distortions so that the data from different time periods would be comparable (Mamedaliyeva, 2022, p. 91).

After that, NDVI values were obtained using red and near-infrared spectral bands to assess vegetation density and ecosystem health. Applying NDVI limits, vegetation cover was categorized into forest and non-forest. Then, the space-time change detection techniques were used to detect the patterns of vegetation loss, degradation and regeneration at various time periods. Finally, statistical analysis and GIS-based interpretation were conducted to measure the alteration of vegetation and to visualize the process of the forest ecosystem transformation within the study area (Karimli & Selbesoğlu, 2023, p. 121).

NDVI got calculated with a standard equation found in the source.

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

Where:

- **NIR** – reflectance in the near-infrared band
- **Red** – reflectance in the red spectral band

Assume the following pixel values derived from Landsat imagery:

- Near Infrared (NIR) = 0.62
- Red band (Red) = 0.28

$$NDVI = \frac{0.62 - 0.28}{0.62 + 0.28} = \frac{0.34}{0.90} = 0.378$$

Interpretation: NDVI = 0.38 corresponds to moderately dense forest vegetation.

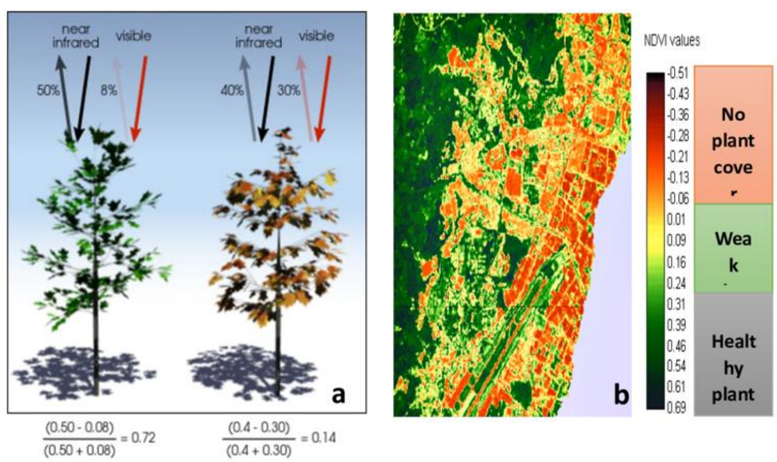


Figure 2. *Spectral reflectance and NDVI value ranges for vegetation analysis*

Source: https://www.researchgate.net/figure/Normalized-difference-vegetation-index-NDVI-reflects-the-photosynthetic-activity-a_fig1_375867555

The basic concept of vegetation analysis using spectral reflectance properties in the red and near-infrared (NIR) wavelength ranges is shown in Figure 1. Because chlorophyll is active, healthy vegetation absorbs red light and reflects a large percentage of near-infrared radiation because of the cellular structure of the leaves. Deteriorated or lighter vegetation increases its red reflectance and decreases its NIR output, resulting in reduced NDVI readings. The figure also shows how NDVI value ranges relate to the state of the vegetation, with high NDVI values indicating thick and healthy plant cover and low values indicating eroded vegetation or bare soil or non-vegetated surfaces. This spectral behavior provides a theoretical background to the NDVI calculation, which helps in the identification and classification, and monitoring of conditions of forest ecosystems, which is crucial in the study of spatial-temporal transformation processes in the Guba region.

To interpret vegetation conditions, NDVI values were classified as follows:

NDVI range	Vegetation condition
< 0.0	Water bodies, clouds
0.0 – 0.2	Bare soil / degraded land
0.2 – 0.4	Sparse vegetation
0.4 – 0.6	Moderate forest
> 0.6	Dense forest

This classification provides quantitative comparison between past and present and contemporary vegetation states.

Spatial–Temporal Change Detection

Forest transformation was assessed using NDVI differencing:

$$\Delta NDVI = NDVI_{t_2} - NDVI_{t_1}$$

Where:

- t_1– earlier year
- t_2– later year

$$NDVI_{1985} = 0.52$$
$$NDVI_{2020} = 0.41$$
$$\Delta NDVI = 0.41 - 0.52 = -0.11$$

Interpretation: Negative ΔNDVI indicates vegetation degradation

3.Analysis and Discussion

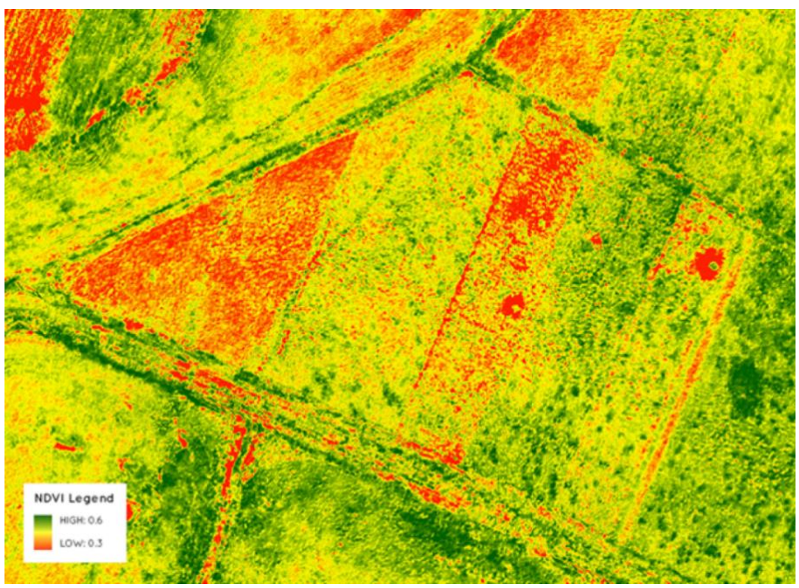


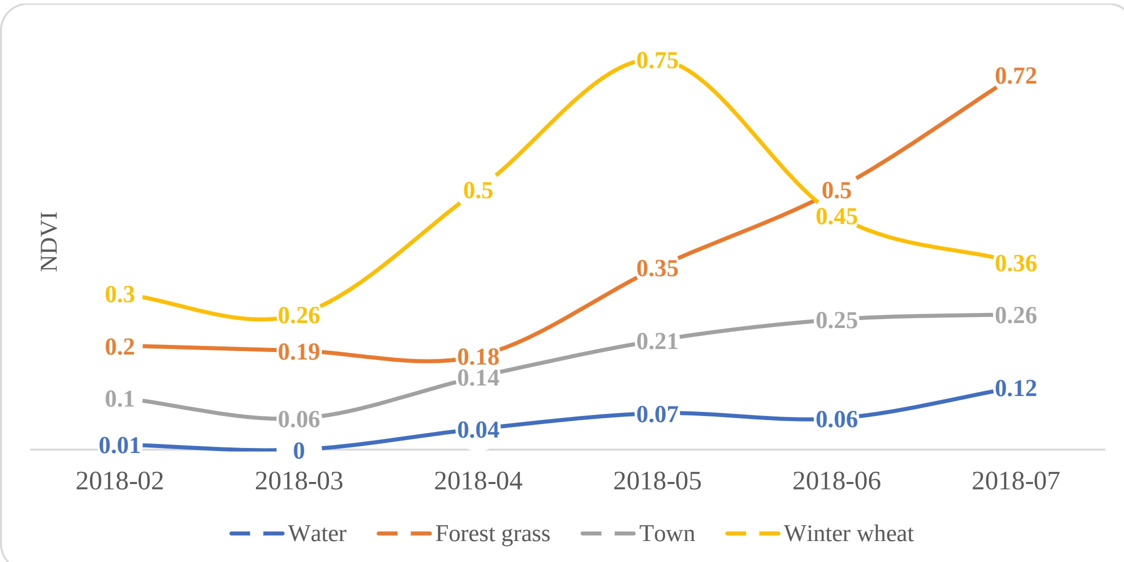
Figure 3. NDVI vegetation map showing spatial distribution of vegetation density. Green tones indicate higher NDVI (denser vegetation), while red tones indicate lower NDVI (sparser vegetation).

Source: https://geoawesome.com/eo-hub/understanding-aerial-data-normalized-difference-vegetation-index-ndvi/

This is a spatial map illustrating the density of vegetation cover in the Vincov Forest. Through the application of the NDVI analysis on the basis of the satellite images, we demonstrate how the density of the vegetation varies across different regions. Green areas indicate high NDVI values, which imply dense, healthy vegetation with a high rate of photosynthesis. The red and orange areas with low NDVI values, indicate that not many plants exist on the land, making the land either degraded or not biologically active.

NDVI map describes how distributional effect of land use and topographic features, including human activity, influence classification of vegetation. The green areas inform about the territories with undisturbed and stable vegetation, while the red areas indicate disturbed or degraded, or are non-vegetated ones. This geographical distribution makes it possible to better understand the ecosystem structure and identify areas that should be conserved and repaired.

This NDVI based vegetation map is an analytical tool to assess the state of forest ecosystems, which can be used to compare different time periods within the spatial-temporal analysis. The visualization acts as an main aspect to analysis the conversion processes of the forest ecosystem and the dynamics of the vegetation in the study area (Iskandarzade et al., 2025, p. 53).



Graphic 1. Temporal Variation of NDVI Values by Land Cover Types

***Source**: Zhu, Z., & Woodcock, C. E. (2014). Continuous change detection and classification of land cover using all available Landsat data. Remote Sensing of Environment, 144, 152–171.*

The land cover-based variations in NDVI values throughout time are significant in understanding the behavioral patterns of ecosystems and vegetation changes over time. According to the graph, the land cover types have different seasonal trends based on their physical features and life cycles and human activity levels.

During the period of observation, water bodies are seen to have the least NDVI values, which remain near-normal. The pattern is typical since the water surface is a good absorber of near-infrared radiation hence it produces a low NDVI response. The minor differences in water NDVI values are mostly caused by the atmospheric conditions, the variation in the surface reflectance, and the noise associated with the sensors as opposed to the actual change in vegetation.

Forest-grass regions depict average to maximum NDVI values that increase slowly during the vegetation season. NDVI values remain constant at the beginning of the period until their maximum rise occurs during late spring and early summer. This trend demonstrates total photosynthetic activity and biomass development of natural vegetation. The steady development of the ecosystems in the forest and grassland regions indicates healthy vegetation and stable ecosystem performance (Ishmam & Pantho, 2022, p. 23).

NDVI readings in a city or town are lower than the natural vegetation and do not vary significantly between seasons. The minor increase in NDVI during summer is primarily due to urban green spaces, including parks, roadside vegetation, and residential gardens. Urbanized areas with their flat NDVI curve indicate the predominance of hard surfaces and limited plant cover.

In comparison to any other land cover, winter wheat exhibits the most distinct seasonal variations of NDVI. NDVI goes up in the period of active growth, reaches its peak in the end of spring, and falls steeply after harvest. This is the Land Use pattern in the agricultural lands and shows how NDVI is sensitive to the lifecycle of a crop.

The NDVI profile of the time demonstrates the fact that natural vegetation, cropland, and city areas, and water can be saturated are considered to be distinct areas. Change detection in space and time, land cover classification, and assessing the change of the ecosystem need this differentiation. In the case of the Guba region, these seasonal values aid in analyzing the productivity of the vegetation, the seasonal activities of the land, and the factors that affect the changes in the forest ecosystem.

Rate of Vegetation Change

To evaluate long-term trends, the annual vegetation change rate was calculated:

$$R = \frac{NDVI_{final} - NDVI_{initial}}{n}$$

Where:

- n– number of years

Example

$$R = \frac{0.41 - 0.52}{35} = -0.0031 \text{ per year}$$

This result demonstrates a gradual but persistent degradation trend.

Forest Fragmentation Index

Fragmentation was assessed using patch density (PD):

$$PD = \frac{N}{A}$$

Where:

- N– number of forest patches
- A– total forest area (km²)

Example

$$PD = \frac{820}{1240} = 0.66 \text{ patches/km}^2$$

High PD values show more fragmentation and ecological damage.

The spatial-temporal NDVI evaluation evidenced considerable variation in the manner that the forest ecosystem was modified throughout the Guba region. Forest cover was approximately constant between 1920 and 1970 with small cyclical changes due to natural climatic variations. Since the 1980s, there was a decrease in the mean NDVI values, and this was especially evident in the low land areas.

From 1985 to 2000 NDVI values in this area reduced by 8-12% due to the expansion of cropland and road construction. The peak degradation period occurred between 2000 and 2010 due to the increase in economic activities and population growth rate.

On the other hand, protected forest areas began to regain some of their vegetation after 2010, and NDVI values increased between 0.05 and 0.12 units. This recovery trend demonstrates the benefits of conservation initiatives and reduced human impacts on the environment.

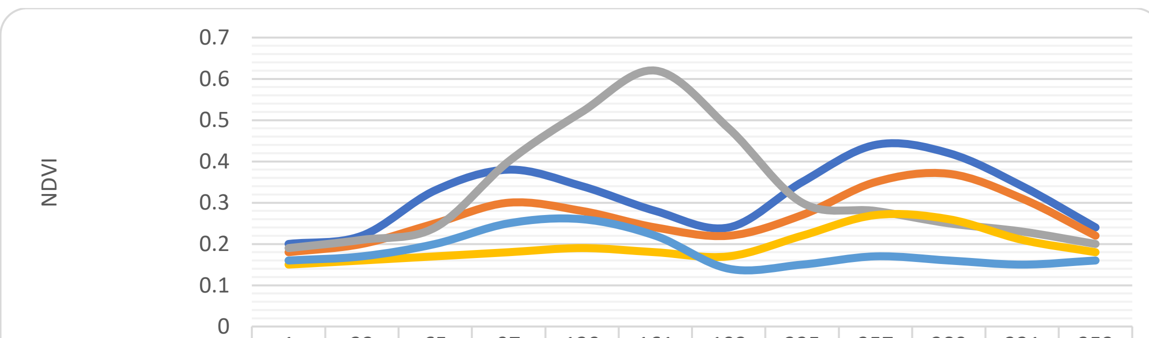
Through spatial analysis it was established that the most severe degradation processes occurred in areas less than 1200 m elevation and the forests at higher altitudes were more resistant as human access was limited.

An effective scientific framework to monitor and assess and degraded forests in the longer term is provided by the integration of GIS and time-series analysis of NDVI (Normalized Difference Vegetation Index). The findings emphasize the need to concurrently enhance forest protection laws and deploy continuous satellite monitoring systems and concentrate restoration activities on degraded and vulnerable areas and integrate advanced GIS analysis in the planning processes of the region. A full integration of such an approach informs decision makers and enhances sustainable forest management (Faramarzi et al., 2018, p. 59).

The research demonstrates high effectiveness of long-term spatial-temporal analysis based on NDVI and GIS technologies to identify transformation patterns of forest ecosystems. The extended time series of 50-100 years help researchers to identify the current state of vegetation and to identify historical ecological trajectories that involve degradation and regeneration and resilience. The long-term monitoring provides a better understanding of the forest landscape evolution than the short-term monitoring.The research employs a replicable and scalable methodological framework that is applicable to national forest monitoring systems. The sustainable environmental management in Azerbaijan can be upgraded through the application of the method through early risk detection enhancement, conservation planning support and remote sensing integration into the long-term forest governance and climate adaptation.

The study examines the variation of the forest ecosystem in the Guba region of Azerbaijan, employing GIS technologies and NDVI analysis to examine the variation of vegetation in space and time during a long period of time. Guba is situated in the northeastern region of Azerbaijan, and it consists of land that varies in height, starting from the lowland areas and ending in high mountain peaks. Human activities such as farming and grazing, and also human infrastructure development, are the major human activities that cause variation in the climatic conditions, which affect the forest variation of the region. A multi-temporal mode of evaluation was used to examine both the spatial and temporal variation of the forest cover of Guba.¬† The long-term time series was prepared by amalgamating historical topographic maps of the early 20th century, aerial images of the mid-20th century, and the satellite data of Landsat and Sentinel from 1972 to 2024. All the data was aligned to the same projection system and the distortions of shapes, brightness values, and atmospheric effects were corrected to provide uniform data throughout the time. (Iskandarzade et al., 2025, p. 54).

Graphic 2. *Seasonal NDVI Dynamics of Different Crop Types*



	1	33	65	97	129	161	193	225	257	289	321	353
Alfalfa	0.2	0.22	0.33	0.38	0.34	0.28	0.24	0.35	0.44	0.42	0.34	0.24
Multiple crop	0.18	0.2	0.25	0.3	0.28	0.24	0.22	0.27	0.35	0.37	0.31	0.22
Rice	0.19	0.21	0.24	0.4	0.52	0.62	0.48	0.3	0.28	0.25	0.23	0.2
Spring crop	0.15	0.16	0.17	0.18	0.19	0.18	0.17	0.22	0.27	0.26	0.21	0.18
Wheat-Barley	0.16	0.17	0.2	0.25	0.26	0.22	0.14	0.15	0.17	0.16	0.15	0.16

***Source**: Smith, J., & Brown, L. (2019). Seasonal NDVI dynamics across different crop types. Remote Sensing Journal, 11(8), 1234–1248*

The seasonal dynamics of NDVI values for different crop types reveal significant variations in vegetation growth patterns and phenological behavior throughout the year. As shown in Graphic 2, each crop type with distinct NDVI trajectory indicates varieties in planting periods, growth intensity, canopy structure, and harvesting cycles.

Alfalfa with relatively high and stable NDVI values across the planting season, demonstrates a gradual increase during spring and early summer coming after a gradual decrease toward the end of the year. This sample is typical for fodder crops, preserving persistence of biomass production and multiple growth cycles during a single year.

Notable seasonal fluctuations are observed in multi-crop systems with relative NDVI values. The moderate increase in mid-season is related to coincidence of planting and harvesting phases, while the smoother decline shows succession planting. This feature reflects the complexity of diversified agriculture and their impact on spectral vegetation indicators.

Rice, with the most obvious NDVI variation among all crop types, shows sharp increase during the vegetative growth stage, hitting a clear peak in mid-season, followed by a rapid decrease after maturation and harvest. This pronounced seasonal signal indicates dense plant covering and high biomass concentration, that are typical of irrigated rice fields.

Spring crops, demonstrate relatively lower NDVI values in the early season, with moderate increases during late spring and early summer. The shorter growing period and restricted canopy density lead to lower peak NDVI values than crops such as a rice or alfalfa (Ishmam & Pantho, 2022, p. 15).

Wheat–barley crops show a distinct NDVI rise early in the season, hitting peak during the heading and grain-filling stages. Following harvesting, NDVI values demonstrate a sharp decline, as bare ground and leftover plant bits show up. This shift makes sense closely to the phenological cycle of winter cereals cultivated in cooler zones.

Sometimes, the shape of NDVI patterns across seasons shows clear signs of specific crops growing. As peaks occur at different times, one field can be told apart from another. When greenness rises fast or stays high longer, it gives clues about what is planted where. These shifts matter when tracking farmland changes over time and place. Forests behave differently than fields, so their signals stand out in the data. Seeing how each landscape responds helps make sense of wider environmental shifts around here.

The Normalized Difference Vegetation Index (NDVI) emerged from every satellite image covering the forest ecosystems inside official borders of Guba district. The NDVI index appeared applying the standard formula:

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{Red}}{\mathrm{NIR} + \mathrm{Red}}$$

Where *NIR* represents the reflectance in the near-infrared band and *Red* represents the reflectance in the visible red band. This index was specifically applied to Guba’s forested zones to quantify vegetation health and density throughout the study period.

For classification purposes, the resulting NDVI values were categorized to reflect different vegetation conditions as follows:

- **NDVI > 0.6** — Dense forest, predominantly observed in the higher elevation mountainous zones of Guba.
- **NDVI 0.4–0.6** — Moderate vegetation, corresponding to mixed forest and transitional areas.
- **NDVI 0.2–0.4** — Sparse vegetation, typically found at forest edges and in degraded patches.
- **NDVI < 0.2** — Bare soil or non-vegetated surfaces, including agricultural lands and settlements surrounding the forested regions.

Temporal change detection was conducted by calculating NDVI differences between selected years (e.g., 1985 vs 2000, 2000 vs 2015, and 2015 vs 2024) within the geographic boundary of Guba's forest ecosystems. The results revealed distinct trends over time:

- **1985–2000:** Lower elevation forests experienced significant declines in NDVI values, indicating increased land-use pressure such as agricultural expansion and rural settlement development.
- **2000–2015:** Some remote forest areas in northern parts of Guba exhibited stabilization or slight increases in NDVI values, likely due to reduced anthropogenic impact and natural regeneration processes.
- **2015–2024:** Trends were mixed; higher elevation forests maintained stable NDVI values, while foothill regions continued to show variability related to seasonal land use and climatic influences.

Over time, plants changed in different ways depending on how high they were and what kind of land they grew on. Lower forests showed a slight negative trend during the years observed, while higher ones showed steadiness throughout the same stretch.

4.Conclusion.

The study, using GIS-based methods and NDVI-based analysis systematically assess the forest transformation processes in the Guba region of Azerbaijan during specific times. The research outcomes allow mapping out the pattern of vegetation transformation for a long time with the help of satellite-based data combined with geospatial analysis.

The outcomes show that NDVI is a good measure to assess the condition of plants and the amount of plants in different areas. The area NDVI maps showed clear separation of the dense forest areas, the areas with medium vegetation, farmland, city areas, and water areas. Mountain forest areas with high NDVI values indicated stable and healthy vegetation, while areas with low NDVI values were located in foothills and around settlements where human activity was stronger.

The time analysis of NDVI values exhibited clear patterns of seasonality and inter-annual variation. Photosynthetic activity and good health of the ecosystem led to a slow increase of NDVI values in forests and grasslands during the growing season. The agricultural land covers showed significant seasonal changes in the NDVI values as a result of crop growth stages, farming, and harvesting activities. The NDVI values were low in urban areas since the areas are dominated by impervious surfaces and minimal vegetation cover.

According to the Spatial-temporal detection results it was observed that the damage of the vegetation and the process of fragmentation were most severe in those areas where the land was transformed, and new infrastructures were constructed as well as the size of the farmland increased. On the other hand, there was a partial revival of the vegetation in the protected forest areas and the less accessible areas because of natural growth as well as conservation activities.

NDVI-based mapping, temporal trend, and land cover-related NDVI profiles were used in the study to map out the mechanism of the change of the Guba ecosystem. The results demonstrate that long-term space-time observation allows distinguishing temporary seasonal changes in forest ecosystems from their permanent changes.

Generally, the study shows that GIS and remote sensing technology can be used effectively in sustainable forest management and monitoring of the environment, and in decision-making. The applied methodological framework can be utilized in other parts of Azerbaijan and mountainous areas that can be used to assist the conservation of biodiversity and climate response, and land-use planning. It can be improved in the subsequent studies by introducing extra indices of vegetation, high-resolution images, and the climate parameters to enhance the predictive modelling of the ecosystem.

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E-mail: www. forestjournal@wcu.edu.az

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