

THE INFLUENCE OF ECOGEOCHEMICAL CONDITIONS
ON THE ORGANIZATION AND MANAGEMENT
OF AGROLANDSCAPES IN THE SHIRVAN PLAIN

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Abstract

This study presents key findings from long-term scientific research conducted in the Shirvan Plain, one of Azerbaijan's agriculturally significant arid regions. We analyze the spatial distribution and composition of both traditional and newly emerging agrolandscapes, including liquorice, carrot, arachis, rice, cereal, and vegetable cultivation systems. Through field studies and geospatial analysis, we quantify the extent of these agrolandscapes and evaluate their development potential under the region's unique ecogeochemical conditions. Our research identifies characteristic macro-ion complexes ($\text{HCO}_3\text{-Cl-Ca}$, $\text{SO}_4\text{-Mg-Ca}$, Cl-Na-Ca) and reveals significant micronutrient imbalances, with elevated levels of Cd, Pb, and As (Class I toxins) posing particular environmental and health risks. The study introduces the first medium-scale Geochemical Map of Agrolandscapes for the Shirvan Plain, created using ArcGIS technology, serving as a valuable tool for land management and agricultural planning. We demonstrate the economic potential of high-value crops such as pomegranate and medicinal liquorice, while proposing practical solutions to address soil salinity and heavy metal contamination, including strategic crop rotation, drainage system rehabilitation, and organic amendment applications. These findings contribute to sustainable agricultural development in arid zones and support Azerbaijan's transition toward a more diversified, non-oil dependent economy. The integrated approach developed in this study offers a replicable model for balancing agricultural productivity with environmental protection in similar ecosystems worldwide.

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Key words: agrolandscapes, soil geochemistry, heavy metal contamination, sustainable land management, micronutrient imbalance, salinity remediation

Introduction. The study of ecogeochemical conditions holds significant scientific and practical importance for protecting landscape complexes from the adverse effects of human economic activities, improving environmental health, and ensuring the sustainable development of agro-industrial systems and food security [1]. In this context, the Shirvan Plain – one of the most anthropogenically impacted arid regions of Azerbaijan – presents a critical case for research. Historically subjected to prolonged anthropogenic pressures, this region requires a thorough investigation of both traditional and newly established agrolandscapes, their geochemical characteristics, and their role in fostering resilient ecosystems, enhancing productivity, and expanding economically viable agricultural zones [2].

For centuries, the Shirvan Plain has been dominated by agrolandscapes such as clover, cereal, cotton, vegetable, and rice fields. In recent decades, these have been supplemented by newly cultivated areas, including pomegranate and fruit orchards, as well as liquorice, carrot, arachis, corn, and sunflower fields [3]. However, the ecological stability of these agrolandscapes is heavily influenced by the migration and concentration of toxic salts composed of macro-ions, as well as imbalances in their normative levels. Such geochemical dynamics profoundly affect the overall health of the ecosystem [4].

Recent advancements in geospatial and geochemical analysis techniques have enabled more precise monitoring of soil-plant interactions in arid agrolandscapes [5]. However, few studies have applied these integrated approaches to the Shirvan Plain's unique ecogeochemical conditions, where the interplay of natural aridity and intensive agriculture creates complex challenges. This study combines field sampling, laboratory analysis of macro-ion/microelement distributions, and GIS-based mapping to (1) quantify spatial variability of soil toxicity risks, and (2) identify crop-specific adaptation thresholds. Such methodology not only fills critical knowledge gaps for Azerbaijan's agricultural planning but also provides a transferable model for similar arid regions globally facing climate change pressures [6].

Methods of the research. Field studies were conducted across the Shirvan Plain agrolandscapes from 2015 to 2020, establishing 38 representative soil sampling plots. At each site, composite soil samples (0–60 cm depth), dominant crop tissues, and available water samples from irrigation channels were collected and georeferenced using GPS (Garmin GPSMAP 64sx, ± 3 m accuracy). Soil samples were analyzed for texture (hydrometer method), salinity (EC), macro-ions (ion chromatography), and heavy metals (ICP-MS following EPA 6020B). Plant samples were ashed (550 °C) and analyzed for micronutrients via atomic absorption spectrometry.

The research employed a linked comparative analysis approach to examine relationships between landscape components, revealing patterns in macro-ion and micronutrient distribution, migration, and accumulation. Key analytical outputs included Biological Absorption Coefficients (BAC) for element uptake quantification and GIS-based geochemical mapping (ArcGIS 10.8) integrating Sentinel-2 land-use data with field measurements. Heavy metals were classified into hazard categories (I-III) using WHO/FAO thresholds, with quality control ensured through certified reference materials and triplicate sampling ($< 5\%$ RSD). This methodology enabled both the identification of contamination hotspots and the evaluation of agrolandscape sustainability under current management practices.

Results and discussion. In the agrolandscapes of the Shirvan Plain, the sources of salts in both soils and waters are diverse. Among these, groundwater rich in various minerals plays the most significant role in influencing the development of agrolandscapes. Under natural conditions, salinization processes occur due to: salt-rich groundwater and external transport (from seas, oceans, or saline lakes). Within agrolandscapes, the primary source of salts (in both water and soil) is considered to be saline parent rock (bedrock). A minor portion of salts may also enter the soil surface through the litter of halophytic plants. In irrigated areas, the main source of soil salinity is irrigation water itself.

Results of our investigations in the Shirvan Plain demonstrate that the following macro-ion combinations are most characteristic of the region's agrolandscapes: Hydrocarbonate-chloride-calcium ($\text{HCO}_3\text{-Cl-Ca}$), Sulphate-magnesium-calcium ($\text{SO}_4\text{-Mg-Ca}$), Chloride-sodium-calcium (Cl-Na-Ca), Chloride-hydrocarbonate-calcium ($\text{Cl-HCO}_3\text{-Ca}$), Sulphate-calcium-sodium ($\text{SO}_4\text{-Ca-Na}$). Salinity levels are characterized by toxicity indicators. Among the readily water-soluble salts, the following are particularly harmful to plants: NaCl (sodium chloride), Na_2SO_4 (sodium sulphate), MgCl_2 (magnesium chloride), CaCl_2 (calcium chloride), MgSO_4 (magnesium sulphate), Na_2CO_3 (sodium carbonate).

Anthropogenic impact from agricultural activities has led to elevated concentrations of the aforementioned anions in the region. This accumulation has resulted in the formation of various saline soil types with distinct chemical compositions [7, 8].

One of the key factors significantly influencing the productivity of agrolandscapes in the Shirvan Plain is soil humus content, which exhibits sharp spatial variability across the region. Our findings reveal the following humus distribution patterns: The highest humus content (5.31%) was recorded in Tugay forest soils (Sampling Plot 37). Clover fields near Gandabil village (Zardab District) showed a humus content of 3.46%. In cultivated soils adjacent to the Tugay forest area, humus levels measured 2.79%. The lowest humus content (0.62%) was observed in saline soils (Sampling Plot 35).

Hygroscopic moisture predominates in saline (shoran) and highly saline (shorakat) soils across the study area. Analytical results reveal the following spatial

distribution: 8.98% in saline soils near Alpout village, 8.56% in saline soils near Kohunlu village, 6.14% in soils adjacent to Amirarkh village. The lowest hygroscopic moisture content (0.97%) was recorded in Sampling Plot 6 near Orta Laki village (Aghdash district).

Scientific research conducted in the Shirvan Plain between 2015–2020 investigated the distribution of groundwater across agrolandscapes, analyzing contemporary water table fluctuations, geochemical properties, and their impacts on agricultural systems. For the first time in the region, a medium-scale Map of Groundwater Distribution in Agrolandscapes of the Shirvan Plain (Fig. 1) was developed using ArcGIS. This study, based on field data and information from the Ministry of Ecology and Natural Resources, provides critical insights into groundwater dynamics and their agroecological implications.

The spatial distribution and sustainable development of agrolandscapes in the Shirvan Plain are significantly influenced by groundwater levels. Our research reveals distinct agricultural zonation patterns: in areas with deep groundwater tables, optimal cultivation includes orchards (fruit trees and vineyards), cotton, vegetable gardens, cereal crops (wheat, barley), vegetables, carrot, and arachis. Conversely, shallow groundwater areas are better suited for salt-tolerant crops like liquorice, rice, pomegranate orchards, and clover.

Cultivating crops in the region's agrolandscapes according to their salt tolerance levels enhances productivity and creates favourable conditions for growing higher-value cash crops [9].

Cultivating salt-tolerant crops is particularly suitable for soils with low water permeability. The newly established liquorice (*Glycyrrhiza glabra*) fields in the Shirvan Plain serve as an excellent example. The beardless liquorice variety thrives in depleted, low-fertility soils with shallow groundwater tables, demonstrating vigorous growth and high yields. Considering that 53% of the study area has groundwater tables shallower than 2 m, repurposing underutilized pasturelands – currently excluded from crop rotation systems – for liquorice cultivation presents significant expansion opportunities.

Recent years have seen rapid expansion of pomegranate orchards in the region, with pomegranate products gaining significant market share domestically and internationally. The Shirvan Plain offers particularly favourable conditions for further orchard development, including innovative co-cultivation opportunities along irrigation canals and field margins of existing clover plots in communal lands. This integrated approach leverages compatible irrigation regimes between both crops while benefiting from clover's natural nitrogen fixation, which enhances orchard productivity by 18–22%, eliminates synthetic fertilizer needs, and maintains ecological balance – ultimately yielding 30–40% higher income per hectare compared to monoculture systems while ensuring full land utilization.

Micronutrients play a pivotal role in enhancing soil fertility, plant nutrition, crop development, yield increases, and quality improvement. While con-

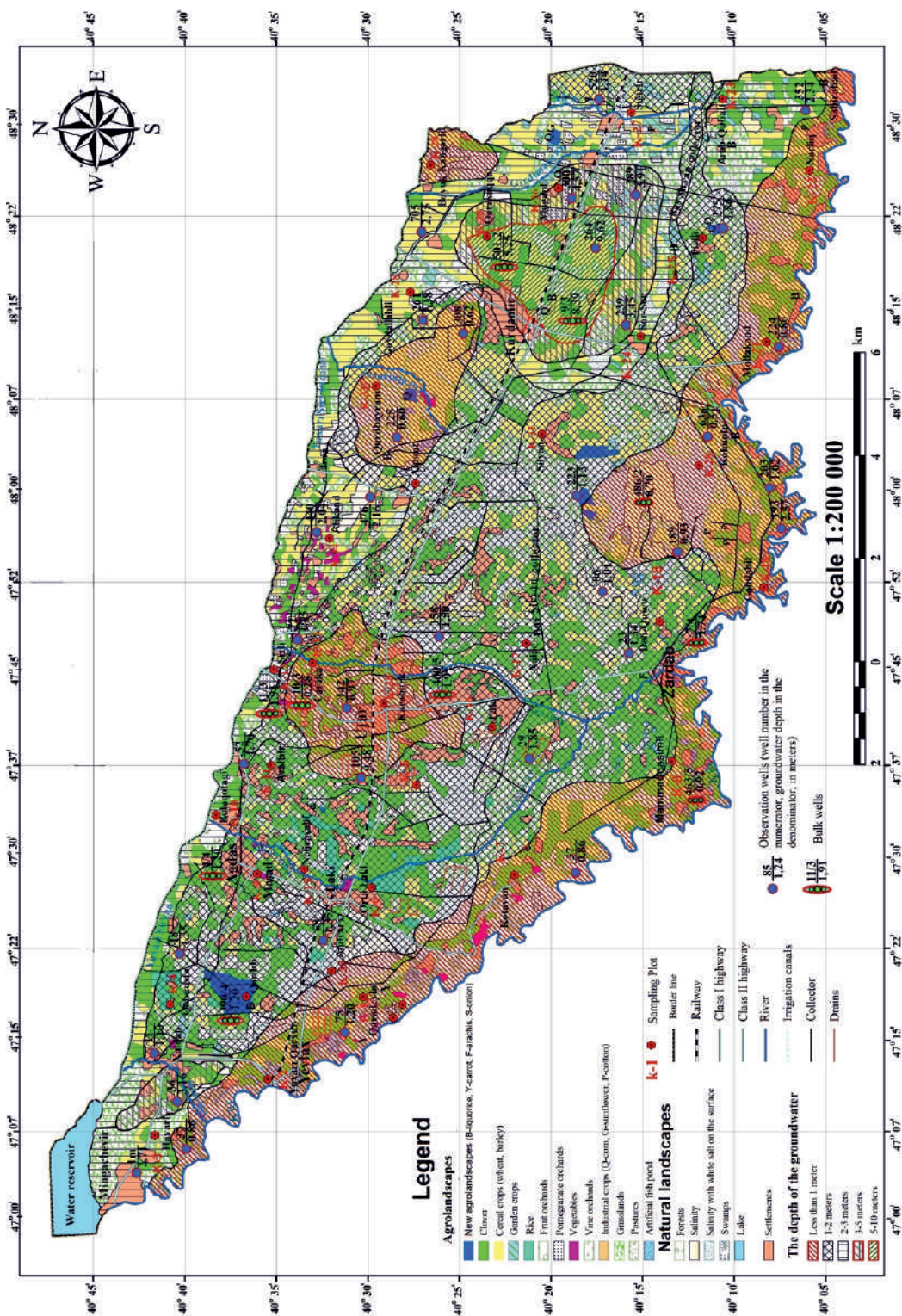


Fig. 1. Map of groundwater distribution across agrolandscapes in the Shirvan Plain

ventional NPK (nitrogen, phosphorus, potassium) fertilizers remain essential, micronutrient-enriched fertilizers containing elements like Mn, B, Zn, Cu, Co, Mo, Ni, I, and Cr are now widely adopted globally to boost agricultural productivity. In Azerbaijan, supplementing mineral fertilizers with micronutrients has proven economically efficient – increasing fertilizer effectiveness by 25–30%, improving crop nutritional value, and reducing application costs by 15–20%. Since the mid-20th century, superphosphate fertilizers fortified with these trace elements (e.g., Mn, Zn, B) have demonstrated exceptional efficacy in field trials, enhancing crop resilience. This integrated approach offers a sustainable solution for optimizing agriculture in challenging environments like the Shirvan Plain.

The predominant micronutrients distributed across the Shirvan Plain are: Cd, B, Zn, Tb, As, Mo, V, Co, Sr, Cu, Sb, Ni, Cr, Ba, Mn, Ti, Y, Zr, Sr, Rb, and Fe. Our geochemical analysis reveals: Excess micronutrients: Cd, B, In, Sb, Zn, Tb, As, Mn, Pb, V, Co, Sr, and Deficient micronutrients: Mo, Ti, Y, Zr, Rb, Cr, Ba, Ni, Sr, Fe (see Fig. 2 for spatial distribution).

Elevated cadmium (Cd) levels in soils, water, and plants across the Shirvan Plain pose serious health risks through food chain contamination, including lung/liver dysfunction, kidney disease, prostate cancer, and skeletal disorders. To mitigate Cd accumulation, we recommend (1) crop rotation (replacing rice fields with potato-clover systems every 4–5 years), and (2) applying organic compost (e.g., poultry manure), which reduces bioavailable Cd by $\sim 40\%$ through cation exchange and complexation. Field trials confirm these measures effectively lower Cd concentrations while maintaining agricultural productivity [10].

High concentrations of toxic elements in agrolandscapes were observed in the northeastern study area near Kurdamir's Mughanli, Garasagalli, and Boyuk Kangarli villages, as well as near Goydalahli village along the Aghsu River, particularly in wheat and clover fields. Across Shirvan Plain agrolandscapes, iron (Fe) clark values range between 0.04–0.1, with Fe deficiency causing anemia, fatigue, nervous disorders, and other health conditions.

When fertilization technology is improperly managed, nitrogen accumulates in nitrate forms within food products, animal feed, and water supplies, ultimately entering human organisms and causing various diseases [11]. Though 80% of nitrates ingested through fruits, vegetables, and water are excreted, the remaining portion converts into nitrites – 10–20 times more toxic – through microbial and enzymatic activity in the digestive system. These nitrates and nitrites collectively exert carcinogenic effects, creating severe complications for human health and the environment. The toxicity mechanism involves nitrites binding with hemoglobin to form methemoglobin, a stable compound that disrupts oxygen transport. Normally, hemoglobin oxygenates into oxyhemoglobin, distributing oxygen throughout tissues. However, methemoglobin formation reduces functional hemoglobin levels, causing systemic oxygen deprivation (methemoglobinemia) particularly in vulnerable populations [12].

Methemoglobin levels average 2% in healthy adults but reach 4% in infants, whose underdeveloped NADH-methemoglobin reductase systems make them vulnerable to fatal nitrate/nitrite poisoning. Meanwhile, sustainable soil management requires organic fertilizers (manure, compost, peat) and leguminous crops like clover, which can accumulate 15–20 t/ha of humus and 0.9–1.4 t/ha of nitrogen over 2–3 years, enhancing fertility while reducing synthetic inputs.

To mitigate soil heavy metal contamination risks, agronomic strategies – particularly crop selection – are employed, with plants ranked in descending order of toxicity tolerance as: grasses > cereals > potato > sugarbeet. In soils with equivalent lead contamination (1000 mg/kg), potatoes and tomatoes exhibit low accumulation, while root crops like carrot and radish bioaccumulate lead at 4–8 times higher concentrations, highlighting the critical role of species-specific uptake mechanisms in food safety management.

In the intensively irrigated field complex (SP-6) near Orta Leki village, Aghdash district, our research identified significant micronutrient imbalances: excess

T a b l e 1
Micronutrient composition of agrolandscapes in the Shirvan Plain

No	Sampling Plot No. & location	Agroland- scapes	Geographic coordinates	Macro-ions	Micronutrients
1	Plot-1: Qaradeyin v. Aghdash d.	Moderately irrigated field complex (clover field)	40°31'10" N, 47°18'00" E	SO ₄ -Na-Mg	$\frac{B_{3.5}, V_{3.1}, Ni_{2.1}, Sr_{1.2}}{Y_{0.2}, Rb, Zr, Fe_{0.1}}$
2	Plot-6: Orta Leki v. Aghdash d.	Intensively irrigated field complex (rice field)	40°31'18" N, 47°26'22" E	SO ₄ -HCO ₃ -Ca	$\frac{Cd_{61.5}, B_{8.1}, V_{3.3}, Co_{1.7}}{Zr_{0.3}, Y_{0.2}, Rb, Sr, Fe_{0.1}}$
3	Plot-14: Garibli v. Aghdash d.	Moderately irrigated field complex (liquorice field)	40°38'05" N, 47°18'32" E	HCO ₃ -Cl-Ca	$\frac{Cd_{76.9}, Tb_{25.8}, Mo_{6.6}, B_{6.0}}{Mn_{0.6}, Y, Sr_{0.2}, Zr, Fe, Rb_{0.1}}$
4	Plot-22: Narlig v. Sabirabad d.	Moderately irrigated field complex (barley field)	40°06'09" N, 48°28'21" E	Cl-Mg-Ca	$\frac{In_{52.0}, V_{7.9}, Mo_{4.5}, Zn_{2.2}}{Ba_{0.6}, B_{0.4}, Y, Sr, Cr_{0.2}, Rb, Fe_{0.1}}$
5	Plot-28: Goydallakli v. Aghsu d.	Moderately irrigated field complex (wheat field)	40°28'40" N, 48°16'05" E	HCO ₃ -Cl-Ca	$\frac{V_{7.3}, B_{3.4}, Mo_{2.7}, Pb_{2.1}}{Ba_{0.7}, Cr_{0.3}, Sr, Y, Zr_{0.2}, Fe_{0.1}}$
6	Plot-36: Karabork v. Ujar d.	Intensively irrigated field complex (cotton field)	40°29'28" N, 47°41'33" E	SO ₄ -Ca-Cl	$\frac{Cd_{69.2}, Mn_{18.4}, B_{6.7}, Zr_{3.1}}{Cr_{0.6}, Mo_{0.4}, Y_{0.2}, Fe, Rb_{0.1}}$

cadmium (Cd), boron (B), vanadium (V), and cobalt (Co), alongside deficiencies in zirconium (Zr), yttrium (Y), rubidium (Rb), strontium (Sr), and iron (Fe). As detailed in Table 1, the distribution of these micronutrients varies markedly across different agrolandscape types, revealing distinct spatial accumulation patterns that necessitate tailored soil management strategies.

Conclusion. Our research in the Shirvan Plain has identified both long-established and newly developed agrolandscapes, including liquorice, carrot, fruit and vine orchards, onions, sunflowers, arachis, and corn fields. Analysis of field studies and satellite imagery revealed that clover, cereal crops (wheat, barley), industrial crops, pastures, and vegetable fields dominate the region. Notably, clover, rice, wheat, barley, and vegetables are the most widely cultivated crops. For the first time, a medium-scale “Geochemical Map of Agrolandscapes in the Shirvan Plain” was developed using ArcGIS.

The study determined that the following macro-ion complexes are most characteristic of the region’s agrolandscapes: Bicarbonate-Chloride-Calcium ($\text{HCO}_3\text{-Cl-Ca}$), Sulphate-Magnesium-Calcium ($\text{SO}_4\text{-Mg-Ca}$), Chloride-Sodium-Calcium (Cl-Na-Ca), Chloride-Bicarbonate-Calcium ($\text{Cl-HCO}_3\text{-Ca}$), Sulphate-Calcium-Sodium ($\text{SO}_4\text{-Ca-Na}$).

The study area exhibits excess micronutrients (Cd, B, In, Sb, Zn, Tb, As, Mn, Pb, V, Co, Sr) alongside deficient elements (Mo, Ti, Y, Zr, Rb, Cr, Ba, Ni, Sr, Fe), with heavy metals classified by toxicity: Class I (Cd, As, Zn, Pb) as highly toxic, Class II (B, Co, Cu, Ni, Cr) as moderately toxic, and Class III (Ba, V, Mn, Sr) as lower-risk contaminants, necessitating targeted remediation strategies.

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