Ampelopedological Peculiarities of Geographical Areas of Crimea Viticulture

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Abstract—The high landscape diversity of the Crimean Peninsula formed by 20 agro-climatic regions and 17 genetic soil groups contributes to the formation of local terroirs for viticulture, which can result in the creation of a wide range of organoleptically individual wine products. The aim of this study includes a comparative analysis of physicochemical and biogeochemical parameters of regional soils in three historical and five modern geographical regions of viticulture. The soil-genetic and biogeochemical approach used for the comprehensive study of vineyard soils enables us to identify unique combinations of soil parameters for viticulture areas, which form key components in combination with local ecological conditions for applying the concept of terroir at the regional level. The pairwise comparison of the total composition of postagrogenic soils from three regions of ancient viticulture (northwestern, southwestern, and Piedmont Crimea) shows that the differences in the content of macroelements CaO, SiO_2, Al_2O_3, MgO, MnO, K_2O, and Na_2O and of trace elements Sr, Rb, and As are the greatest. The comparison of soils under vineyards testifies to the leading role of the geographical factor in their classification according to agrophysical parameters and the content of 18 compared chemical elements. Soils of the Southwestern and Piedmont Crimea are characterized by a favorable biogeochemical potential, since the content of a number of essential elements (Ca, P, and K) in them is 1.5–2 times higher than in soils of other regions. The geochemical features of vineyard soils of the southern coast of Crimea are diagnosed by such elements as Cr, Co, and Ba. Elevated levels of heavy metals—Cu, Cr, Ni, Pb, and V—have been detected in soils under modern vineyards. The expansion of vineyard areas stimulates the use of the ampelopedological approach to assess the potential of agro-productive soil groups, which can provide high-quality distinctive products (bouquet-rich wine), and the formation of a system of intra-regional terroirs will help to identify the geographical origin of wines.

Keywords: Haplic Chernozems, Cambisols, terroir, soil biogeochemistry, physicochemical soil properties

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INTRODUCTION

The area of modern fruit-bearing vineyards on the Crimean Peninsula is 20 100 ha (25% of the total area of vineyards in Russia) [20]. The increase in the production (80 000 tons of grapes per year) is slowed down by the age of vineyards, which are over 20 years old on more than half of the area. Land resources in traditional viticulture areas should be used more efficiently to increase the competitiveness, which is stimulated by the law adopted in 2019 by the Government of the Russian Federation. The law is aimed at increasing the area of vineyards and improving the quality of products, which will be protected with respect to geographical location.

The concept of terroir in viticulture includes a combination of the local landscape and environmental conditions typical only for this area, which ensures the distinctive product evaluated as "bouquet-rich wine" [49]. The geographical factor, which is called the "taste of the place" [30] or the "geographical fingerprint of wine" [44], is directly or indirectly determined by the effect of seven main factors, which include the ecogeopedological environment, in particular characterized by moisture availability and mineral nutrition [44]. When individualizing a land plot, the climate, soil, and grape variety are the main factors in determining the terroir. The efficiency of viticulture on slopes significantly depends on the location of the site above sea level, slope aspect and gradient, and position in the macrorelief (frost hazard assessment, etc.) [9]. Soil scientists mainly adopt the term *terroir* in the interpretation of the Bordeaux school (*Institut des Sciences de la Vigne et du Vin*) as an ecophysiological concept. According to it, the organoleptic characteristics of wine are related to its geographical origin [48, 49]. Since terroir is a multifactor concept, the distinctive characteristics of wine from a particular area are related to a unique combination of soil parameters,

Table 1. Study objects on fallow soils in the ancient vineyards of the Crimea

Ancient settlement	Object no.*	Altitude above sea level, m	Inclination, degree	Aspect	Main (internal) size of plot	Soil, rock**
Herakleion	1, 2	15	3–5	SW	100 ×100	S-C, El.
Pantikapaion	3–5	95	3–5	SE	250 ×200	S-C, El.
Kitej	8	12–15	1–2	E	210 × 210	CHs, Cl.
Tauric Chersonesos	33	50	1–2	SE	630 ×420 (210 × 210)	B, El.-Del.
Ortli	40, 41	5–8	1–2	WSW	210 × 210	CHc, S.
Mamaj-Tyup	42	2–8	0–3	S, SE	220 × 270 (52.5 × 52.5)	S-C, El.
Ojrat	43, 44	6–10	2–3	SE	210 × 210 (52.5 × 52.5)	S-C, El.
Kalos-Limen	45	7–8	1–2	E	52.5 × 52.5	CHc, Lm.

*The object number corresponds to Fig. 1.
**S-C, El.—rendzina on eluvium of hard calcareous rock; K, El.-Del.—cinnamonic mountain calcareous soils on eluvium and deluvium of bedrock; CHc, Lm.—medium loamy calcareous chernozem on loess–like loams; CHc, S.—calcareous stony chernozem on loam, CHs, Cl.—southern clayey chernozem.

which interact with the local climate, grape variety, harvest, and winemaking technique and thus form the terroir of a particular site [50].

A vine plant can grow in one place for a long period (about 60–80 years) and is characterized by a developed root system, which penetrates into the soil to a depth of 6–8 m. Therefore, vine is characterized by a high ability to extract nutrients from a great depth of the root layer, but is very sensitive to environmental factors: its yield and quality significantly differs under various conditions [15, 33, 35, 36]. The elemental composition of wine depends on the biogeochemistry of the soil, on which vine is grown, and is used to determine the geographical origin of various wines [45]. Their quality is affected by almost all soil properties and fertility in general, and this determines the important role of ampelopedology, which provides data of the genetic study of soils under vineyards.

The aim of the ampelopedological study of the Crimean Peninsula is a comparative assessment of soils in five geographical viticulture areas, in which the largest enterprises can increase the production by expansion of the planted area, as well as on promising lands for vine growing, taking into account the rich history of the region.

OBJECTS AND METHODS

Objects of research. The empirical basis includes recent soils under vineyards (32 objects), postagrogenic soils on measured land plots and terraces (13 objects), and references (virgin soils) in each of the five viticulture areas (Fig. 1). Soils under vineyards are a generalized term: under conditions of a complicated soil cover pattern, it signifies agrotechnical soil transformation (trench plowing, regular cultivation of areas between rows, significant agrochemical load, etc.) and does not replace the genetic and classification simllarity of soils. Terrain researches in historical areas of viticulture were performed on fallow land with evidences of parceling and deep plowing in the ancient time [5, 21]. Such objects were studied in the Southwestern (Herakleian Peninsula), Northwestern (Cape Ojrat, lands near ancient centers and estates: Kalos-Limen, Orth, and Mamaj-Tyup), and Eastern Crimea (vine terraces on the Kazantip Peninsula and to the west of Kerch (Pantikapaion) near the village of Oktyabr'skoe) (Table 1).

The historical centers of viticulture in Taurida in the ancient time occupied significant areas in the Southwestern and Eastern Crimea and isolated land massifs in the Northwestern Crimea and the foothills. However, agriculture of the Greeks did not extend to the areas inhabited by the Tauri and, in particular, to the southern coast of the Crimea from Balaklava to Theodosia with favorable soil and climatic conditions for vine cultivation. Bosporan vine growers in the Eastern Crimea began to introduce vine plant in the 6th–5th centuries BC, and two centuries later, perennial plantations appeared in the Southwestern Crimea. Viticulture as a branch of agriculture dominated in the rural district of the Chersonese state in the pre-Scythian period: the coastal zone of the Herakleian Peninsula was occupied by vineyards in the 4th and early 3rd centuries BC [5]. Horticulture and viticulture began to develop in the Northwestern Crimea since the first quarter of the 4th century BC, which is evidenced by traces of the ancient land demarcation near eight settlements and estates [46]. Ancient Greek farmers considered vine cultivation in various regions of the Crimea to be very important, and wine-making technology was paid a great attention in the economy

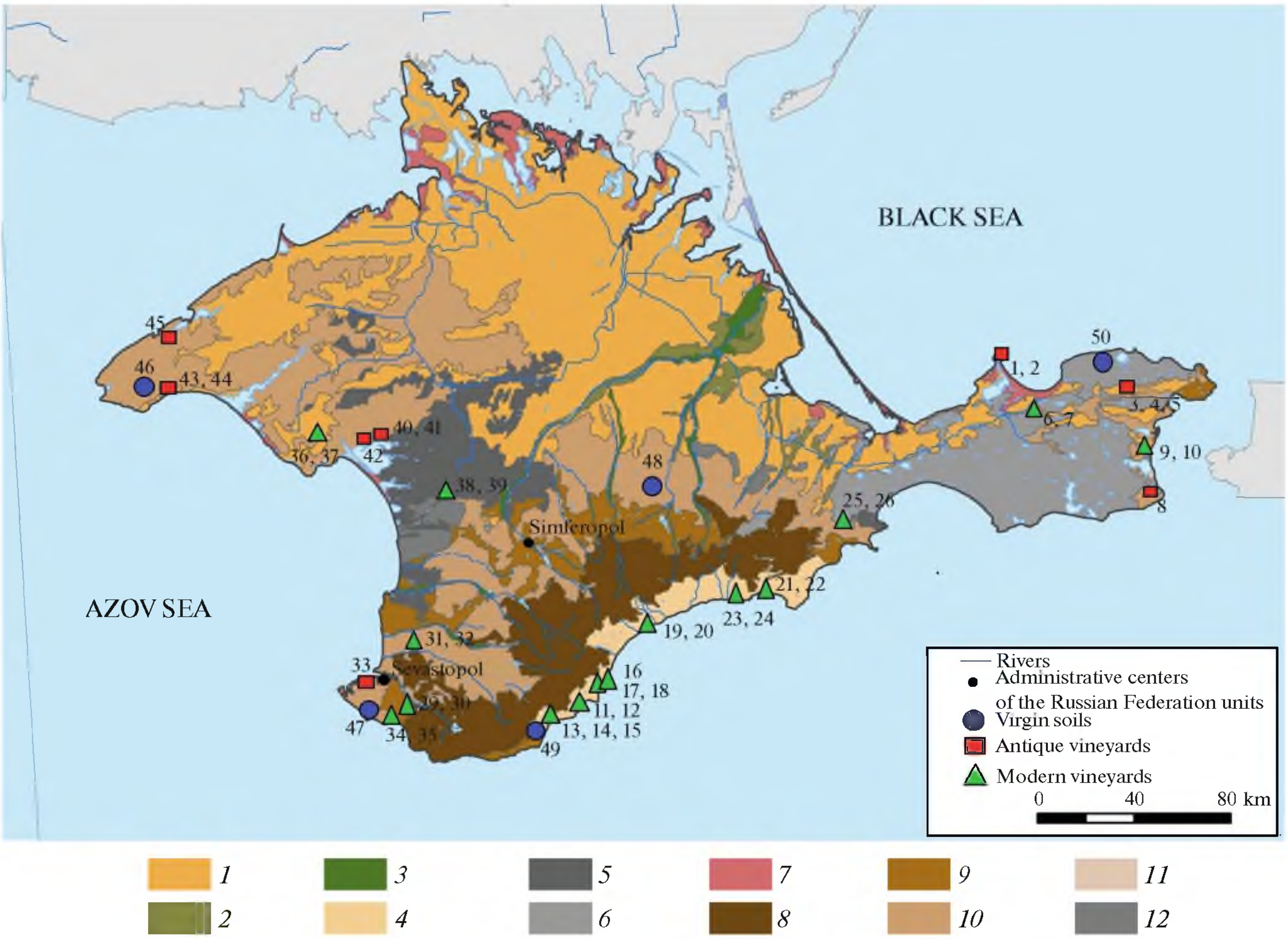

Fig. 1. Location of soil sampling sites on post-antique fallow land and in modern vineyards of the Crimean Peninsula (the background reflects a layer of parent rocks from a vectorized map (Soil map of the Crimean Peninsula, Ukrzemproekt, 1972, on a scale of 1 : 200000): (*1*) loess and loesslike loam; (*2*) ancient alluvium; (*3*) recent alluvium; (*4*) eluvium of shale and sands; (*5*) clays; (*6*) saline clays; (*7*) recent marine sediments; (*8*) clays, conglomerates, and sandstones; (*9*) colluvium of calcareous rocks; (*10*) eluvium of calcareous rocks; (*11*) eluvium of ore rocks; and (*12*) pebbles and conglomerates.

of ancient states, which favored the spread of the complete cycle of viticulture among the Scythians and Taurians. This is proved by archaeological data at the settlements of the Late Scythians (the 2nd–3rd centuries AD), as well as by paleobotanical analyses of seeds, which testify to the development of local breeding of cultivated vine based on a variety of wild forest vine of the mountainous Crimea [5, 8, 16, 28, 31]. The production of wine materials exceeded the own needs in most Bosporan settlements from the 1st century BC to the 3rd century AD. The intensive development of this industry continued at the end of the 3rd–5th centuries BC [5]. Winemaking on local raw materials was developed in the Southwestern Crimea in the Middle Ages, as is evidenced by findings of about 200 wineries, which could simultaneously produce at least 2 million liters of wine products [7].

Soils formed on the eluvium of carbonate rocks are widely spread both in the Northwestern (56% of the area) and in the Eastern Crimea (on rocky limestone ridges of the Kerch hills). These are calcareous chernozems (Haplic Chernozems) and rendzinas (Calcaric Chernic Rendzic Phaeozems) underlain by limestone from a depth of 40–55 cm, which were deeply plowed in viticulture areas. Ancient vineyards of the Northwestern Crimea 1.2 km to the northeast of the ancient center of Kalos-Limen (from the beginning of the 4th century BC to the beginning of the 2nd century AD) and near the estates of Ortli and Mamaj-Tyup (the second half of the 4th and the 3rd centuries BC) discovered by Crimean archaeologists [22, 46] were studied during the interdisciplinary research, which confirmed the soil profiles to be representative in the systems of intra-field parcels. The remote and geophysical studies of a well-preserved allotment for perennial plantations at Cape Ojrat near an estate of the late 4th–2nd centuries BC [21] revealed the planning structure (plot fences and stone walls). These data contributed to the organization of a detailed soil survey with the use of a geodesic-class satellite navigation system. Soil samples on the Herakleian Peninsula were taken on 69 best preserved land plots of the rural district of Tauric Chersonese.

Two similar objects—ancient land plots for vineyards on the southern slopes with stony rendzinas on the eluvium of hard carbonate rocks—were studied in the Eastern Crimea: at the settlement of Kazantip I (the 2nd century BC–the 3rd century AD) and at an ancient farmstead (the 4th–3rd centuries BC) near the village of Oktyabr'skoe (9 km to the west of Kerch (ancient Panticapaion)). In 2019–2020, we also repeatedly studied land plots 15–16 m wide with fences 520 m long to the west of the settlement of Kitej (the 5th century BC–the 5th century AD) in the south of the Kerch Peninsula, where chernozems on compact gray-green (2.5Y 6/4 (Munsell, dry)) clays are formed in the littoral zone. The earlier soil survey showed that the turbated horizon (70-cm-thick) was formed 2400 years ago [26]. Soils of the Eastern Crimea on eluvium of hard rocks and clays significantly differ in the content of calcium carbonate ($CaCO_3$): 38 and 16% on average, respectively. Therefore, these groups of objects are individually analyzed.

Terrain studies in modern areas of viticulture were performed in the Southwestern (Balaklavskii and Nakhimovskii districts), Northwestern (Sakskii district), and Eastern (Leninskii district) Crimea, in the foothills (Belogorskii district), and on the southern coast of the Crimea (**SCC**) (city districts of Yalta, Alushta, Sudak, and Theodosia) (Table 2). The most promising for viticulture sub-Mediterranean landscapes of the SCC occupy the lowest belt of the Main ridge of the Crimean Mountains 1–15 km wide on the total area of 1255 km^2 [39]. Cinnamonic soils (according to the nomenclature of soils of the Crimea) or Cambisols [34] are mainly formed in this belt and in the foothills to the west and east of the Main Ridge.

Soil samples were taken in modern vineyards from the A, AB, and B horizons (from 0- to 120-cm layer) in the area between rows, as well as from the A and AB horizons both in the row of vine and in the area between rows to compare agrophysical parameters. In addition, 41 samples were taken from the B horizon (>80 cm) and along the vertical profile in two pits on soil-loess deposits 2.5 and 6.5 m deep (near a modern vineyard and on virgin land) to construct geochemical diagrams. A horizon with regenerated natural properties 21–25-cm-thick was identified under the sod layer 3–6-cm-thick on post-antique fallow land. This was the study object.

Research methods. The scientific approach based on the integration of soil science, archeology, landscape geomorphology, remote sensing data, and GIS technologies, which enables the detection of evidences of ancient land management and agriculture [37], has already proved its efficiency. It was supplemented by the results of remote sensing and geomagnetic survey data processing for the historical areas of viticulture [23, 46]. Data of the integrated soil-genetic and biogeochemical study of vineyard soils are a key component for the practical use of the concept of terroir.

The comphcated geological structure of the Crimean Peninsula is manifested in a great variety of soil-forming rocks. Their spatial distribution was analyzed by cartographic methods in a local GIS on the multifunctional platform ArcGIS 10.5 from ESRI. The cartographic material was compiled and digitized in the geographical coordinate system WGS-1984. Sheets of a topographic map at a scale of 1 : 200000 were converted and referred to the mapping grid to provide a basis in GIS for the entire peninsula (Soil map of the Crimean Peninsula. Ukrzemproekt, 1972). Modern (2017–2020) detailed sateilite images provided by cartographic web services of Google and Yandex were also used.

The agrophysical soil status was determined in the A and the AB (0–35 cm) horizons of recent soils at 45 sites under vineyards (in the row and the space between rows) and for post-antique failow land by fractionation of air-dry soil and assessment of the water stability of mesoaggregates. A set of eight Fritch GmbH sieves with square cells (diameter <0.25, 0.25–1, 1–2, 2–3.15, 3.15–5, 5–7, 7–10, and >10 mm) was used for dry sieving to analyze structural units according to the method by N.I. Savvinov. The Ferret triangle was used for visuahzation of the structural composition of soils [27]. The soil structure coefficient (C_{str}) was calculated as the ratio of the mass of structural units from 1 to 7 mm to the mass of structural units <1 and >7 mm [18]. The deflation hazard coefficient was determined by the portion of macroaggregates >1 mm. The water stability of mesoaggregates by gradations of 1–2, 2–3.15, and 3.15–5 mm in diameter was analyzed by the disintegration rate of aggregates ($n = 50$) determined on moistened filter paper in a Petri dish over the time period recommended in [3]. The water stability criterion (A) was calculated by the ratio of the percentage of water stable aggregates to the portion of structural units of 3.15–5 mm in diameter.

The color of dry soil samples was determined by the Munsell color charts [42]. The method by I.V. Tyurin (modified by TSINAO) was used to assess the organic matter content. We also determined CO_2 of carbonates by the acidometric method, pH of water extract by the potentiometric method, total nitrogen by the titrimetric method (*GOST* R 58596-19), available phosphorus and exchangeable potassium by Machigin's method (*GOST* 26205-91), mobile copper compounds by the method of Krupskii and Aleksandrova (*GOST* R 50683-94), and available boron compounds according to the approach by Berger and Truog (*GOST* R 50688-94).

The bulk analysis in powder samples of soils and rocks was performed according to the method of measuring the mass fraction of chemical elements on a

Table 2. Study objects on soils of modern vineyards in the Crimean Peninsula

Settlement	Object no.*	Altitude above sea level, m	Inchnation, degree	Aspect	Soils	Particle-size composition of soil
Ostanino	6, 7	30	1–2	S	Low-humus southern chernozem on loess-like clays and loams	Light clay
Chelyadinovo	9, 10	64	2–3	SW	Low-humus high-carbonate mycelary southern chernozem on loess-like clays and loams	Medium and heavy clay
Yalta	11, 12	20	2–3	S	Noncalcareous cinnamonic mountain soils on eluvium and colluvium of hard rocks	Heavy loamy with rock fragments
	13–15	260	3–5	S	Calcareous cinnamonic mountain soils on eluvium and colluvium of hard rocks	Light clay with rock fragments
Hurzuf	16	155	2–3	SE	Noncalcareous cinnamonic mountain soils on eluvium and colluvium of hard rocks	Heavy loamy with rock fragments
	17, 18	75	5–7	SE		
Alushta	19, 20	65	2–3	S	Noncalcareous cinnamonic mountain soils on eluvium and colluvium of hard rocks	Heavy loamy with rock fragments
Sudak	21, 22	67	1–2	SE	Noncalcareous cinnamonic mountain soils on eluvium and colluvium of hard rocks	Heavy loamy with rock fragments
Novyi Svet	23, 24	140	2–3	E	Solonetzic cinnamonic mountain soils on colluvium of hard rocks	Light clay with rock fragments
Theodosia	25, 26	93	1–2	SE	Solonetzic chernozem on compact clays	Light clay with rock fragments
Krinichnoe	27, 28	270	3–5	SE, E	Rendzina on eluvium of hard calcareous rock	Light clay
Sevastopol	29, 30	115	1–2	S, SE	Calcareous cinnamonic mountain soils on eluvium and colluvium of hard rocks	Heavy loamy with rock fragments
	34, 35	180	1–2	SE		
Solnechnyi	31, 32	102	2–3	S	Calcareous cinnamonic mountain soils on eluvium and colluvium of hard rocks	Heavy loamy with rock fragments
Romashkino	36, 37	35	1–2	S, SE	High-carbonate low-humus southern chernozem on loess-like clays and loams	Light clay
Skvortsovo	38, 39	43	1–2	SE	Mainly calcareous stony and pebbly chernozem on eluvium of hard rock and pebble, calcareous and carbonate-enriched	Light clay

* Object number corresponds to Fig. 1.

Spectroscan Maks-GV vacuum wave-dispersive X-ray fluorescence spectrometer. A set of state standard samples of soil composition was used for the quantitative cahbration. The most informative geochemical coefficients for the diagnostic of agrogenic transformation of soils are substantiated in a number of special works [10, 13]. We used formulas for calculating the eluviation coefficient: $C_e = Al_2O_3/(MnO + CaO + K_2O + MgO + Na_2O)$ [41] and the mobility coefficient of chemical elements: $C_m = \sum(Na, K, Mg, Zn)/SiO_2$ [12], as well as the index of potential soil fertility: $FI = (CaO + MgO + 10P_2O_5)/SiO_2$ [47] and the formula for calculating the soil quality coefficient [12], which was adapted according to [15] for vine plant: $SQ = (P_2O_5 K_2O CaO Zn Ee_2O_3 MgO)^{1/6}$.

The sample of organic material of a vine bush to determine the chemical composition of ash was prepared by ignition in porcelain crucibles in a muffle furnace at 450°C.

The data were statistically processed by standard methods in Excel and STATISTICA 10.0 programs. The variation coefficient (V, %) was used for the most informative geochemical parameters. The classification similarity of objects (soils and rocks) was determined by interpreting the results of cluster analysis in the STATISTICA 10.0 software product, using the method of multidimensional cluster analysis (the Ward hierarchical clustering algorithm in the squared Euclidean distance by normalized values).

RESULTS AND DISCUSSION

Agrophysical status of soils. Vine plant is relatively tolerant to growing conditions on skeletal soils. A classification of soils with coarse skeletal material by the stone content has been elaborated in relation to vine culture. It shows that vine plantations on shghtly and medium skeletal soils (the content of particles >3 mm ranges from 1 to 30%) are long-hving, and their yield is high and of good quality [15]. It has been shown [38] that, contrary to natural soil formation, which results in the divergence of soil properties, agropedogenesis causes their convergence. It should be mentioned that the technology of ancient viticulture included deep plowing; therefore, all soils under vineyards in the historical areas of viticulture in the Crimea at the initial stage of agropedogenesis were characterized by the homogeneous upper root layer. Ancient winegrowers stored large stones at the border of the land plot of perennial plantations, as it is seen at Cape Ojrat [21], or laid in walls of 1 m high and wide [25]. The study of ancient vineyards of the 3rd–2nd centuries BC in the rural district of Chersonese show that a trench 0.70–0.80 m deep was laid during plowing, and the preserved depth of the ancient plowing is 0.50–0.80 m [25], which penetrates into the turbated horizon with particular agrotechnological characteristics. Eor example, carbonate eluvium in virgin soil contains 34% of particles >3 mm (strongly skeletal soil), while the plowed horizon of the similar depth under an ancient vineyard in Kalos–Limen is medium skeletal (the portion of stone fragments >3 mm ranges from 18% (0–63 cm) to 23% (63–84 cm) as a result of removing stones from the soil.

The structure and water resistance of soil are of great importance for its agronomic assessment. Aggregates from 0.25 to 7 mm in diameter are the most agronomically valuable [18]. Structureless loose aggregates (<0.25 mm) and lumpy aggregates (>7 mm [18]) are characterized by poor water and air permeability and are compacted [27].

The analysis of the data (Eig. 2) shows that without taking into account modern fallow land with strongly fluctuating data, soils sampled in the rows of modern vineyards are usually characterized by better structure as compared to the space between them, which undergoes regular mechanical processing. The significant difference test with respect to the content of agronomically valuable aggregates (0.25–7 mm) in two samplings (soil in a row and in the area between rows of the vineyard) shows that $t_{fact} > t_{05} < t_{01}$, that is, the difference is significant at the 5% significance level. At the 1% significance level, soil samples are assigned to one population. Turbations during the period, corresponding to the age of the vineyard, are absent in vine rows after the initial trench plowing of soils. The decrease in the portion of agronomically valuable aggregates in areas between vine rows is related to the high content of blocks (>7 mm) due to trench plowing and subsequent soil cultivation of these areas (4–6 times per year to a depth of 10–12 cm) in case of traditional agrotechnology.

The values of the water resistance coefficient are significantly higher in post-antique and recent fallow land (>85%) unlike vineyards (40–60%) with more strongly plowed-out soils (Table S1). The weighted mean for three gradations of the d_W parameter (water resistance of aggregates of 1 to 5 mm in diameter) under modern vineyards is different for soils in the row and space between rows. The mean d_W is 46.9% in soils of the row and twice as low (20.8%) between rows due to regular turbations, which determines the soil structure as unsatisfactory.

The fallow regime enables the restoration of soil structural status in the range of units of 0.25–7 mm, and residual features of mechanical tillage are preserved in the silt fraction (<0.25 mm). This is revealed in post-antique fallow soils (objects 1–5) and in post-agrogenic soils of the modern development stage of the Kerch Peninsula (objects 34–35).

The cluster analysis was performed, using normalized values of parameters by standard deviation, for groups of the studied objects by the portion of meso- and microaggregates and by values of agrophysical soil properties (Table S1). The analysis of Eig. 3 shows that soils under vineyards may be specified by their agro-

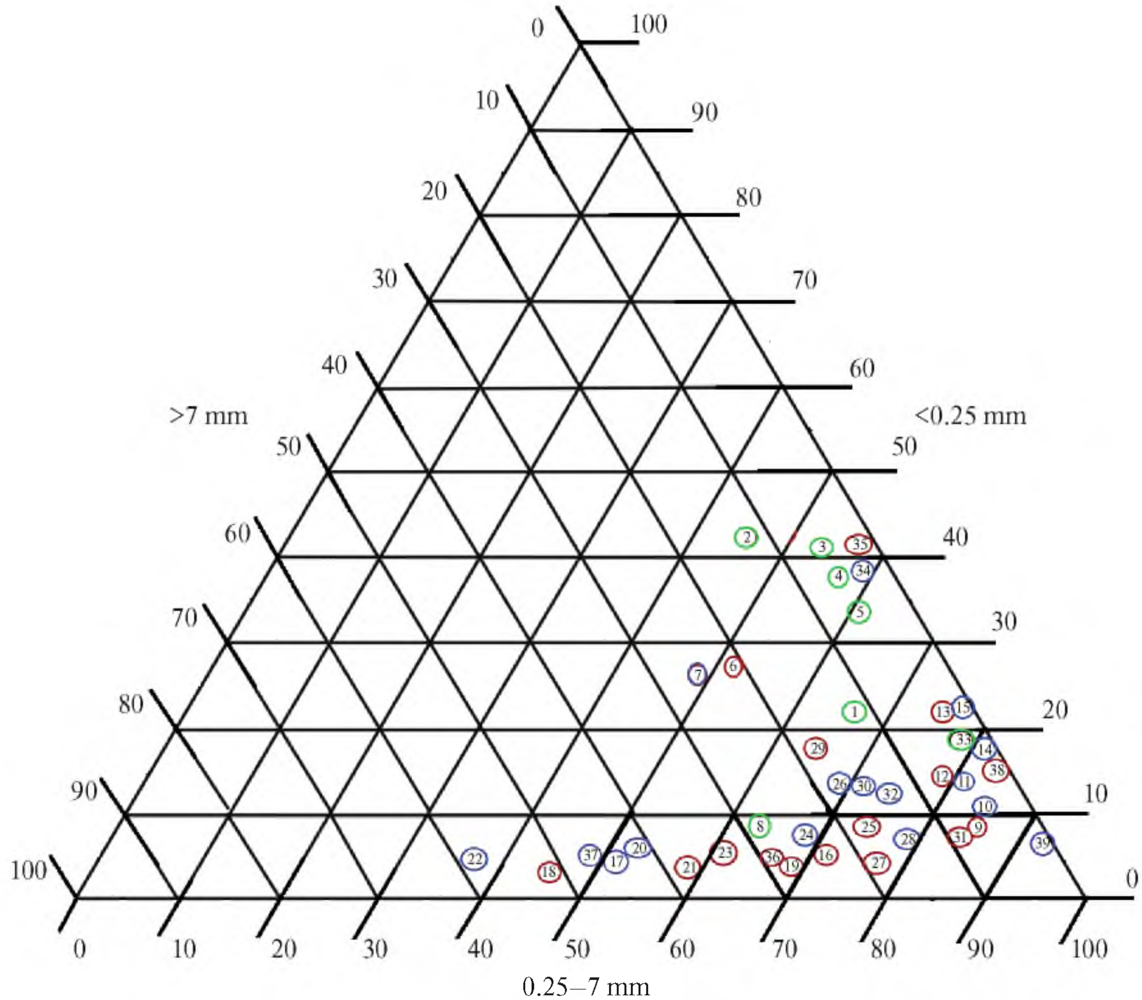

Fig. 2. Determination of differences in soil structure (the A horizon) by the Ferret triangle (object number correspond to Fig. 1): red icons—samples in the row of vine plants, blue icons—samples in the area between rows, and green icons—samples on post-antique fallow land.

physical status into three main groups, using the threshold distance (D). The first group mainly includes soils of modern vineyards located in the Southwestern (objects 29–32) and Northwestern (objects 36, 37) Crimea. They are united by similar deflation hazard coefficient (50–70%) and the water stability of aggregates 3.15–5 mm (40–60%). The second group incorporates post-antique deposits of the Eastern Crimea (objects 1–5, 8) and recent fallow land of the Southwestern (objects 33–35) and Northwestern (objects 38 and 39) Crimea. The aggregate status of soils of groups 1 and 2 varies within 0.6–1.2, which corresponds to satisfactory structure. Group 1 is characterized by the largest mean content of agronomically valuable aggregates in comparison with other groups: 82.8%. The water stability coefficients are significantly higher in post-antique and recent fallow land (>85%) than in modern vineyards (40–60%), which characterizes the plowing-out rate of their soils. There is an increase in the fraction <0.25 mm in group 2 to 30–40%. This indicates that structural units were transformed from agronomically valuable ones into silty material as a result of agrogenic impact, that is, residual (after a long fallow regime) evidences of soil plowing-out are revealed.

Group 3, which is referred to a high level of the hierarchical classification, includes modern vineyards of the SCC (objects 13–24) and modern fallow land in the piedmont Crimea (objects 27, 28). At a higher level, soils from the vineyard of the Magarach Institute (objects 11, 12) and the abandoned vineyard on the Kerch Peninsula (objects 9, 10) are associated with this group.

Group 3 differs from groups 1 and 2 by a significantly high structural coefficient, which enables the evaluation of its structure as good ($C_{str} > 1.5$). Not all objects are characterized by sufficient amount of agronomically valuable aggregates: blocky aggregates (>7 mm) predominate in the between-row areas of modern vineyards in Gurzuf (29.8%), Alushta (37.5%),

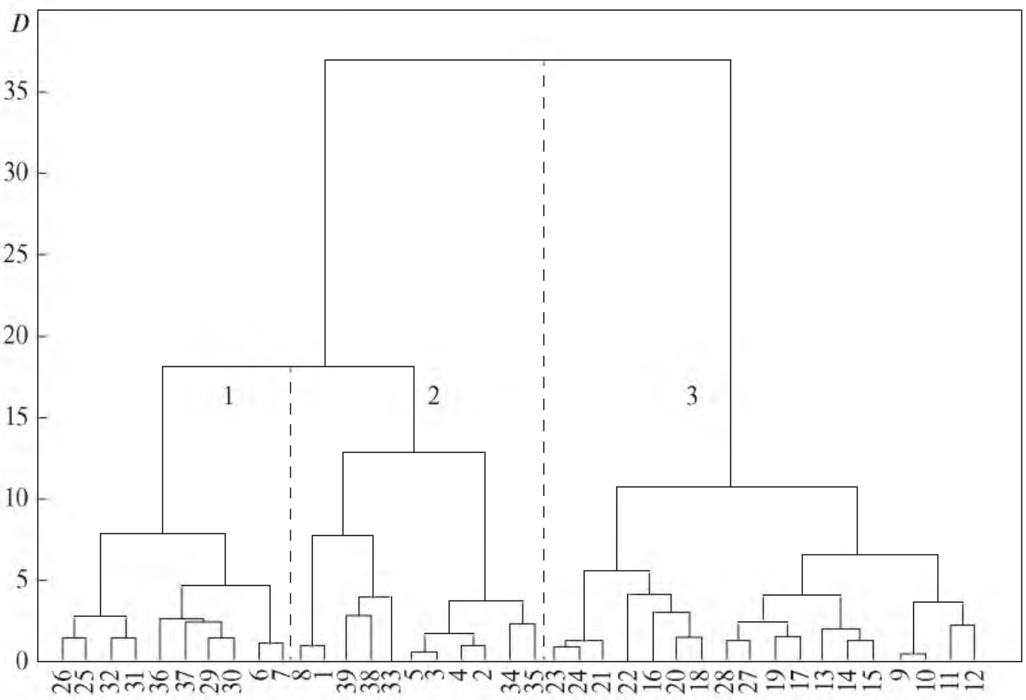

Fig. 3. Dendrogram of the cluster analysis of 39 soils under the vineyards of the Crimean Peninsula by parameters of their structural status (*D* is the distance of association).

and Sudak (53.3%). The parameters of water stability also differ. The coefficient is among the lowest—37% on average under rows of modern vineyard and is twice as low—19% in the area between rows due to regular turbations. The soil structure here is unsatisfactory. The mean water stability coefficient in modern fallow land is, on the contrary, high: about 93%. The results of the assessment of the agrophysical status of soils under vineyards confirm the leading role of the geographical factor in their typology, even in case of different history and the intensity of agrogenic transformations.

Soil geochemistry in historical areas of viticulture. The statistical processing of the entire array of geochemical data (n = 153) for the studied objects (Table S3) shows a significant variability of all chemical elements concentrations (variation coefficients are from 19 to 120%). Therefore, they are highly informative for determining the intraregional (from district to district) differences. However, the approach based on comparing the standard deviation and the variation coefficient for different variants of the dispersion of values with an increase in the means [32] enables us to determine a short list of diagnostic parameters among 22 macro- and microelements, which can best manifest soil differences between the three historical regions of viticulture in the Crimea. Four diagnostic macroelements (oxides) with variation coefficients more than 28% are distinguished among ten macroelements with relatively stable standard deviation in the sampling: CaO, Fe_2O_3, Al_2O_3, and SiO_2 (Fig. 4). Four elements (Pb, As, Rb, and Zn) may be recognized among 12 trace elements as the most informative to identify soils of geographical areas (Fig. 5).

When comparing the content of 22 macro- and microelements in soils of three historical areas of viticulture, no one element was excluded by the chosen criterion: the ratio between individual pairs of objects of more or less than 20%. The comparison of three ancient viticulture regions (Table S3) shows that the differences between the pairs are the greatest in the content of such oxides as CaO, SiO_2, Al_2O_3, MgO, MnO, K_2O, and Na_2O in the A horizon and in the content of trace elements Sr, Rb, and As. The greatest differences among the historical districts (with respect to the content of 19 chemical elements) are typical for soils of one area, namely, the Kerch Peninsula, formed on different parent rocks: carbonate eluvium and heavy loam. Soils of the rural district of Chersonese (on the Herakleian Peninsula) are very specific in comparison with calcareous soils of the Northwestern Crimea (by a higher content (among 17 elements) of iron, lead, rubidium, and aluminum and by a lower content of sodium and strontium) and of the ancient Bosporus (by a higher content (among 16 elements) of Fe, Rb, Pb, Si, Al, and V and a lower content of Sr, Na, and P). Soils under vineyards on fallow land of the Northwestern Crimea and Bosporus formed on calcareous rocks and underwent trench plowing in ancient times were the most similar with respect to their geochemical composition. These two regions differ only in nine macro- and microelements among

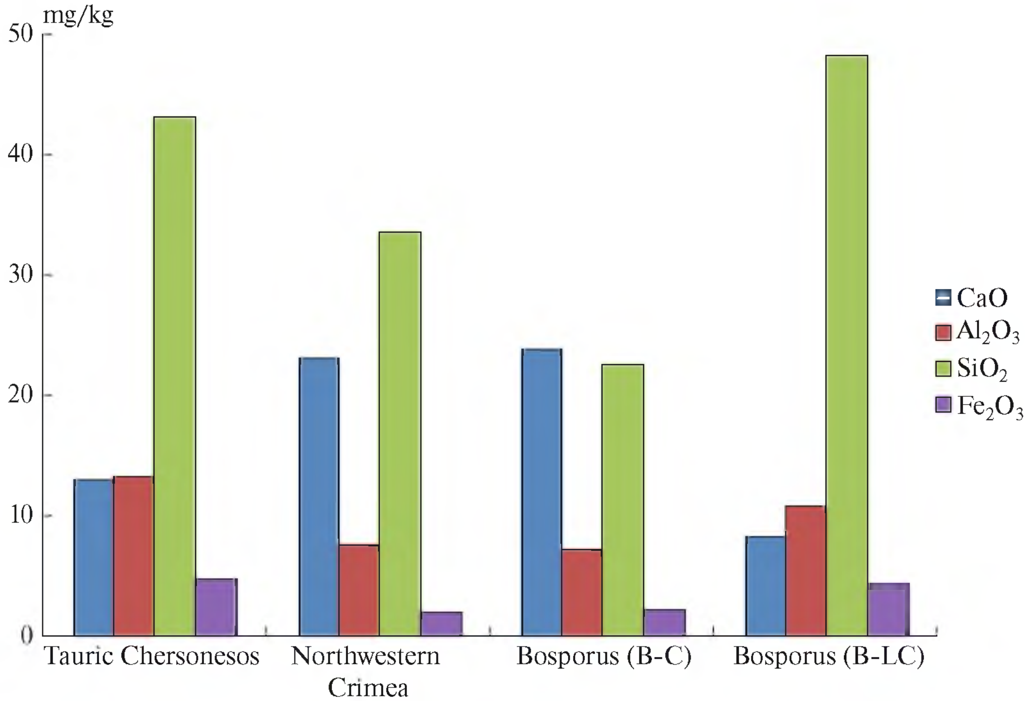

Fig. 4. Distribution of concentrations of diagnostic macronutrients (oxide form) in historical areas of viticulture of the Crimean Peninsula. For the Eastern Crimea: B-C—soils on eluvium of compact rocks and B-LC—soils on compact clays.

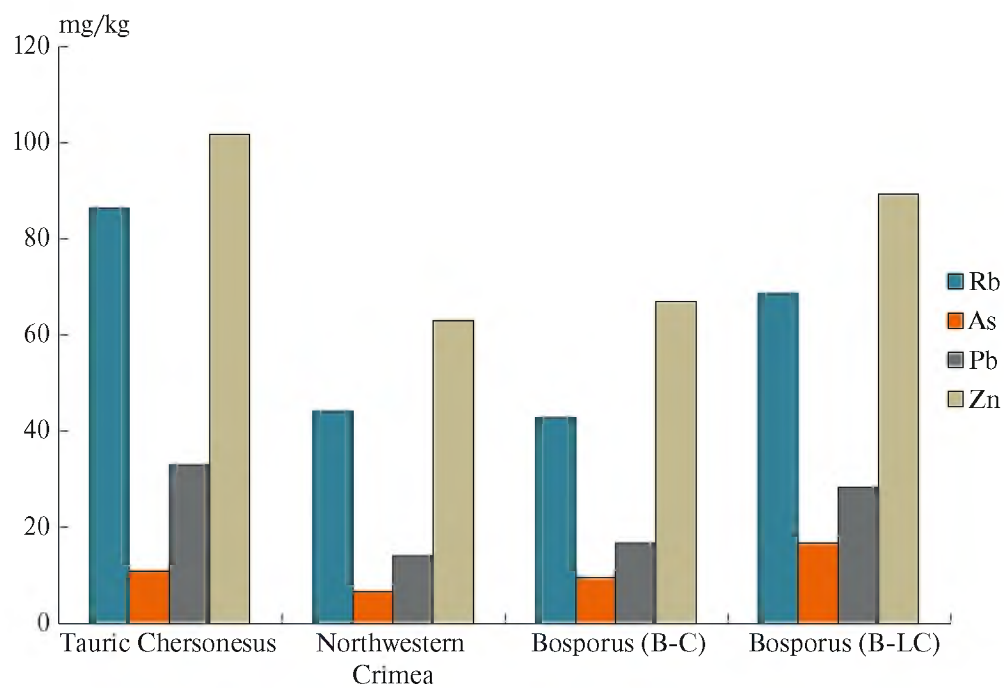

Fig. 5. Distribution of concentrations of diagnostic microelements in historical viticulture areas of the Crimean Peninsula. For the Eastern Crimea: B-C—soils on eluvium of compact rocks and B-LC —soils on compact clays.

22 ones; the difference in the content of Mg and Sr is the most significant.

Soils of vineyards near ancient estates of the Northwestern Crimea are characterized by high carbonate content, which makes them very close to soils on the eluvium of limestone of the Eastern Crimea. They are better than soils on clays in the same area (Kitej district) only due to Ca content. Viticulture in the south of the Kerch Peninsula during the existence of ancient Kitej (5th century BC–5th century AD) was successful [26] obviously due to the features of local soils, which differed from their calcareous analogues under vineyards on slopes of the Kazantip Peninsula and of the Oktyabr'skii estate by a higher content (1.3–2.1 times) of elements useful for vine plants: Si, Fe, K, Rb, Mg, and Mn.

The combination of priority elements, affecting the taste qualities of wine materials (Fe_2O_3, Ni, Cu, Zn, Co, and Rb) is substantiated from the ampelopedological point of view [2, 11, 15]. Soils of the Herakleian Peninsula (the rural area of Chersonese) are in advantage of other areas of ancient viticulture owing to a higher content of Fe, Si, Mg, K, and Rb. Pedogenesis on the SCC differed slightly from the current one since the Phocene due to stable climatic conditions for soil formation [1]. The Herakleian Peninsula is assigned to the southern-coast moderately hot arid agroclimatic region with very mild winters and the sum of temperature >10°C of 3400–3800°C for the period [39]. It significantly differs from other historical viticulture areas by the continuity and intensity of soil-forming processes diagnosed by the Rb/Sr weathering index. It reflects the difference in the stability of micas and potassium feldspar in relation to carbonates, with which Sr is associated [10]. Calcareous soils of the Northwestern and Eastern Crimea are characterized by 3 to 17 times lower Rb/Sr index as compared to soils of the Southwestern Crimea.

After the creation of the agricultural zone for viticulture and wine export in the 4th–3rd centuries BC, the Chersonese state began to develop grain farming in the remote district (in the Northwestern Crimea) with the subordinate role of viticulture. Biogeochemical differences in soils and parent rocks along with chmate could be a significant factor of variations in the quality of wines in two regions of the Western Crimea. This is related to the present-day differences in viticulture of these areas, if the concept of terroir is used [40]. These conclusions correspond to the different role of winemaking in the Southwestern and Northwestern Crimea (export and local consumption, respectively) in the ancient period [5].

Geochemistry of soils in modern areas of viticulture. The role of microelements in soil is no less important for high-quality grape production than of the main elements of mineral nutrition: N, P, K, Ca, S, and Mg [11, 29, 43]. Variation coefficient (V) was used to determine the most informative macro- and microelements in soils under vineyards of the Crimean Peninsula (Table S2). Four chemical elements, which may be assigned to background ones by $V < 25\%$ (K_2O, Cr, MnO, and Ba), were excluded from further analysis. Soils under vineyards were classified according to data on the content of 18 chemical elements, using the method of multidimensional cluster analysis (Fig. 6).

The results of the hierarchical classification show that soils under vineyards may be specified into five main groups according to their biogeochemical features. The objects in groups 1 and 5 are the most contrasting at a high level of the threshold distance. Fallow soils from ancient vineyards of the Kerch Peninsula and the Northwestern Crimea (group 5) are characterized by the most significant differences in the geochemical composition as compared to other objects on the peninsula. Old fallow soils, which are more often formed on limestone eluvium and underwent trench plowing in antiquity, are characterized by a high content of CaO (25.1%), MgO (2.5%), and P (0.36%) and by smaller (almost two times) amount of Al, TiO_2, Fe_2O_3, V, Cu, and Pb. Group 1 includes the objects of the SCC on cinnamonic mountain mainly non-calcareous soils. The relatively high concentration of Fe_2O_3 (6.01%) and Al_2O_3 (19.85%) in soils of this group is confirmed by their color: brown (10YR 5/3) and yellowish-brown (10YR 5/4). The main difference from the other groups consists in a low CaO content (from 0.6 to 1.8% in the upper horizon) and in a higher content of Al_2O_3, V, Cr, Co, Ni, Zn, Rb, and Pb. Groups 2–4 include recent soils under vineyards of the Southwestern, Piedmont, Northwestern, and Eastern Crimea, which form one cluster, though are significantly different. Groups 2 and 4 differ, first of all, by the content of Co, Sr, Cu, As, Cr, Mn, and Ni, which is 1.5–2 times higher in group 4 (these are mainly loamy soils of vineyards on the Kerch Peninsula). Groups 2 and 3 are the closest to each other: they differ only in the content of Cu, Ni, and Co among 18 chosen chemical elements, which is directly related to various agricultural chemicals used by enterprises.

Geochemical ratios and coefficients may reflect the results of processes related to weathering of parent rocks and to pedogenesis. The coefficient of potential soil fertility (FI) [47] and the eluviation coefficient (C_e) [41] are the most informative for differences between post-antique fallow land and modern vineyards in this study (Table 3).

Soils in areas between rows of modern vineyards differ from fallow soils of ancient vineyards by 2.5–3-time higher Ce (due to the loss of alkahne compounds) and leaching coefficient (Ba/Sr). The weathering coefficient ($Al_2O_3/(CaO + Na_2O + MgO + K_2O)$) is also significantly higher: it varies for soils of modern vineyards from 0.97 to 2.39 and does not exceed 0.69 for soils of ancient vineyards. This testifies to stronger weathering and removal of mobile elements, which is related to longer farming period and greater intensity of

Fig. 6. Dendrogram of the cluster analysis of 45 samples from the A and AB soil horizons under vineyards of the Crimean Peninsula by concentrations of 18 chemical elements (the Wards method, Euclidean distance, and values of parameters normalized by standard deviation).

geochemical transformation of soil-forming rocks and soils under the former and recent climatic conditions.

The parameter of potential soil fertility *FI* [47] is represented by the ratio of the sum of total phosphorus and oxides of calcium and magnesium to silicon. It varies from 0.41 to 1.40 on fallow soils of ancient vineyards, and is <0.20 for soils of modern vineyards. The coefficient of mobility of chemical elements (C_m), which is expressed by the ratio of the sum of four mobile elements to the silicon oxide content [12], is greater in post-antique fallow soils, which testifies to slighter leaching of Na, K, Mg, and Zn in them as compared to soils of modern vineyards.

The soil quality coefficient *SQ* [12] was adapted for vine plant, using six chemical elements (P_2O_5, K_2O, CaO, Zn, Fe_2O_3, and MgO), which are most neces-

Table 3. Geochemical ratios and coefficients ($X \pm Sx$) for five agro-climatic regions of the Crimean Peninsula

Ratios and coefficients*	*1*		*2*		*3*	*4*	*5*		*V*, %
	pf	mv	pf	mv	mv	mv	pf	mv	
FI	1.2 ± 0.1	0.2 ± 0.02	0.4 ± 0.03	0.2 ± 0.02	0.2 ± 0.01	0.14 ± 0.02	1.4 ± 0.3	0.14 ± 0.02	87
$(CaO + MgO)/Al_2O_3$	4.0 ± 0.2	0.7 ± 0.1	1.2 ± 0.1	0.8 ± 0.04	0.6 ± 0.03	0.4 ± 0.1	2.9 ± 0.5	0.5 ± 0.01	77
$Al_2O_3/(CaO+Na_2O+MgO+K_2O)$	0.23 ± 0.01	1.2 ± 0.1	0.7 ± 0.1	0.9 ± 0.04	1.18 ± 0.04	2.4 ± 0.2	0.5 ± 0.1	1.4 ± 0.02	63
Ca+Mg+K	30.7 ± 0.9	9.1 ± 0.6	17.0 ± 0.8	10.4 ± 0.8	9.7 ± 0.5	7.5 ± 0.7	22.0 ± 2.8	6.1 ± 0.1	59
C_e	0.8 ± 0.1	5.7 ± 0.4	2.3 ± 0.1	4.7 ± 0.4	4.8 ± 0.2	7.2 ± 0.5	2.0 ± 0.4	5.6 ± 0.1	53
MnO/Sr	3.1 ± 0.2	9.7 ± 0.4	6.9 ± 1.1	8.8 ± 0.9	7.2 ± 0.2	9.1 ± 0.7	2.0 ± 0.5	11.6 ± 0.4	45
Ba/Sr	1.2 ± 0.1	3.8 ± 0.1	3.9 ± 0.2	4.1 ± 0.1	3.5 ± 0.04	3.6 ± 0.2	1.1 ± 0.2	4.5 ± 0.1	40
$(K_2O + Na_2O)/Al_2O_3$	0.5 ± 0.03	0.2 ± 0.01	0.3 ± 0.004	0.3 ± 0.01	0.2 ± 0.01	0.2 ± 0.01	0.5 ± 0.04	0.2 ± 0.01	37
C_m	2.6 ± 0.1	1.6 ± 0.1	2.9 ± 0.4	1.6 ± 0.1	1.8 ± 0.1	2.3 ± 0.2	3.3 ± 0.5	1.6 ± 0.1	29
TiO_2/Zr	24.0 ± 0.8	28.1 ± 0.8	39.4 ± 1.9	37.5 ± 2.4	36.7 ± 1.2	40.7 ± 1.5	27.7 ± 1.2	25.8 ± 0.8	21
SQ	3.6 ± 0.1	3.2 ± 0.1	3.8 ± 0.2	2.6 ± 0.1	3.9 ± 0.1	3.2 ± 0.1	4.1 ± 0.1	2.2 ± 0.1	17
$(Fe_2O_3+MnO)/Al_2O_3$	0.3 ± 0.01	0.4 ± 0.01	0.4 ± 0.01	0.4 ± 0.02	0.4 ± 0.01	0.3 ± 0.01	0.4 ± 0.02	0.3 ± 0.003	14

1—Northwestern Crimea, *2*—Southwestern Crimea, *3*—Piedmont Crimea, *4*—Southern coast of Crimea, *5*—Eastern Crimea, *pf*—post-antique fallow land, *mv*—modern vineyards. **FI* is the coefficient of potential soil fertility [47], C_e is the eluviation coefficient [41], C_m is the coefficient of chemical elements mobility [12], *SQ* is the coefficient of soil quality [12]. *V* is the variation coefficient.

Table 4. Agrochemical properties of soils in abandoned and modern vineyards

No.		Layer, cm	Color of dry soil (Munsell)	CO_2, %	pH H_2O	C_{org}	N_{tot}	C/N	P_{avail}	K_{avail}	B_{avail}	Cu_{avail}
						%			mg/kg			
Eastern Crimea												
6	mv	2–13	10YR 4/3	0.47	8.11	1.8	0.16	11.25	16	367	1.59	0.139
		13–24	10YR 4/3	0.55	8.16	1.76	0.18	9.78	7	307	1.25	0.093
Southern Coast of Crimea												
19	mv	0–14	10YR 6/2	0.23	8.08	1.50	0.54	4.63	35	240	1.03	0.188
		14–25	10YR 6/2	0.15	8.14	1.26	0.44	5.15	17	129	1.00	0.212
21	mv	0–17	10YR 6/1.5	0.85	8.00	1.53	–	–	16	224	2.13	0.079
		17–28	10YR 6/1.5	0.93	8.06	1.17	–	–	23	222	2.44	0.085
Piedmont Crimea												
28	mf	0–13	10YR 5/2.5	3.29	7.99	1.54	0.4	3.85	18	491	1.98	0.421
		13–26	10YR 5/2.5	2.97	7.83	1.86	0.26	7.14	8	339	2.15	0.243
Southwestern Crimea												
29	mv	0–18	10YR 6/3.5	4.29	8.13	1.99	–	–	33	447	1.67	0.440
		18–32	10YR 5/4	4.51	8.06	1.69	–	–	8	252	1.14	0.410
31	mv	0–14	10YR 4/4	4.47	8.05	1.53	0.26	13.56	32	510	1.96	0.382
		14–26	10YR 4/4.5	5.11	8.01	1.28	0.20	16.42	29	546	1.94	0.465
Northwestern Crimea												
36	mv	0–16	7.5YR 5/4	3.85	8.04	1.85	0.24	11.89	10	520	2.33	0.084
		16–34	7.5YR 4/4	4.07	8.10	1.16	0.20	15.82	8	352	2.14	0.050
39	mf	0–16	7.5YR 5/4	5.83	8.12	1.32	–	–	29	542	–	–
		0–21	10YR 5/3	19.48	8.06	1.53	–	–	9	221	–	–

Dash signifies the absence of data; mf—modern fallow land, mv—modern vineyards.

sary for its growth and development [15]. The comparison of *SQ* calculated as the geometric mean of the content of these elements shows that fallow soils are the most fertile: the content of useful chemical elements in them is significantly higher (1.2–1.5 times) than in modern soils under vineyards. The piedmont Crimea has *SQ* (3.87) close to the parameters of fallow lands, which may prove the high soil-genetic prospects for viticulture development in this area. The biological activity coefficient (MnO/Sr) is elevated in the areas of modern viticulture, which is related to the involvement of MnO in biogenic accumulation and migration. The TiO_2/Zr ratio is specific for each of five geographical regions of the Crimean Peninsula, which indicates the lithological and geochemical heterogeneity of soils.

The increased content of Cu, Cr, Ni, Pb, and V is revealed in soils under modern vineyards of the Crimean Peninsula. These heavy metal contents testify to the geochemical specifics of the region and to contamination of the studied area. The total accumulation of heavy metals and metalloids in soil relative to the background concentrations (index Z_c [6]) calculated for five geographical regions of viticulture of Crimea is the strongest for eight chemical elements (Ni, Cr, Cu, Pb, Zn, V, Co, and As) in the A soil horizon on the SCC (10.7) and in the Southwestern Crimea (10.0). The SCC is an important recreational area, where 35% of the agricultural land area is occupied by vineyards, so the main task there consists in the development of organic viticulture to avoid the use of pesticides and mineral fertilizers [24].

Agrochemical properties of soils under vineyards. The key agrochemical properties of soils of abandoned and modern vineyards were analyzed in detail to determine their agrogenic transformation (Table 4). The comparison of soils of five geographical regions shows that the content of necessary nutrients (N, P, and K) is higher on the SCC (N = 0.49%, P = 34.8 mg/kg, and K = 286 mg/kg) and in the Southwestern Crimea (N = 0.23%, P = 25.5 mg/kg, and K = 438 mg/kg), that is, in traditional viticulture and winemaking areas. The C_{org} content in postagrogenic soil horizons shows that the dehumification level in cultivated soils under vineyards is two times higher. The C/N ratio reflects the humus enrichment with nitrogen and thus characterizes its quality [17]. Soils of the piedmont Crimea (5.5) and the South Caucasus (4.9) are the most rich in humus as compared to other geographical areas.

Table 5. Concentration of chemical elements in ash of grapes and soil (B horizon) of modern vineyards of the Crimean Peninsula

ChE*	Measurement units	In ash of grapes					In B soil horizon (>70 cm)				
		study region**									
		1	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*
CaO		3.1	2.9	8.7	3.1	2.3	7.9	14.0	14.3	6.5	3.6
P_2O_5		2.2	2.1	3.5	2.5	2.7	0.1	0.3	0.3	0.2	0.1
Na_2O		0.7	1.5	1.4	–	2.0	0.9	1.3	1.1	2.1	0.9
K_2O		10.5	8.3	11.1	8.7	3.7	1.7	1.8	1.5	2.9	1.3
Al_2O_3	%	0.2	0.2	0.3	0.1	0.2	11.4	10.2	9.2	18.4	9.8
MgO		0.5	0.4	1.3	0.3	0.8	1.7	1.3	1.1	1.9	1.1
TiO_2		0.02	0.01	0.01	0.04	0.01	0.78	0.62	0.52	0.47	0.84
Fe_2O_3		0.4	0.2	0.2	0.6	0.01	5.0	3.9	3.8	5.3	3.2
SiO_2		3.1	2.8	3.3	2.8	2.2	51.6	44.2	41.6	47.3	40.5
Co		39.3	41.3	2.9	73.5	27.3	9.0	1.8	0.7	13.5	14.6
Rb		64.0	51.2	66.9	38.1	39.5	88.3	64.8	57.4	140	68.9
Ni		8.2	8.3	8.3	7.4	8.4	53.3	42.5	34.5	77.6	53.0
Cu		–	–	–	–	–	27.7	52.1	56.2	45.6	31.1
Zr		–	–	–	–	–	276	199	151	209	320
MnO		0.01	0.01	0.01	0.02	–	0.12	0.12	0.06	0.13	0.13
Zn	mg/kg	81.0	121.0	68.0	108.0	79.0	81.2	87.1	103	120	62.5
Sr		157	112	350	102	121	182	179	157	136	108
As		–	–	–	–	–	9.1	10.9	9.1	12.3	7.4
Ba		23.5	34.0	10.0	35.0	28.0	543	393	332	432	490
Pb		10.9	9.7	9.5	9.9	10.1	21.8	17.0	17.0	25.1	21.6
Cr		–	–	–	20.6	–	93.1	91.7	67.7	109	103
V		–	–	0.34	–	–	100	80	66	96	89

* *ChE*—chemical elements.
** *1*—Northwestern Crimea, *2*—Southwestern Crimea, *3*—Piedmont Crimea, *4*—Southern coast of Crimea, *5*—Eastern Crimea. The results are obtained in replications, which provide an acceptable error. Dash signifies values below the detection limit.

Neutral or slightly alkaline soils are the best ones for vineyards. Soils of the piedmont Crimea correspond to this criterion: their pH averages 7.9 (weakly alkaline soils). All other studied objects are characterized by pH > 8, which corresponds to medium (8–8.5) and highly alkaline (>8.5) conditions. Plants may not receive the necessary nutrients from the soil. Such inverse relationship is the case for mobile boron: its content is increasing at pH < 8 (objects 21, 28, 36).

It is shown [14] that there is most significant excess of copper in vine leaves on the SCC due to intensive and long-term processing of vineyards by copper-containing preparations. The regression analysis of the relationship between the content of Cu_{tot} and Cu_{avail} in soils of five geographical regions of the Crimean Peninsula shows that parallel to two-time increase in Cu_{tot} in the soil, the content of its mobile form rises 3.3 times.

Results of translocation in the soil–plant system. Test plots in land use areas within large modern wineries in four districts of the Crimean Peninsula were studied for the interrelated geochemical characteristics of soil and vine plant. The fifth district includes lands in the piedmont Crimea, which can be regarded among the priorities for the redevelopment of the wine industry due to the reserve of suitable lands and the agro-climatic potential. In this regard, we studied the vineyard of state farm-plant "Predgor'e", which has not been cultivated since 2010. The comparison of the geochemical compositions of berry ash from aged vineyards characterized by a developed root system and of the B horizon of soils (Table 5) shows the selective absorption of chemical elements by the vine plant. The acropetal distribution of elements is typical for the five studied areas of the Crimean Peninsula: the concentration of chemical elements is the greatest in roots of vine plant [14]. Grape berries mainly accumulate useful elements: P_2O_5, K_2O, and CaO. Elevated concentrations of heavy metals, such as Co and Sr, are revealed in all studied regions, and Zn is detected in the Southwestern and Eastern Crimea. This is related to the anthropogenic impact on soil and vineyards (the application of herbicides and fungicides). On the contrary, the concentration of other heavy metals (Cr, V, Cu, and Zr) and As is low in grape produced on soils with high heavy metals content.

The assessment of the ampelopedological conditions of the Crimean Peninsula shows that the Southwestern and Piedmont Crimea are characterized by a favorable biogeochemical potential: the content of plant nutrients (CaO, P_2O_5, and K_2O) is 1.5–2 times higher than in other areas. Lands of the Massandra enterprise (the SCC) are the most polluted: the concentrations of heavy metals Co, Ni, Zn, Pb, V, and Cr in the upper soil horizon under vine are exceeded. The results of the study enable us to substantiate the criteria for the identification of geographical areas of viticulture of the Crimean Peninsula. In particular, there is an increased content of Zn in grape ash in the Southwestern Crimea and of Ni in the Eastern Crimea. Grapes from the Piedmont Crimea are characterized by higher concentration of MgO, Al_2O_3, SiO_2, P_2O_5, CaO, Sr, and K_2O, as well as Rb (more than two times). The accumulation of Fe and Pb is more intensive in soil and ash of berries in the Northwestern Crimea. Such chemical elements as Cr, Co, and Ba are responsible for geochemical features of grape on the SCC. The criteria obtained can help the identification of the geographical location of wine products from the Crimea to protect them from falsification.

CONCLUSIONS

Initial trench plowing results in different structural status and water stability of aggregates in vine rows and in areas between rows over several ten-year periods of vineyard growth due to regular cultivation (four–six times a year). This is reflected in the decrease in the portion of agronomically valuable aggregates (0.25–7 mm) by 16% and in the water stability index of aggregates of 1–5 mm in diameter by 26% in soils between rows as compared to soils under vine. It is argued that the geographical factor plays the leading role in the classification of soils of vineyards by a comblnation of agrophysical parameters despite the different development history and the intensity of agrogenic transformations of soils. This is especially obvious in the specific properties of soils of the sub-Mediterranean region on the SCC in comparison with four other areas of modern viticulture.

The comparison of geochemical features of soils from the three main regions of ancient viticulture of the Crimea (in the northwest and southwest of the peninsula and on the Kerch Peninsula) shows that the greatest differences in the postagrogenic horizon are determined by the content of macroelements Ca, Al, Si, Mg, and K and of microelements Sr, Rb, As, and Pb.

The comparison of soils under modern vineyards by a combination of 18 diagnostic elements and their oxides shows a fundamental difference in geochemical conditions in five geographical regions of the Crimea. This is related to differences in the genesis and parameters of soils, which can potentially affect the quality of wine materials in these regions. Soils of the Southwestern and Piedmont Crimea are characterized by the most favorable biogeochemical potential: the content of a number of plant nutrients (Ca, P, K) in them is 1.5–2 times higher as compared to that in other areas. The analysis of the factors of geochemical differences in soils from many viticulture regions, which are differentiated in the hierarchical classification of the study objects, shows that specific features of soils under vineyards of the SCC are determined by concentrations of Cr, Co, and Ba.

The potential of the soil and climatic diversity of the Crimean Peninsula (51 soil types of 17 genetic groups according to [19] and 20 agro-climatic regions) makes promising further research: the use of an ampelopedological approach to substantiate agroproduction groups of soils, which can provide high-quality products, and to form a wide range of terroirs in the entire region.

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SUPPLEMENTARY INFORMATION

The online version contains supplementary materials available for authorized users at https://doi.org/10.1134/S1064229322700065.

Table S1. The content of macroaggregates and parameters of the structural status of soils.

Table S2. Geochemical features of soils (the A and AB horizons) in historical and modern viticulture regions.

Table S3. The results of the bulk elemental analysis of fallow soils (the A horizon) from the areas of ancient viticulture in Crimea.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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