Methodological framework for characterizing vineyards subjected to soil degradation in Piedmont

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Methodological framework for characterizing vineyards subjected to soil degradation in Piedmont

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The IN-GEST SOIL project aims to address soil degradation, particularly soil erosion by water, in hillslope vineyards in the Piedmont region of Italy. This study proposes a methodological framework for comprehensive vineyard characterization to establish a baseline for soil health investigations. The characterization involves using regional databases for climatic, geological, and pedological data, integrated through field surveys. Soil samples were collected to determine bulk density, granulometry, and organic matter content. The results indicate significant variability in geology, soil texture, organic matter content, and bulk density across different sites. Bulk density measurements revealed that soil compaction was close to or exceeded the threshold affecting root growth, particularly in the track position, where compressive effects from tractor wheels or tracks are concentrated. These findings highlight the need for site-specific soil management strategies to optimize vineyard productivity and sustainability. This preliminary study serves as a foundation for future research focused on long-term monitoring of soil management practices and their impact on vineyard sustainability and resilience in the face of climate change. Engaging local farmers and stakeholders in adopting sustainable practices is crucial. The choice of management strategies will be informed by data from this study and insights from a parallel study on winegrowers' perceptions and behaviours.

Keywords: *vineyard, soil, characterization, Piedmont, geology, climate.*

1. Introduction

Viticulture, one of the most ancient and widespread agricultural practices (Corti *et al.*, 2011), plays a crucial role in the Mediterranean region, providing not only economic benefits through grape and wine production but also contributing significantly to the cultural and environmental landscape (UNESCO, 2014; Foronda-Robles, 2018). However, the intensification of vineyard management practices has led to several environmental challenges, particularly concerning soil and water conservation, soil biodiversity and ecosystem services (Giffard *et al.*, 2022). Effective management of these resources is essential to ensure the sustainability and resilience of vineyards, especially in the face of climate change (Salomè *et al.*, 2016; Kowalczyk *et al.*, 2024).

The conservation of soil and water resources in vineyards is crucial for sustainable viticulture, especially in Mediterranean regions where water scarcity and soil erosion are significant concerns (Prada *et al.*, 2024; Cataldo *et al.*, 2020; Novara *et al.*, 2011). Effective soil management practices can mitigate these issues and enhance the overall health and productivity of vineyards (Cárceles Rodríguez *et al.*, 2021; Kopta *et al.*, 2024). The use of cover crops in the vineyards has been shown to reduce soil erosion and runoff significantly (Abad *et al.*, 2021; Prosdocimi *et al.*, 2016). Cover crops, such as grasses or legumes, help to stabilize the soil, increase organic matter, and improve soil structure (Scavo *et al.*, 2022). They also enhance water infiltration and reduce surface runoff, which is particularly beneficial in sloping vineyards. Managing the inter-row space with grass cover or mulching can control soil erosion and improve water retention (Gómez *et al.*, 2011). Studies have shown that grass cover can reduce runoff by up to 65% and soil erosion by 72% (Capello *et al.*, 2020). However, in semi-arid regions, the competition for water between cover crops and vines needs careful management to avoid negative impacts on grape yields (Ruiz-Colmenero *et al.*, 2011). Efficient water management practices ensure that water is used judiciously, reducing wastage and conserving this precious resource. This is particularly important in regions prone to drought (Medrano *et al.*, 2015). Minimizing soil disturbance through reduced tillage practices can help maintain soil structure and reduce erosion (Biddoccu *et al.*, 2016). This practice also promotes the accumulation of organic matter and enhances soil moisture retention (Steponavičienė *et al.*, 2024). By conserving soil and water resources, vineyards can maintain sustainable production levels, ensuring long-term viability and profitability. This also contributes to the preservation of the landscape and cultural heritage associated with viticulture (Garcia, 2018).

Italy is recognized as the leading wine producer globally (Organisation Internationale de la Vigne et du Vin [OIV], 2021a, 2021b), with a production of 54.8 million liters in 2021. It ranks fourth in vineyard cultivation with 718,000 hectares, following Spain, France, and China (OIV, 2023). Most of the vineyards are located in the administrative provinces of Cuneo, Asti, and Alessandria, which include the UNESCO World Heritage Site "The Vineyard Landscape of Piedmont: Langhe, Roero, and Monferrato" (UNESCO, 2014). Piedmont is the Italian administrative region with the highest number of DOCG (Denominazione di Origine Controllata e Garantita, 19 out of 73 in Italy) and DOC (Denominazione di Origine Controllata, 41 out of 332 in Italy) designations (Regione Piemonte, 2024a), producing 11% of the grapes for DOP (Denominazione di Origine Protetta, including both DOC and DOCG) wines in Italy (ISTAT, 2024; Fig. 1).

The IN-GEST SOIL project aims to address soil degradation processes, especially soil erosion by water, in hillslope vineyards in the Piedmont region of Italy. This initiative focuses on enhancing soil and vine quality through the implementation of innovative soil management practices. The project introduces three main innovations: improved best soil management practices, agro-meteorological monitoring to optimize water and soil management, and the use of ICT tools for data management and decision-making support. Piedmont, a region renowned for its wine production, faces significant challenges due to its vineyards being predominantly located on sloping terrains, which are highly susceptible to soil erosion (Biddoccu *et al.*, 2016; Tarolli *et al.*, 2014). The IN-GEST SOIL project seeks to mitigate these issues by promoting sustainable agricultural practices that not only preserve soil health but also enhance the overall productivity and quality of the vineyards (Baldi 2021). By engaging local farmers and stakeholders, the project aims to foster a deeper understanding of soil conservation techniques and encourage the adoption of practices that can lead to long-term environmental and economic benefits (Strauss *et al.*, 2023; Velten *et al.*, 2021; Salvia *et al.*, 2018). The project represents a novel approach by conducting an in-depth investigation of local farmers' perceptions, thereby providing a unique perspective on soil conservation in vineyards, particularly in the Piedmont region, which has not been extensively studied before.

In this study, we suggest a methodological framework to perform a comprehensive characterization of vineyards, in order to define a baseline for further investigation about soil health. The characterization is carried out, initially, (i) using data available from regional databases, including climatic, geological, and pedological data, which are crucial for understanding the environmental conditions of the vineyards. These databases provide foundational knowledge but need to be (ii) integrated and validated through field surveys to better understand spatial and temporal variability. The field surveys provide detailed information on soil, allowing for precise site characterization.

The aim of the study is to propose a way to characterize each vineyard, in order to determine which innovative soil management practices are better to adopt to mitigate the identified issues, comparing them with traditional methods. The selection of innovative techniques will also be based on the results of a parallel study, which involved questionnaires on the perceptions and behaviors of Piedmontese winegrowers (Caffaro *et al.*, 2024). These questionnaires and field data offer extensive and current insights into the existing approaches to soil conservation in vineyards. By integrating data-driven insights with the practical knowledge and experiences of local farmers, we aim to develop tailored management strategies that address both environmental and economic challenges.

This work serves as a preliminary step for future studies, where we will divide the vineyards into two plots and determine which management practices to implement. One plot will follow traditional farming practices, while the other will adopt innovative techniques compatible with the site characteristics identified through this study. This approach is expected to provide valuable insights into the effectiveness of different soil management practices in reducing soil erosion and enhancing vineyard sustainability in the region and beyond (Topp *et al.*, 2024; Veisi *et al.*, 2024; Cerdà & Rodrigo-Comino, 2021).

2. Materials and Methods

2.1. Study area

In the Piedmont region, there are more than 44 thousand hectares of vineyards (ISTAT, 2024), mostly located in hilly (92%) and mountainous (7%) areas (Fig. 1). The presence of various mountain formations and the geographical position contribute to a diverse climate.

Most areas with a high propensity for viticulture are classified by the current Köppen-Geiger climate classification of the European Alps (Rubel *et al.*, 2017) as Cfa: a warm temperate climate with hot summers and no dry season. Vineyards in the foothill areas have a similar warm temperate climate but with warm summers and no dry season (Cfb), while the Apennines have a warm temperate climate with warm and dry summers (Csb). The Ovadese Monferrato area experiences a warm temperate climate with hot and dry summers (Csa).

The distribution of rainfall, due to the region's geographical diversity, varies accordingly. Precipitation is more abundant in the mountainous and foothill areas, especially during spring and autumn, while the plains area generally experiences less intense precipitation. However, strong thunderstorms can occur during the summer. The annual average of daily cumulative precipitation in the viticultural areas, calculated for the period 1991-2020 (ARPA, 2024), showed a minimum in the plain area between Asti and Alessandria of just over 700 mm per year. The minimum precipitation occurs in winter and summer (about 40 mm in July), with precipitation concentrated in spring and autumn. Moving away from this area, the average annual precipitation increases; for example, the Gavi area has an average annual precipitation of around 1000 mm.

The orography also influences the temperature distribution in the region. In the plains and hilly areas, summers are hot and muggy, while winters are cold and humid, often with dense fog. In the same area where the minimum precipitation is recorded, the annual average of the daily maximum temperature, calculated for the period 1991-2020, reaches a peak of 18.5°C, with temperatures just below 30°C in the summer period (exceeding 30°C only in July and August). In the same area, the winter maximum temperatures do not drop below 5°C. Considering the same period, the minimum temperatures in the viticultural areas have an annual average below 10°C: they remain below 18°C in the summer period (July and August can exceed 19°C), while in the winter period they settle around 0°C (generally, January is the coldest month) (ARPA, 2024).

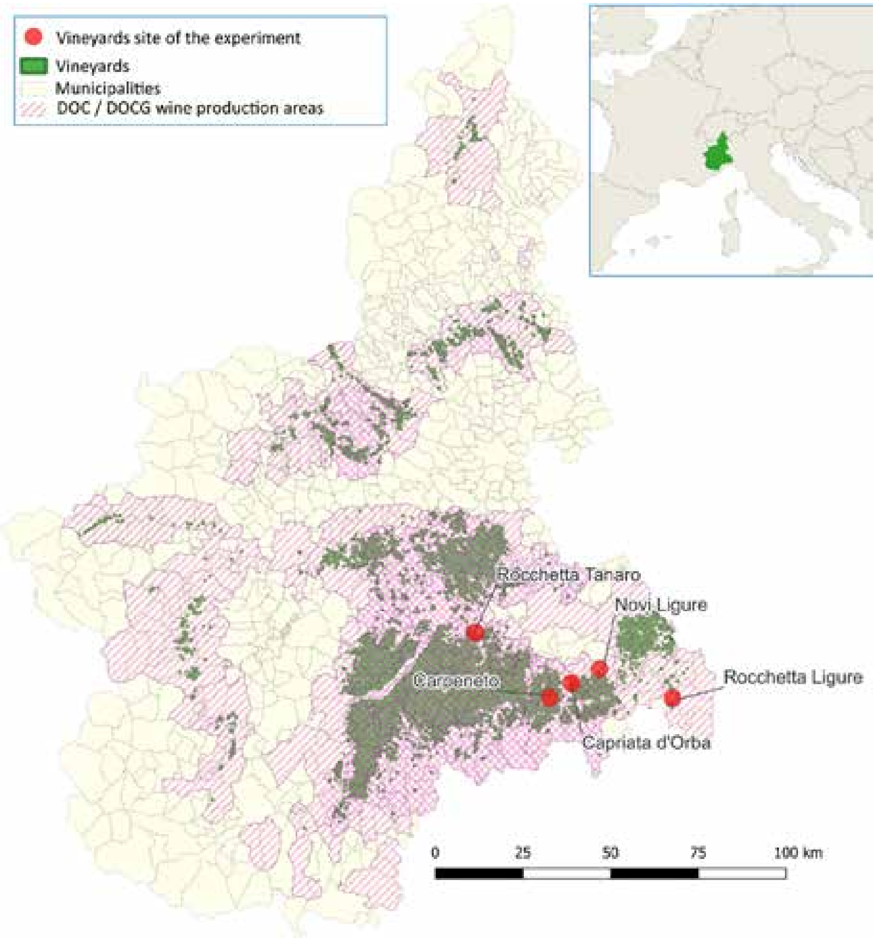

Fig. 1 – The map depicts the Piedmont region. Municipalities included in one or more DOC and/or DOCG wine production areas (Regione Piemonte, 2024b) are marked with purple hatching and cross-hatching. Vineyard parcels, based on the regional cadastral mosaic (Regione Piemonte, 2024f), are highlighted in green. The selected vineyards under study are indicated with red dots.

The vineyards selected as the study area for the In-Gest Soil project (Fig. 1) are located outside the UNESCO World Heritage Site "The Vineyard Landscape of Piedmont: Langhe, Roero, and Monferrato", but they are all within the Piemonte DOC and other DOC or DOCG wine production areas (Regione Piemonte. 2024b). Rocchetta Tanaro is located in the province of Asti, while the other sites are in the province of Alessandria. Four out of five sites are located within the "Alto Monferrato" area. Rocchetta Ligure is very close to Alto Monferrato, but it is situated in a different region, namely Val Borbera. Rocchetta Tanaro is one of the municipalities of Ovadese, a historical-cultural area of Lower Piedmont and Monferrato, which also includes Carpeneto, situated on a ridge between the Orba and the Bormida rivers. Novi Ligure and Capriata d'Orba are located on the right bank of the Orba river and are part of the Novese, a geographical region of Lower Piedmont named after the city of Novi Ligure.

2.2. Vineyards Management

Table 1 provides key information about the five vineyards selected

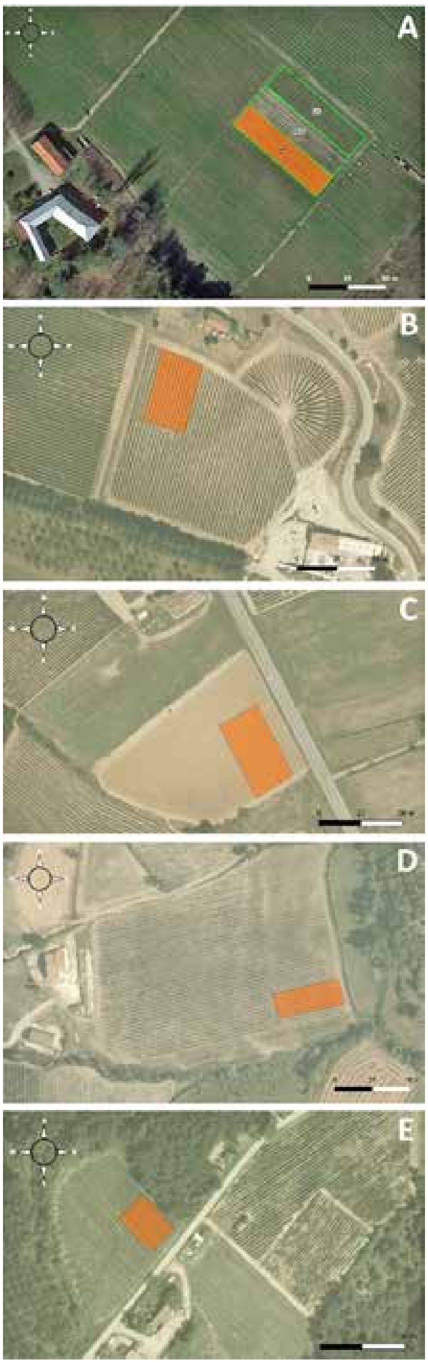

Fig. 2 – The figure highlights in orange the plots delineated in the vineyards selected for the IN-GEST SOIL project: A) Carpeneto; B) Novi Ligure; C) Capriata d'Orba; D) Rocchetta Ligure; E) Rocchetta Tanaro. In Carpeneto (A), the three existing plots are delineated in green. The selected plot is the one managed with conventional tillage of the inter-row soil twice a year.

as test areas for the IN-GEST SOIL project; Figure 1 shows their locations in the Region. In all the vineyards, the rows of vines are planted along the line of maximum slope. At the Experimental Center for Viticulture "Tenuta Cannona" of the Agrion Foundation, in Carpeneto (Fig. 2, A), three experimental plots were already established. The plot where data collection took place is managed using conventional tillage (CT). In both spring and autumn, following the harvest, the soil is tilled using a ripper to a depth of 25 cm across all rows. During the summer, up until the harvest, mowing operations are conducted as needed to manage spontaneous vegetation. The second plot is managed with permanent spontaneous grass cover (GC), controlled through periodic mowing. The third plot employs alternate cover crops (ACC), with alternating rows between CT and GC.

At the Capriata site (Fig. 2, C), there is a recently established vineyard (planted between 2017 and 2018). Organic fertilization is applied using a manure spreader, followed by soil tillage with a ripper to a depth of 40 cm to ensure the incorporation of the fertilizer into the soil. In spring and summer, to prevent the establishment of vegetation, and if the summer is particularly dry, repeated soil tillage is performed using various implements (ripper, rotary harrow, rototiller) in alternating rows. The under-row area is managed with mechanical weeding using an under-vine hoe, which works the topsoil layer (5-10 cm depth).

At the Novi Ligure site (Fig. 2, B), the vineyard is managed with an alternating row system. The green manure (GM) rows are sown in autumn with a mixture of typical green manure species, consisting of Fabaceae: fava bean (*Vicia faba*), vetch (*Vicia villosa*), and pea (*Pisum sativum*); and Poaceae: varieties of barley (*Hordeum vulgare*). The GC rows are predominantly covered with spontaneous vegetation. In the GM rows, deep tillage to a depth of 40 cm is performed using a subsoiler, followed by the application of organo-mineral fertilizer using a manure spreader, and then the sowing of the GM mixture. The GM is sown in a single pass using a combined seeder preceded by a rotary harrow, with a roller following the seeder to ensure seed-soil contact. From early spring, mowing is performed in the GC rows to control spontaneous vegetation. In summer, mowing is also carried out in the GM rows. The mowed biomass is left on the ground to provide a mulching effect and reduce erosion risk. If necessary, multiple mowing operations are conducted across all rows. In the GC rows, if the summer is particularly dry, superficial tillage to a depth of 5-10 cm is performed using a flexible tine harrow to prevent soil cracking. Mechanical weeding is conducted under the vine rows through repeated passes with a brush cutter. In autumn, the row management is reversed: after the GM is incorporated into the soil, the inter-row becomes GC in the following growing season, while in autumn, when tillage and sowing occur, the GC inter-row becomes the GM row.

The management of the vineyard in Rocchetta Ligure (Fig. 2, D), is similar to that of the Novi Ligure site. The GM rows are sown with a mixture of typical green manure species, consisting of Fabaceae: fava bean (*Vicia faba*), vetch (*Vicia sativa*), and pea (*Pisum sativum*); Poaceae: varieties of barley (*Hordeum vulgare*); and Brassicaceae: present in smaller quantities and belonging to the genus *Brassica* sp. The GC rows with spontaneous vegetation are characterized by the presence of spontaneous aromatic plants such as Mentha sp. and Anethum graveolens. In this site, soil tillage is performed to a depth of approximately 30 cm using a subsoiler equipped with discs. Organic fertilization is carried out with a machine that incorporates the fertilizer into the soil, and the

GM mixture is broadcast sown. The other operations are similar to those performed at Novi Ligure, including the reversal of row management at the end of the growing season.

At the Rocchetta Tanaro site (Fig. 2, E), the inter-row area is managed with spontaneous vegetation, controlled mechanically through mowing. If necessary, light superficial tillage is performed. The under-vine area is managed using chemical herbicides to eliminate weeds. These operations are repeated as needed.

2.3. Investigation

A thorough investigation was conducted using national and regional public databases to classify each vineyard based on climatic, geological, and pedological characteristics. Figure 3 provides a schematic overview of all the data sources and references used in this study. Climatic classification was based on the current Köppen-Geiger climate classification of the European Alps (Rubel *et al.*, 2017), the Bagnouls and Gaussen (1957) xerothermic index, and the Land Capability Classification (LCC) developed by the Soil Conservation Service (SCS) of the United States (Klingebiel and Montgomery, 1961). Rainfall distribution was studied using the map provided by ARPA Piemonte on the Climate Portal of Piemonte, with data interpolated from available

Fig. 3 – Schematic overview of all the data sources and references used in this study.

Tab. 1 – Characteristics of the five plots in the vineyards site of study in the Piedmont region.

Municipality (province)	**Carpeneto (AL)**	**Novi Ligure (AL)**	**Capriata d'Orba (AL)**	**Rocchetta Ligure (AL)**	**Rocchetta Tanaro (AT)**
Farming company	Experimental Center for Viticulture "Tenuta Cannona" of the Agrion Foundation	Azienda Agricola "Cascina Binè"	Azienda Agricola "Cascina Gentile"	Azienda Agricola "Nebraie"	Azienda Agricola "Porzio"
Vineyard coordinates	44° 40′ 56.42″ N, 8° 37′ 34.27″ E	44° 44′ 12.91″ N, 8° 47′ 23.34″ E	44° 43′ 18.63″ N, 8° 42′ 8.41″ E	44° 40′ 34.90″ N, 9° 3′ 18.40″ E	44°50′40.3″ N, 8°22′07.3″E
Exposure	134° (Southeast)	196° (South-Southwest)	191° (South)	269° (West)	315° (Northwest)
Average elevation [m a.s.l.]	273.3	225.3	227.5	510.5	197.0
Average slope [%]	15.3	14.2	2.5	16.8	19.0
Plot area [m^2]	1221	1275	1344	768	600
Plot length and width [m]	74 x 16.5	42.5 x 30	40 x 33.6	40 x 19.2	30 x 20
Number of rows	6	12	14	8	8
Inter-row width [m]	2.75	2.5	2.4	2.4	2.5
Plant spacing in row [m]	1	0.9	0.9	0.9	0.9
Grape variety	Barbera	Cortese	Dolcetto	Timorasso	Barbera

regional weather stations (ARPA, 2024). Additional sources on historical rainfall data in the region were also consulted for comparison and further information. Geological information was obtained from the Piemonte Geoportal, specifically from the geological map of Piemonte (Piana *et al.*, 2017) and its subsequent updates. Additional maps available on the Piemonte Geoportal, including those covering lithology, hydrogeology, soil and pedological characteristics, risks, erosion, and other relevant data, were examined. An analysis was performed using cadastral data and pedological information on vineyard areas to calculate which soil types host vineyards.

Field surveys were conducted in each vineyard to collect soil samples for determining bulk density (BD) and analysing granulometry and organic matter content (OM). Measurements were taken in both the track position (T), where compressive effects from tractor wheels or tracks are concentrated (Söhne, 1953), and the no-track position (NT), which is not directly affected by tractor wheels or tracks. Five core samples ($V = 100\ cm^3$) were collected from both T and NT positions at depths of 0.0-0.2 m and 0.2-0.4 m, resulting in a total of 20 soil cores per site. These samples were oven-dried at 105°C for 48 hours and then weighed. BD was calculated as the average of values obtained from the five repetitions at each position and depth. Additionally, soil samples were collected at depths of 0.0-0.2 m and 0.2-0.4 m. These samples were mixed from multiple points within the vineyard to ensure representativeness. They were then analysed by an external laboratory for granulometry and organic carbon content. The BD values were then compared to the threshold values reported for every different soil types in the Soil quality test kit guide (USDA, 2011). Field capacity (SWCfc) and wilting point (SWCwp) values were calculated based on the methodology described by Román Dobarco *et al.* (2019).

The elaboration of the maps, the spatial database processing and the analyse of geographic data were performed using open-source software QGIS version 3.38 (QGIS Development Team, 2024).

3. Results and discussion

The vineyards selected for this study, which are located in the Novese area (Novi Ligure and Capriata d'Orba) and Carpeneto, according to the Köppen-Geiger climate classification for the European Alps (Rubel *et al.*, 2017), are classified as Csa, indicating a warm temperate climate with hot and dry summers. Rocchetta Tanaro, on the other hand, is classified as Cfa, which denotes a warm temperate climate with hot summers and no dry season. Additionally, Rocchetta Ligure, situated in the Borbera Valley of the Apennine Mountains, is classified as Csb, characterized by a warm temperate climate with warm and dry summers.

According to the climate classification method by Bagnouls and Gaussen (1957), also known as the xerothermic index, all five study areas fall within the Xerothermic zone (long dry days) and the Sub-Mediterranean subregion. These areas experience one or two arid months in summer. Rocchetta Ligure is located at the boundary of the mesoxeric climate area (hypomesoxeric temperate subregion). In this region, there are no arid months, and the average monthly temperatures of the coldest month range between zero and ten degrees Celsius. This method, which relates average monthly precipitation to average monthly temperatures to determine dry periods, is particularly useful for identifying drought periods and evaluating climatic limitations that may affect agricultural techniques in a given area.

Another possible classification is the pedoclimatic classification developed by the Soil Conservation Service (SCS) of the United States, known as the Land Capability Classification (LCC). This system, developed by Klingebiel and Montgomery (1961), evaluates the land's capability for use by classifying soils into Land Capability Classes based on their physical and chemical characteristics, as well as the limitations that may affect their agricultural use. This method is particularly useful as it helps determine the productive capacity and the most appropriate agricultural practices for each type of soil. It also identifies areas that require interventions to prevent erosion and maintain soil fertility. According to this classification, all five vineyards under study fall within the Ustic Mesic area. The Ustic moisture regime is characterized by significant periods of dryness, making it essential to choose drought-resistant crops or resort to irrigation. The Mesic temperature regime indicates sufficiently high temperatures to support crop development. Also in this case, Rocchetta Ligure is located at the boundary of the Udic Mesic area, where dry periods are of limited duration and frequency.

An analysis of the annual average daily cumulative precipitation, calculated over the period 1991-2020 through interpolation of the ARPA Piemonte pluviometric network (2024), for each study site, reveals a clear seasonal trend (Tab. 2). Autumn emerges as the wettest season, with November being the rainiest month across all sites. Conversely, summer is the driest season for most study sites. Rocchetta Ligure stands out for having both the highest number of rainy days and the highest annual, autumnal, and November precipitation, whi-

Tab. 2 – Principal information on precipitation, climate (Köppen-Geiger classification) and soil characteristics for each study site.

Site	Carpeneto	Novi Ligure	Capriata d'Orba	Rocchetta Ligure	Rocchetta Tanaro
Number of rainy days (threshold 1 mm)	82.4	80.8	81.7	99.1	77.2
Annual precipitation (mm)	817.2	815.0	785.7	1083.4	695.7
Wettest month (mm)	November (144.0)	November (145.1)	November (137.6)	November (181.6)	November (94.5)
Driest month (mm)	July (35.4)	July (34.9)	July (35.0)	July (43.9)	February (37.6)
Wettest season (mm)	Autumn (333.8)	Autumn (343.4)	Autumn (324.0)	Autumn (445.1)	Autumn (238.6)
Driest season (mm)	Summer (125.2)	Summer (122.4)	Summer (124.0)	Summer (173.6)	Winter (118.7)
Climatic zone	Csa (warm temperate with hot and dry summers)	Csa (warm temperate with hot and dry summers)	Csa (warm temperate with hot and dry summers)	Csb (warm temperate with warm and dry summers)	Cfa (warm temperate with hot summers and no dry season)
USDA soil classification	Alfisols of ancient terraces / hillside Alfisols	Alfisols of ancient terraces / hillside Inceptisols	Alfisols of ancient terraces	hillside Inceptisols	hillside Alfisols

le Rocchetta Tanaro records the lowest values in these categories. Summer is the driest season for most sites, with Rocchetta Ligure recording the highest summer precipitation (173.6 mm). However, for Rocchetta Tanaro, winter is the driest season (118.7 mm compared to 139.3 mm in summer). Notably, July is the least rainy month for all sites except Rocchetta Tanaro, where February is the least rainy month (37.6 mm compared to 39.4 mm in July).

In the city of Novi Ligure, a few kilometers from the vineyard under study, there is a centennial weather station with data recorded since 1879. Cortemiglia *et al.* (1999) conducted a climatic analysis of the data series from 1879 to 1979, yielding results comparable to those obtained by ARPA Piemonte. Annual precipitation was found to range between 745.6 and 860.8 mm, with an average summer precipitation of 138.6 mm and an autumn average of 329.7 mm. The wettest summer was in 1960, with 491.5 mm of rainfall over 29 rainy days, while the driest summer was in 1884, with only 22.6 mm over 4 rainy days. Additionally, the wettest autumn occurred in 1976, with 713.4 mm of rainfall over 30 rainy days, whereas the driest autumn was in 1921, with just 37.7 mm over 3 rainy days.

Biancotti *et al.* (1998) report the rainfall data of the period 1951-1986 from several weather stations near the study sites. The Carpeneto site is located between the weather stations of Sezzadio and Ovada. Ovada, situated at an altitude of 187 meters, has an average annual precipitation of 965 mm and 70 rainy days. October is the wettest month with 149 mm of rainfall, although November has more rainy days (8 days) compared to October (7 days). The driest month is July, with 29 mm of rainfall over 3 days. Sezzadio, located more towards the plains at an altitude of 127 meters, has lower average annual precipitation of 741 mm and 99 rainy days. Here too, October is the wettest month with 104 mm of rainfall, while July is the driest with 36 mm. Considering that Carpeneto is situated at an intermediate distance between these two stations, the data obtained by interpolation from ARPA (2024) are reliable.

The nearest weather station to Rocchetta Ligure is Stazzano, located at the beginning of the Borbera Valley. The station is at an altitude of 219 meters, with an average annual precipitation of 966 mm over 111 rainy days. November is the wettest month with 141 mm of rainfall over 10 rainy days, while July is the driest with 33 mm over 6 rainy days. Given that the vineyard is further into the valley, the higher average values calculated by ARPA (2024) are expectable and reliable.

Capriata is centrally located among the previously analyzed stations of Sezzadio, Ovada, and Novi Ligure. Although it is farther from these stations, the data are comparable to those from the ARPA Piemonte pluviometric network (2024).

Finally, Rocchetta Tanaro does not have nearby weather stations for comparison.

Based on the available lithological information (ARPA, 2011a, 2011b) and the geological map of Piemonte (Piana *et al.*, 2017) and its subsequent updates up to a scale of 1:70,000 (ARPA & CNR IGG, 2021), the hills of Alto Monferrato are composed of sedimentary units from synorogenic basins. These sources provide a detailed graphic representation of the region's geology grounded in an extensive

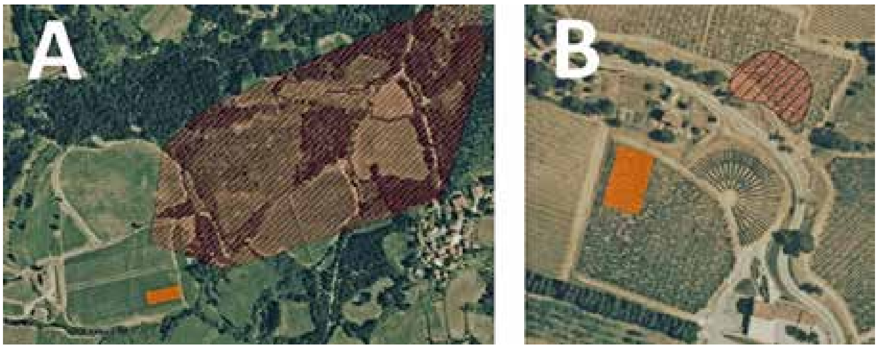

Fig. 4 – The figure highlights the landslide areas with red hatching and the vineyard plots selected for the IN-GEST SOIL project with orange delineation: A) Rocchetta Ligure; B) Novi Ligure.

geodatabase. These basins were deformed and uplifted during the Cenozoic and Quaternary periods. The geological units of Capriata d'Orba, Novi Ligure, and Carpeneto are composed of fluvial deposits with sands and gravel. Specifically, Carpeneto is on the boundary with the geological unit of the Rocca Grimalda chaotic complex, characterized by blocks of sandstones, hybrid sandstones, and calcarenites embedded in a clast-supported breccia matrix. The vineyard located in Rocchetta Tanaro is situated in the upper part on the geological unit of Ferrere Sands and S.Martino Silts, with Piacenzian silty and sandy-gravelly successions, while the lower part lies on the geological unit of Maranzana of the Villafranchian, with fluvial deposits of sands, gravels, and clays. Rocchetta Ligure is located on the geological unit of Pagliaro Shales, with sandstones locally interbedded with marly limestones and shales (Arenite, Impure limestone). The site of Rocchetta Ligure is located in the Val Borbera, situated within the Ligurian Apennines. This valley extends into the Piedmont region, bordering Liguria. The landscape of Val Borbera is characteristic of Apennine valleys, featuring rounded ridges and steep slopes, often subject to erosion phenomena, and it encompasses a wide variety of geological formations. Throughout the valley, the Antola Flysch, a sequence of sedimentary rocks, is prevalent. Near Persi (Borghetto di Borbera), the Cessole Marls are observable, characterized by a succession of fine layers overlain by sandstone beds. In Cantalupo Ligure, Puddinga Conglomerates can be found, a sedimentary rock composed of rounded pebbles cemented by a calcareous matrix. Finally, between Rocchetta Ligure and Mongiardino Ligure, the Pagliaro Shales emerge. The vineyard object of study is situated on this formation, which includes sandstones locally interbedded with marly limestones and shales (Arenite, Impure limestone).

Only the vineyard located in Rocchetta Ligure is subject to hydrogeological constraints (Regione Piemonte, 2016). No fires have been recorded in the areas surrounding the vineyards under study (Regione Piemonte, 2024c). None of the sites fall within protected areas (Regione Piemonte, 2024d).

Regarding the presence of landslides (Regione Piemonte *et al.*, 2015; ARPA, 2013a, 2013b; Regione Piemonte, 2024e), an active landslide with high potential hazard is located upstream of the Rocchetta Ligure vineyard, reaching the vineyard (Fig. 4A). The landslide has been activated in 1980 and 2002, following heavy rainfall events. Geognostic surveys and geophysical investigations were carried out, which confirmed the presence of Pagliaro Clays and the presence of the water table between 2 and 4 m. In Novi Ligure, there is also an active rapid earthflow with very high potential hazard, situated upstream of the road above the vineyard under study (Fig. 4B). The event occurred following rainfall between late April and early May 2013. The landslide blocked traffic along the SP 158 road. There is a water well located downstream of the vineyard, which is registered in the National Archive of Subsoil Investigations (ARPA, 2011c). The water table is at a depth of 15.3 meters. Downstream of the Capriata d'Orba vineyard, there is a dormant landslide due to the saturation of the superficial cover. In Rocchetta Tanaro, there are dormant landslides, but only on the opposite side of the hill from the study area. Finally, there are no landslides near the vineyard located in Carpeneto. Approximately one hundred meters from the vineyard of Carpeneto, near the Tenuta Cannona building, there is a well, with the water table located around 12 meters deep. Unfortunately, the values for the depth to groundwater (Regione Piemonte, 2002a) and the piezometric levels (Regione Piemonte, 2002b) of the shallow aquifer for the other vineyards are not available.

The recharge areas of deep aquifers (Regione Piemonte, 2023a) are vital for replenishing underground water tables, particularly those used for human consumption. Typically located at the edges of plains, these areas benefit from coarse alluvial deposits left by watercourses, which enhance permeability and facilitate effective deep aquifer recharge. Their morphology supports the infiltration of rainwater and interaction with surface water bodies like lakes and rivers (Regione Piemonte, 2003a). In Piemonte, these recharge areas have been meticulously mapped and delineated to ensure sustainable water resource management (Regione Piemonte, 2003b). The vineyards of Novi Ligure, Capriata,

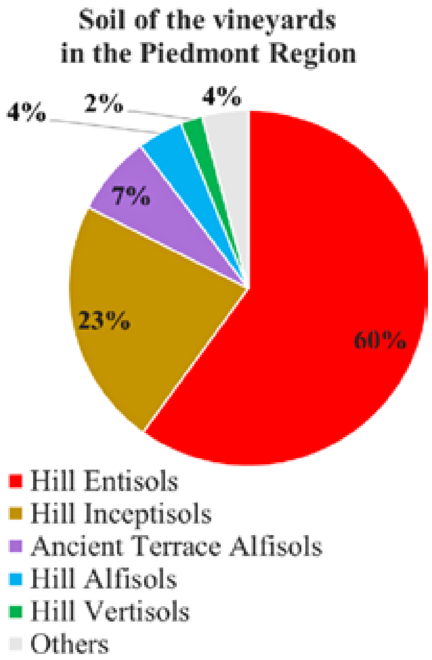

Fig. 5 – The graph illustrates the soil distribution of Piedmont vineyards. It has been elaborated by overlaying the soil map (Regione Piemonte, 2023b) and the vineyards on the regional cadastral mosaic (Regione Piemonte, 2024f).

and Rocchetta Tanaro are situated within these zones, while the experimental area near Carpeneto lies at the edge of the buffer zone, and Rocchetta Ligure is outside of it.

As shown in Figure 5, in the Piedmont vinegrowing areas, most of the soils are Entisols (60%) or Inceptisols (23%), with only a few vineyards located on Alfisols (13%) and Vertisols (2%) (Regione Piemonte, 2023b, 2024f).

Based on the Soil Map of the Piedmont Region at a scale of 1:50,000 (Regione Piemonte, 2023b), the vineyards under study are situated on soils with either very low skeletal content or a negligible percentage of it. These soils have a texture ranging from loam-clay to clay or silt, are free from reversible or irreversible cracks, and lack hydromorphic horizons within 150 cm of depth. In all cases, these soils present significant limitations that restrict the choice of agricultural crops and require specific agronomic practices. The limiting factor is consistently the slope (even for the vineyard on the flat land of Capriata d'Orba), and, in the case of Novi Ligure, also the risk of erosion. The majority of the selected sites (Fig. 6) present Alfisols. Specifically, Capriata d'Orba is on Alfisols of ancient terraces, while Carpeneto and Novi Ligure are located on the boundary between Alfisols of ancient terraces and hillside Alfisols, and between Alfisols of ancient terraces and hillside Inceptisols, respectively. Rocchetta Tanaro is situated on hillside Alfisols, whereas Rocchetta Ligure is on hillside Inceptisols.

According to the Real Erosion Map at a 1:250,000 scale (Regione Piemonte, 2023c), which uses one-hectare pixels and is calculated using the Revised Universal Soil Loss Equation (RUSLE) methodology (Renard *et al.*, 1997), the vineyards in Rocchetta Tanaro and Capriata are classified as having low erosion rates, below 3 t ha^{-1} $year^{-1}$. Vineyards in Novi Ligure fall into an intermediate erosion class, with rates ranging from 3 to 15 t ha^{-1} $year^{-1}$. Meanwhile, Carpeneto and Rocchetta Ligure are categorized under high erosion, with rates exceeding 15 t ha^{-1} $year^{-1}$ and 35 t ha^{-1} $year^{-1}$, respectively. However, the map's small scale and discrete pixel-based representation introduce certain limitations. This level of generalization may not capture localized variations in erosion rates, especially in heterogeneous landscapes. Previous studies have shown values that are fairly aligned with those presented by the map, reinforcing its overall accuracy despite certain limitations. A more detailed scale analysis reveals that erosion in vineyards can actually be much higher, particularly depending on soil management practices, slope gradients, and vineyard planting systems (e.g., contour planting or up-and-down slope planting). For instance, Darouich *et al.* (2022) highlighted the significant impact of inter-row soil management on controlling surface runoff and soil water recharge in Mediterranean vineyards. Similarly, Biddoccu *et*

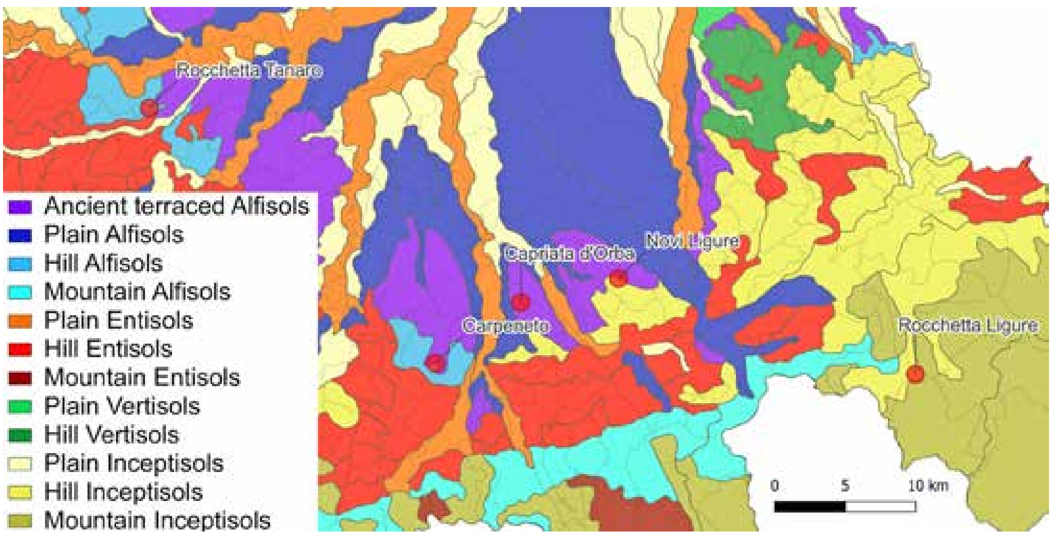

Fig. 6 – Soil map of the Alto Monferrato region (Regione Piemonte, 2023b). The positions of the selected vineyards under study are indicated with red dots.

al. (2020) identified that erosion rates in European vineyards vary considerably based on climate, soil, topography, and adopted soil management practices.

The Table 3 of soil analyses from the five sites at two depths (0.0-0.2 and 0.2-0.4 m) reveals several key characteristics that can influence soil management and agricultural productivity. The particle size distribution shows a general trend of increasing sand and decreasing clay with depth. The silt percentage is relatively stable or slightly variable with depth. The sandy loam soil of Rocchetta Tanaro has the highest sand content, with 73.3% at 0.0-0.2 m and 76.4% at 0.2-0.4 m, and the lowest clay content, with 8.5% at 0.0-0.2 m and 7.5% at 0.2-0.4 m. At the opposite Carpiata d'Orba has a clay loam soil with the lowest sand e the highest clay content. These variations in texture can affect the soil's ability to retain water and nutrients, as well as its physical structure.

The amount of organic matter tends to decrease with depth in all sites except Rocchetta Tanaro, where it remains almost constant. This is consistent with the general trend of organic matter concentrating in the upper soil layers, where there is more biological activity and organic matter decomposition. Carpeneto shows the greatest reduction, by more than half, from 0.95% at 0.0-0.2 m to 0.44% at 0.2-0.4 m. Rocchetta Tanaro has the lowest OM values, with 0.53% at 0.0-0.2 m and 0.55% at 0.2-0.4 m, while the highest values are in Capriata d'Orba. Organic matter is crucial for soil fertility, as it contributes to soil structure, water retention, and nutrient availability.

Bulk density generally increases with depth and tends to be higher in the soil in track position (T) compared to less disturbed soil (NT). All BD values, except those in NT at the surface, are close to or exceed the ideal BD threshold, reaching levels that can affect root growth. This suggests that the passage of agricultural machinery may have caused surface compaction. The increase in BD with depth may be due to greater soil compaction in deeper layers, where there is less organic matter and biological activity. Compacted soil layers have high bulk densities, restrict root growth, and inhibit the movement of air and water through the soil (USDA, 2011).

Field capacity (SWCfc) and wilting point (SWCwp) values, calculated based on Román Dobarco *et al.*, 2019, are generally higher in uncompacted soil, suggesting better water retention in undisturbed soil. The variability among sites

Tab. 3 – Physical soil parameters, measured at 0.0-0.2 and 0.2-0.4 m depth, in the five vineyards under study: soil texture, organic matter content (OM), bulk density (BD), soil water content at field capacity (SWCfc) and at wilting point (SWCwp) for both the soil in the most disturbed track position (T) and the less disturbed (NT). The table also provides information, calculated from soil textures, on the ideal bulk density (BD) and on the values that influence and limit root growth in vineyards.

Site	**Capriata**		**Carpeneto**		**Rocchetta Ligure**		**Novi Ligure**		**Rocchetta Tanaro**	
Depth (m)	**0.0-0.2**	**0.2-0.4**	**0.0-0.2**	**0.2-0.4**	**0.0-0.2**	**0.2-0.4**	**0.0-0.2**	**0.2-0.4**	**0.0-0.2**	**0.2-0.4**
Sand (2.0-0.20 mm)	22.5	24.5	48.7	54.4	45.5	45.5	48.0	48.5	73.3	76.4
Silt (0.20-0.002 mm)	38.5	38.5	30.9	33.1	32.0	30.5	26.0	27.0	18.3	16.1
Clay (<0.002 mm)	39.0	37.0	20.5	12.6	22.5	24.0	26.0	24.5	8.5	7.5
OM (%)	2.89	2.40	0.95	0.44	0.89	0.66	1.35	1.05	0.53	0.55
BD NT	1.20	1.51	1.36	1.37	1.22	1.41	1.38	1.45	1.22	1.51
BD T	1.47	1.53	1.39	1.30	1.33	1.45	1.40	1.43	1.42	1.48
SWCfc NT (m^3 m^{-3})	0.377	0.348	0.277	0.247	0.294	0.284	0.293	0.283	0.224	0.201
SWCfc T (m^3 m^{-3})	0.361	0.347	0.276	0.251	0.287	0.282	0.291	0.284	0.212	0.203
SWCwp T (m^3 m^{-3})	0.234	0.232	0.144	0.106	0.148	0.159	0.170	0.164	0.080	0.084
SWCwp NT (m^3 m^{-3})	0.243	0.233	0.144	0.104	0.152	0.161	0.170	0.163	0.086	0.083
Texture	clay loam	clay loam	loam	sandy loam	loam	loam	sandy clay loam	sandy clay loam	sandy loam	sandy loam
Ideal BD < (g/cm^3)	1.10	1.10	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40
BD influences root growth > (g/cm^3)	1.49	1.49	1.63	1.63	1.63	1.63	1.60	1.60	1.63	1.63
BD limits root growth > (g/cm^3)	1.58	1.58	1.80	1.80	1.80	1.80	1.75	1.75	1.80	1.80

is evident, with Capriata d'Orba showing the highest SWCfc and SWCwp values. Rocchetta Tanaro has the lowest SWCfc and SWCwp values, with 0.224 and 0.086 m^3 m^{-3} at 0.0-0.2 m in undisturbed soil, respectively, and 0.212 and 0.080 m^3 m^{-3} in disturbed soil. These differences likely reflect variations in soil composition, agricultural management practices, and local environmental conditions.

4. Conclusions

This preliminary study is essential to determine which soil management strategies to adopt in order to reduce compaction and increase OM, thereby improving water retention and nutrient availability, and contributing to greater agricultural productivity. The analysis of soil samples from different vineyards revealed high variability in soil texture, organic matter content, and bulk density. These variations highlight the need for site-specific soil management strategies to optimize vineyard productivity and sustainability. The implementation of innovative soil management practices shows promise in enhancing soil quality and reducing erosion. These practices, when combined with traditional methods, can provide a balanced approach to soil conservation.

Engaging local farmers and stakeholders in the adoption of sustainable practices is essential. The study's approach of integrating data-driven insights with the practical knowledge of local farmers can lead to more effective and widely accepted soil management strategies. Importantly, the choice of management strategies will be based on the data presented in this article and the results from a parallel study, which involved questionnaires on the perceptions and behaviors of Piedmontese winegrowers. These studies serve as a preliminary step for future research; further investigations should focus on long-term monitoring of soil management practices and their impact on vineyard sustainability. Comparative studies between traditional and innovative practices will provide deeper insights into their effectiveness.

In conclusion, the IN-GEST SOIL project demonstrates the potential of combining innovative and traditional soil management practices to address the environmental challenges faced by vineyards in the Piedmont region. By fostering a deeper understanding of soil conservation techniques and encouraging their adoption, this research contributes to the sustainability and resilience of viticulture in the face of climate change. Continued collaboration among researchers, farmers, and stakeholders will be crucial in advancing sustainable viticulture practices.

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