

Doctoral Dissertation.
Interuniversity Doctoral Program in
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**Innovative soil management and
technological integration to enhance
sustainability and soil health in hilly
vineyards of North-West Italy**
**Adopting good practices and advanced technologies
for investigation of water-soil dynamics and
mitigation of soil degradation in viticulture**

Giorgio CAPELLO

Supervisor(s):

Prof. S. F., Supervisor
Dott.ssa M. B., Co-Supervisor

Doctoral Examination Committee:

Prof. P. A. , Referee, University of Padova
Prof. G.D. M.A. , Referee, Instituto Andaluz de Investigación y Formación Agraria,
Pesquera, Alimentaria y de la Producción Ecológica, Centro IFAPA Camino De
Purchil Granada, Spain
Prof. C. C. , Member, Polytechnic of Turin

Politecnico di Torino - Università degli Studi di Torino
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Giorgio Capello

Turin, May 15, 2026

Summary

In recent decades, the intensification of agricultural management has introduced significant environmental challenges, particularly in soil and water conservation, biodiversity, sustainability, and ecosystem services. The increasing awareness of soil as a non-renewable resource and its crucial role in climate change mitigation has driven global efforts to adopt sustainable soil management practices in various agri-ecosystems, including viticulture.

This thesis aims to evaluate the effects of introducing and promoting optimal soil management techniques in hilly wine-growing environments in North-West Italy to mitigate soil degradation phenomena such as erosion and compaction. The conservation and improvement of soil health, while maintaining vine quality and production, is pursued through three main innovations: enhanced soil management practices, agro-meteorological monitoring of water and soil, and ICT tools for data management and field observation to support farmers in vineyard management and water-soil conservation. The goal is to understand how enhanced soil management practices in hilly vineyards can enhance soil water content, reduce runoff and erosion, and increase the availability of water and nutrients for the vines. Additionally, the research examines the impact of repeated vehicle passage on soil compaction and hydrological conditions.

The second part of the thesis introduces new technologies alongside traditional methods in a joint measurement campaign to collect data for analysing water, soil, and energy dynamics in a sloping vineyard environment. A W-band radar, a coupled microwave and optical scintillometer, and a CRNS sensor have been installed in an experimental vineyard where current and long-term monitoring of water dynamics, soil erosion, and soil moisture is available. These instruments enable proximal sensing to overcome near-point scale measurement limitations, providing estimations of precipitation characteristics, energy fluxes, and soil moisture at temporal and spatial scales beyond the reach of traditional sensors.

This research represents a first attempt to use these technologies in a complex environment, such as sloping vineyards with different soil management practices. It offers a perspective for data collection to study water and energy fluxes at field and landscape scales and supports the management of agricultural land.

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Dedication

A Margherita.

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Chapter 1

Introduction

1.1 Research topic

In recent decades, the intensification of agricultural management has introduced environmental challenges, particularly in soil and water conservation, biodiversity, sustainability, and ecosystem services (Giffard et al., 2022). The increasing awareness of soil as a non-renewable resource and its key role in climate change mitigation has stimulated global efforts to adopt sustainable soil management practices in many agri-ecosystems, including viticulture (Lazcano, 2020).

The first part of this thesis aims to evaluate the effects of introducing and promoting optimal soil management techniques (good practices) in hilly wine-growing environments in North-West Italy to mitigate soil degradation phenomena such as erosion and compaction. The conservation and improvement of soil health, while maintaining vine quality and production, is pursued by implementing three main innovations: (i) the introduction of enhanced soil management practices, (ii) agro-meteorological monitoring of water and soil, and (iii) ICT tools for data management and field observation to support farmers in vineyard management and water-soil conservation. The goal is to understand how enhanced soil management practices in hilly vineyards can enhance soil water content, reduce runoff and erosion, and increase the availability of water and nutrients for the vines. Additionally, the research will examine the impact of repeated vehicle passage on soil compaction and hydrological conditions. The evaluation is based on a field-

scale approach, using traditional techniques to measure variables related to soil and water conservation.

The second part of the thesis introduces new technologies alongside traditional methods in a joint measurement campaign to collect data for analysing water, soil, and energy dynamics in a sloping vineyard environment. A W-band radar, a coupled microwave and optical scintillometer, and a CRNS sensor have been installed in an experimental vineyard where current and long-term monitoring of water dynamics, soil erosion, and soil moisture is available. These instruments enable proximal sensing to overcome near-point scale measurement limitations, providing estimations of precipitation characteristics, energy fluxes, and soil moisture at temporal and spatial scales beyond the reach of traditional sensors.

This part of the research represents a first attempt to use these technologies in a complex environment, such as sloping vineyards with different soil management practices. It offers a perspective for data collection to study water and energy fluxes at field and landscape scales and supports the management of agricultural land.

1.2 Motivations

This experimental research aims to apply the findings from CNR-STEMS' long-term studies on soil conservation and optimal management in vineyards to practical field use. It directly addresses soil erosion and water lost, a significant issue in the sloping vineyards of Piedmont. Soil erosion is closely linked to other degradation phenomena such as the decline of organic matter and soil compaction, which are major threats to soil health in Europe, as highlighted in the European Union's Soil Thematic Strategy. These issues impact the ecosystem services of vineyards, soil quality and fertility, and water resource availability, ultimately affecting the quality and quantity of grape production.

At the community level, these concerns are discussed in the PEI-AGRI focus group report "Water & Agriculture: Adaptive Strategies at Farm Level." European projects like VineDivers, RE CARE, DIVERFARMING, and SoilCare have also addressed these issues. Nationally, the objectives align with the MiPAAF "Strategic Plan for Innovation and Research in the Agricultural, Food, and Forestry Sector," focusing on sustainable agriculture. Regionally, these topics have been emphasized in the PSR 2007-2013. The high participation and interest of Piedmont winemakers in training and demonstration days on these topics underscore their importance.

To address these challenges, this study proposes adapting and adopting alternative soil management solutions in Piedmont vineyards. This involves a process of adaptation by farmers regarding agronomic strategies for inter-row management and collaboration within technicians and researchers to monitor and prevent soil degradation. This approach aims to increase knowledge and awareness, and to verify the effects of these practices on production and soil quality. This integration of field and sensor monitoring will support farmers in organizing field activities and choosing appropriate agronomic strategies.

Concrete and measurable results are achieved. These results have validated scientific and technological research products in real operating conditions, improving agricultural assistance services, both in terms of knowledge and in terms of the availability of new tools and technologies.

Additionally, innovative tools and technologies will be introduced through collaboration with a company experienced in agro-meteorological monitoring. Within the paradigm of Agriculture 4.0, the integration of traditional point and field-based measurements technologies and proximal or remote sensing is one of the key processes to improve the information related to water availability, soil and plant health, crop status at field and landscape scale. Investigation and modelling of the processes occurring in the Soil-Plant-Atmosphere continuum, which has been traditionally based on near-point spatial scale data (e.g. soil water content or precipitation measurements) is transforming thanks to new technologies, which allow measurements with different spatial and temporal scales. The second part of this work explores how data from some new technologies can be used to improve the knowledge of hydrological or soil degradation processes and related models, in order to preserve resources and production in agriculture.

1.3 Research questions

The target is to understand how soil management with enhanced practices in hilly vineyards can improve the response in terms of soil water content, runoff and erosion, increasing the availability of water and nutrients for the vine, and understand what effect the repeated passage of vehicles has on the compaction and hydrological conditions of the soil:

- 1) How soil management with enhanced practices in hilly vineyards can improve the response in terms of soil water content, runoff and erosion, increasing the availability of water and nutrients for the vine?

2) What is the effect of the repeated passage of vehicles on compaction and hydrological conditions of the soil?

3) How far data from proximal sensing can be used to improve the knowledge of hydrological or soil degradation processes at field-scale and related models?

1.4 Objectives

The objectives of this work are multifaceted and aim to enhance significantly agricultural practices. The first part of the thesis focuses on introducing and promoting optimal soil management techniques (good practices) in hilly wine-growing environments to mitigate soil degradation phenomena such as erosion and compaction. This will improve soil and vine quality through the introduction of three main innovations:

Enhanced soil management practices.

Agro-meteorological monitoring to improve water and soil management.

ICT tools for managing monitored data and field observations to support farmers in vineyard management and water-soil conservation.

Secondly, by introducing innovative tools and technologies through collaboration with companies experienced in agro-meteorological monitoring, the second section of the thesis aims to achieve concrete and measurable results by testing scientific and technological research products in real-world conditions. This validation is expected to enhance agricultural assistance services by expanding both the knowledge base and the availability of new tools and technologies. Within the framework of Agriculture 4.0, the integration of traditional point and field-based measurement technologies with proximal or remote sensing is a critical process. This integration is essential for improving information related to water availability, soil and plant health, and crop status at various scales. Furthermore, the research involves investigating and modelling processes occurring within the Soil-Plant-Atmosphere continuum. By leveraging new technologies that facilitate measurements across different spatial and temporal scales, this study aims to enhance the understanding of hydrological and soil degradation processes. Ultimately, this improved understanding will contribute to the preservation of resources and the sustainability of agricultural production.

The expected results aim to advance agricultural practices by leveraging innovative technologies and improved data integration, ultimately supporting more sustainable and efficient farming methods:

Improved Soil Quality and Management: Achieving better soil quality and reducing degradation phenomena in vineyards through enhanced management practices. These practices will mitigate surface runoff, soil erosion, nutrient losses, and surface compaction, favouring water conservation and improving soil physico-chemical characteristics.

Implementation of Integrated Monitoring Systems: Establishing an integrated agro-environmental monitoring system. This includes the introduction and testing of innovative agro-meteorological monitoring systems, soil condition assessments, and modern forecasting and decision support systems (DSS). The DSS will process alerts and enhance functions related to field accessibility, mechanized activity programming, soil compaction limitation, and operator safety.

Knowledge Dissemination and Practical Demonstration: Conducting practical field demonstrations and training activities to transfer knowledge of good practices to winegrowers, other farms, and schools. This includes the definition and dissemination of a "Charter of Good Agricultural Practices" for soil protection in wine-growing environments, summarizing the main project results and providing guidelines for better soil management.

Validation and Enhancement of Agricultural Technologies: Demonstrating the effectiveness and reliability of innovative tools and technologies in real-world agricultural settings, leading to improved agricultural assistance services through an expanded knowledge base and the availability of new tools.

Improved Data Integration and Process Understanding: Successfully integrating traditional measurement technologies with proximal or remote sensing to provide more accurate and comprehensive data on water availability, soil and plant health, and crop status. This integration will enhance the understanding of hydrological and soil degradation processes within the Soil-Plant-Atmosphere continuum.

Sustainable Resource Management: Contributing to the preservation of natural resources and the sustainability of agricultural production through improved management practices and scalable solutions that can be applied to various agricultural contexts.

Chapter 2

Innovation in vineyard soil management through the adoption of good practices and support tools for field activities

2.1 Introduction

The research aims to introduce and promote optimal soil management techniques (good practices) in hilly wine-growing environments to mitigate soil degradation phenomena such as erosion and compaction. By implementing three main innovations (enhanced soil management practices, agro-meteorological monitoring for improved water and soil management, and ICT tools for data management and field observation to support farmers in vineyard management and water-soil conservation) this study seeks to improve soil and vine quality. The goal is to understand how enhanced soil management practices in hilly vineyards can enhance soil water content, reduce runoff and erosion, and increase the availability of water and nutrients for the vines. Additionally, the research will examine the impact of repeated vehicle passage on soil compaction and hydrological conditions.

The research activity initially focused on identifying the soil management practices to be implemented in each vineyard throughout the project. In each vineyard, two practices were selected from proven good soil management techniques identified through long-term research by Agrion and CNR-STEMS, such as:

- reduced tillage,
- spontaneous permanent grassing,

- cover crops,
- Green manure practices,
- limitation of chemical weeding.

The research aims to demonstrate:

A. The applicability of these practices at the farm level, in a fully operational context rather than an experimental one.

B. The positive effects of adopting these practices on soil and water resource conservation, including reduced runoff, soil compaction, and erosion, as well as increased infiltration and improved soil quality.

C. The positive effects of adopting these practices on grape quality.

Throughout the research, these practices were translated into application protocols. These protocols were verified and adapted during the research period and subsequently included in the Charter of Good Practices.

During the project, monitoring systems were installed to track runoff and erosion, soil moisture, meteorological parameters (temperature, air humidity, and precipitation). Additionally, agronomic monitoring was conducted, focusing on vegetative development, production quality, and cultivation operations. The runoff and erosion monitoring system used in the study was an innovative, simplified version of the system typically employed by CNR-STEMS for its research.

To introduce suitable agronomic techniques and equip farmers with decision-making and field activity organization tools, the third level of innovation involves using a Decision Support System (DSS) in the regular management of farms. Winegrowers and technicians were able to use the IT platform to: consult meteorological data recorded by weather sensors, view the results of the forecast model, insert field observations, record treatments and fertilizers that can influence and affect soil degradation phenomena related to erosion.

The use of the tool by operators was crucial for integrating end-user experiences with field data and farmers' empirical knowledge. This helped in developing an ad hoc module capable of providing optimal scheduling indications for field operations involving agricultural machinery.

The data collected during the research was used to develop indices based on commonly measured agro-meteorological parameters (temperature, humidity, and precipitation) and their thresholds. These indices provide information on whether or not to intervene in the field with agricultural machinery. Integrating these indices with vineyard management data and existing DSS functions (such as the forecasting model for Downy mildew development) will enable correct planning of field interventions, preventing soil degradation and improving soil conservation.

A multidisciplinary monitoring plan was defined to evaluate the effects of the enhanced management techniques introduced both on the conservation of the soil and its functions, and on wine production. The monitoring plan aims to evaluate the effect of soil management on the components relating to the soil-plant-atmosphere continuum through continuous surveying with sensors, periodic field surveys and field monitoring (chemical-physical characteristics and measurement of the erosion of the soil, hydrological characteristics of the soil, phenological phases and production of the vine, agro-meteorological parameters).

The selected vineyards were analysed, starting from an inspection, in order to design and correctly place the various measurement systems provided, aimed at agro-meteorological monitoring of the water content of the soil (continuous) and the consequent response in terms of runoff and water erosion of the soil.

The physical and chemical conditions of the soil were periodically monitored across all vineyard plots where different soil management practices were applied. Seasonal surveys were conducted to measure soil characteristics and degradation in various portions of the inter-row soil: the track position (corresponding to the tractor tracks or wheels) and the centre (less disturbed). Specifically, the following aspects were investigated:

- soil compaction degree, assessed through: (i) in-field measurements of bulk density and resistance to penetration, and (ii) determination of the relationships between bulk density and soil moisture by means the Proctor test;
- soil water content and hydraulic conductivity, measured with newly designed automatic infiltrometers (Concialdi et al., 2020);
- development of cover crops, by measuring the degree of soil cover (expressed in %) and the biomass produced (expressed in Mg ha^{-1});

- additionally, a chemical-physical analysis was conducted at least once a year at the end of the production season.

Furthermore, training meetings and practical demonstrations were held for winegrowers to showcase the results and effects of good practices. These results were disseminated locally to other farms in the sector, to those involved in agricultural training, and to schools. The findings were also shared with the international scientific community through the publication of scientific articles and participation in conferences and meetings. The dissemination efforts through national and European networks aimed to connect with existing networks at local, regional, and national levels, thereby strengthening the exchange of knowledge.

The physical and chemical conditions of the soil were periodically checked in all the vineyard parcels where the different soil management practices are applied. To this end, seasonal surveys were carried out to measure the characteristics and degradation of the soil, in the different portions that make up the inter-row: the track position, where the tracks or tractor wheels pass, and the centre, less disturbed. In particular, the following were investigated: i) the degree of compaction of the soil, evaluated through measurements of bulk density and resistance to penetration; ii) soil hydraulic conductivity with newly developed automatic infiltrometers; iii) the development of cover crops, by measuring the degree of soil coverage (expressed in %) and the biomass produced (expressed in Mg ha^{-1}).

2.2 Questionnaire and focus groups to assess the level of perception and knowledge regarding soil degradation phenomena, their causes, and possible mitigation actions

Initially, Piedmontese wine producers and winegrowers were interviewed using both quantitative (questionnaires) and qualitative (focus groups/group interviews) tools. I collaborated in creating a questionnaire to assess the level of perception and knowledge regarding soil degradation phenomena, their causes, and possible mitigation actions. This questionnaire was designed for owners and workers of wineries to evaluate their understanding of soil-related issues and the extent of soil degradation in Piedmont as perceived by winemakers. The questionnaire was implemented and disseminated using the EUSurvey platform and was administered digitally to about 200 companies, receiving excellent feedback with responses from approximately half of the surveyed companies (Figure 1).

The screenshot displays the header of the 'IN-GEST SOIL' questionnaire. At the top, it states 'Innovazione nella gestione dei suoli viticoli attraverso l'adozione di buone pratiche e strumenti di supporto alle attività di campo'. Below this are logos for the European Union, the Italian Republic, the Piedmont Region, and the PSR (Piano di Sviluppo Rurale) 2014-2020. Text indicates funding from the FEASR (Fondo europeo agricolo per lo sviluppo rurale). A checkbox option is present for saving a backup on a local computer. The main title of the survey is 'Indagine sulla gestione dei suoli viticoli piemontesi attraverso l'adozione di buone pratiche e strumenti di supporto alle attività di campo', specifically for the PSR 2014-2020, Regione Piemonte, Operazione 16.1.1, Progetto IN-GEST SOIL. A note specifies that fields marked with an asterisk are mandatory. A 'Clausola di esclusione della responsabilità' (Liability disclaimer) is provided, stating that the European Commission is not responsible for the content of the questionnaire. A 'Pagine' (Pages) section shows a progress bar with buttons for 'Inizio', 'Qualità percepita del suolo', 'Pratiche di gestione del suolo', 'Sistemi di monitoraggio', 'Informazioni socio-anagrafiche', and 'Contatti'. The main body of the questionnaire begins with a greeting to the company and explains the survey's purpose, coordinated by Agrion, the Foundation for research, innovation, and technological development in agriculture. It mentions the survey is part of the 16.1.1 operation of the PSR Piemonte 2014-2020, aimed at understanding soil management practices to prevent erosion and organic matter loss. It asks the respondent to complete the questionnaire in all parts, which will take no more than 10 minutes. A thank you message follows, and a final note states that the collected information will be shared exclusively in an anonymous and aggregated form, respecting privacy regulations (Reg. UE n. 2016/679, known as GDPR).

IN-GEST SOIL
Innovazione nella gestione dei suoli viticoli attraverso l'adozione di buone pratiche e strumenti di supporto alle attività di campo

FEASR – Fondo europeo agricolo per lo sviluppo rurale:
l'Europa investe nelle zone rurali

☒ Salva un backup sul computer locale (disattiva in caso di uso di un computer pubblico/condiviso)

Indagine sulla gestione dei suoli viticoli piemontesi attraverso l'adozione di buone pratiche e strumenti di supporto alle attività di campo
(PSR 2014-2020, Regione Piemonte, Operazione 16.1.1, Progetto IN-GEST SOIL)

I campi contrassegnati con un * sono obbligatori.

Clausola di esclusione della responsabilità
La Commissione europea non è responsabile del contenuto dei questionari creati utilizzando il servizio EUSurvey, che invece ricade sotto l'esclusiva responsabilità del creatore o del gestore del modulo. L'uso del servizio EUSurvey non implica alcuna raccomandazione o condivisione, da parte della Commissione europea, delle opinioni espresse nei questionari.

Pagine
Inizio Qualità percepita del suolo Pratiche di gestione del suolo Sistemi di monitoraggio Informazioni socio-anagrafiche Contatti

Gentile azienda,
Il Gruppo Operativo IN-GEST SOIL, coordinato da Agrion, la Fondazione per la ricerca, l'innovazione e lo sviluppo tecnologico dell'agricoltura piemontese, sta conducendo nell'ambito dell'operazione 16.1.1 del PSR Piemonte 2014-2020 un'indagine rivolta alle aziende vitivinicole piemontesi sul livello di adozione delle pratiche di gestione del vigneto volte a prevenire l'erosione del suolo e a mitigarne i fenomeni di degrado (es. compattamento, perdita sostanza organica).
Si prega di rispondere al questionario in tutte le sue parti, la compilazione non richiederà più di 10 minuti.

Grazie per la preziosa collaborazione!

*Si precisa che le informazioni raccolte verranno diffuse in forma esclusivamente anonima e aggregata nel pieno rispetto delle normative sulla privacy (Reg. UE n. 2016/679 noto come GDPR).

Figure 1: Screen of the online questionnaire created on the EUSurvey platform.

Participants for the questionnaire and focus groups were recruited primarily through farmer associations and complementary direct contacts. While this strategy facilitates access to practitioners with operational expertise, it can introduce selection bias and does not guarantee statistical representativeness. We mitigated these risks by purposively seeking diversity in farm size, slope classes and climate sub-zones, and by integrating quantitative and qualitative strands. Importantly, qualitative analysis was conducted to thematic saturation within the focus groups, favouring depth and internal validity over nominal sample size. Given reported stakeholder fatigue with survey/focus-group activities, this approach prioritised engaged contributors whose inputs are more likely to reflect active decision-making contexts. Sample characteristics and spatial distribution are detailed in Table 1 and Figs. 6–7 (section 2.2.2) to support transparent appraisal of coverage.

The preliminary analysis of the responses to the questionnaire helped define the focus groups. Due to the pandemic and consequent social restrictions, the focus groups were held online. We decided to conduct interviews with smaller groups of wine sector operators (4-6 farmers) and reduce the duration of the in-depth interviews to a maximum of one hour, instead of the usual two. I conducted and moderated two focus groups, involving field technicians, freelancers, and winemakers (Figure 2). Despite the challenges and limitations posed by the pandemic, we successfully gathered information on: the knowledge and perception of soil degradation phenomena by winegrowers; skills related to good practices for better soil conservation and environmental sustainability; the problems, obstacles, and needs for adopting good practices.



Figure 2: Screenshot of the two "virtual focus groups"

Results from the questionnaire and focus groups were first presented at the 12th AIIA Conference “Biosystems Engineering Towards the Green Deal” (Palermo, Italy, 19–22 September 2022). The related contribution, “Drivers of Adoption of Sustainable Practices and Technologies for Soil Protection Among Vine-Growers

in North-West Italy”, published in the AIIA 2022 proceedings (Lecture Notes in Civil Engineering, vol. 337; pp. 411–419), is reproduced in section 2.2.1 in its published form, with formatting adapted to the style of this thesis.

Building on that conference contribution, a journal article entitled “Winegrowers’ Perceptions and Adoption of Sustainable Soil Management Practices and Technologies: A Case Study in Piedmont, Italy” has been published open access in *Land Degradation & Development* and is reproduced in section 2.2.2 in its published version (Version of Record) (<https://doi.org/10.1002/ldr.70621>), with layout harmonized to the thesis format.

Overall, the questionnaire and focus-group evidence was instrumental in guiding the selection of innovative techniques suitable for vineyards and in shaping the project’s dissemination activities with participating farms.

2.2.1 Drivers of adoption of sustainable practices and technologies for soil protection among vine-growers in North-west Italy

Federica Caffaro^{1,2}, Eugenio De Gregorio³, Giorgio Capello^{2,4}, Lucia Vigoroso^{1,2}, Giorgia Bagagiolo², Eugenio Cavallo², Marcella Biddoccu²

1 Roma Tre University, Department of Education, 2 Institute of Sciences and Technologies for Sustainable Energy and Mobility (STEMS) of the National Research Council of Italy (CNR), 3 Link Campus University, 4 Interuniversity Department of Regional and Urban Studies and Planning (DIST), Politecnico di Torino and Università di Torino.

Abstract

The study aimed at investigating the drivers of adoption of good practices and technological innovations for soil protection in a group of vine-growers in Piedmont region, Northwest Italy. Four focus groups have been conducted with 16 vine-growers, to investigate 1) perception of soil erosion and the role of the human factor in preventing/causing it, 2) adoption and intention to adopt good practices and technological innovations for soil protection and, 3) barriers and drivers for adoption. A questionnaire regarding vineyard management practices was also used to encourage the discussion. The results showed that soil erosion was perceived as a relevant issue by the majority of the participants. Wide use of machinery during vineyard plantation and management was acknowledged as affecting soil and water conservation. The adoption of sustainable practices and technological innovations appeared to be promoted by landscape protection, whereas tradition and habits were cited as barriers to adoption. To maximize the fit between farmers' needs and sustainable innovation, personal values and habitual processes should be targeted with awareness raising and education interventions. These interventions should be based on a participatory approach and the co-creation of tailor-made solutions to better support the transition toward a more sustainable farming paradigm.

Keywords:

Soil management, Mixed methods research, Sustainability, Vine-growers perception.

Introduction

Over the last decades, there has been increasing attention toward ecosystem services (ES), which can be defined as “the direct and indirect contributions of ecosystems to human well-being” [1]. Regarding the agricultural compartment in

general, on the one hand, previous research suggested that intensive agriculture and unsustainable practices have contributed to the loss of habitat and biodiversity, an increase of soil erosion and nutrient runoff [2]. On the other hand, several studies showed that vineyard management practices that consider the presence of cover crops or natural vegetation positively impact ecosystem services and can help decrease runoff, sediment, and nutrient loss [3-7].

Management of the plantations, and in particular the orientation of the rows in relation to the slope lines of the field, is an additional measure able to limit the erosion phenomena. Practices adopted for vineyard management, including soil management, have an impact on both production (quality and quantity) and the environment. However, management decisions in tree crops such as orchards and vineyards are usually influenced not only by the area's water availability and pedoclimatic conditions but also by the perception of benefits and drawbacks in adopting ES such as inter-row cover crops or natural grass cover.

Grass cover in vineyards has been comprised in the most relevant European policies for soil conservation, including the Standards of Good Agricultural and Environmental Condition (GAEC), established by Council Regulation No. 73/2009 (CEC, 2009). Grass covering measures have been supported also at a local level by Rural Development Programmes (RDPs) that are drawn up by Member States and regions addressing Common Agricultural Policy (CAP) EU priorities that include prevention of soil erosion and improvement of soil management. Concerning Italy and the Piedmont region, the measures envisaged during the 2007–2013 RDP for soil erosion prevention were essentially based on the grass covering of orchards and vineyards areas and involved more than 13,000 ha (15.4% of Piedmont's agricultural area utilized for orchards and vineyards).

Spontaneous grass cover is nowadays widespread in Piedmont's vineyards. However, its adoption is not always supported by awareness and knowledge about the effects on soil quality and its conservation. Soil erosion processes imply soil losses and soil degradation, nevertheless, vine-growers are not always aware of what factors contribute to the increase of the soil erosion risk and what techniques and management choices they can carry out to prevent soil degradation and maintain healthy soil. In Piedmont, during recent years, the occurrence of very warm and dry vine-growing seasons led some vine-growers to quit the adoption of permanent spontaneous grass cover, but do they have adequate knowledge of what are the possible other choices and their advantages/disadvantages for both the crop and the soil, in relation to pedoclimatic conditions? The IN-GEST SOIL project [8]

aims to reduce the soil erosion in hillslope vineyards in Piedmont, improving soil and vine quality through the introduction of improved best soil management practices.

Farmers' behaviour has a significant impact on the environment, and this behaviour is strongly influenced by their knowledge and perception of environmental issues and sustainable measures [9]. Many previous studies addressed soil conservation and degradation, but the points of view of land operators have not been frequently addressed. Particularly in Italy, little attention has been paid to farmers' perceptions of soil erosion and attitude toward the adoption of soil conservation practices and technologies [10]. Understanding farmers' perceptions, intentions and needs could help in a better-suited implementation of measures for soil protection in vineyards. The present contribution reports the first results from the first phase of the IN-GEST SOIL project, in which the vine-growers' perception of soil erosion risk, factors influencing it and possible solutions were investigated. In particular, the present study aimed at investigating the drivers of the adoption of good practices and technological innovations for soil protection in a group of vine-growers in the Piedmont region, Northwest of Italy.

Materials and methods

Participants

Sixteen vine-growers from the Piedmont region, Northwest Italy, took part in the study. Regarding their sociodemographic characteristics, all the involved participants were men, with a mean age of 48 years ($SD=14.50$), and a mean of work experience in agriculture of 29.06 years ($SD=17.49$). The participants were recruited by vine-growers' associations: those who were willing to take part in the study were then contacted by telephone to explain the aims of the study and collect their consent to participate.

Instruments and procedure

Four online focus groups have been conducted in the spring of 2021 with the Microsoft Teams platform. Topics addressed in the focus groups were designed based on previous evidence [11-13] about the most critical factors involved in the adoption of soil conservation measures, concerning: the perception of soil erosion and the role of the human factor in preventing/causing it, adoption, and intention to adopt good practices and technological innovations for soil protection and, finally,

barriers and drivers for adoption. Before each focus group, a questionnaire was emailed to the participants and the responses were then used to encourage discussion. The questionnaire assessed vineyard characteristics and management practices, and perceived causes of soil erosion. A standardised procedure was adopted to design the focus groups, to ensure consistency of responses across all the groups. All steps, including invitations to participants, topics to be addressed and the questionnaires, were drafted and collected into a guidance document. The meetings were recorded and lasted about one hour each.

Data analysis

Questionnaire responses were analyzed using descriptive statistics. The focus group transcripts were subjected to a qualitative content analysis through a coding procedure for narrative themes [14]. Next, in each of the transcribed files, an attempt was made to identify emergent themes. In the tradition of the qualitative approach, a theme is important because it captures something significant about the data as it relates to the research questions [15]. We used ATLAS.ti software to perform computer-supported qualitative content analysis [16] to filter the structure of our transcripts and then code them. In the first step, major themes were identified through reading the transcripts. This led to the identification of the main content analysis categories (codes and code sets). Each segment featuring the above-described topics was (re)coded so as to detect, with greater precision, the specific theme around which the discourse of the participants was built; for each theme, the corresponding segment was identified and defined (coded). More dense segments (articulate, complex, polysemic) were coded with more than one code.

From the qualitative content analysis of the focus groups, 44 codes were identified and subsequently grouped into 6 themes. A detailed analysis of these themes answers the research questions. The themes were:

- good practice
- considerations on the problem of erosion
- methods and techniques of vineyard management
- obstacles to the implementation of the best erosion prevention solutions
- resources useful for implementing solutions
- geographic areas.

Among these issues, in this contribution, we will examine in detail the obstacles and resources for best practices implementation. In addition to this, we tried to understand how much awareness the people who participated in the focus groups had of the problem of soil erosion and how willing they were to find innovative solutions.

Results

Descriptive statistics and quantitative data

Concerning the vineyard characteristics, their size ranged between 4 and 56 hectares (mean=17.44 ha, SD=12.24) and the steep slopes ranged between 4% and 25% (mean=16.23%). Concerning the vineyard management, in 9 cases vineyards had rows arranged along contour lines, 5 had rows along the slope, 1 with terraces and 1 was in a flat area; inter-rows were mainly managed with grass cover in every inter-rows (adopted by 7 participants), followed by grass cover every two inter-rows (6 participants) and bare soil obtained by mechanical cultivation (3 participants).

Concerning the factors affecting soil erosion, climate change was perceived as the main cause, with a mean score of 3.25 (SD=0.77), followed by soil management, topography and soil texture, with a mean score of 3.06 (SD=0.85), 2.94 (SD=0.85) and 2.68 (SD=0.79) respectively.

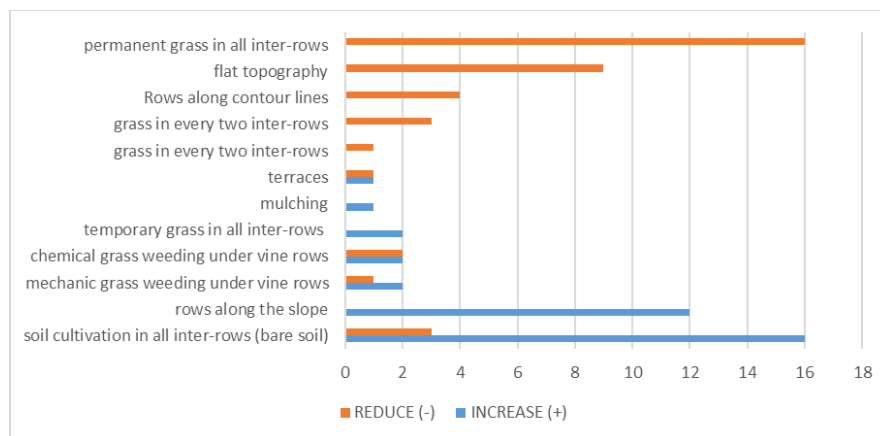


Figure 3: Vineyard management techniques that contribute to increasing and reducing soil erosion.

Regarding the main vineyard management techniques that contribute to increased soil erosion, participants indicated mechanical cultivation resulting in

bare soil in all inter-rows for the whole year, whereas, as concerns the main vineyard management techniques that contribute to reduce soil erosion, participants indicated the permanent grass cover in all inter-rows, see (Fig. 3).

Thematic maps and qualitative content analysis

As stated, we focus attention on obstacles and resources for the implementation of preventive actions against soil erosion. Fig. 4 shows the map of concepts connected to each other as causes or consequences of soil erosion, or as limits to the repair intervention. In the figure, the numbers corresponding to the letter G (Grounded) indicate the frequency of that code in the four focus groups. Based on this evidence, we note that according to the participants the climatic conditions, different types of tillage, and the modifications and conformation of the territory are the relevant obstacles in determining the difficulties in preventing soil erosion in the vineyards, as well as some cultural customs and practices.

Similarly, Fig. 5 shows the codes pertaining to the theme resources. Also, in this case, specific types of soil tillage are called into question, but with a meaning that characterizes them as resources, i.e., a useful procedure to prevent soil erosion.

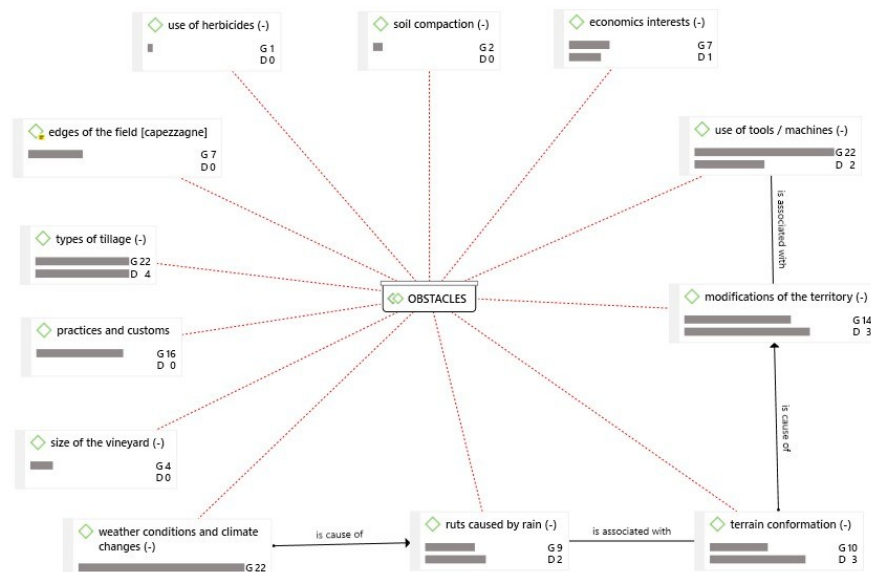


Figure 4: Thematic map of obstacles and their links as detected by the narrative flow of the focus groups.

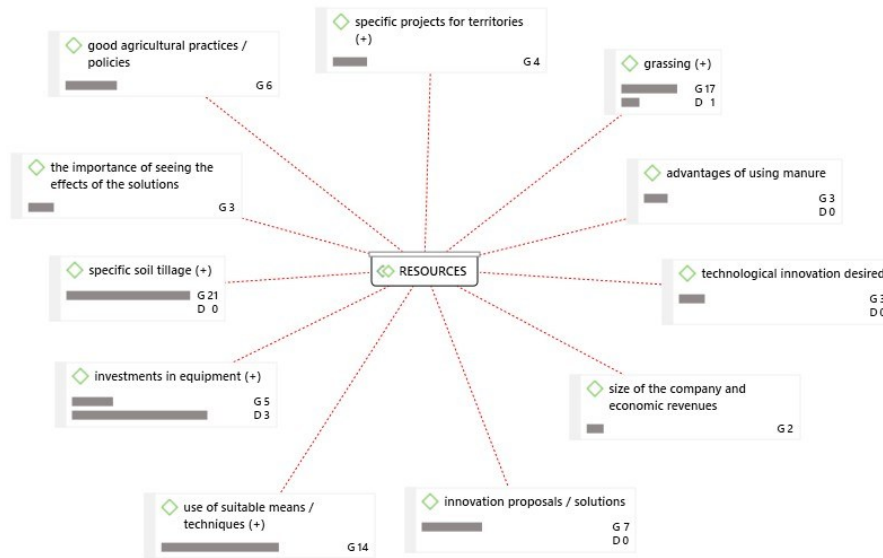


Figure 5: Thematic map of resources and their links as detected by the narrative flow of the focus groups.

Participants also suggested the use of some specific techniques or procedures. Among these, grassing was the one that characterized most of the debates in the four focus groups.

It is evident that some concepts expressed by the participants can be used both as obstacles and as resources. We have seen that this was true for the types of tillage: if facilitated by agricultural machinery it is a problem, but it can also be a resource when using traditional systems and benefiting from new technologies. We also consider that the contents expressed with respect to obstacles and resources were quite equivalent in terms of frequencies. This gave us another type of information, that the participants had a high awareness of the problem but also of the possible solutions.

Traditions and cultural habits had a weight, of course, we can see it from the figure concerning the obstacles. In 16 citations this aspect was mentioned. Finally, we note that technological innovation (which in some cases is desired) did not find a broader consensus; we explain this data on the basis of two possible interpretations: the first is that some technological solutions are actually considered obstacles and not resources; the second possible interpretation, on the other hand, concerns solid roots in traditions.

Discussion and conclusions

The present results showed that soil erosion was perceived as a relevant issue by most of the participants. Wide use of machinery during vineyard plantation and management was acknowledged as affecting soil and water conservation. Cost-benefit ratio appeared not to sufficiently capture the complexity of farmers' decision-making and behaviours, since the adoption of sustainable practices and technological innovations was more often related to place attachment and landscape protection. Whereas tradition and habits appeared to play a role in hindering adoption. Some recommendations arise from the present study: to encourage the adoption of soil protection practices and technologies, access to economic support should be spread but it does not seem to be enough. Personal values and habitual processes emerged as critical variables which could be targeted with awareness raising and education interventions. To maximize the fit between farmers' needs and sustainable innovation, these interventions should be based on a participatory approach and the co-creation of tailor-made solutions to better support the transition toward a more sustainable farming paradigm.

References

1. Sukhdev, P., Wittmer, H., Schröter-Schlaack, C., Nesshöver, C., Bishop, J., ten Brink, P., Gundimeda, H., Kumar, P., Simmons, B.: The economics of ecosystems and biodiversity: mainstreaming the economics of nature: a synthesis of the approach. Conclusions and Recommendations of TEEB, (333.95), E19. (2010).
2. Dunbar, M.B., Panagos, P., Montanarella, L.: European perspective of ecosystem services and related policies. *Integrated Environmental Assessment and Management*, 9(2), 231–236. (2013).
3. Bagagiolo, G., Biddoccu, M., Rabino, D., Cavallo, E.: Effects of rows arrangement, soil management, and rainfall characteristics on water and soil losses in Italian sloping vineyards. *Environmental Research*, 166, 690–704. (2018).
4. Ferreira, C.S.S., Keizer, J.J., Santos, L.M.B., Serpa, D., Silva, V., Cerqueira, M., Ferreira, A.J.D., Abrantes, N.: Runoff, sediment and nutrient exports from a Mediterranean vineyard under integrated production: An experiment at plot scale. *Agriculture, Ecosystems & Environment*, 256, 184–193 (2018).
5. Gómez, J.A.: Sustainability using cover crops in Mediterranean tree crops, olives and vines – Challenges and current knowledge. *Hungarian Geographical Bulletin*, 66(1), 13–28. (2017).
6. López-Vicente, M., Gómez, J.A., Guzmán, G., Calero, J., García-Ruiz, R.: The role of cover crops in the loss of protected and non-protected soil organic carbon fractions due to water erosion in a Mediterranean olive grove. *Soil and Tillage Research* 213, 105119. (2021).
7. Winter, S., Bauer, T., Strauss, P., Kratschmer, S., Paredes, D., Popescu, D., Landa, B., Guzmán, G., ... Batáry, P.: Effects of vegetation management intensity on biodiversity

- and ecosystem services in vineyards: A meta-analysis. *Journal of Applied Ecology*, 55(5), 2484–2495 (2018).
8. IN-GEST SOIL - Innovazione nella gestione dei suoli viticoli attraverso l'adozione di buone pratiche e strumenti di supporto alle attività di campo, <https://ec.europa.eu/eip/agriculture/en/find-connect/projects/gest-soil-innovazione-nella-gestione-dei-suoli>
 9. Guo, R., Li, Y., Shang, L., Feng, C., Wang, X.: Local farmer's perception and adaptive behavior toward climate change. *Journal of Cleaner Production*, 287, 125332. (2021).
 10. Bechini L, Costamagna C, Zavattaro L, Grignani C, Bijttebier J, Ruyschaert G.: Drivers and barriers to adopt best management practices. Survey among Italian dairy farmers. *Journal of Cleaner Production* 245, 118825. (2020).
 11. Prosdocimi M, Cerdà A, Tarolli P.: Soil water erosion on Mediterranean vineyards: A review. *Catena* 141, 1–21. (2016)
 12. Gómez, J.A., Montero, A.S., Guzmán, G., Soriano, M.A.: In-depth analysis of soil management and farmers' perceptions of related risks in two olive grove areas in southern Spain. *International Soil and Water Conservation Research* 9, 461–73. (2021).
 13. Marques, M.J., Bienes, R., Cuadrado, J., Ruiz-Colmenero, M., Barbero-Sierra, C., Velasco, A.: Analysing Perceptions Attitudes and Responses of Winegrowers about Sustainable Land Management in Central Spain. *L Degrad Dev* 26, 458–67. (2015).
 14. Ryan, G.W., Bernard, H.R.: Techniques to Identify Themes. *Field Methods*, 15(1), 85–109 (2003).
 15. Braun, V. Clarke, V.: *Thematic Analysis. A Practical Guide*. Sage, London (2021).
 16. Frieze, S.: *Qualitative Data Analysis with ATLAS.ti*. 3rd edn. Sage, London (2019).

2.2.2 Winegrowers' perceptions and adoption of sustainable soil management practices and technologies: a case study in Piedmont, Italy

Federica Caffaro^{1,2}, Eugenio De Gregorio³, Giorgio Capello^{2,4}, Lucia Vigoroso^{1,2}, Giorgia Bagagiolo², Eugenio Cavallo², Marcella Biddoccu²

1 Roma Tre University, Department of Education, 2 Institute of Sciences and Technologies for Sustainable Energy and Mobility (STEMS) of the National Research Council of Italy (CNR), 3 Link Campus University, 4 Interuniversity Department of Regional and Urban Studies and Planning (DIST), Politecnico di Torino and Università di Torino.

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Abstract

Soil is crucial for human survival but is threatened by erosion and contamination. Farmers play a pivotal role in soil conservation, thus, understanding what influences their decisions is crucial. The IN-GEST SOIL project aimed to mitigate soil erosion and improve soil and vine quality in Piedmont vineyards, NW Italy. Adopting a mixed-methods approach, specifically by administering a questionnaire followed by focus groups, the study surveyed 72 winegrowers, with 22 then participating in the group discussions, to assess perceptions of soil quality, adoption of sustainable practices and its enablers, and barriers to soil protection. Results showed that most participants were aware of soil degradation in their vineyards (mean score 2.50 on a 1-4 scale). Grass cover was the most common practice (mean score 2.86), and over half of the participants used soil monitoring systems. However, qualitative data revealed a need for more information on soil degradation risks and management practices. Winegrowers with larger vineyards ($F(2,71) = 4.496$, $p = .015$) and those on steeper slopes ($F(2,71) = 3.316$, $p = .042$) perceived higher soil degradation. Additionally, those in climatic areas mainly with dry summers (non-Cfa) reported greater degradation effects ($t(70) = 3.81$, $p = .000$; $t(70) = 2.00$, $p = .049$). No significant differences based on farm size, steepness and climatic areas emerged either for the adoption of cover crops or soil monitoring systems. Despite the small sample size, the study provides valuable insights into farmers' perceptions and identifies intervention areas for sustainable farming. The mixed-methods approach proved effective in enriching quantitative data with qualitative insights into the farmers' mindset.

Keywords:

Soil conservation, Soil management, Mixed methods research, Sustainability, Winegrowers' perception

INTRODUCTION

Soil is a lifeline for human existence, serving as the primary source of food, biomass, and raw materials. Given its crucial role in water, nutrient, and carbon transformation, storage and filtration, soil is practically a non-renewable resource due to the extremely slow process of soil formation (Groth, 2007). At the global level, the concept of soil degradation and its assessment have been considered part of more holistic assessments of human-induced degradation carried out by Food and Agriculture Organization, Intergovernmental Technical Panel on Soils (Food and Agriculture Organization [FAO] & International Technical Panel on Soils [ITPS], 2015; FAO, 2020), United Nations Environment Programme (United Nations Environment Programme [UNEP], 2017), and other UN agencies. In Europe, sustainable soil management has been a priority across various European Union policies. Specifically, within the Common Agricultural Policy (CAP), soil protection has been part of the Good Agricultural and Environmental Conditions (GAEC) since the introduction of cross-compliance in 2003. CAP support for rural development included agri-environment schemes to encourage soil protective operations and, more recently, the sustainable management of natural resources to support climate mitigation and adaptation. Indeed, the CAP Greening introduced in 2013 made direct payments to the farming sector conditional on the adoption of 'agricultural practices beneficial for the climate and the environment' (Council Regulation (EU) No 1370/2013). One of the key objectives of the CAP for the period 2023–27 is to "foster sustainable development and efficient management of natural resources such as water, soil, and air, including by reducing chemical dependency" (EC, n.d). The relevance of efficient management practices is especially focused on soils. This objective also considers concerns related to soil health and highlights the importance of policies that promote soil protection. A holistic and collaborative approach to soil management, as proposed in agro-ecology, is considered crucial. Land use and cover management practices are part of the new framework of GAEC proposed for the following years to contribute to soil conservation and restoration. The new CAP suggests several practices, some of which are suitable for vineyards, where soils are particularly subjected to soil erosion and compaction (Hamza & Anderson, 2005; Igor et al., 2020). Soil cover, especially by cover crops, not only prevents nutrient and pesticide runoff and soil erosion by water but also improves soil fertility and water infiltration by enhancing

soil structure (Bavorova et al., 2020; Cataldo et al., 2020; Giffard et al., 2022; Ruiz-Colmenero et al., 2011). Also, tillage management practices, with a reduction of tillage intensity and tractor passages, can diminish soil compaction, runoff, and erosion and improve soil structure and water infiltration (Capello et al., 2019, 2020). Finally, the introduction of digital techniques to monitor and optimise production has increased in viticulture in the last decade for intensive and large production but has the potential to become widespread also in regions characterized by small farms for high-quality wine production (Mirás-Avalos, & Araujo, 2021).

Turning to the role of farmers, decision-making regarding the adoption of soil protection practices has a significant impact on the environment, making it necessary to investigate the triggers of farmers' choices and behaviours. Previous studies showed the significant role of demographic and farm characteristics in predicting the adoption of sustainable practices and measures, such as years of farming experience (Mamun et al., 2021) and farm size (Marques et al., 2015). The financial and economic aspects have been widely investigated as critical variables in determining sustainable innovation adoption among farmers (García-Cortijo et al., 2019). However, previous research also revealed that farmers occasionally do not adopt a sustainable measure despite economic evidence suggesting they should. Vice versa, they adopt a sustainable measure even when the economic outlook is unclear or unfavorable (Wheeler, 2008), highlighting the importance of taking a variety of psychological factors into account (Sapbamrer & Thammachai, 2021). In particular, perceiving that climate and temperature are changing and that these changes lead to adverse effects in terms of flood, drought, riverbank erosion, and heat waves appeared to encourage the adoption of climate change adaptation behaviors (Guo et al., 2021; Mamun et al., 2021).

Despite this, applying these insights to viticulture can be challenging since wine prices vary widely (Caracciolo et al., 2013), which means that winegrowers are more influenced compared to farmers by market trends, consumer preferences, marketing strategies, and their own interpretations of best practices (D'Amico et al., 2016). Furthermore, geographical origin is closely associated with the quality of grapevine products, and in particular wine: this connection was included in the notion of "terroir" (Organisation Internationale de la Vigne et du Vin [OIV], 2010, 2024). The soil, the climate, the biological environment are all natural factors that interact with the plant, but also the technical routes chosen by winegrowers, contribute to produce grapes whose characteristics are intrinsically linked to these different factors (Leturcq, 2020). The "terroir" is a relevant marketing and

promotion term, thus any factor that plays a role in it, including decisions about vineyard management practices, can contribute to the value of wine.

The existing research on decision-making in viticulture is somewhat sparse. Winegrowers are sometimes included in broader studies (Demartini et al., 2017; Fantappiè et al., 2020), but these studies typically do not focus specifically on winegrower decision-making. Most studies examining viticulture decision-making address longer-term choices, such as transitioning to organic farming, engaging in environmental programs, or adopting agroecological practices (Garini et al., 2017; Marquez-García et al., 2019; Siepmann & Nicholas, 2018). A few studies do examine soil management by winegrowers. For instance, Marques et al. (2015) investigated the challenges that winegrowers in central Spain faced when transitioning from conventional tillage to using cover crops between vineyard rows, finding that factors like water constraints, lack of knowledge, and resistance to yield loss often hindered the adoption of cover crops. Cerdà and Rodrigo-Comino (2021) conducted a survey among winegrowers, along with direct assessment of the biophysical impact of crops, in Eastern Spain, concluding that the perception of farmers was mainly not favourable towards the use of cover crops. Schütte and Bergmann (2019) used a qualitative approach to compare cover crop adoption in French and Spanish vineyards whereas Chen et al. (2022) investigated winegrowers' decision-making regarding inter-row management and pesticide use in five European regions, finding that driving factors and barriers vary per case study, and implying the need to identify and address the local bottlenecks to sustainability to design targeted strategies.

Despite the importance of mapping winegrowers' decision-making processes and their determinants at the local scale, within Europe in Italy little attention has been paid to farmers' perceptions of soil degradation and adoption of soil conservation practices and technologies (Bechini et al., 2020). Italy stands as the world's largest wine producer (Organisation Internationale de la Vigne et du Vin [OIV] 2021a, 2021b), with 54.8 mhl of wine produced in 2021, ranking in the fourth position for vineyard cultivation with 718,000 ha, after Spain, France, and China (OIV, 2023). Most of vineyards (90%) are in the administrative provinces of Cuneo, Asti and Alessandria, which includes the UNESCO World Heritage Site of "The Vineyard Landscape of Piedmont: Langhe, Roero, and Monferrato" (UNESCO, n.d.). Piedmont is the Italian administrative region with the highest number of DOCG (Denominazione di Origine Controllata e Garantita, 19 over 73 in Italy) and DOC (Denominazione di Origine Controllata, 41 over 332 in Italy) (Regione Piemonte, 2024a), producing 11% of the grapes for DOP (Denominazione di

Origine Protetta, including both DOC and DOCG) wines in Italy (Istituto Nazionale di Statistica [ISTAT], 2024). Since vineyards are generally located in sloping areas with high susceptibility to soil erosion by water (Regione Piemonte, 2023), Piedmont represents a relevant case study to investigate winegrowers' perception of soil erosion and other soil degradation risks, and their adoption or intention to adopt soil protection practices, to face the environmentally and economically relevant challenge of making winegrowing more sustainable.

In fact, in recent years, some winegrowers have become reluctant in adopting permanent spontaneous grass cover due to increasingly warm and dry vine-growing seasons, but the question is if do they have adequate knowledge of the other possible choices and their advantages and disadvantages for both the crop and the soil in relation to pedoclimatic conditions? The IN-GEST SOIL project (<https://ec.europa.eu/eip/agriculture/en/find-connect/projects/gest-soil-innovazione-nella-gestione-dei-suoli>) aims to reduce soil erosion risk in hillslope vineyards in Piedmont, improving soil and vine quality by means of the introduction of improved best soil management practices.

In this context, a deeper understanding of local winegrowers' perceptions, intentions, and needs could facilitate the implementation of better-suited soil protection measures in vineyards. The present contribution reports the first results from the first phase of the IN-GEST SOIL project, in which the perception of soil erosion risk, factors influencing it, and adoption of possible solutions were investigated in a group of winegrowers in the Piedmont region, Northwest of Italy, a context which has not been extensively studied before. The results will provide useful insights to develop targeted and multilevel interventions to encourage the adoption of soil protection practices, based on the unique winegrowers' perspective on soil conservation in vineyards, together with the regional pedo-climatic conditions, for a more sustainable vine-growing cropping system (Panagos et al., 2024).

MATERIALS AND METHODS

This section describes in detail the methodological approach adopted in this study. It is structured into two main parts. The first, Study Area, provides a detailed description of the geographical, environmental, and contextual characteristics of the area in which the research was carried out, providing the necessary background for understanding the study's context. The second part, Methodological theoretical introduction, describes the research design and procedures used for data collection

and analysis. Specifically, it includes subsections on Participants and Procedures, outlining the recruitment criteria and data collection process; then, quantitative instruments used and the methods for analyzing them were discussed, along with qualitative instruments adopted and the procedures used to analyze them.

Study area

The study was conducted in Piedmont, a region in NW Italy. This region, distinguished by more than 44 thousand hectares of vineyards (ISTAT, 2024) primarily located in hilly areas (95%), features a diverse climate due to its geographical position and the presence of various mountain formations. When considering areas with a high propensity for viticulture and based on the current Köppen-Geiger climate classification of the European Alps (Rubel et al., 2016), most vineyards experience a warm temperate climate, with hot summers and no dry season (Cfa). Vineyards in the foothill area have a similar warm temperate climate, but with warm summers and no dry season (Cfb). The Ovadese Monferrato area experiences a warm temperate climate, with hot and dry summer season (Csa), while the Apennines have a warm temperate climate, with warm and dry summer season (Csb). Similarly, the distribution of rainfall varies greatly due to the region's geographical diversity. In the mountainous and foothill areas, precipitation is more abundant, especially during spring and autumn. The plains area is characterized by generally less intense precipitation. However, strong thunderstorms can occur during the summer. Specifically, in the viticultural areas, the annual average of daily cumulative precipitation, calculated for the period 1991-2020, showed a minimum of just over 700 mm per year in the plain area between Asti and Alessandria, with precipitation concentrated in spring and autumn, and a minimum in winter and summer (about 40 mm in July). Moving away from this area, the average annual precipitation increases; for example, the Gavi area has an average annual precipitation of around 1000 mm (Agenzia Regionale per la Protezione Ambientale [ARPA], 2024) (Figure 6).

The temperature distribution in the region also depends on the orography: in the plains and hilly areas, winters are cold and humid, often with dense fog, while summers are hot and muggy. The annual average of the daily maximum temperature, calculated for the period 1991-2020, reached a peak of 18.5 °C in the same area where the minimum precipitation is recorded, with a temperature 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. The minimum temperatures in the viticultural areas, considering the same period, have

an annual average below 10°C, with the winter period settling around 0 °C (generally, January is the coldest month), while in summer they remain below 18°C (July and August can exceed 19 °C) (ARPA Piemonte, 2024). According to the Soil Map of Italy (Costantini et al., 2012) and cadastral data on vineyards provided by Regione Piemonte (2024b), in hilly vine-growing areas the majority of soils are classified as Cambisols and Regosols (89.3%, soil province 17), followed by Luvisols and Cambisols (7.9%, soil province 22). Only a small proportion of vineyards are located on Vertisols (1.0%, soil province 20), Luvisols, Cambisols, Leptosols, and Phaeozems (0.9%, soil province 6), or Cambisols, Arenosols, and Fluvisols (0.5%, soil province 24).

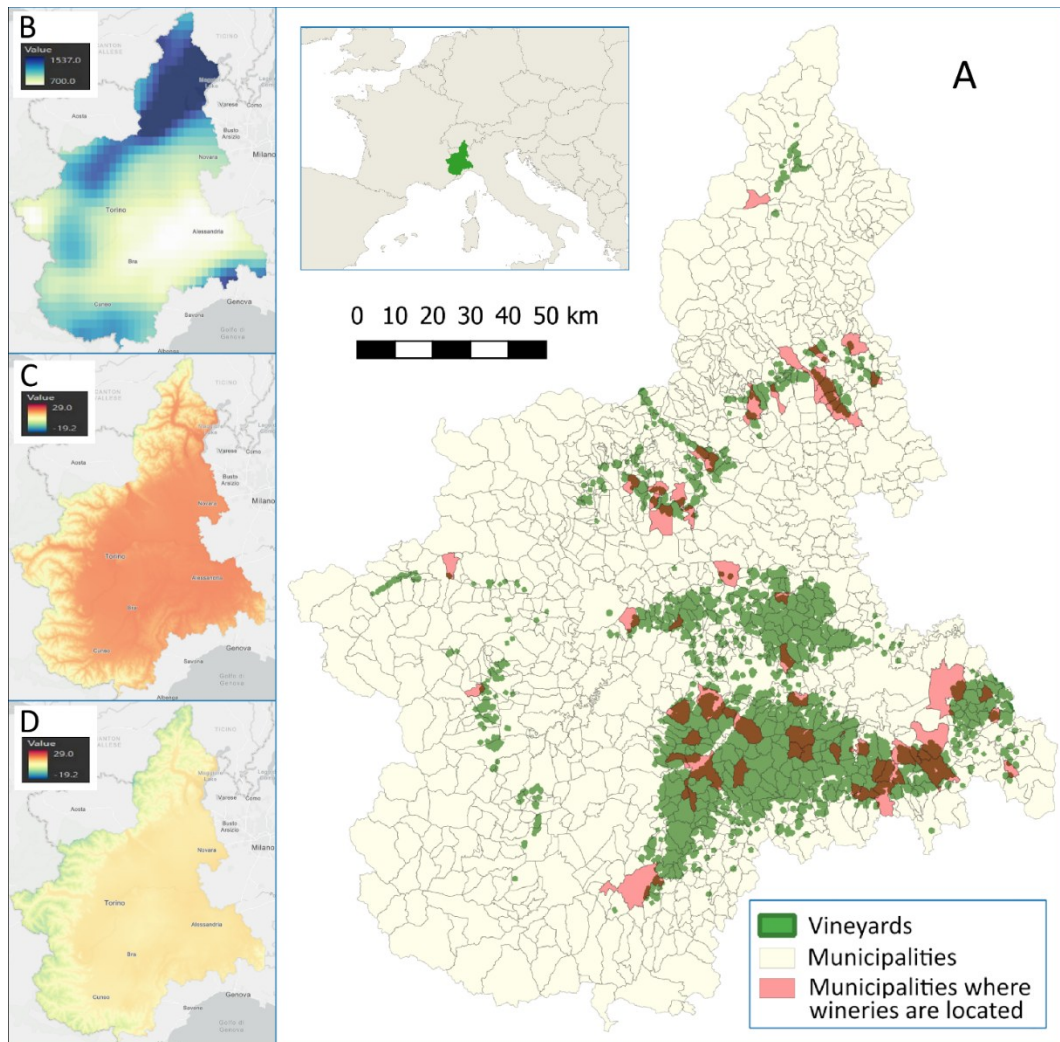


Figure 6. Map of Piedmont illustrating the distribution of vineyards (in green; Regione Piemonte, 2024b) and the municipalities where wineries that responded to our survey are

located (highlighted in red) (A). Maps on left side display mean annual precipitation (B), annual average of daily maximum temperature (C), and minimum temperature (D) (ARPA Piemonte, 2024).

A methodological theoretical introduction

Given the complexity and breadth of the topic, we implemented a multi-method research design. This involved collecting both quantitative data (via questionnaires) and qualitative data (via focus groups) to analyze perceptions of soil erosion, its causes, and potential preventive solutions. The use of mixed methods in social research has been growing over the past 20 years (Bergman, 2008; Bazeley, 2018; Tashakkori & Teddlie, 2010), offering a broader and more complete overview of the data and allowing different levels of in-depth analysis. Our quantitative data provided insights into the extent of soil erosion perceived by participants, the most adopted soil management strategies and soil monitoring systems, and potential differences based on various vineyard characteristics, i.e., climatic area, steepness and size. The qualitative approach then allowed us to delve into participants' unique perspectives and experiences, exploring the connections between the concepts of soil erosion and soil management practices.

Participants and procedure

The study was conducted at the beginning of 2021, when the COVID-19 pandemic control measures were fully in force in Italy, not allowing in-person meetings or events. These constraints significantly affected the researchers' choices regarding participants' recruitment and data collection activities, opting for online questionnaire spreading and focus group meetings. The possible biases related to these choices will be further discussed in section 4.1 of this paper.

The questionnaire was administered online using the EUSurvey platform and can be reached at the link https://ec.europa.eu/eusurvey/runner/IN-GEST_SOIL_PSR_Piemonte_2014-2020. It was disseminated from January 2021 to April 2021, with periodic reminders through mailing lists and social networks by the winegrowers' associations involved in the IN-GEST SOIL project, which reach about 325 wine cellars in Piedmont (the location of the involved cellars is represented in Figure 6).

Seventy-two winegrowers filled in the questionnaire. The main sociodemographic characteristics of the participants and their vineyards are reported in Table 1. Among these participants, twenty-two agreed to take part also

in the subsequent focus groups and were then contacted by telephone by the last author to explain the aims of the study and collect their consent to participate. Five online focus groups were therefore conducted in the spring of 2021 with the Microsoft Teams platform, as it may be used from mobile devices, display multiple users on the screen simultaneously and allows for recording audio and visual communications. Each focus group was composed of 4-5 participants, based on their availability. The meetings were recorded and lasted about one hour each. Based on Daniels et al. (2019), the procedure to be followed to design the focus groups, including invitations to participants and topics to be addressed, were drafted and collected into a guidance document, to ensure consistency of responses across all the groups.

Each focus group was facilitated by the same moderator to ensure consistency across sessions. At the beginning of each meeting, the moderator briefly introduced himself and reiterated the purpose of the session and invited participants to introduce themselves to create a comfortable and open atmosphere. Participants were then asked for consent to record the session. The moderator was responsible for guiding the discussion in accordance with a pre-established topic guide (see 2.4 instruments) and for fostering an open and honest exchange of opinions among participants. The moderator controlled a power point slide presentation on which each question posed verbally was also displayed on the screen, to help participants maintain focus on the topic being discussed. Efforts were made to involve, without pressuring, those who were less inclined to speak, and share their experiences and point of view. The moderator also observed the dynamics of interaction within the group emphasizing that the study aimed to capture the diversity of opinions regarding the research topic, and when appropriate, end or change the direction of discussion and proceed to the next question. A second researcher was always available to help set up or address any issues (Grønkjær et al., 2011; Prosser et al., 2024).

Table 1: Main characteristics of the participants and their vineyards (N=number of respondents, M=mean, SD= standard deviation).

Respondents' characteristics		N	%
Gender	Male	63	87.5
	Female	9	12.5

		(M, SD)	
Age		48.13 (13.53)	
Years of farming experience		20.93 (12.02)	
Vineyards' characteristics		N	%
Size (ha)	0-4	27	37.5
	5-19	25	34.7
	20 and above	20	27.8
Slope (degrees)	0-4	21	29.2
	5-10	22	30.6
	11 and above	29	40.3
Climate zone ¹	Cfa	40	55.6
	Non-Cfa	32	44.4

¹ Note: the climate zone has been identified for each participant, considering the location of their farm, on the basis of the current Köppen-Geiger climate classification of the European Alps (Rubel et al., 2016): Cfa = Warm temperate climate, with hot summer and no dry season; Non-Cfa climate include: Cfb = Warm temperate climate, with warm summer and no dry season (8 vineyards out of 32); Csa = Warm temperate climate, with hot and dry summer season (20 vineyards out of 32); Csb = Warm temperate climate, with warm and dry summer season (4 vineyards out of 32).

Quantitative data

Instruments

The questionnaire was designed based on previous instruments (Carmona et al., 2015; Guzmán et al., 2015) and it included 4 sections: (1) perception of soil quality, in term of perceived soil degradation and observation of its direct and indirect effects (two sub-sections) (2) adoption of vineyard management practices and most suitable practice for their vineyard (nine sub-sections), (3) adoption of soil monitoring systems (five sub-sections), and (4) sociodemographic characteristics of the respondents and vineyard characteristics. Only the two sub-sections of section (1), two sub-sections of section (2) and one subsection of section (3) were considered for the aim of the present study (Table 2) and will be described hereafter.

Table 2: Subsections (question and answer options) of the survey considered in the present study.

Sections	Responses
Section 1.1: What of the following problems did you observe in your vineyards in recent years?	
1. Formation of channels or accumulation of sediment after precipitation events within or adjacent to the vineyard	For each option: 1= not at all present, 2= little present, 3= present, 4= strongly present
2. Obstruction of drainage systems	
3. Small landslides	
4. Difficulty in accessing the field due to soil conditions	
Section 1.2: At what degree the following phenomena are affecting soils of your vineyards?	
1. Soil erosion (loss of surface soil)	For each option: 1= not at all present, 2= little present, 3= present, 4= strongly present
2. Soil compaction	
3. Loss of soil organic matter	
4. Surface landslides	
5. Flooding due to extreme events	
6. Decrease in soil permeability	
Section 2.1: Indicate what % of your vineyards is managed with each method (with regards to the inter-rows):	
Bare soil obtained by tillage	For each option: 1= not at all used (0%), 2= little use (<50%), 3= moderately used (>50%), 4= strongly used (>90%)
Permanent spontaneous grass cover in all inter-rows	
Temporary spontaneous grass cover in all inter-row (with summer tillage operations)	
Temporary spontaneous grass cover in one inter-row and bare soil by tillage in the second inter-row	
Sown grass cover (with specific species for mulching)	
Mineral fertilization	
Organic fertilization	
Section 2.2: Indicate which of the methods mentioned in Section 2.1 is more suitable for your vineyard and explain the reason.	For each option: 0= not selected, 1=selected For the reasons: Open answer
Section 3.1: Indicate if you are using some of the following tools for monitoring the vineyard and support decisions in its management and how long you are using them.	

1. Soil moisture sensors	For each option:
2. Software/APP for register field work	4=Used for more than 5
3. Software/APP with models for insects and pathogens	years, 3=Used for less
4. Detailed maps using drones	than 5 years, 2=Will
5. Precipitation maps from local authorities	adopt shortly, 1=Will
	adopt in the future,
	0=Will not adopt at all

Note. Section 1.1 referred to soil degradation observed indirect effects. These are visible in the field and are a consequence of a single degradation process or a combination of more processes. These effects are various and not frequent, but a common feature is that they cause difficulties in managing the vineyards, or even damages that require exceptional intervention (and costs) to restore the previous conditions of the vineyard (Martínez-Casasnovas et al., 2005; Martínez-Casasnovas & Ramos, 2006). Section 1.2. investigated instead the observed direct effects, which referred to in-field evidence of soil degradation processes that can be challenging for winegrowers to notice, as they require specific knowledge or evidence from soil analysis and measurements. Moreover, their impact on soil quality and production is typically observed over a mid/long-term basis (Hontoria et al., 2018).

Data analysis

Descriptive statistics were computed for the variables of interest. The internal consistency of the items on the perception of soil quality and adoption of soil monitoring systems (i.e., questions belonging to Sections 1.1, 1.2, and 3.1 of the questionnaire), was measured by computing the Cronbach's Alpha coefficient (Cronbach 1951). A value between 0.60 and 0.80 indicate an acceptable level of reliability of a scale, while a value above this threshold indicates a very good level (Daud et al. 2018). After the reliability analysis, an aggregated score was computed on the considered items, as the sum of the responses, leading to the creation of three scales, namely “Observed direct effects” ($\alpha = 0.820$) and “Observed indirect effects” ($\alpha = 0.721$), and “Soil monitoring systems” ($\alpha = 0.773$).

Regarding the items on the adoption of soil management practices in inter-rows, descriptive statistics were computed for all of them. The item related to the percentage of vineyards managed with permanent spontaneous grass cover practice in all inter-rows, which is the most sustainable option currently adopted in the study area (Bavorova et al., 2020; Cataldo et al., 2020; Giffard et al., 2022; Ruiz-Colmenero et al., 2011), was used as dependent variable in the subsequent analysis.

Then, the three aggregated scores and the item related to the adoption of permanent spontaneous grass cover were then used as dependent variables in two one-way ANOVA and a T-test aimed to explore any significant differences based on vineyard characteristics, i.e., steepness of the vineyard and farm size, and climatic area in which the vineyard was. The analyses were performed using IBM SPSS Statistical Package for Social Science v. 26.

Qualitative data

Instrument

Topics addressed in the focus groups were designed based on previous instruments (Gómez et al., 2021; Marques et al., 2015; Prosdocimi et al., 2016) on the most critical factors involved in the adoption of soil conservation measures. The topic guide used for conducting the focus groups is reproduced in full in Table 3.

Table 3: List of topics and questions used by the focus group moderator to guide the discussion.

Topic 1: Perception of soil erosion
1. Do you perceive erosion as a problem (for production, for the territory)? Have you ever had problems related to erosion in your vineyard? or do you know any neighbours who have suffered damage? 2. When is it best to intervene to combat the phenomenon of soil erosion? What should be done to prevent it? 3. What methods do you know or apply to reduce soil erosion? What would you be willing to do? How much would you be willing to spend?
Topic 2: Causes, natural and human factors in preventing/causing soil erosion
1. In your opinion, what are the main causes of erosion? 2. What anthropogenic factors can cause erosion or other land degradation phenomena? 3. Can agricultural vehicle traffic increase erosion? To what extent? 4. Which types of soil management reduce erosion, and which increase it? 5. In which season do you think there is the greatest risk of erosion? Why?
Topic 3: Adoption, perception of effectiveness of good practices and intention to adopt them

-
1. Do you know what are the good agricultural practices for soil protection? What do you think? Do you consider yourself sufficiently informed?
 2. What do you think of techniques that involve grassing as soil management?
 3. What are the advantages and what are the disadvantages?
 4. Is grassing effective in every situation?
 5. Are you willing to convert the type of soil management currently adopted in your vineyards to adopt some good practices?
-

Topic 4: Adoption, perception of technological innovations and intention to adopt them

-
1. Which technologies and soil monitoring systems can help the winegrowers protect the soil?
 2. Does anyone use Information and Communication Technologies (ICT) systems within your farm and vineyard? Or are you willing to adopt them in your farm?
 3. What are the obstacles to using them? (Economic? Perceived usefulness? Complexity?) Would you like to be informed/follow courses to learn how use them?
-

Data analysis

We conducted a reflexive thematic analysis to examine the data, identifying recurring patterns in winegrowers' experiences and their proposals for preventing soil erosion. Following Braun and Clarke (2019), we viewed this approach as creative and reflexive, treating researcher subjectivity as a resource. Qualitative analysis, in this sense, seeks to reconstruct processes of meaning-making, situating data within the storytellers' lived experiences.

Guided by our research question, we explored participants' perspectives, motivations, and criteria for sense-making (Braun & Clarke, 2021). In the first stage, we used a selective coding approach (Braun & Clarke, 2013) to reduce the dataset and identify relevant analytic concepts. After familiarization with the data, one Author engaged in prolonged immersion before moving to the coding phase, where all segments related to the research question were labelled. These codes were then examined and grouped to identify shared patterns of meaning, i.e., themes supported by a core concept (Braun & Clarke, 2019). Codes reflect concise labels for participants' comments, while themes link multiple codes through a broader narrative.

Potential themes were then shared with the wider team. Group discussion allowed the analysis to be shaped both by the data and by theoretical insights, helping identify overarching themes. These were subsequently reviewed, refined, and defined, clarifying their hierarchical relationships and their contribution to answering the research question. The following section presents the results and a thematic map illustrating the relationships between overarching themes.

RESULTS

Quantitative data

Regarding the perception of soil quality, mean rating scores attributed to each item investigated are reported in Table 4. As it can be seen, our participants seemed to be highly aware of the presence of channels or accumulated sediment in their vineyard ($M=2.78$) and they acknowledged the presence of small landslides and soil compaction as an indicator of degraded soil ($M=2.46$ each), followed by the difficulty in accessing the field due to soil condition ($M=2.44$). The item related to the “Surface landslides” yielded the lowest average score ($M=1.87$), which nonetheless showed that our participants were moderately aware of the presence of this direct erosive phenomenon.

Table 4: Mean rating (M) and standard deviation (SD) for items on the perception of soil quality. To interpret the computed means, the following mean range based on Alico and Guimba (2015) was used: 1.00 – 1.74 = low, 1.75 – 2.49 = moderate, 2.50 – 3.24 = high and 3.25 – 4.00 = very high.

Scale	Items	M	SD
Observed indirect effects	Formation of channels or accumulation of sediment after precipitation events within or adjacent to the vineyard	2.78	.68
	Obstruction of drainage systems	2.35	.56
	Small landslides	2.46	.63
	Difficulty in accessing the field due to soil conditions	2.44	.58
Observed direct effects	Soil erosion (loss of surface soil)	2.29	.84
	Soil compaction	2.46	.78
	Loss of soil organic matter	2.30	.83
	Surface landslides	1.87	.92

Flooding due to extreme events	2.00	.96
Decrease in soil permeability	1.99	.75

Regarding the adoption of inter-row management practices (Table 5), permanent grass cover appeared as the most widely used practice (M=2.86), with 61.1% of the respondents reportedly using this practice in more than 50% of their cultivated area. This is followed by the adoption of grassing one in two inter-rows (M=2.07). The least used practice is tillage, resulting in bare soil in all inter-rows (M=1.43). Permanent spontaneous grass cover in all inter-rows was then indicated as the most suitable practice to be used for inter-row management (48.6%). Among the main motivations reported by the participants (i.e., open question, section 2.2) to adopt it, the winegrowers mentioned “reduction of soil erosion and soil compaction” on the one hand, and “increase of vineyard biodiversity and soil health, soil trafficability and topsoil moisture” on the other hand.

Table 5: Inter-row management practices adopted in the participants' vineyards (N=number of respondents and % = corresponding percentage).

Items	Cultivated area managed through the practice			
	0%	<50%	>50%	>90%
	N (%)			
Permanent spontaneous grass cover in all inter-rows	17 (23.6)	11 (15.3)	9 (12.5)	35 (48.6)
Organic fertilization	15 (20.8)	12 (16.7)	25 (34.7)	20 (27.8)
Mineral fertilization	18 (25)	20 (27.8)	22 (30.6)	12 (16.7)
Temporary spontaneous grass cover in one inter-row and bare soil by tillage in the second inter-row	34 (47.2)	14 (19.4)	9 (12.5)	15 (20.8)
Temporary spontaneous grass cover in all inter-row (with summer tillage operations)	37 (51.4)	19 (26.4)	9 (12.5)	7 (9.7)
Sown grass cover (with specific species for mulching)	45 (62.5)	19 (26.4)	5 (6.9)	3 (4.2)
Bare soil obtained by tillage	54 (75)	9 (12.5)	5 (6.9)	4 (5.6)

Regarding the adoption of soil monitoring systems, Table 6 shows that winegrowers' choices can be considered quite dichotomous: on the one hand, a high percentage of the participants reported currently using the investigated systems, but on the other hand, the intention among the non-adopters seemed to remain not to adopt them even in the future. Only a small percentage of our participants showed some intention to adopt these systems in the short-medium term.

Table 6: Adoption and intention to adopt different soil monitoring systems (N=number of respondents and % = corresponding percentage).

Scale	Item	Current adoption ¹	Intention to adopt ¹	Will not adopt
		N (%)		
Soil monitoring systems	Soil moisture sensors	51 (70.8)	1 (1.4)	20 (27.8)
	Software/APP for register field work	47 (65.3)	3 (4.2)	22 (30.6)
	Software/APP with models for insects and pathogens	51 (70.8)	10 (13.8)	11 (15.3)
	Detailed maps using drones	43 (59.8)	6 (8.4)	23 (31.9)
	Precipitation maps from local authorities	39 (54.1)	17 (23.6)	16 (22.2)

¹ Note: For better readers' clarity, here the responses "used for more than 5 years" and "used for less than 5 years" were collapsed in the "current adoption" category, whereas "will adopt shortly" and "will adopt in the future" were grouped under the "intention to adopt" label.

Looking more in-depth at the possible differences in the perception of soil quality and adoption of permanent spontaneous grass cover practices and monitoring systems based on vineyards characteristics, the t-tests showed that winegrowers with vineyards in non-Cfa climatic areas perceived significantly higher direct and indirect degradation effects ($t(70) = 3.81, p=.000$ and $t(70) = 2.00, p = .049$, respectively). No significant differences based on climatic areas emerged for the adoption of grass-cover as an inter-row management practice and adoption of soil monitoring systems. Nevertheless, Figure 7A shows that most of

vineyards with lower adoption (less than 50% of vineyard's area) of permanent cover were located in the Csa climate area, with hot and dry summer season. On the contrary, in this climate area, there were some vineyards mainly managed with tillage to obtain bare soil. The adoption of other soil management practices was likely not influenced by climate (Figure 10, SM1).

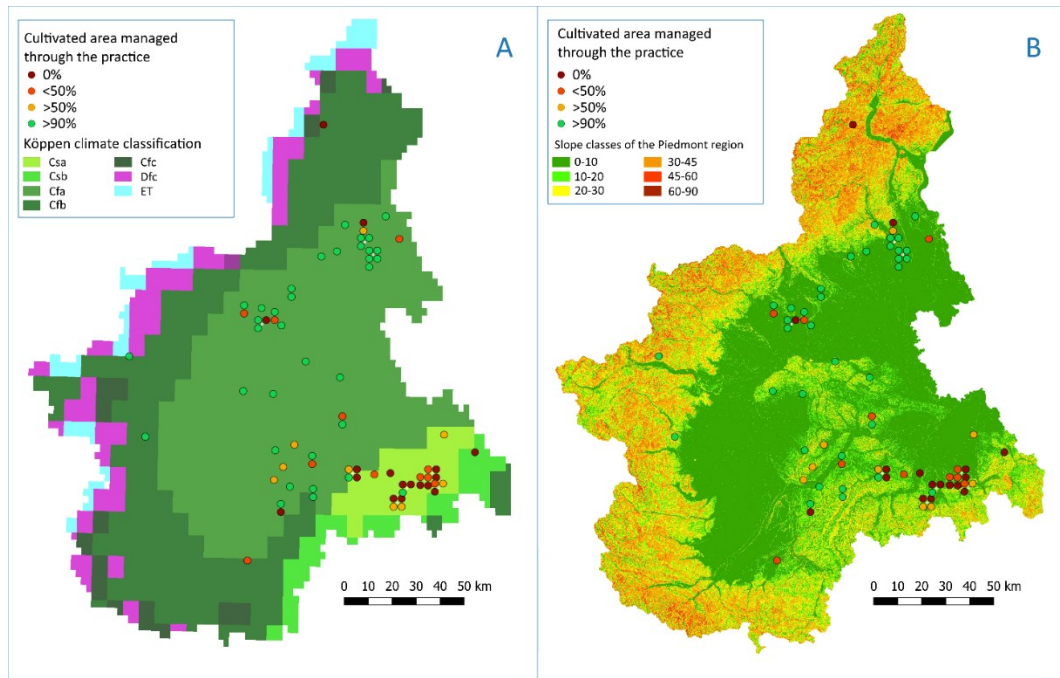


Figure 7. Maps showing the location of vineyards where permanent grass is adopted. Different dot colours indicate the percentage of the vineyard area managed with this practice. The background layers represent (A) the climatic zones of Piedmont according to the Köppen–Geiger classification (Rubel et al., 2016), and (B) the slope classes (Regione Piemonte, 2024d).

The ANOVA pointed out that the slope of the vineyard influenced with nearly significant values ($F(2,71) = 3.129$, $p = .050$) the perception of indirect effects of soil degradation. According to the statistical analysis and the map shown in Figure 7B, slope did not show any evident relationship with the degree of adoption of permanent inter-row grass cover management practices. Furthermore, there was a significant difference in the observation of indirect soil degradation effects based on the farms' size, with larger vineyards being associated with a higher observation of the phenomena ($F(2,71) = 4.496$, $p = .015$). No significant differences were reported for the other investigated variables (Table 7).

Table 7. Results from statistical analysis.

	Steepness (one-way ANOVA)			Farm size (one-way ANOVA)			Climatic area (t-test)	
	df	F	<i>p</i>	df	F	<i>p</i>	<i>t</i>	<i>p</i>
Observed indirect effects	2,71	3.129	.050	2,71	4.496	.015	2.008	.049
Observed direct effects	2,71	1.020	.366	2,71	2.316	.106	3.814	.000
Vineyards managed with permanent spontaneous grass cover	2,71	.400	.672	2,71	2.148	.125	-.667	.507
Soil monitoring systems	2,71	.018	.982	2,71	1.822	.169	-.184	.854

Qualitative data

The data gathered from the focus groups allowed us to have a deeper comprehension of how winegrowers' perceptions of soil degradation and the use of different prevention practices considered by the quantitative analyses were linked. In particular, the three items that emerged as indirect effects (Table 4: difficulty in accessing the field due to soil conditions, small landslides, the formation of canals or sediment accumulation after precipitation) of soil erosion and the observable direct effects of soil degradation (Table 4: decrease in soil permeability, surface landslides, flooding due to extreme events) were fully confirmed in the description of the critical issues for soil protection, as discussed in the focus groups.

Figure 8 shows how winegrowers' perceptions were connected as subthemes to the “hindering factors” theme, that includes aspects perceived as problematic for soil protection. In addition to a greater specification of what emerged with the highlighting of the codes and their link with the themes (referring to the objectives and thus to the representations and perceptions already described), here it is also possible to detect the thread of the discourse that develops within the focus groups, that is the discursive 'plot' that links certain themes together. In the interactions within the groups, the winegrowers referred heavy rainfalls and the local terrain conformation (i.e., degree of slope or depressions in the field), combined with machinery misuse, led to land alterations which make field access difficult or hazardous (i.e., holes, canals). These issues require additional work to restore the affected areas.



Figure 8: Conceptual map of hindering factors for soil protection emerging by the focus groups. The dashed lines indicate the connection between the codes and the themes in the centre; the continuous black lines (and labels) represent the sequence of discourse (plot) of what is being narrated, they are the causal links represented in people interpretations of events. The symbol (-) indicates a criticality in the prevention of soil erosion.

The reference to practices and customs emerged unexpectedly, including the use of machinery which - paradoxically - can amplify soil erosion due to the weight of vehicles and the type of operations performed, often consistent with soil characteristics. Furthermore, economic interests (particularly, the balance between the costs of alternative soil and land management and the medium to long term benefits) did not always allow decisions that maximize gains and limit losses. Based on this evidence, we note that according to the participants, the climatic conditions, different tillage type, and the modifications and conformation of the territory were

the more relevant issues in determining the difficulties in preventing erosion in vineyards, along with certain cultural customs and practices. In these cases, the debate also addressed weather issues and climate change, aspects on which winegrowers can have little influence, but which are definitely relevant to their management strategies. To illustrate these aspects, some quotations extracted from the focus group analysis can clarify the experts' perspectives.

Quot. #1: *Epecially where there is grassing, whether spontaneous or dedicated, the problems are very much reduced. And especially where certain equipment is used, which in any case means that the inter-row can have problems with erosive phenomena, especially when there are heavy summer storms.*

Quot. #2: *With the adoption of mulcher, things have certainly improved a lot (with respect the use of the rotary hoes 3 or 4 times along the year), because compared to 10 cm of soil erosion, maybe it has been reduced to just two... but as L. also said before, using the mulcher as a tiller can create that dust every time I do it, every time a storm arrives that exceeds 30 mm (of rainfall), it takes a lot of soil downstream*

Quot. #3: [Yes, there are] *The thunderstorms, the winters and summers..., for me it's changed so much what man used to do that he has kind of forgotten to do now, because the size of the farm, the way of working, the machinery itself has changed. If certain things were done (i.e., maintenance of channels), in my opinion, the type of soil, the rainfall event, would weigh less.*

Winegrowers were aware that soil management practices such as grass cover and mulching can reduce soil losses and damage caused by intense rainfall (see Quot.#1 and Quot.#2). Although natural events are beyond human control, winegrowers can adopt countermeasures and get support from technologies and innovations, while also revisiting traditional management solutions (Quot.#3). Creative approaches that adapt “old systems” to current conditions allow combining previous knowledge with innovation. Similarly, Figure 8 shows the codes pertaining to the theme “enablers”. Also, in this case, specific types of soil tillage practices are mentioned as enablers, i.e., as useful procedures to prevent soil erosion. The figure also includes the theme of 'good practices', as some codes identified under 'enablers' correspond to actions (practices, in fact) that should be preserved and transmitted, thus serving both as effective practices and promoting factors (or enablers). An example is the code 'specific projects for territories', which in Figure 9 is linked to both themes.

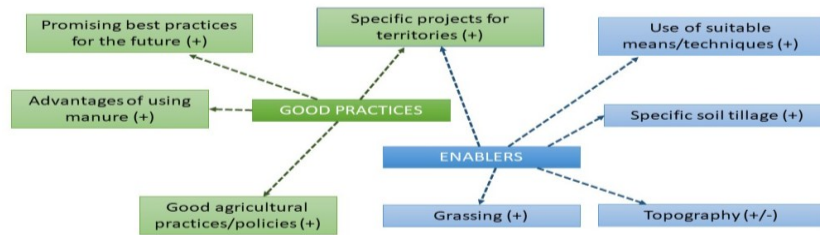


Figure 9: Conceptual map of enablers emerging by the focus groups. The dashed lines indicate the connection between the codes and the themes in the centre; The symbol (+) indicates a resource for the prevention of soil erosion.

Regarding the soil management practices addressed in the questionnaire, grassing emerged as relevant strategy for soil erosion prevention in both questionnaires and focus groups. It is a “nature-based solution”, although its extent depends on human activity. The discussion among the participants gave reason for the usefulness of this practice; more specifically, the code recurred in conjunction with other good practices such as "specific tillage" (4 quotations are coded with both codes) and "use of suitable means". This code also appeared to be related to (bad) practices and customs, but in a contrasting sense: grassing practices were perceived as a suitable solution, compared to practices that fail to prevent or even increase soil erosion. In this regard, the practices of grassing proved to be a widely accepted and powerful solution within the community of winegrowers. Here are two examples of an excerpt from the transcripts of the focus groups that makes the point very well:

Quot #4: *What we winegrowers can do, whether the soil is tilled in intern-rows or grassed, the important thing is that if you till it, there should then be some grass cover and perhaps before the rainfall event would be ideal. If you leave the grass cover in place for a long time, perhaps it should be rejuvenated. Then collaterally one should not forget to use those good practices: furrows, water drainage and design the vineyard very well to reduce the impact of water runoff depending also on the slope of the vineyard.*

Quot #5: *From here we moved on to grassing, first of a few sectors, then almost the entire farm, and where, on the one hand clearly this phenomenon of shifting earth has diminished drastically, or rather if it has unblocked, but the water has less chance of penetrating and so we see that when the rainfall phenomenon is intense, we see the water flowing over the grassed ground.*

It should be noted that the term “topography” is included both as a hindering factor and an enabler (symbol + and – in Figure 8 and 9): this code represents the qualitative difference between a practice that can be both beneficial or not beneficial

to soil preservation and erosion prevention. However, we noted solutions and hypotheses emerged from the focus groups that are not reflected in other data. First, aspects related to the economy are highlighted: farm size and the need to invest in modern equipment. Furthermore, political decision-makers are called into question with the request for concrete institutional actions, with the need to promote a transition to innovative technologies and the implementation of specific projects for the type of territory. Finally, it is noted how some topics already identified as hindering factors become - with appropriate reinterpretations linked to the specific discursive context - useful enablers to face the problem.

DISCUSSION

The present study intended to investigate the perception of soil quality and soil erosion phenomena and possible strategies to prevent it, in a group of winegrowers in northern Italy, considering also possible differences based on pedoclimatic conditions and farm size.

Perception of soil erosion

The results showed that participants were aware of several indicators of declining soil quality in their vineyards, particularly related to the indirect effects of soil degradation. This awareness is encouraging, since as highlighted by the psychological literature, being aware of a phenomenon is a significant predictor of individuals' intention to adopt and of actual adoption of ecological behaviours (Klöckner & Blöbaum, 2010). The results are consistent with other studies conducted in the Mediterranean area: 45% of winegrowers participating in a survey in central Spain observed soil degradation in their vineyards (Marques et al., 2015). Also, in France (Coteaux du Layon), during a focus group, some winegrowers mentioned the perception of soil compaction as one of the main reasons for adopting cover crops, together with an improved quality of soil and production (Schutte & Bergmann, 2019). In the present study, questionnaire responses indicate awareness of channels or accumulated sediment in their vineyards, as well as the threat of soil erosion, despite the fact that more than 48% of participants adopted permanent grass cover as inter-row management practice. This can be explained if observation of soil erosion refers to a previous period, when participants were not yet implementing sustainable inter-row management practices. Thus, the observation of soil erosion occurrence likely motivated them in adopting inter-row soil management with grass cover. Furthermore, as participants to focus groups noted, signs of soil erosion were often observed around the vineyards, especially on

surrounding roads not covered by grass, or along rows during periods when grass cover was absent (e.g., under alternate or temporary inter-row management) or poorly developed. This was the case observed in 2023 in a vineyard monitored by Biddoccu et al. (2025), where, after a very dry spring, high soil erosion was observed a few weeks after spring tillage and cover crop mulching in a vineyard managed with alternate rows (one inter-row managed with spontaneous grass, tilled in spring/summer, and the adjacent inter-row managed with a cover crop). When deepening these perceptions through the qualitative analysis, it emerged that winegrowers may benefit from education and training interventions aimed to increase their knowledge about soil erosion and its causes: natural events and anthropic activities appeared as strictly interwoven in winegrowers' discourses, with particular reference to the former. Similar request of much information about soil erosion and its control came from many winegrowers interviewed during a similar study conducted in central Spain (Marques et al., 2015). Becoming aware of the role that individuals and agricultural activities with their equipment play in contributing to soil degradation may help winegrowers developing a higher perceived behavioral control (Ajzen, 1991) on their management practice choices and the relevance of their adoption for an effective soil protection (Ahnström et al., 2009).

Winegrowers' perceptions in our study varied according to vineyard characteristics, such as climatic area, steepness of the terrain and farm size. In particular, winegrowers operating in non-Cfa climatic areas showed a significantly higher perception of both direct and indirect degradation effects compared to those in Cfa areas, whereas no significant differences emerged in the adoption of inter-row management practices or soil monitoring systems. The Cfa climate is warm, with hot summer but no dry season, while most of the vineyards were located in Csa and Csb climate zones, characterized by dry summers, commonly referred to as Mediterranean climate (Shakesby, 2011), with a precipitation regime that leads to higher erosivity than in other main biogeographical zones (Alpine and Continental) (Panagos et al., 2015a; Borrelli et al., 2016). These conditions also create water competition between grass cover and vines, especially in flat areas (Novara et al., 2018). Spatial climate variability in the region may explain the observed trends in perception of soil degradation processes, which align with findings from warm temperate areas such as Coteaux du Layon (i.e. soil compaction) and more arid vine growing regions like central Spain. Furthermore, the more frequent adoption of soil tillage practice (and reduced adoption of permanent inter-row grass cover) in areas with hot, dry summer is consistent, albeit to a lesser extent, with the low willingness to adopt cover crops management

practice reported by around one third of winegrowers and olive growers in studies from central (Marques et al., 2015) and southern Spain (Gómez et al., 2021), mainly due to water limitations for both main and service crops under rain fed conditions. The Mediterranean climatic zone also has a high soil loss rate ($4.61 \text{ t ha}^{-1} \text{ yr}^{-1}$) in Europe, and the observation of direct effects of soil degradation (particularly soil erosion) is likely easier in areas with such climate (Panagos et al., 2015b). A similar increased perception of soil degradation was indicated from Spanish winegrowers with sloping vineyards, with respect to those who have flat vineyards (Marques et al., 2015). Likewise, participants with larger vineyards and on steeper slopes perceived nearly significant higher direct effects of soil degradation compared to vineyards in the plain. Indeed, topography, intended as slope gradient and length, is one of the primary factors influencing soil water erosion (Wischmeier & Smith, 1978), especially in permanent crops such as vineyards (Cerdan et al., 2010; Corti et al., 2011; Prosdocimi et al., 2016), as they are often located in sloping areas (hill or mountain slopes), which is the case of vinegrowing areas in Piedmont.

Furthermore, there was a significant difference in the observation of indirect soil degradation effects based on the farms' size, with larger vineyards being associated with a higher observation of the phenomena. This result adds a contribution related to the wine growing sector in a European country to the mixed body of evidence on the relationship between farm size and the perception of climate change consequences, which is usually investigated in crop farms from African or Asian countries. Indeed, some recent studies have pointed out a negative association, with larger farms reporting lower perceived risks from drought or rainfall variability or lower probability to perceive climate change at all (Diyyala et al., 2025; Uddin et al., 2017). Other contributions instead highlighted that the role of farm size is complex and context-dependent, with smaller farm holders often taking more intense adaptation measures against perceived climatic change (Mairura et al., 2021; Makate et al., 2017).

Adoption of inter-row management practices and soil monitoring systems

In the present study, questionnaire responses indicated that winegrowers are more inclined to adopt permanent inter-row grass cover (48.6% declared to using it in more than 90% of their vineyards) rather than temporary grass cover (15%). Covering the soil during the rainiest periods constitutes one of the good agricultural and environmental conditions standards for agricultural areas (GAECs) introduced in the CAP to protect soils from erosion. According to Panagos et al. (2021), the adoption of cover crops is a preferable option to mitigate soil erosion in the CAP

2023-2027; in one scenario, a cover rate of 75%, would reduce soil erosion in permanent crops by 30%. Data from the Piedmont region administration for the CAP 2014-2020 indicate that, in 2022, 50% of vineyards in Piedmont received economic support through the Rural Development Programme (RDP) for adopting integrated production principles, which requires the use of grass cover management practices in vineyard's inter-rows during autumn and winter. Permanent grass cover management has been further incentivated and was adopted in 35% of vineyards. In this case, soil can be tilled in autumn, after harvest, to allow fertilizers incorporation (Regione Piemonte, 2024c). Nevertheless, data on winegrowers receiving RDP support may not represent the totality of those adopting grass cover management practices, since some of them adopt it without asking or receiving funding. The CAP 2023-2027 Strategic Plans (https://agriculture.ec.europa.eu/cap-my-country/cap-strategic-plans_it) include some support to the adoption of minimum soil cover (GAEC 6) across Europe with a greater extent than in the previous years. In permanent crops, adoption of minimum soil cover allows a certain flexibility considering certain agronomic practices during the sensitive period, which can be relevant in light of the types of soil and pedo-climatic conditions. Most sensitive periods are autumn and winter, but some Member States focused more on the summer months when great heat and intense rainfall occur. Italy, like other 22 Member States, set explicit requirements for areas of permanent crops, varying according to the considered farming systems and in certain cases targeting only areas with some slope conditions. In general, minimum soil cover can be obtained either by spontaneous vegetation or sowing cover crops, leaving stubble, or crop residues on the land or by mulching. The complex framework of this GAEC proves the variety of factors (soil, climate, slope, agricultural system) that must be considered in the adoption of measures for contrasting soil degradation in permanent crops, such as vineyards. In Piedmont, 2022 and 2023 were marked by very dry vine growing seasons (Capello et al., 2024), that resulted in suggestions for modification of the section related to agronomic practices of the "National guidelines for integrate management" (MASAF, 2024). The changes allowed soil tillage in spring and summer in case of particular soil and cumulated precipitation conditions, based also on evidence from previous studies in the region (Bagagiolo et al., 2018; Biddoccu et al., 2016; Capello et al., 2019).

The qualitative investigation of the winegrowers' perception about the strategies and technologies available to prevent soil degradation pointed out once again (as discussed before for the phenomenon of soil erosion) the need for increased knowledge. The discourses of our participants regarded both technologically advanced systems and different techniques of soil tillage as factors

that can help protect soil. They pointed out that more information about soil degradation risks and related solutions is needed, especially knowledge and recommendations on management practices and technical solutions to positively contribute to soil conservation, avoiding a misuse which may lead to increased soil degradation. An example is the use of mulcher to control the height of grass: if it is not used correctly, it damages the grass and soil surface pulverizing the soil, favouring the formation of soil crust that makes it difficult for grass to grow and water to infiltrate. Based on our results, winegrowers must know the risks related to soil degradation, available solutions, possible advantages and disadvantages, and finally, they should receive support in adopting them correctly. Tools and services should be made available to winegrowers to inform and educate them on the smart farming solutions for soil protection that better suit their needs in terms of farm size, availability of funds, terrain characteristics, with a clear communication on the features, the concrete benefits and limits of the different technologies, to allow them to perform a conscious choice when managing their vineyards. Perceived usefulness of sustainable measures and technologies appeared to be a significant predictor of their adoption among farmers in previous studies (Caffaro et al., 2020; Pierpaoli et al., 2013), and it claims for educational interventions based on a proper needs analysis and a participatory approach, to identify the most relevant aspects to be stressed during training for different types of users (Caffaro et al., 2017; Tovar Aguilar et al., 2014).

No significant differences emerged based on vineyard characteristics either in the use of grass-cover as an inter-row management practice or in the adoption of monitoring systems. This issue would deserve further investigation, if we consider some recent evidence from other countries. Indeed, in France, bigger landowners are most interested in soil protection measures, since they can benefit from subsidies and can respond to the CAP request of higher quality and downsizing production (Marques et al. 2015, Schütte & Bergman, 2019). Similarly, a recent study among farmers growing olives in southern Spain, showed that farmers preferring bare soil managed significantly less olive area than those using always or partially a cover crop (Gómez et al., 2021). In contrast, in central Spain, the larger size of vineyards seemed to determine low willingness of farmers to change behaviour in soil management, due to higher level of mechanization and lower concern about soil erosion compared to smallholders (Marques et al., 2015). Future research would be useful to clarify these inconsistent results on the relationship between farm size and soil management practices.

Limitations of the study and future research developments

Some limitations of the present study should be acknowledged. First, our respondents were a small group recruited among the members of the winegrowers' associations taking part in the IN-GEST SOIL project, which may have led to a self-selection bias: the responses we collected may come from the most "sustainability-sensitive" winegrowers in the considered areas (which could also explain the high rate of declared adoption of smart soil monitoring systems showed in Table 6) and therefore the results should be taken with caution and cannot be generalized. Our results appear to be considerably more prominent when compared to the most recent data on land management by Italian winegrowers since it is crucial to remember that not all relevant variables may be included in all official statistics.

In the face of the critical issues described above, we believe that multi-methodological integration is appropriate to investigate aspects related to the problems and strategies inherent in soil erosion prevention. In fact, the quantitative data made it possible to take a snapshot of reality, and through the focus groups this snapshot acquired a context made up of a plot (the history of the area) and a future evolution (the participants' goals and proposed strategies). The methodology we proposed gave voice to real participants in real contexts and this is one of the main criteria of validity of multi-methodological research, beyond the golden adherence to statistical principles such as the representativeness of the sample under investigation. However, we acknowledge that our qualitative analysis may involve (re)interpretations and positioning of the researchers involved (De Gregorio, 2009; Harré & Moghaddam, 2003).

Second, our investigation relied on self-reported measures, which do not allow to know if the respondents' answers were consistent with their real behaviors, due to the inherent complexity of human nature. In fact, even though self-reported behavior is one of the most common methods in social research, questionnaires and interviews frequently do not reflect the actual adoption of a behavior but are more subject to a social desirability bias (Gifford & Sussman, 2012). Future research triangulating (MacLeod et al., 2000) indicators of soil quality and direct observations of winegrowers' behavior would be useful to provide further consistent results (Rodrigo-Comino, 2018).

Finally, as previously mentioned in the text, the channels used to recruit participants and conduct the data collection were strongly affected by the COVID-

19 pandemic control measures at the time the research was performed. Even though technology-mediated communication and research may be challenging regarding sampling and engagement (Flayelle et al., 2022; Wright, 2005), the practicality and feasibility of these data collection methods proved to allow to pursue reliable, honest, and high-quality research outputs (Moises jr., 2020).

Despite these limitations and considering the lack of previous studies shedding light on winegrowers' perceptions and behaviors, we strongly believe that our investigation provided a novel contribution to the field of knowledge and laid the foundation for future wider investigations on winegrowers' mindset and decision making for a more sustainable soil management.

CONCLUSIONS

Since soil erosion in vineyards is a common issue especially in several European countries (Rodrigo-Comino, 2018), the present study provided a contribution towards the enhanced knowledge of adoption and effectiveness of best management practices to mitigate erosion in different pedo-climatic conditions in the vine-growing cropping system in Europe, as needed according to Panagos et al. (2024). While the present results provided useful insights, they should be interpreted considering the limited generalizability of the sample, which includes a relatively small number of winegrowers involved in a regional innovation project and may therefore reflect a higher-than-average awareness of sustainability issues. Despite this, our findings highlight several elements that can inform future research and targeted interventions in other viticultural contexts. First, the results suggest that perceived soil degradation is strongly shaped by local pedoclimatic conditions, particularly slope and drier climatic areas, which should be considered when designing soil conservation strategies. Further research should consider conditions of increasingly dry periods and intense rainfall to investigate how water scarcity, by one side, and extreme precipitation resulting in damages, on the other side, shape growers' perceptions, constraints, and decisions. Comparative studies across Mediterranean and Continental wine regions would help clarify the transferability of current findings and identify context-specific solutions for sustainable soil management practices. Despite the recognised role of economic incentives, qualitative analysis' results highlighted that improving information, training, and technical assistance remain essential, especially in areas facing increasing aridity. Winegrowers expressed a clear need for guidance on both traditional and innovative soil management options, to better know their benefits, limits, and correct implementation. Tailored advisory services and participatory approaches may

therefore support more effective and context-specific adoption of sustainable practices.

From a methodological point of view, this study confirmed the usefulness of a mixed-methods approach. The integration of quantitative and qualitative data can reveal results that might not be as clear if only one of the two methods were used: quantitative data provided a snapshot of the current situation, while qualitative insights shed light on the contextual, experiential, and motivational aspects underlying growers' decisions. Broader applications of mixed-method designs in agricultural research may be encouraged, to help design interventions based on more robust research results, to support the transition towards sustainable soil management.

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Declarations:

Data availability: The datasets generated during and analysed during the current study are not publicly available but are available from the corresponding author upon request.

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Competing interests: all authors certify that they have no affiliations with or involvement in any organisation or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Ethics approval: During the project we neither collected any identifying information of individual persons (e.g., name, address, email address, etc.), nor the researchers can link individual responses with participants' identities. Identifying information of research participants was not collected. Thus, ethics approval was not required for this study.

Consent: Informed consent was obtained from all subjects involved in the study.

Authors' contribution statements: All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by F.C., G.C., L.V., G.B., E.C., M.B. Qualitative data analysis was performed by E.D.G. Results validation was performed by F.C., L.V. and M.B. The first draft of the manuscript was written by F.C., L.V., E.D.G., M.B. and all authors commented on previous versions of the manuscript. L.V. reviewed and edited the drafts and F.C., M.B. supervised the work. All authors read and approved the final manuscript. E.C. and M.B. contributed to resources acquisition.

Supplementary materials

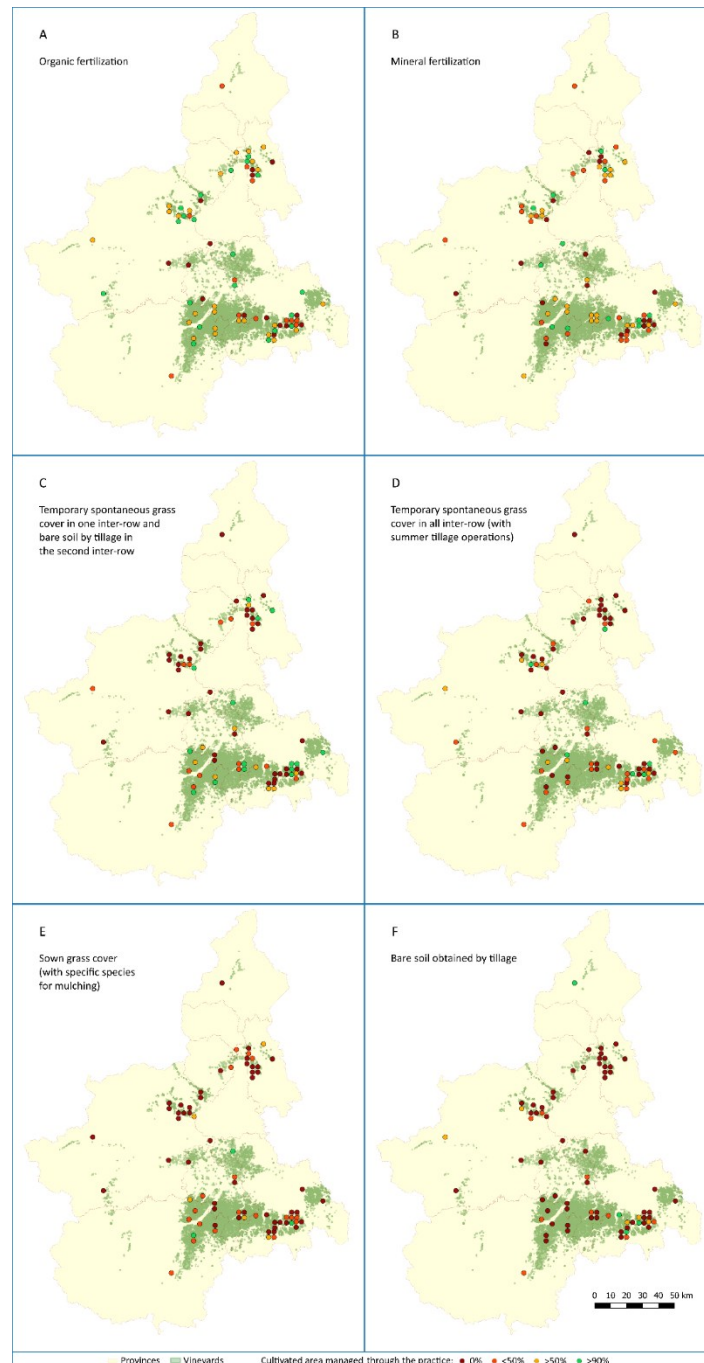


Figure 10 (SM1): Map showing the localization of different soil management practices in the inter-rows, with different colours indicate the percentage of vineyard's area managed through the practice. The green area in the map indicates the distribution of vineyards in the region.

References

- Agenzia Regionale per la Protezione Ambientale Piemonte [ARPA Piemonte] (2024). Portale sul clima in Piemonte. https://webgis.arpa.piemonte.it/secure_apps/portale-sul-clima-in-piemonte/ (accessed on 8 August 2024)
- Ahnström, J., Höckert, J., Bergeå, H.L., Francis, C.A., Skelton, P., & Hallgren, L. (2009). Farmers and nature conservation: What is known about attitudes, context factors and actions affecting conservation?. *Renewable Agriculture and Food Systems*, 24, 38–47. <https://doi.org/10.1017/S1742170508002391>
- Bagagiolo G., Biddoccu M., Rabino D., Cavallo E. 2018. Effects of rows arrangement, soil management, and rainfall characteristics on water and soil losses in Italian sloping vineyards. *Environmental Research*, 166, 690-704. <https://doi.org/10.1016/j.envres.2018.06.048>
- Biddoccu, M., Ferraris, S., Opsi, F., & Cavallo, E. (2016). Long-term monitoring of soil management effects on runoff and soil erosion in sloping vineyards in Alto Monferrato (North–West Italy). *Soil and Tillage Research*, 155, 176-189. <https://doi.org/10.1016/j.still.2015.07.005>
- Biddoccu, M., Pittarello, M., Capello, G., Moretti, B., Matranga, G., Chiriack, O.P., & Zavattaro, L. (2025). Vegetation management in vineyard's inter-row as a strategy to improve soil health: direct observations, evaluation and recommendations. *Proceedings of the 54th Conference of the Italian Society of Agronomy* (Bindi M., Di Miceli G., Maggio A., Eds.), Torino, Italy, 18th-19th September 2025, pag.13-14.
- Alico, J., & Guimba, W. (2015). Level and causes of pre-university students' English test anxiety: a case study on Mindanao State University. *Researchers World-Journal of Arts, Science & Commerce*, 3 (1), 1-10.
- Ajzen, I. (1991). The theory of planned behavior. *Organizational behavior and human decision processes*, 50(2), 179-211. [https://doi.org/10.1016/0749-5978\(91\)90020-T](https://doi.org/10.1016/0749-5978(91)90020-T)
- Bavorova, M., Ponkina, E. V., Imamverdiyev, N., & Hirschauer, N. (2020). Effect of adoption of sustainable crop production systems on farm economics. *Environment, Development and Sustainability*, 22, 6961-6984. <https://doi.org/10.1007/s10668-019-00522-1>
- Bazeley, P. (2018). *Integrating analyses in mixed methods research*. SAGE, London, <https://dx.doi.org/10.4135/9781526417190>
- Bechini, L., Costamagna, C., Zavattaro, L., Grignani, C., Bijttebier, J., & Ruyschaert, G. (2020). Drivers and barriers to adopt best management practices. Survey among Italian

dairy farmers. *Journal of Cleaner Production*, 245, 118825. <https://doi.org/10.1016/j.jclepro.2019.118825>

Bergman, M. (2008). *Advances in Mixed Methods Research*, London, Sage, 2008. Borrelli, P., Diodato, N., & Panagos, P. (2016). Rainfall erosivity in Italy: a national scale spatio-temporal assessment. *International Journal of Digital Earth*, 9(9), 835-850. <https://doi.org/10.1080/17538947.2016.1148203>

Braun, V. & Clarke, V. (2013), *Successful Qualitative Research: A Practical Guide for Beginners*. Sage: Thousand Oaks, CA.

Braun, V. & Clarke, V. (2019), Reflecting on reflexive thematic analysis. *Qualitative Research in Sport Exercise Health*, 11, 589-597. <https://doi.org/10.1080/2159676X.2019.1628806>.

Braun, V. & Clarke, V. (2021), Can I use TA? Should I use TA? Should I not use TA? Comparing reflexive thematic analysis and other pattern-based qualitative analytic approaches. *Counselling and Psychotherapy Research*, 21 (1) 37-47. <https://doi.org/10.1002/capr.12360>

Caffaro, F., Bagagiolo, G., Micheletti Cremasco, M., & Cavallo, E. (2017). Participatory ergonomic design of a safety training tool for migrant workers in agriculture. *Chemical Engineering Transactions*, 58, 25-30. <https://dx.doi.org/10.3303/CET1758005>

Caffaro, F., Micheletti Cremasco, M., Roccato, M., & Cavallo, E. (2020). Drivers of farmers' intention to adopt technological innovations in Italy: The role of information sources, perceived usefulness, and perceived ease of use. *Journal of Rural Studies*, 76, 264-271. <https://doi.org/10.1016/j.jrurstud.2020.04.028>

Capello, G., Biddoccu, M., Ferraris, S., & Cavallo, E. (2019). Effects of tractor passes on hydrological and soil erosion processes in tilled and grassed vineyards. *Water*, 11(10), 2118. <https://doi.org/10.3390/w11102118>

Capello, G., Biddoccu, M., & Cavallo, E. (2020). Permanent cover for soil and water conservation in mechanized vineyards: A study case in Piedmont, NW Italy. *Italian Journal of Agronomy*, 15(4), 323-331. <https://doi.org/10.4081/ija.2020.1763>

Capello, G., Biddoccu, M., Palazzi, F., Allemanno, L., Maggi, F., Tasca, M., Ferrarese, D., Tornato, D., Manunta, A., Bussotti, S., & Paravidino, E. (2024). The IN-GEST SOIL Project: results of the introduction of good practices for soil management in piedmont vineyards, EGU General Assembly 2024, Vienna, Austria, 14-19 Apr 2024, EGU24-13581, <https://doi.org/10.5194/egusphere-egu24-13581>.

Caracciolo, F., Cembalo, L., & Pomarici, E. (2013). The hedonic price for an Italian grape variety. *Italian Journal of Food Science*, 25(3), 289.

Carmona, I., Griffith, D.M., Soriano, M.A., Murillo, J.M., Madejón, E., & Gómez-Macpherson, H. (2015). What do farmers mean when they say they practice conservation agriculture? A comprehensive case study from southern Spain. *Agriculture, ecosystems & environment*, 213, 164-177. <http://dx.doi.org/10.1016/j.agee.2015.07.028>

Cataldo, E., Salvi, L., Sbraci, S., Storch, P., & Mattii, G. B. (2020). Sustainable viticulture: Effects of soil management in *Vitis vinifera*. *Agronomy*, 10(12), 1949. <https://doi.org/10.3390/agronomy10121949>

Cerdà, A., & Rodrigo-Comino, J. (2021). Regional farmers' perception and societal issues in vineyards affected by high erosion rates. *Land*, 10(2), 1-18. <https://doi.org/10.3390/land10020205>

Cerdan O, Govers G, Le Bissonnais Y, et al. (2010). Rates and spatial variations of soil erosion in Europe: a study based on erosion plot data. *Geomorphology*. 122, 167-177. <https://doi.org/10.1016/j.geomorph.2010.06.011>

Chen, Y., Herrera, R. A., Benitez, E., Hoffmann, C., Möth, S., Paredes, D., ... & Schwarz, N. (2022). Winegrowers' decision-making: A pan-European perspective on pesticide use and inter-row management. *Journal of Rural Studies*, 94, 37-53. <https://doi.org/10.1016/j.jrurstud.2022.05.021>

Corti, G., Cavallo, E., Cocco, S., Biddoccu, M., Brecciaroli, G., & Agnelli, A. (2011). Evaluation of Erosion Intensity and Some of Its Consequences in Vineyards from Two Hilly Environments Under a Mediterranean Type of Climate, Italy. In D. Godone & S. Stanchi (Eds), *Soil Erosion Issues in Agriculture*. InTech. <http://dx.doi.org/10.5772/25130>

Costantini, E.A.C., L'Abate, G., Barbetti, R., Fantappiè, M., Lorenzetti, R., & Magini, S. (2012). Soil Map of Italy. Consiglio per la Ricerca e la Sperimentazione in Agricoltura (CRA), Ministero delle Politiche Agricole Alimentari e Forestali. Retrieved from <https://esdac.jrc.ec.europa.eu/content/carta-dei-suoli-ditalia-soil-map-italy> (accessed on 2 November 2025).

Council Regulation (EU) No 1370/2013 of 16 December 2013 determining measures on fixing certain aids and refunds related to the common organisation of the markets in agricultural products 2013. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32013R1370> (accessed on 19 June 2024).

Cronbach L. (1951). Coefficient alpha and the internal structure of tests. *Psychometrika*. 16(3), 297-334. <https://doi.org/10.1007/BF02310555>

D'amico, M., Di Vita, G., & Monaco, L. (2016). Exploring environmental consciousness and consumer preferences for organic wines without sulfites. *Journal of Cleaner Production*, 120, 64-71. <https://doi.org/10.1016/j.jclepro.2016.02.014>

Daud, K. A. M., Khidzir, N. Z., Ismail, A. R., & Abdullah, F. A. (2018). Validity and reliability of instrument to measure social media skills among small and medium entrepreneurs at Pengkalan Datu River. *International Journal of Development and sustainability*, 7(3), 1026-1037.

Demartini, E., Gaviglio, A., & Pirani, A. (2017). Farmers motivation and perceived effects of participating in short food supply chains: Evidence from a North Italian survey. *ZEMEDELSKA EKONOMIKA*, 63(5), 204-216. <https://dx.doi.org/10.17221/323/2015-AGRICECON>

Daniels, N., Gillen, P., Casson, K., & Wilson, I. (2019). STEER: Factors to Consider When Designing Online Focus Groups Using Audiovisual Technology in Health Research. *International Journal of Qualitative Methods*, 18 <https://doi.org/10.1177/1609406919885786>

De Gregorio, E. (2009), Narrating a crime: Contexts and accounts of deviant actions. *International Journal of Multiple Research Approaches*, 3, 177–190. <https://doi.org/10.5172/mra.3.2.177>. 31

Diyyala, R., Wang, Q.J., Mushtaq, S., Palanichamy, N. V., Murugananthi, D., Geethalakshmi, V., & Rajavel, M. (2025). Risk attitude and risk perceptions of climate change among Indian cotton farmers. *Scientific Reports*, 15(1), 19550.

European Commission (n,d). Key policy objectives of the CAP 2023-27. https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/cap-2023-27/key-policy-objectives-cap-2023-27_en (accessed on 19 June 2024).

Fantappiè, M., Lorenzetti, R., De Meo, I., & Costantini, E. A. (2020). How to improve the adoption of soil conservation practices? Suggestions from farmers' perception in western Sicily. *Journal of Rural Studies*, 73, 186-202. <https://doi.org/10.1016/j.jrurstud.2019.11.001>

Flayelle, M., Brevers, D., Billieux, J. (2022). The advantages and downsides of online focus groups for conducting research on addictive online behaviours. *Addiction*. 117(8), 2142-2144. <https://doi.org/10.1111/add.15944>.

Food and Agriculture Organization [FAO]. (2020). Global Symposium on Soil Erosion. Food and Agricultural Organization of the United Nations (FAO).

Food and Agriculture Organization [FAO]. (2015). Status of the World's Soil Resources (Main Report); FAO: Rome, Italy, 2015; p. 608. <https://www.fao.org/3/i5199e/i5199e.pdf>

García-Cortijo, M.C., Castillo-Valero, J.S., & Carrasco, I. (2019). Innovation in rural Spain. What drives innovation in the rural-peripheral areas of southern Europe? *Journal of Rural Studies*, 71, 114–124. <https://doi.org/10.1016/j.jrurstud.2019.02.027>.

Garini, C.S., Vanwindekens, F., Scholberg, J.M.S., Wezel, A., & Groot, J.C.J. (2017). Drivers of adoption of agroecological practices for winegrowers and influence from policies in the province of Trento, Italy. *Land Use Policy*, 68, 200–211. <https://doi.org/10.1016/j.landusepol.2017.07.048>

Giffard, B., Winter, S., Guidoni, S., Nicolai, A., Castaldini, M., Cluzeau, D., ... & Leyer, I. (2022). Vineyard management and its impacts on soil biodiversity, functions, and ecosystem services. *Frontiers in Ecology and Evolution*, 10, 850272. <https://doi.org/10.3389/fevo.2022.850272>

Gifford, R., & Sussman, R. (2012). “Environmental attitudes,” in *The Oxford Handbook of Environmental and Conservation Psychology*, ed S. Clayton (New York, NY: Oxford University Press), 65–80. <https://doi.org/10.1093/oxfordhb/9780199733026.013.0004>

Gómez, J.A., Montero, A.S., Guzmán, G., & Soriano, M.A. (2021). In-depth analysis of soil management and farmers' perceptions of related risks in two olive grove areas in southern Spain. *International Soil and Water Conservation Research* 9, 461–73.

Grønkjær, M., Curtis, T., De Crespigny, C., & Delmar, C. (2011). Analysing group interaction in focus group research: Impact on content and the role of the moderator. *Qualitative studies*, 2(1), 16-30. <https://doi.org/10.7146/qs.v2i1.4273>

Groth, C. (2007). A New-Growth Perspective on Non-Renewable Resources. In: Bretschger, L., Smulders, S. (eds) *Sustainable Resource Use and Economic Dynamics. The Economics of Non-Market Goods and Resources*, 10. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-6293-3_7

Guo, R., Li, Y., Shang, L., Feng, C., & Wang, X. (2021). Local farmer's perception and adaptive behavior toward climate change. *Journal of Cleaner Production*, 287, 125332. <https://doi.org/10.1016/j.jclepro.2020.125332>

Guzmán, G., Portero, Á., Vanwallenghem, T., Laguna, A., Vanderlinden, K., Giráldez, J. V., ... & ten Berge, H. (2015, April). Adoption and farmer perception of best management practices in Southern Spain. In *EGU General Assembly Conference Abstracts* (p. 465).

Hamza, M.A., & Anderson, W.K. (2005). Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil and tillage research*, 82(2), 121-145. <https://doi.org/10.1016/j.still.2004.08.009>

Harré, R., & Moghaddam, F.M. (2003), *The Self and Others. Positioning Individuals and Groups in Personal, Political, and Cultural Contexts*. Praeger: West Port.

Hontoria, C., Gómez-Paccard, C., Vázquez, E., Mariscal-Sancho, I., Ordóñez-Fernández, R., Carbonell-Bojollo, R., & Espejo, R. (2018). Mid-long term effects of no tillage and Ca-amendment on degraded acid soils under contrasting weather conditions. *Soil and Tillage Research*, 183, 83-92. <https://doi.org/10.1016/j.still.2018.06.002>

Igor, B., Leon Josip, T., & Paulo, P. (2020). Agriculture management impacts on soil properties and hydrological response in Istria (Croatia). *Agronomy*, 10(2), 282. <https://doi.org/10.3390/agronomy10020282>

Istituto Nazionale di Statistica [ISTAT], 2024. Istat Data La banca dati dell'Istituto Nazionale di Statistica. <https://esploradati.istat.it/databrowser/#/it/dw>

Klößner, C.A., & Blöbaum, A. (2010). A comprehensive action determination model: Toward a broader understanding of ecological behaviour using the example of travel mode choice. *Journal of Environmental Psychology*, 30(4), 574-586. <https://doi.org/10.1016/j.jenvp.2010.03.001>

Leturcq, S. (2020). *Le terroir, un concept anhistorique*. Jean-Louis Yengué; Kilien Stengel. *Le terroir viticole. Espace et figures de la qualité*, Presses universitaires François-Rabelais, (pp.23-31) HAL Id: hal-02878504

MacLeod, I.S., Wells, L., & Lane, K. (2000). The practice of triangulation. In P. T. McCabe, M. A. Hanson, & S. A. Robertson (Eds.), *Contemporary ergonomics 2000* (pp. 244-248). London: Taylor & Francis.

Mairura, F.S., Musafiri, C.M., Kiboi, M.N., Macharia, J.M., Ng'etich, O.K., Shisanya, C.A., ... & Ngetich, F.K. (2021). Determinants of farmers' perceptions of climate variability, mitigation, and adaptation strategies in the central highlands of Kenya. *Weather and Climate Extremes*, 34, 100374.

Makate, C., Makate, M., & Mango, N. (2017). Smallholder farmers' perceptions on climate change and the use of sustainable agricultural practices in the Chinyanja Triangle, Southern Africa. *Social Sciences*, 6(1), 30.

Mamun, A.A., Roy, S., Islam, A.R.M., Alam, G.M., Alam, E., Chandra Pal, S., ... & Mallick, J. (2021). Smallholder Farmers' Perceived Climate-Related Risk, Impact, and

Their Choices of Sustainable Adaptation Strategies. *Sustainability*, 13(21), 11922. <https://doi.org/10.3390/su132111922>

Marques, M.J., Bienes, R., Cuadrado, J., Ruiz-Colmenero, M., Barbero-Sierra, C., & Velasco, A. (2015). Analysing perceptions attitudes and responses of winegrowers about sustainable land management in Central Spain. *Land Degradation & Development*, 26(5), 458-467. <https://doi.org/10.1002/ldr.2355>

Márquez-García, M., Jacobson, S. K., & Barbosa, O. (2019). Wine with a bouquet of biodiversity: assessing agricultural adoption of conservation practices in Chile. *Environmental Conservation*, 46(1), 34-42. <https://doi.org/10.1017/S0376892918000206>

Martínez-Casasnovas, J. A., Ramos, M. C., & Ribes-Dasi, M. (2005). On-site effects of concentrated flow erosion in vineyard fields: some economic implications. *Catena*, 60(2), 129-146. <https://doi.org/10.1016/j.catena.2004.11.006>

Martínez-Casasnovas, J. A., & Ramos, M. C. (2006). The cost of soil erosion in vineyard fields in the Penedès–Anoia Region (NE Spain). *Catena*, 68(2-3), 194-199. <https://doi.org/10.1016/j.catena.2006.04.007>

MASAF, Direzione Generale Dello Sviluppo Rurale (2023). LINEE GUIDA NAZIONALI DI PRODUZIONE INTEGRATA 2024 Per la redazione dei disciplinari regionali/sezione tecniche agronomiche di cui al punto 10.2.1 del documento: SQNPI – Adesione, Gestione, Controllo/2024. <https://www.reterurale.it/flex/cm/pages/ServeAttachment.php/L/IT/D/e%252F2%252F1%252FD.5cd340ef74db30f523a3/P/BLOB%3AID%3D25555/E/pdf>

Mirás-Avalos, J.M., & Araujo, E.S. (2021). Optimization of vineyard water management: Challenges, strategies, and perspectives. *Water*, 13(6), 746. <https://doi.org/10.3390/w13060746>

Moises Jr, C. (2020). Online data collection as adaptation in conducting quantitative and qualitative research during the COVID-19 pandemic. *European Journal of Education Studies*, 7(11). <http://dx.doi.org/10.46827/ejes.v7i11.3336>

Novara, A., Cerdà, A., Gristina, L. (2018). Sustainable vineyard floor management: An equilibrium between water consumption and soil conservation. *Current Opinion in Environmental Science & Health*, 5, 33-37. <https://doi.org/10.1016/j.coesh.2018.04.005>

Organisation Internationale de la Vigne et du Vin [OIV]. (2010). Definition of vitivinicultural "terroir". <https://www.oiv.int/node/3362> (accessed on 19 August 2024)

Organisation Internationale de la Vigne et du Vin [OIV]. (2021a). State of the vitiviniculture world market 2021. <https://www.oiv.int/en/technical-standards-and-documents/statistical-analysis/state-of-vitiviniculture> (accessed on 17 November 2023).

Organisation Internationale de la Vigne et du Vin [OIV]. (2021b). Annual Assessment of the World Vine and Wine Sector in 2021. https://www.oiv.int/sites/default/files/documents/OIV_Annual_Assessment_of_the_World_Vine_and_Wine_Sector_in_2021.pdf (accessed on 17 November 2023).

Organisation Internationale de la Vigne et du Vin (OIV). (April, 2023). State of the World Vitiviniculture Sector in 2022 –April 2023. https://www.oiv.int/sites/default/files/documents/OIV_State_of_the_world_Vine_and_Wine_sector_in_2022_2.pdf

Organisation Internationale de la Vigne et du Vin [OIV]. (2024). 12 months, 12 resolutions: the definition of Terroir. <https://www.oiv.int/press/12-months-12-resolutions-definition-terroir> (accessed on 19 August 2024)

Panagos, P., Ballabio, C., Borrelli, P., Meusburger, K., Klik, A., Rousseva, S., ... & Alewell, C. (2015a). Rainfall erosivity in Europe. *Science of the Total Environment*, 511, 801-814. <https://doi.org/10.1016/j.scitotenv.2015.01.008>

Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L., & Alewell, C. (2015b). The new assessment of soil loss by water erosion in Europe. *Environmental Science & Policy*, 54, 438-447. <https://doi.org/10.1016/j.envsci.2015.08.012>

Panagos, P., Ballabio, C., Himics, M., Scarpa, S., Matthews, F., Bogonos, M., Poesen, J., & Borrelli, P. (2021). Projections of soil loss by water erosion in Europe by 2050. *Environmental Science & Policy*, 124, 380–392. <https://doi.org/10.1016/j.envsci.2021.07.012>

Panagos, P., Vieira, D., Eekhout, J.P.C., Biddoccu, M., Cerdà, A., Evans, D.L., ... & Borrelli, P. (2024). How the EU Soil Observatory contributes to a stronger soil erosion community, *Environmental Research*, 248, 118319, <https://doi.org/10.1016/j.envres.2024.118319>

Pierpaoli, E., Carli, G., Pignatti, E., & Canavari, M. (2013). Drivers of precision agriculture technologies adoption: a literature review. *Procedia Technology*, 8, 61-69. <https://doi.org/10.1016/j.protcy.2013.11.010>

Prosdocimi, M., Cerdà, A., & Tarolli P. (2016). Soil water erosion on Mediterranean vineyards: A review. *Catena* 141, 1–21. <https://doi.org/10.1016/j.catena.2016.02.010>

Prosser, A. M., Heung, L. N., Blackwood, L., O'Neill, S., Bolderdijk, J. W., & Kurz, T. (2024). 'Talk amongst yourselves': designing and evaluating a novel remotely-moderated focus group methodology for exploring group talk. *Qualitative Research in Psychology*, 21(1), 1-43. <https://doi.org/10.1080/14780887.2023.2257614>

Regione Piemonte (2023). Geoportale. Carta dell'erosione reale 1:250.000. https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/r_piemon:286c8488-9390-4683-a515-22bc7dfd0774/formatters/xsl-view?root=div&view=advanced&approved=true (accessed on 19 June 2024).

Regione Piemonte (2024a). Vini a Denominazione di origine, DOCG e DOC, <https://www.regione.piemonte.it/web/temi/agricoltura/viticultura-enologia/vini-denominazione-origine-docg-doc> (accessed on 19 June 2024).

Regione Piemonte. (2024b). Vitigni su mosaicatura catastale di riferimento regionale 2023, https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/r_piemon:95aed80b-69d3-452a-9635-bae4f498227b (Accessed on: 20 June 2024).

Regione Piemonte (2024c). Disciplinari di produzione integrata 2024, <https://www.regione.piemonte.it/web/temi/agricoltura/servizi-fitosanitari-pan/disciplinari-produzione-integrata-2024> (accessed on 19 August 2024).

Regione Piemonte (2024d). Mappa delle classi di pendenza del territorio piemontese, https://www.geoportale.piemonte.it/geonetwork/srv/api/records/aripa_to:12.02.25-D_2024-11-19-15:40 (accessed on 23 November 2025).

Rodrigo-Comino, J. (2018). Five decades of soil erosion research in "terroir". *The State-of-the-Art. Earth-Science Reviews*, 179, 436-447. <https://doi.org/10.1016/j.earscirev.2018.02.014>

Rubel, F., Brugger, K., Haslinger, K., & Auer, I. (2017). The climate of the European Alps: Shift of very high resolution Köppen-Geiger climate zones 1800-2100. *Meteorologische Zeitschrift*, 26(2), 115-125. <https://doi.org/10.1127/metz/2016/0816>

Ruiz-Colmenero, M., Bienes, R., & Marques, M.J. (2011). Soil and water conservation dilemmas associated with the use of green cover in steep vineyards. *Soil and Tillage Research*, 117, 211-223. <https://doi.org/10.1016/j.still.2011.10.004>

Sapbamrer, R., & Thammachai, A. (2021). A systematic review of factors influencing farmers' adoption of organic farming. *Sustainability*, 13(7), 3842. <https://doi.org/10.3390/su13073842>

Schütte R., & Bergmann H. (2019) The attitudes of French and Spanish winegrowers towards the use of cover crops in vineyards, *Journal of Wine Research*, 30:2, 107-121, <https://doi.org/10.1080/09571264.2019.1568975>

Shakesby, R.A. (2011). Post-wildfire soil erosion in the Mediterranean: Review and future research directions. *Earth-Science Reviews*, 105(3-4), 71-100. <https://doi.org/10.1016/j.earscirev.2011.01.001>

Siepmann, L., & Nicholas, K. A. (2018). German winegrowers' motives and barriers to convert to organic farming. *Sustainability*, 10(11), 4215.

Tashakkori, A., & Teddlie, C. (2010). *SAGE handbook of mixed methods in social & behavioral research*. SAGE, Thousand Oaks. <https://dx.doi.org/10.4135/9781506335193>

Tovar-Aguilar, J.A., Monaghan, P.F., Bryant, C.A., Esposito, A., Wade, M., Ruiz, O., & McDermott, R.J. (2014). Improving eye safety in citrus harvest crews through the acceptance of personal protective equipment, community-based participatory research, social marketing, and community health workers. *Journal of Agromedicine*, 19(2), 107-116. <https://doi.org/10.1080/1059924X.2014.884397>

Uddin, M.N., Bokelmann, W., & Dunn, E. S. (2017). Determinants of farmers' perception of climate change: a case study from the coastal region of Bangladesh. *American Journal of Climate Change*, 6(1), 151-165.

United Nations Environment Programme [UNEP]. (2017) Land degradation – factsheet. <https://www.unep.org/resources/factsheet/land-degradation-factsheet> (accessed on 19 June 2024).

United Nations Educational, Scientific and Cultural Organization [UNESCO]. (n.a). *Vineyard Landscape of Piedmont: Langhe-Roero and Monferrato* Available online: <http://whc.unesco.org/en/list/1390> (accessed on 19 November 2023).

Wheeler, S.A., 2008. What influences agricultural professionals' views towards organic agriculture? *Ecological Economics*, 65 (1), 145–154. <https://doi.org/10.1016/j.ecolecon.2007.05.014>

Wischmeier, W. H., & Smith, D. D. (1978). Predicting rainfall erosion losses: a guide to conservation planning (No. 537). USDA, Department of Agriculture, Science and Education Administration.

Wright, K.B. (2005). Researching Internet-based populations: Advantages and disadvantages of online survey research, online questionnaire authoring software packages, and web survey services. *Journal of Computer-mediated Communication*, 10(3), JCMC1034. <https://doi.org/10.1111/j.1083-6101.2005.tb00259.x>

2.3 Geological, pedological and climatic characterization of the vineyards under study

In order to evaluate the effective applicability and effectiveness of some enhanced and innovative soil management practices, which allow limiting erosion and preserving its functionality, field tests were set up in five vineyards (three of commercial farms and two demonstration sites):

Capriata d'Orba (AL) – Cascina Gentile

Novi Ligure (AL) – Cascina Binè

Rocchetta Ligure (AL) – Cascina Nebraie

Carpeneto (AL) - AGRION (Parcelle sperimentali Tenuta Cannona)

San Damiano D'Asti (AT) – Torchio, then replaced with Rocchetta Tanaro (AT) – Porzio

In each vineyard, two theses with different soil management have been defined: two plot of at least six contiguous rows were chosen and prepared to be conducted one with usual management of the vineyard, and the other one with enhanced practices. The soil management practices to be adopted were identified based on the results of the questionnaires and focus groups survey. Then were concerned in collaboration with the winegrowers, and adapted to the specific situation of each vineyard. First surveys were carried out in every thesis, aimed at the initial characterization of the vineyard parcels affected by the project, through physic-chemical analyses on soil samples.

A geological, pedological, and climatic characterization of the vineyard under study was carried out using regional databases, complemented by targeted field surveys. The paper “Methodological Framework for Characterizing Vineyards Subjected to Soil Degradation in Piedmont” (DOI: <https://doi.org/10.19199/2024.172-173.1121-9041.012>) is reported in the following section in its published version (Version of Record), originally published open access in *Geingegneria Ambientale e Mineraria* in the latest issue of the 2024 journal. The content of the paper is reported unchanged, with formatting adapted to the style of this thesis.

The study provides a baseline characterization of the investigated vineyards by integrating climatic, geological, and pedological information with initial field surveys, and is intended to support the selection and site-specific adaptation of soil and vineyard management practices. Consequently, no inferential hypothesis testing is undertaken. Instead, the results establish the physical context and boundary conditions against which subsequent monitoring activities and comparative analyses (focused on runoff and erosion, soil physical properties, ground cover, and soil moisture dynamics) are interpreted in Chapters 2.4–2.6.

2.3.1 Methodological framework for characterizing vineyards subjected to soil degradation in Piedmont

Giorgio Capello^{1,2}, Stefano Ferraris², Marcella Biddoccu¹

1 Interuniversity Department of Regional and Urban Studies and Planning (DIST), Politecnico di Torino and Università di Torino; 2 Institute of Sciences and Technologies for Sustainable Energy and Mobility (STEMS) of the National Research Council of Italy (CNR).

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Abstract

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.

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 litres 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; Figure 11).

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 behaviours 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)

Materials and Methods

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 (Figure 11). 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).

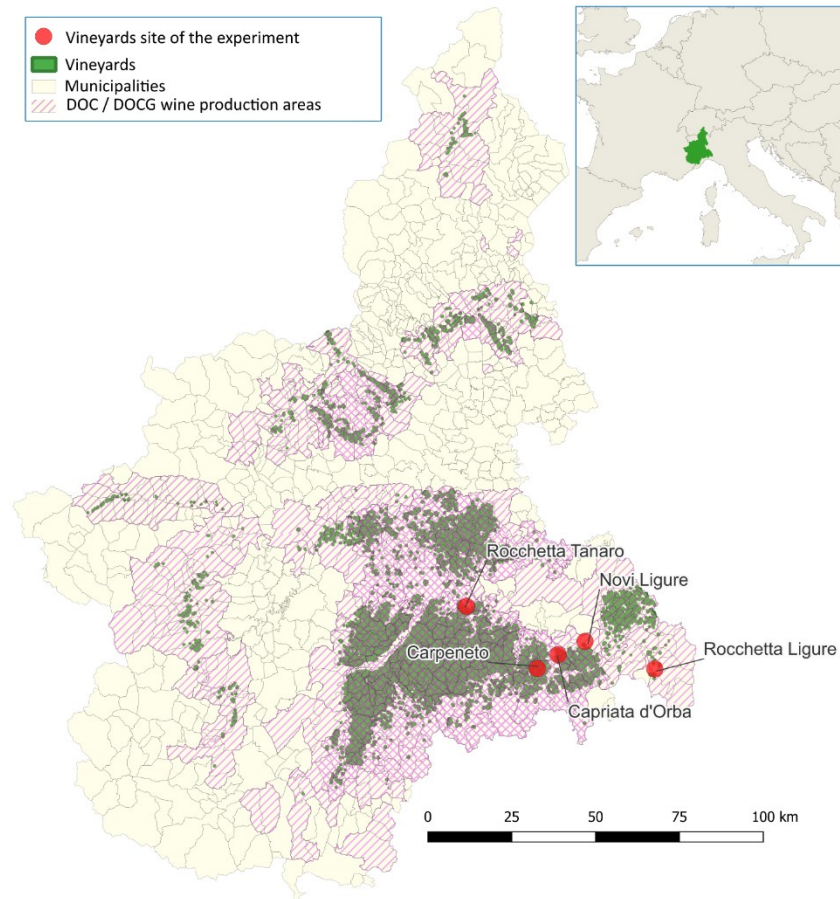


Figure 11: The map depicts the Piedmont region. Municipalities included in one or more DOC and/or DOCG wine production areas (Regione Piemonte, 2024b) are marked with purple hatching and cross-hatching. Vineyard parcels, based on the regional cadastral mosaic (Regione Piemonte, 2024f), are highlighted in green. The selected vineyards under study are indicated with red dots.

The 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).

The vineyards selected as the study area for the In-Gest Soil project (Figure 11) 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.

Vineyards Management

Table 8 provides key information about the five vineyards selected as test areas for the IN-GEST SOIL project; Figure 11 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 (Figure 12, 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.



Figure 12: 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.

At the Capriata site (Figure 12, 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 (Figure 12, 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 (Figure 12, 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 (Figure 12, 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.



Figure 13: Schematic overview of all the data sources and references used in this study

Investigation

A thorough investigation was conducted using national and regional public databases to classify each vineyard based on climatic, geological, and pedological characteristics. Figure 13 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 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 ($V = 100 \text{ cm}^3$) 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 (SWC_{fc}) and wilting point (SWC_{wp}) 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).

Table 8: 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 [m²]	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

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 (Table 9). 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, while 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).

Table 9: 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 1mm)	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

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 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).



Figure 14: 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.

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 (Figure 14, A). 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 (Figure 14, B). 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, 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 15, 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).

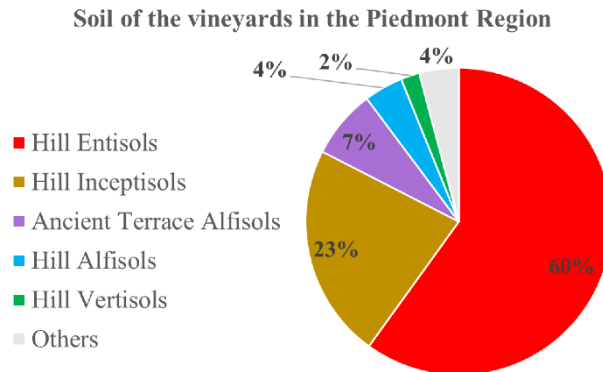


Figure 15: The graph illustrates the soil distribution of Piedmont vineyards. It has been elaborated by overlaying the soil map (Regione Piemonte, 2023b) and the vineyards on the regional cadastral mosaic (Regione Piemonte, 2024f).

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 (Figure 16) 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.

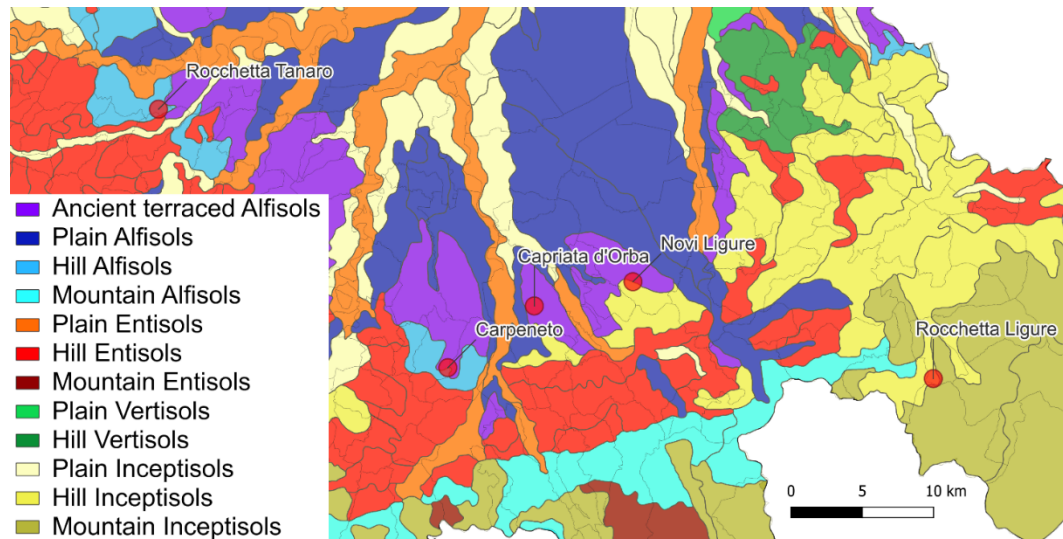


Figure 16: Soil map of the Alto Monferrato region (Regione Piemonte, 2023b). The positions of the selected vineyards under study are indicated with red dots.

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 $3 \text{ t ha}^{-1} \text{ year}^{-1}$. Vineyards in Novi Ligure fall into an intermediate erosion class, with rates ranging from 3 to $15 \text{ t ha}^{-1} \text{ year}^{-1}$. Meanwhile, Carpeneto and Rocchetta Ligure are categorized under high erosion, with rates exceeding $15 \text{ t ha}^{-1} \text{ year}^{-1}$ and $35 \text{ t ha}^{-1} \text{ year}^{-1}$, 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 al. (2020) identified that erosion rates in European vineyards vary considerably based on climate, soil, topography, and adopted soil management practices.

The table 10 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 Capriata d'Orba has a clay loam soil with the lowest sand and 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 (SWC_{fc}) and wilting point (SWC_{wp}) 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 is evident, with Capriata d'Orba showing the highest SWC_{fc} and SWC_{wp} values. Rocchetta Tanaro has the lowest SWC_{fc} and SWC_{wp} values, with 0.224 and 0.086 m³ m⁻³ at 0.0-0.2 m in undisturbed soil, respectively, and 0.212 and 0.080 m³ m⁻³ in disturbed soil. These differences likely reflect variations in soil composition, agricultural management practices, and local environmental conditions.

Table 10: 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

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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Reference list

Abad, J., Hermoso de Mendoza, I., Marín, D., Orcaray, L., & Santesteban, L. G. (2021). Cover crops in viticulture. A systematic review (1): Implications on soil characteristics and biodiversity in vineyard. *OENO One*, 55(1). <https://doi.org/10.20870/oeno-one.2021.55.1.3599>

Agenzia Regionale per la Protezione Ambientale [ARPA] Piemonte. (2024). Portale sul clima in Piemonte. Retrieved from https://webgis.arpa.piemonte.it/secure_apps/portale-sul-clima-in-piemonte/. Accessed on: 8 agosto 2024

Arpa Piemonte, CNR IGG. (2021). Carta geologica, GeoPiemonte Map. https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/arlp_a_to:07-11-00-D_2017-05-22-12:00 Accessed on: 20 June 2024

Arpa Piemonte. (2011a). BDGeo100 – Litologia. Retrieved from https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/arlp_a_to:07.02.06-D_2011-06-27:15:23 Accessed on: 20 June 2024

Arpa Piemonte. (2011b). Carta Litologico Giacimentologica. Retrieved from https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/arlp_a_to:07.02.05-D_2011-06-27:15:23 Accessed on: 20 June 2024

Arpa Piemonte. (2011c) Banca Dati Geotecnica - Sondaggi geognostici, campioni di terreno e indagini geofisiche. Retrieved from https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/arlp_a_to:07-01-01-D_2011-06-01-13:40 Accessed on: 20 June 2024

Arpa Piemonte. (2013a). BDGeo100 - Aree instabili. Retrieved from https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/arlp_a_to:07-04-01_ai-D_2013-11-20:09:30 Accessed on: 20 June 2024

Arpa Piemonte. (2013b). BDGeo100 – Frane. Retrieved from https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/arlp_a_to:07-04-01_f-D_2013-11-20:11.35 Accessed on: 20 June 2024

Bagnouls, F., & Gaussen, H. (1957). Les climats biologiques et leur classification. *Annales de Géographie*, 355, 193-220.

Baldi, E. (2021). Soil–plant interaction: Effects on plant growth and soil biodiversity. *Agronomy*, 11, 2378. <https://doi.org/10.3390/agronomy11122378>

Biancotti, A., Bellardone, G., Bovo, S., Cagnazzi, B., Giacomelli, L., & Marchisio, C. (1998). Distribuzione regionale di piogge e temperature. *Collana Studi Climatologici del Piemonte*, vol. 1. Regione Piemonte, Torino, Italy.

Biddoccu, M., Ferraris, S., Opsi, F., & Cavallo, E. (2016). Long-term monitoring of soil management effects on runoff and soil erosion in sloping vineyards in Alto Monferrato (North–West Italy). *Soil and Tillage Research*, 155, 176-189. <https://doi.org/10.1016/j.still.2015.07.005>

Biddoccu, M., Guzmán, G., Capello, G., Thielke, T., Strauss, P., Winter, S., Zaller, J. G., Nicolai, A., Cluzeau, D., Popescu, D., Bunea, C., Hoble, A., Cavallo, E., & Gómez, J. A. (2020). Evaluation of soil erosion risk and identification of soil cover and management factor © for RUSLE in European vineyards with different soil management. *International*

Soil and Water Conservation Research, 8, 337–353.
<https://doi.org/10.1016/j.iswcr.2020.07.003>

Caffaro, F., De Gregorio, E., Capello, G., Vigoroso, L., Bagagiolo, G., Cavallo, E., & Biddoccu, M. (2024). Winegrowers' Perceptions and Adoption of Sustainable Soil Management Practices and Technologies: A Case Study in Piedmont, Italy. *Land Degradation & Development*. In review.

Capello, G., Biddoccu, M., & Cavallo, E. (2020). Permanent cover for soil and water conservation in mechanized vineyards: A study case in Piedmont, NW Italy. *Italian Journal of Agronomy*, 15, 323–331. <https://doi.org/10.4081/ija.2020.323-331>.

Cárceles Rodríguez, B., Durán Zuazo, V. H., Soriano Rodríguez, M., Gálvez Ruiz, B., & García-Tejero, I. F. (2021). Soil erosion and the efficiency of the conservation measures in Mediterranean hillslope farming (SE Spain). *Eurasian Soil Science*, 54, 792–806. <https://doi.org/10.1134/S1064229321050069>

Cataldo, E., Salvi, L., Sbraci, S., Storch, P., & Matti, G. B. (2020). Sustainable viticulture: Effects of soil management in *Vitis vinifera*. *Agronomy*, 10, 1949. <https://doi.org/10.3390/agronomy10121949>

Cerdà, A., & Rodrigo-Comino, J. (2021). Regional farmers' perception and societal issues in vineyards affected by high erosion rates. *Land*, 10, 205. <https://doi.org/10.3390/land10020205>

Cortemiglia, G. C., Biancotti, A., Cagnazzi, B., Marchisio, C., Motta, L., & Turrone, E. (1999). *Serie Climatiche Ultracentenarie*. Regione Piemonte, Torino, Italy.

Corti, G., Cavallo, E., Cocco, S., Biddoccu, M., Brecciaroli, G., & Agnelli, A. (2011). Evaluation of Erosion Intensity and Some of Its Consequences in Vineyards from Two Hilly Environments Under a Mediterranean Type of Climate, Italy. *Soil Erosion Issues in Agriculture*. InTech. <http://dx.doi.org/10.5772/25130>

Darouich, H., Ramos, T. B., Pereira, L. S., Rabino, D., Bagagiolo, G., Capello, G., Simionesei, L., Cavallo, E., & Biddoccu, M. (2022). Water use and soil water balance of Mediterranean vineyards under rainfed and drip irrigation management: Evapotranspiration partition and soil management modelling for resource conservation. *Water*, 14, 554. <https://doi.org/10.3390/w14040554>

Foronda-Robles, C. (2018). The territorial redefinition of the Vineyard Landscape in the sherry wine region (Spain). *Misc. Geogr.*, 22, 95–101. <https://doi.org/10.2478/mgrsd-2018-0010>

Garcia, L., Celette, F., Gary, C., Ripoche, A., Valdés-Gómez, H., & Metay, A. (2018). Management of service crops for the provision of ecosystem services in vineyards: A review. *Agriculture, Ecosystems & Environment*, 251, 158–170. <https://doi.org/10.1016/j.agee.2017.09.030>

Giffard, B., Winter, S., Guidoni, S., Nicolai, A., Castaldini, M., Cluzeau, D., Coll, P., Cortet, J., Le Cadre, E., d'Errico, G., Forneck, A., Gagnarli, E., Griesser, M., Guernion, M., Lagomarsino, A., Landi, S., Bissonnais, Y. L., Mania, E., Mocali, S., Preda, C., Priori, S., Reineke, A., Rusch, A., Schroers, H.-J., Simoni, S., Steiner, M., Temneanu, E., Bacher, S., Costantini, E. A. C., Zaller, J., & Leyer, I. (2022). Vineyard management and its impacts on soil biodiversity, functions, and ecosystem services. *Frontiers in Ecology and Evolution*, 10, 850272. <https://doi.org/10.3389/fevo.2022.850272>

Gómez, J. A., Llewellyn, C., Basch, G., Sutton, P. B., Dyson, J. S., & Jones, C. A. (2011). The effects of cover crops and conventional tillage on soil and runoff loss in vineyards and olive groves in several Mediterranean countries. *Soil Use and Management*, 27, 502–514. <https://doi.org/10.1111/j.1475-2743.2011.00367.x>

Istituto Nazionale di Statistica [ISTAT]. (2024). Istat Data La banca dati dell'Istituto Nazionale di Statistica. Retrieved from <https://esploradati.istat.it/databrowser/#/it/dw>. Accessed on: 19 June 2024.

Klingebiel, A. A., & Montgomery, P. H. (1961). Land capability classification. U.S. Department of Agriculture, Soil Conservation Service, Agriculture Handbook No. 210.

Kopta, T., Nedorost Ragasová, L., Sotolář, R., Sedláček, J., Ferby, V., Hurajová, E., & Winkler, J. (2024). The influence of different methods of under-vine management on the structure of vegetation and the qualitative parameters of the grapes in the Moravian wine region. *Folia Horticulturae*, 36(2), 1-23. <https://doi.org/10.2478/fhort-2024-0015>

Kowalczyk, W., Nowak, J., & Zieliński, P. (2024). The impact of climate change on the phenology of grapevines in Central Europe. *Folia Horticulturae*, 36(1), 123-134. <https://doi.org/10.2478/fhort-2024-0015>

Medrano, H., Tomás, M., Martorell, S., Escalona, J.-M., Pou, A., Fuentes, S., Flexas, J., & Bota, J. (2015). Improving water use efficiency of vineyards in semi-arid regions. A review. *Agronomy for Sustainable Development*, 35, 499–517. <https://doi.org/10.1007/s13593-014-0280-z>

Novara, A., Gristina, L., Saladino, S. S., Santoro, A., & Cerdà, A. (2011). Soil erosion assessment on tillage and alternative soil managements in a Sicilian vineyard. *Soil and Tillage Research*, 117, 140-147. <https://doi.org/10.1016/j.still.2011.09.007>

Organisation Internationale de la Vigne et du Vin [OIV]. (2021a). State of the vitiviniculture world market 2021. Retrieved from <https://www.oiv.int/en/technical-standards-and-documents/statistical-analysis/state-of-vitiviniculture>. Accessed on: 17 August 2024.

Organisation Internationale de la Vigne et du Vin [OIV]. (2021b). Annual Assessment of the World Vine and Wine Sector in 2021. Retrieved from https://www.oiv.int/sites/default/files/documents/OIV_Annual_Assessment_of_the_World_Vine_and_Wine_Sector_in_2021.pdf. Accessed on: 17 August 2024.

Organisation Internationale de la Vigne et du Vin [OIV]. (April, 2023). State of the World Vitiviniculture Sector in 2022 – April 2023. Retrieved from https://www.oiv.int/sites/default/files/documents/OIV_State_of_the_world_Vine_and_Wine_sector_in_2022_2.pdf. Accessed on: 17 August 2024.

Piana, F., Fioraso, G., Irace, A., Mosca, P., d'Atri, A., Barale, L., Falletti, P., Monegato, G., Morelli, M., Tallone, S., & Vigna, G. B. (2017). Geology of Piemonte region (NW Italy, Alps–Apennines interference zone). *Journal of Maps*, 13(2), 395–405. <https://doi.org/10.1080/17445647.2017.1316218>

Prada, J., Dinis, L. T., Soriato, E., Vandelle, E., Soletkin, O., Uysal, Ş., Dihazi, A., Santos, C., & Santos, J. A. (2024). Climate change impact on Mediterranean viticultural regions and site-specific climate risk-reduction strategies. *Mitigation and Adaptation Strategies for Global Change*, 29, 52. <https://doi.org/10.1007/s11027-024-10146-0>

Prosdocimi, M., Cerdà, A., & Tarolli, P. (2016). Soil water erosion on Mediterranean vineyards: A review. *Catena*, 141, 1–21. <https://doi.org/10.1016/j.catena.2016.02.010>

QGIS Development Team. (2024). QGIS Geographic Information System. Open Source Geospatial Foundation Project. Retrieved from <https://qgis.org>.

Regione Piemonte, Arpa Piemonte, & Citta' Metropolitana di Torino. (2015). Banca Dati Eventi. Retrieved from https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/arlp_a_to:07.04.06-D_2015-03-31-11:07 Accessed on: 20 June 2024

Regione Piemonte. (2002a). Idrogeologia - Soggiacenza della falda superficiale. Retrieved from https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/r_piemon:d9efa660-f69e-49f7-86dc-25c33637771f Accessed on: 20 June 2024

Regione Piemonte. (2002b). Idrogeologia - Piezometria della falda superficiale. Retrieved from

https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/r_piemon:91d1eaa0-38c2-4875-9da4-fba98dbd420f Accessed on: 20 June 2024

Regione Piemonte. (2003a). Idrogeologia - Permeabilità prevalente della zona non satura 1:100.000. Retrieved from https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/r_piemon:47b602ce-56fb-4a7e-a7ee-d6df1bc203c0 Accessed on: 20 June 2024

Regione Piemonte. (2003b). Idrogeologia - Vulnerabilità intrinseca dell'acquifero superficiale (metodo GOD). Retrieved from https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/r_piemon:caef5410-14dc-4f6e-8049-f711d8dcd4f3 Accessed on: 20 June 2024

Regione Piemonte. (2016). Vincolo Idrogeologico alla scala 1:10.000 (Edizione 2016). Retrieved from https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/r_piemon:ce086790-3411-45c2-bac3-2699b5e3a21f Accessed on: 23 September 2024

Regione Piemonte. (2023a). Aree di ricarica dell'acquifero profondo - scala 1:250000. Retrieved from https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/r_piemon:3fcae3ad-cf09-438d-99d7-a432b5b5c57f Accessed on: 23 July 2024

Regione Piemonte. (2023b). Carta dei suoli 1:50.000. Retrieved from https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/r_piemon:37c6413b-b07f-4f4c-9344-f2e43ea52bbd Accessed on: 23 July 2024

Regione Piemonte. (2023c). Carta dell'erosione reale 1:250000. Retrieved from https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/r_piemon:286c8488-9390-4683-a515-22bc7dfd0774 Accessed on: 23 July 2024

Regione Piemonte. (2024a)., Vini a Denominazione di origine, DOCG e DOC. Retrieved from <https://www.regione.piemonte.it/web/temi/agricoltura/viticolturenologia/vini-denominazione-origine-docg-doc> (accessed on 19 May 2024).

Regione Piemonte. (2024b). Aree di produzione dei vini a Denominazione di Origine Controllata (DOC) e a Denominazione di Origine Controllata e Garantita (DOCG). Retrieved from https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/r_piemon:bb722e24-ed1e-4b00-8fb0-6a205fbbda67 Accessed on: 23 September 2024

Regione Piemonte. (2024c). Incendi boschivi - Aree e Punti di innesco. Retrieved from https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/r_piemon:5d8d0dd5-c0ac-4403-afb9-c116ccefedc8 Accessed on: 23 September 2024

Regione Piemonte. (2024d). Aree protette e altre aree tutelate. Retrieved from https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/r_piemon:4368c018-6b58-4834-b233-c45360cb1206 Accessed on: 23 September 2024

Regione Piemonte. (2024e). PAI - Quadro del dissesto. Retrieved from https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search;jsessionid=05D5FE3C9C1CFA552C88D8D85DE73085.clu001node01_tc1-catregp-gaas?node=srv#/metadata/r_piemon:6640f61c-74be-4ae8-964a-3b466fda813f Accessed on: 20 June 2024

Regione Piemonte. (2024f). Vitigni su mosaicoltura catastale di riferimento regionale 2023. Retrieved from https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/r_piemon:95aed80b-69d3-452a-9635-bae4f498227b Accessed on: 20 June 2024

Renard, K. G., Foster, G. R., Weesies, G. A., McCool, D. K., & Yoder, D. C. (1997). Predicting soil erosion by water: A guide to conservation planning with the revised universal soil loss equation (RUSLE). USDA Agriculture Handbook No. 703.

Román Dobarco, M., Cousin, I., Le Bas, C., & Martin, M. P. (2019). Pedotransfer functions for predicting available water capacity in French soils, their applicability domain and associated uncertainty. *Geoderma*, 336, 81-95. <https://doi.org/10.1016/j.geoderma.2018.08.022>

Rubel, F., Brugger, K., Haslinger, K., & Auer, I. (2017). The climate of the European Alps: Shift of very high resolution Köppen-Geiger climate zones 1800-2100. *Meteorologische Zeitschrift*, 26, 115-125. <http://dx.doi.org/10.1127/metz/2016/0816>

Ruiz-Colmenero, M., Bienes, R., & Marques, M. J. (2011). Soil and water conservation dilemmas associated with the use of green cover in steep vineyards. *Soil and Tillage Research*, 117, 211–223. <https://doi.org/10.1016/j.still.2011.10.004>

Salomé, C., Coll, P., Lardo, E., Metay, A., Villenave, C., Marsden, C., Blanchart, E., Hinsinger, P., & Le Cadre, E. (2016). The soil quality concept as a framework to assess management practices in vulnerable agroecosystems: A case study in Mediterranean vineyards. *Ecological Indicators*, 61, 456–465. <https://doi.org/10.1016/j.ecolind.2015.09.047>

Salvia, R., Simone, R., Salvati, L., & Quaranta, G. (2018). Soil conservation practices and stakeholder's participation in research projects—Empirical evidence from Southern Italy. *Agriculture*, 8, 85. <https://doi.org/10.3390/agriculture8060085>

Scavo, A., Fontanazza, S., Restuccia, A., Pesce, G. R., Abbate, C., & Mauromicale, G. (2022). The role of cover crops in improving soil fertility and plant nutritional status in temperate climates. A review. *Agronomy for Sustainable Development*, 42, 93. <https://doi.org/10.1007/s13593-022-00825-0>

Söhne, W. (1953). Druckverteilung im Boden und Boden-verformung unter Schlepperreifen. *Grundlagen der Landtechnik*, 5, 49–63.

Soil Quality Institute. (2011). Soil quality test kit guide. USDA-ARS-NRCS. Retrieved from <http://ocw.tufts.edu/data/32/383298.pdf>. Accessed on: 11 September 2023.

Steponavičienė, V., Žiūraitis, G., Rudinskienė, A., Jackevičienė, K., & Bogužas, V. (2024). Long-term effects of different tillage systems and their impact on soil properties and crop yields. *Agronomy*, 14, 870. <https://doi.org/10.3390/agronomy14040870>

Strauss, V., Paul, C., Dönmez, C., et al. (2023). Sustainable soil management measures: a synthesis of stakeholder recommendations. *Agronomy for Sustainable Development*, 43, 17. <https://doi.org/10.1007/s13593-022-00864-7>

Tarolli, P., Preti, F., & Romano, N. (2014). Terraced landscapes: From an old best practice to a potential hazard for soil degradation due to land abandonment. *Anthropocene*, 6, 10-25. <https://doi.org/10.1016/j.ancene.2014.03.002>

Topp, E., El Azhari, M., Cicek, H., et al. (2024). Perceptions and sociocultural factors underlying adoption of conservation agriculture in the Mediterranean. *Agriculture and Human Values*, 41, 491–508. <https://doi.org/10.1007/s10460-023-10495-7>

UNESCO. (2014). Vineyard Landscape of Piedmont: Langhe-Roero and Monferrato. Retrieved from <https://whc.unesco.org/uploads/nominations/1390rev.pdf>. Accessed on: September 8, 2024.

Veisi, A., Khoshbakht, K., Veisi, H., Mirzaei Talarposhti, R., & Haghparast Tanha, R. (2024). Integrating farmers' and experts' perspectives for soil health-informed decision-making in conservation agriculture systems. *Environmental Systems and Decisions*, 44, 199–214. <https://doi.org/10.1007/s10669-023-09923-0>

Velten, S., Jager, N. W., & Newig, J. (2021). Success of collaboration for sustainable agriculture: A case study meta-analysis. *Environment, Development and Sustainability*, 23, 14619–14641. <https://doi.org/10.1007/s10668-021-01261-y>

2.4 Continuous monitoring of erosion and runoff

The monitoring system of the erosion and runoff on a parcel scale (plot) were installed in four sites, excluding the Capriata d'Orba vineyard, because of the absence of slope.

The on-site monitoring of the runoff and soil erosion of the monitored plots takes place through “micro-plots”, i.e. sample areas representative of each soil management adopted, with 3 replicates for each thesis. The collection system of the runoff from the sample area was specially designed by CNR-STEMS for the monitoring of runoff and erosion in the vineyard. It is a system consisting of a Gerlach-type collection tank (Gerlach, 1967) with a capacity of 20 l, partially underground, equipped with a sedimentation area and septum for the retention of suspended parts (leaves, grass, and chopped shoots). Two delimiting bars in steel convey the water that flows on the surface into the tank, to collect all the water that flows on the inter-row, from one sub-row to the other. In the event of small rainfall events, any runoff is collected and contained within the collection tank. The volume of water contained at the end of the event is therefore measured, the sediment collected, filtered, dried and weighed, thus obtaining the runoff volume and soil erosion measurements on the sample area.

The tanks have been designed to be able to collect even exceptional outflows correctly. In addition to the common Gerlach tank, a divider is made on the downstream side of the tank by making eight holes. Seven of which discharge the water, while one hole is connected by a pipe to an underground tank placed downstream with a useful volume of approximately 15 litres.



Figure 17: Components for the realization of the runoff and erosion measurement system in the vineyard (at Biné vineyard, Novi Ligure): bars for the delimitation of micro-plots and Gerlach-type tanks with dividers and lids (made of galvanized iron), and tanks with holes for the collection of runoff.

These systems for monitoring the runoff on "micro plots" (Figure 17) have been designed and built in such a way as to allow the normal operations (including mechanized, both with wheeled and both tracked vehicles) to manage the vineyard (with the exception of soil tillage operations). In fact, tanks and canisters have a minimum height with respect to the ground and a width that allows agricultural vehicles to pass over them, the delimitation bars are made of very robust metal, and equipped with deep pegs, able to resist the passage of vehicles without deforming or move (Figure 18).

The collection system can be appropriately sized, increasing or reducing the size of the sample area, moving the tanks further downstream or upstream, based on the recorded flow volumes. Based on the slope and the width of the inter-rows of the sites under study, the tanks were positioned at a distance between 10 and 15 meters from the upstream point.



Figure 18: Installation of runoff measurement systems (tanks and delimitation bars with second tank) at Tenuta Cannona, Carpeneto.

Carpeneto (Cannona experimental parcels - AGRION) hosts the "historical" experimental parcel, on which the effects of soil erosion managed with different techniques have been measured for about 20 years in collaboration with CNR-STEMS. This system was used as an example to develop the relevant tools to be provided to the other companies involved in this project.

An analysis of the long and short term monitoring of the site was provided in the manuscript “Effects of some extreme rainfall events on Hydrological and Soil Erosion Processes in Tilled and Grassed Vineyards” presented at the 7th International Congress of Mountain and Steep Slopes Viticulture 2022, held in Vila Real (Portugal), May 12nd-14th, 2022, reported in the next section.

The analysis of the monitoring of runoff, erosion and microelements losses at the four sites is detailed in the manuscript titled “Evaluating sustainable soil management practices in mitigating runoff, soil erosion and nutrient losses in commercial vineyards of Piedmont”, which has been submitted to *Soil Use and Management*, and is under review. The manuscript is reported in the section 2.4.2

2.4.1 Effects of some extreme rainfall events on Hydrological and Soil Erosion Processes in Tilled and Grassed Vineyards

Giorgio Capello^{1,2}, Marcella Biddoccu¹, Simone Bussotti³, Elisa Paravidino³, Eugenio Cavallo¹

¹Institute of Sciences and Technologies for Sustainable Energy and Mobility (STEMS) of the National Research Council of Italy (CNR); ²Interuniversity Department of Regional and Urban Studies and Planning (DIST), Politecnico di Torino and Università di Torino; ³AGRION - The Foundation for Research, Innovation and Technological Development of Piedmont Agriculture.

Keywords: runoff, sloping vineyard, soil erosion, compaction, soil management

Abstract. Vineyards soils are especially threatened by the risk of soil compaction and soil erosion, with negative consequences for wine production and provisioning of ecosystem services. Indeed, adopting proper soil management in vineyards is crucial to avoid water losses and erosion by runoff, thus improving water infiltration. The use of cover crops in vineyards is widely considered as an effective agricultural conservation measure, providing reduction of runoff and erosion processes and several other ecosystem services. Within the IN-GEST SOIL project, a preliminary study was conducted in a sloping vineyard located in Piedmont, NW Italy, in order to assess the role of permanent grass cover in protecting the vineyard's soil from degradation, especially in relation to soil compaction due to machinery traffic and soil erosion. Rainfall characteristics, runoff and its turbidity, soil erosion, and soil water content were hourly measured during extreme events occurred in the last two years (2020 and 2021), in two different inter-row soil managements: 26 runoff events were recorded, 5 of which due to extreme rainfall with more than 100 mm in the autumn/winter period. Results show how the soil management adopted in a trafficked vineyard strongly influences the infiltration and water retention capacity of the soil and the risk of erosion. Indeed, the grass cover halves the runoff by more than 5 times and reduces the soil erosion by more than 25 times, compared to conventional tillage. Extreme rainfall events were responsible for more than $\frac{3}{4}$ of the runoff and 95% of the soil eroded in the period (> 5 t/ha), highlighting the need to improve the environmental sustainability of these agricultural systems, considering the challenge of climate change, with forecasts indicating increasing temperatures and decreasing rainfall in

the Mediterranean region associated with extreme events such as drought and intense rainfall.

Introduction

One of the most widespread cultivations in the world, which has been practiced in the Mediterranean area for millennia, is viticulture (Corti et al., 2011). Vineyards are often associated with several environmental problems resulting from the intensification of production systems, which evidences the need for better management of soil and water resources, namely in sloping fields in sub-humid to humid climates (Salomé et al., 2016). First step in optimizing the use of water and soil in sloping vineyard is avoiding water losses and erosion by runoff, improving water infiltration (Renard et al., 1997). Mechanical tillage and weeding contribute to runoff and erosion, mainly when intense rainfall occurs and when the soil structure is poor with unstable aggregates (Biddoccu et al. 2020). Differently, a cover crop in the inter row, even temporary, benefits soil functioning whatever the soil type (Biddoccu et al. 2014). Research results reported by Gómez et al. (2011), Prosdocimi et al. (2016), and Capello et al. (2020) confirm those conclusions. Reduction of soil erosion, control and retardation of runoff, water infiltration, increase in organic matter (OM), carbon sequestration, and nutrient supply and retention are some of the positive effects of using cover crops (Salomé et al., 2016; Ruiz-Colmenero et al., 2011; Napoli et al., 2017). However, the ground cover plants generally compete for water with the grapevines and require special care in water scarce areas. Furthermore, in vineyards the use of machinery is fundamental, thus it is crucial a better understanding of its impact on soil compaction, that directly affects soil physical properties negatively, resulting in reduction of soil porosity, of water infiltration capacity and increased runoff and consequent erosion, with decrease of storage and supply of water in the soil (Capello et al., 2020; Pessina et al., 2021). This soil loss is particularly important when the soil is left bare in the inter-row and exposed to intense rainfall events (Bagagiolo et al., 2018; Rodrigo-Comino et al., 2017).

The objectives of IN-GEST SOIL Project (Innovazione nella gestione dei suoli viticoli attraverso l'adozione di buone pratiche e strumenti di supporto alle attività di campo), funded by the EU and Regione Piemonte within Rural development program 2014-2020 for Operational Groups, is the reduction of soil erosion in hillslope vineyards in Piedmont, improving soil and vine quality by means of the introduction of three main innovations: 1) Improved best soil management practices; 2) Agro-meteorological monitoring, to improve water and soil

management; 3) ICT tools for managing of monitored data and field observation to support farmers in vineyard management and water-soil conservation. The focus of this preliminary study, which was carried out during the first year of the project development, is to investigate how the soil management adopted in a trafficked vineyard influences the infiltration and water retention capacity of the soil and the risk of erosion, in particular when extreme rainfall events occur.

Methods and sources

The study was conducted in a sloping rainfed vineyard located at the “Tenuta Cannona” Experimental Vine and Wine Center of Agrion Foundation (44°40' N, 8°37' E, 296 m a.s.l.), in the municipality of Carpeneto (AL), in the “Alto Monferrato” (southern part of the Monferrato hilly area), in Piedmont, NW Italy. At the experimental site, over the period 2000–2021, the average annual precipitation was (870,7 mm), ranging from a maximum of 1455 mm (2019) to a minimum of 493 mm (2017), mainly concentrated in autumn and spring, while the driest season is summer (12% of annual precipitation) and particularly July. The mean annual air temperature was 13 °C.

Since 2000, the vineyard was divided in two plots (1221 m² each) with a different inter row management: (i) conventional tillage (CT, hereafter) cultivation with chisel (at a depth of about 0.25 m, usually carried out twice a year, in spring and autumn); and (ii) controlled grass cover (GC), i.e., mulching of the spontaneous grass cover. Most of the farming operations in the vineyard were carried out using tracked or tyre tractors carrying or towing implements, with intensification of passages from spring to grape harvest time (up to 27 passages per year). A weather station hourly measured rainfall characteristics, runoff (RO) and its turbidity, soil loss (SL), and soil water content (SWC; Dorigo *et al.*, 2021) during events occurred in the last two years (January 2020 - December 2021), in the two plots.

Theoretical framework and operational concepts

According to Capello *et al.* (2019a), the average annual soil loss measured in the 2000-2016 period was 6.6 Mg ha⁻¹ and 1.5 Mg ha⁻¹ in CT and GC, respectively; the mean annual runoff coefficient measured in the same period was 21 % in CT and 11 % in GC.

Rainfall events were defined as the time between the initiation and cessation of rainfall or runoff with a lack of both of them for at least 12 h. Runoff coefficient (RC, %) indicates RO depth divided by precipitation depth (P) of the event. Total

soil loss (SL, kg ha^{-1}) related to each erosive event was calculated as sediment concentration multiplied by the runoff volume and added to the weight of deposited sediments. To get an hourly estimation of the eroded soil, water turbidity value (g l^{-1}) was multiplied for the volume of RO (l) (Linjama *et al.*, 2009). All runoff events recorded were checked and only events with runoff higher than 0.03 mm in at least one of the two plots or, according to the RUSLE procedure, with cumulative rainfall higher than 12.7 mm, were selected and considered as significant for this study. Following these criteria, 26 runoff events were selected, 5 of which due to extreme rainfall with more than 100 mm precipitation in the autumn/winter period.

Results

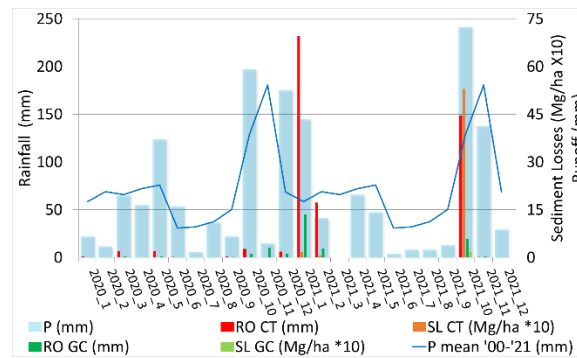


Figure 19: Monthly precipitation (P) and mean precipitation in 2000–2019 period (P mean), runoff (RO) and soil losses (SL) in CT and GC.

Considering the last 19 years, 2020 and 2021 were drier (90 % and 85 % of the mean annual precipitation, respectively). In particular, winter and autumn in 2020 and spring and summer in 2021 were very dry (only 20.6 mm, 20% of usual precipitations, in summer 2021), while winter 2020-2021 was the only rainiest period, with rainfall exceeding twice the usual in December and January (Figure 19). As consequence of low precipitations, yearly runoff was lower than in previous years (Table 11). Despite 786.6 mm rainfall in 2020, RO was only 9.6 and 6.4 mm in CT and GC, respectively, with very low erosion. In fact 93 % and 78 % of RO and almost all the SL of the 2 years was concentrated in 2021, mainly in winter and autumn. In particular, 2021 RC and SL were lower than in previous years principally in GC (3 % and 0.21 Mg ha^{-1} , respectively), but not in CT, where RC (18 %) and SL (5.5 Mg ha^{-1}) were closer to the previous years mean value. This difference in RO and SL between the two years, although the total rainfall is similar, may be due to the different distribution of rainfall among the seasons and its characteristics: as stated by Capello *et al.* (2020), SL and RO are influenced by the

type of event and by the soil conditions. In fact, in 2020, there were low precipitations in winter and autumn, that are the seasons in which RO and SL are usually higher. Comparing in detail the month of October of the two years, despite a similar high value of P, the distribution of rain was very different: in 2020 there were several small events, while in the second year there was only a single event with a very high rain intensity. These results show also how the soil management adopted in a trafficked vineyard strongly influences the infiltration and water retention capacity of the soil and the risk of erosion. Indeed, the grass cover, compared to conventional tillage, halves the runoff by more than 5 times, and reduces the soil erosion by more than 25 times.

Table 11: Precipitation (P, mm), runoff (RO, mm), runoff coefficient (RC, %) and soil losses (SL, Mg ha⁻¹) in CT and GC, in the period of study (20+21) and for the selected events (Sel_all), divided in normal (Sel_normal) and extreme (Sel_extreme).

Events	P	RO CT	RC CT	SL CT
20+21	1528.4	141.56	9.3%	5.55
2020	786.6	9.62	1.2%	0.01
% of 20+21	51.5%	6.8%		0.1%
2021	741.8	131.94	17.8%	5.54
% of 20+21	48.5%	93.2%		99.9%
Sel_all	1256.6	141.32	11.2%	5.55
% of 20+21	82.2%	99.8%		100.0%
Sel_normal	579	31.31	5.4%	0.07
% of sel_all	46.1%	22.2%		1.3%
Sel_extreme	677.6	110.01	16.2%	5.47
% of sel_all	53.9%	77.8%		98.7%

Events	P	RO GC	RC GC	SL GC
20+21	1528.4	29.15	1.9%	0.22
2020	786.6	6.40	0.8%	0.01
% of 20+21	51.5%	22.0%		2.5%
2021	741.8	22.75	3.1%	0.21
% of 20+21	48.5%	78.0%		97.5%
Sel_all	1256.6	25.74	2.0%	0.22
% of 20+21	82.2%	88.3%		100.0%
Sel_normal	579	6.86	1.2%	0.01
% of sel_all	46.1%	26.6%		6.7%
Sel_extreme	677.6	18.89	2.8%	0.20
% of sel_all	53.9%	73.4%		93.3%

The selected events (Table 11) account for more than 80 % of the precipitations and almost all the RO and SL of the 2 years. Only in GC, a little more than 10 % of RO was generated by other little events. In particular, 5 runoff events, due to extreme precipitation with more than 100 mm, in the autumn/winter period, accounting half of the precipitations, are responsible of $\frac{3}{4}$ RO and more than 90 % of SL in the two plots.

The extreme event occurred on 3-4th October 2021 ($P = 235.4$ mm, concentrated in less than 24 h), responsible for most of the runoff and erosion of the period, was analysed to understand the runoff generation process. Due to the passage of agricultural machinery for the harvesting, which took place a few weeks before, the soil, in both plots, had a resistance to penetration greater than 2.5 MPa below 15 cm depth. The bulk density values were high, especially in correspondence of the track position. Despite this, the hydraulic conductivity was higher than 100 mm h^{-1} in both plots. As observable in Figure 20, SWC increased in a few hours from the start of the rain event, reaching the saturation in both plots,

when the runoff began. It is evident how the RO intensity matches the rain intensity, in particular in CT, where RO is more intense than in GC. It is also interesting to note how the suspended sediments in runoff water have a peak only at the start of the runoff process, when the water washes away the finer, non-cohesive soil surface particles. Also in this case the quantity of soil transported by water is greater in CT than in GC.

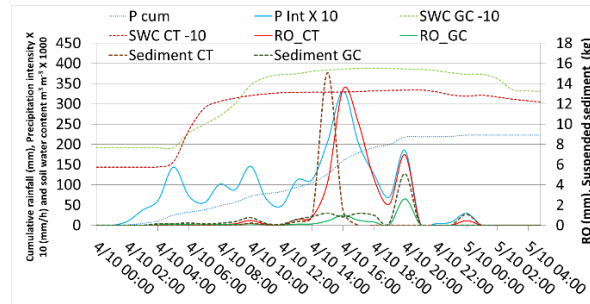


Figure 20: Cumulative precipitation (P cum, mm), Precipitation intensity (P int, X10, mm), runoff (RO, mm), soil water content (SWC, $\text{m}^3 \text{m}^{-3} \times 1000$) and suspended sediment (kg) in CT and GC.

It is clear that this is a case of *saturation excess overland flow*: when the soil reaches the saturation, water can no longer infiltrate, generating runoff (Castillo *et al.*, 2003). It is also possible that *subsurface return flow* has occurred: on slopes, especially where the soil is characterized by layers with different hydraulic conductivity, after the water has infiltrated the upper part and saturated it, it can flow by gravity under the surface and then re-emerge further downstream (Govi *et al.*, 1985; Luino, 2005). The presence of the grass roots ensured a higher hydraulic conductivity, also in depth, greatly reducing the runoff in the grassed plot. The grass also protected the soil from the direct impact of raindrops, slowing down the surface runoff, and restraining the suspended particles.

The results confirm that the use of cover crops in vineyards is an effective agricultural conservation measure, providing various ecosystem services, primarily reduction of runoff and erosion processes, besides many others (increasing soil organic matter, weed control, pest and disease regulation, water supply, water purification, improvement of field trafficability, and conservation of biodiversity (Garcia *et al.*, 2018; Winter *et al.*, 2018; Hall *et al.*, 2020). Nevertheless, in the Mediterranean region wine growers are reluctant to use permanent cover crops due to concerns over soil water competition with the vine (Celette *et al.*, 2008; Ruiz-Colmenero *et al.*, 2011). In the context of increasing temperatures, wine growers tend to use temporary or partial cover crops. To further investigate how different

soil management systems and an adequate programming of the field operations, within the IN-GEST project other 4 study cases have been implemented in 2021 in other 4 vineyards (“Cascina Binè” at Novi Ligure, “Nebraie” at Rocchetta Ligure, “Cascina Gentile” at Capriata d’Orba and “Torchio” at San Damiano d’Asti). This study will aim to improve the environmental sustainability of the vineyard, the relevance of which is further enhanced in the context of the climate change, with forecasts indicating increasing temperatures and decreasing rainfall in the Mediterranean region associated with extreme events such as drought and intense rainfall (IPCC, 2018).

Conclusions

As consequence of low precipitations in 2020 and 2021, yearly RO and SL were lower than in previous years, mainly in GC than in CT. Most of the erosion was generated by a single extreme precipitation occurred in the autumn 2021, during which the grass cover had a great efficiency in reducing water and soil losses. These results highlight the necessity to protect the soil and adopt adequate soil management to reduce water and soil losses in the different seasons of the year. This is particularly necessary especially in periods where high levels of soil compaction, due to tractors trafficking, are associated to relevant rainfall events. These extreme events are increasing in frequency in the context of the climate change.

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References

Bagagiolo, G.; Biddoccu, M.; Rabino, D.; Cavallo, E. (2018). Effects of rows arrangement, soil management, and rainfall characteristics on water and soil losses in Italian sloping vineyards. *Environ. Res.* 2018, 166, 690–704. <https://doi.org/10.1016/j.envres.2018.06.048>.

Biddoccu, M.; Opsi, F.; Cavallo, E. (2014). Relationship between runoff and soil losses with rainfall characteristics and long-term soil management practices in a hilly

vineyard (Piedmont, NW Italy). *Soil Sci. Plant Nutr.* 2014, 60, 92–99. <https://doi.org/10.1080/00380768.2013.862488>.

Biddoccu, M.; Guzman, G.; Capello, G.; Thielke, T.; Strauss, P.; Winter, S.; Zaller, J.G.; Nicolai, A.; Cluzeau, D.; Popescu, D.; *et al.* (2020). Evaluation of soil erosion risk and identification of soil cover and management factor (C) for RUSLE in European vineyards with different soil management. *Int. Soil Water Conserv. Res.* 2020, 8, 337–353. <https://doi.org/10.1016/j.iswcr.2020.07.003>.

Capello, G.; Biddoccu, M.; Cavallo, E. (2019a). L'influenza della gestione del suolo e del traffico agricolo sulla conservazione dell'acqua e del suolo: un caso studio in Piemonte. *Atti del XXII Convegno Nazionale di Agrometeorologia - Ricerca ed innovazione per la gestione del rischio meteo - climatico in agricoltura*, pp 38-43. Bologna: Dipartimento di Scienze Agrarie - Università di Bologna.

Capello, G.; Biddoccu, M.; Ferraris, S.; Cavallo, E. (2019b). Effects of tractor passes on hydrological and soil erosion processes in tilled and grassed vineyards. *Water* 11(10), 2118.

Capello, G.; Biddoccu, M.; Cavallo, E. (2020). Permanent cover for soil and water conservation in mechanized vineyards: A study case in Piedmont, NW Italy. *Italian Journal of Agronomy*, 15(4), 323–331. <https://doi.org/10.4081/ija.2020.1763>.

Castillo, V. M.; Gomez-Plaza, A.; Martínez-Mena, M. (2003). The role of antecedent soil water content in the runoff response of semiarid catchments: a simulation approach. *J. Hydrol.* 2003; 284: 114–130.

Celette, F.; Gaudin, R.; Gary, C. Spatial and temporal changes to the water regime of a Mediterranean vineyard due to the adoption of cover cropping. *Eur. J. Agron.* 2008, 29(4), 153-162. <https://doi.org/10.1016/j.eja.2008.04.007>

Corti, G.; Cavallo, E.; Cocco, S.; Biddoccu, M.; Brecciaroli, G.; Agnelli, A. (2011). Evaluation of Erosion Intensity and Some of Its Consequences in Vineyards from Two Hilly Environments Under a Mediterranean Type of Climate, Italy. In *Soil Erosion Issues in Agriculture*; Godone, D., Stanchi, S., Eds.; InTechOpen, London, UK: 2011; pp. 113–160.

Dorigo, W.; Himmelbauer, I.; Aberer, D.; Schremmer, L.; Petrakovic, I.; Zappa, L.; Preimesberger, W.; Xaver, A.; Annor, F.; Ardö, J.; Baldocchi, D.; Bitelli, M.; Blöschl, G.; Bogaen, H.; Brocca, L.; Calvet, J.-C.; Camarero, J. J.; Capello, G.; Choi, M.; Cosh, M. C.; van de Giesen, N.; Hajdu, I.; Ikonen, J.; Jensen, K. H.; Kanniah, K. D.; de Kat, I.; Kirchengast, G.; Kumar Rai, P.; Kyrouac, J.; *et al.* (2021). The International Soil Moisture

Network: serving Earth system science for over a decade, *Hydrol. Earth Syst. Sci.*, 25, 5749–5804, <https://doi.org/10.5194/hess-25-5749-2021>.

Garcia, L.; Celette, F.; Gary, C.; Ripoche, A.; Valdés-Gómez, H.; Metay, A. (2018). Management of service crops for the provision of ecosystem services in vineyards: A review. *Agriculture, Ecosystems and Environment*, 251, 158–170. <https://doi.org/10.1016/j.agee.2017.09.030>.

Gómez, J.A.; Llewellyn, C.; Basch, G.; Sutton, P.B.; Dyson, J.S.; Jones, C.A. (2011). The effects of cover crops and conventional tillage on soil and runoff loss in vineyards and olive groves in several Mediterranean countries. *Soil Use Manage.* 2011, 27, 502–514. <https://doi.org/10.1111/j.1475-2743.2011.00367.x>.

Govi, M.; Mortara, G.; Sorzana, P. F. (1985) Hydrological events and landslides [Eventi idrologici e frane]. *Geologia Applicata e Idrogeologia* 1985; 20 (2); 359–375.

Hall, R. M.; Penke, N.; Kriechbaum, M.; Kratschmer, S.; Jung, V.; Chollet, S.; Guernion, M.; Nicolai, A.; Burel, F.; Fertil, A.; Lora, A.; Sánchez-Cuesta, R.;

Guzmán, G.; Gómez, J.; Popescu, D.; Hoble, A.; Bunea, C.-I.; Zaller, J. G.; Winter, S. (2020). Vegetation management intensity and landscape diversity alter plant species richness, functional traits and community composition across European vineyards. *Agricultural Systems*, 177, 102706. <https://doi.org/10.1016/j.agsy.2019.102706>

IPCC (2018). Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V.; Zhai, P.; Pörtner, H.-O.; Roberts, D.; Skea, J.; Shukla, P.R.; Pirani, A.; Moufouma-Okia, W.; Péan, C.; Pidcock, R.; Connors, S.; Matthews, J.B.R.; Chen, Y.; Zhou, X.; Gomis, M.I.; Lonnoy, E.; Maycock, T.; Tignor, M.; Waterfield, T. (eds.)].

Linjama, J.; Puustinen, M.; Koskiahho, J.; Tattari, S.; Kotilainen, H.; Granlund, K. (2009). Implementation of automatic sensors for continuous monitoring of runoff quantity and quality in small catchments. *agricultural and food science* Vol. 18: 417–427.

Luino, F. (2005) Sequence of instability processes triggered by heavy rainfall in the northern Italy. *Geomorphology* 2005; 66; 13–39.

Napoli, M.; Dalla Marta, A.; Zanchi, C.A.; Orlandini, S. (2017). Assessment of soil and nutrient losses by runoff under different soil management practices in an Italian hilly vineyard. *Soil Till. Res.* 2017, 168, 71–80. <https://doi.org/10.1016/j.still.2016.12.011>.

Pessina, D.; Galli, L.E.; Santoro, S.; Facchinetti, D. (2021). Sustainability of Machinery Traffic in Vineyard. *Sustainability* 2021, 13, 2475. <https://doi.org/10.3390/su13052475>.

Prosdocimi, M.; Cerdà, A.; Tarolli, P. (2016). Soil water erosion on Mediterranean vineyards: A review. *Catena* 2016, 141, 1–21. <https://doi.org/10.1016/j.catena.2016.02.010>.

Renard, K. G.; Foster, G. R.; Weesies, G. A.; McCool, D. K.; Yoder, D. C. (1997). Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). US Department of Agriculture Agricultural Handbook No. 703, USDA Washington, DC, USA.

Rodrigo-Comino, J.; Senciales, J.M.; Ramos, M.A.; Martínez-Casasnovas, J.A.; Lasanta, T.; Brevik, E.C.; Ries, J.B.; Sinoga, J.R. (2017). Understanding soil erosion processes in Mediterranean sloping vineyards (Montes de Málaga, Spain). *Geoderma* 2017, 296, 47–59. <https://doi.org/10.1016/j.geoderma.2017.02.021>.

Ruiz-Colmenero, M.; Bienes, R.; Marques, M.J. (2011). Soil and water conservation dilemmas associated with the use of green cover in steep vineyards. *Soil Till. Res.* 2011, 117, 211–223. <https://doi.org/10.1016/j.still.2011.10.004>.

Salomé, C.; Coll, P.; Lardo, E.; Metay, A.; Villenave, C.; Marsden, C.; Blanchart, E.; Hinsinger, P.; Le Cadre, E. (2016). The soil quality concept as a framework to assess management practices in vulnerable agroecosystems: A case study in Mediterranean vineyards. *Ecol. Indic.* 2016, 61, 456–465. <https://doi.org/10.1016/j.ecolind.2015.09.047>.

Winter, S.; Bauer, T.; Strauss, P.; Kratschmer, S.; Paredes, D.; Popescu, D.; Landa, B.; Guzmán, G.; Gómez, J. A.; Guernion, M.; Zaller, J. G.; Batáry, P. (2018). Effects of vegetation management intensity on biodiversity and ecosystem services in vineyards: A meta-analysis. *Journal of Applied Ecology*, 1e12. <https://doi.org/10.1111/1365-2664.13124>

2.4.2 Evaluating sustainable soil management practices in mitigating runoff, soil erosion and micronutrient losses in commercial vineyards of Piedmont

Giorgio Capello^{1,2}, Stefano Ferraris², Simone Bussotti³, Elisa Paravidino³, Marcella Biddoccu¹

¹Institute of Sciences and Technologies for Sustainable Energy and Mobility (STEMS) of the National Research Council of Italy (CNR); ²Interuniversity Department of Regional and Urban Studies and Planning (DIST), Politecnico di Torino and Università di Torino; ³AGRION - The Foundation for Research, Innovation and Technological Development of Piedmont Agriculture.

Abstract.

Viticulture in the Mediterranean is vital for its economic, cultural, and environmental benefits. However, intensified vineyard management poses environmental challenges, particularly in soil and water conservation and sustainability of this agro-ecosystem. Climate change exacerbates these issues, impacting grape and wine quality due to rising temperatures and altered water regimes. This study investigates the effectiveness of sustainable soil management practices in reducing surface runoff, soil erosion, and nutrient losses in four vineyards located in the Piedmont region, Italy. With one exception, the monitored vineyards are part of commercial farms, and vine-growers were involved in the project activities, as part of the IN-GEST SOIL Operational Group (OG). The project aimed to collaborate in defining best practices for enhancing soil conservation in vineyards of their region. The research compares different soil management practices, with different level of sustainability by monitoring soil runoff and erosion using Gerlach throughs, over a two-year period. The period of observation was characterized by prolonged drought, interspersed with intense rainfall events. However, results highlight the effectiveness of enhanced soil management practices, such as permanent grass cover and cover cropping, in mitigating surface runoff and soil erosion during rainfall events. The transitioning from bare soil and traditional tillage to permanent grass cover significantly reduces runoff, erosion and nutrient loss, especially during intense rainfall events. Alternating rows management showed higher vulnerability to erosion. No-till seeding minimized soil disturbance and improved water availability. Soil management practices should be optimized to minimize water, soil and nutrient losses, taking into account local climate and seasonal meteorological conditions.

These findings contribute to the growing body of knowledge on sustainable viticulture practices and offer practical recommendations for vineyard managers aiming to enhance soil health and reduce environmental impacts.

Keywords: soil and water conservation, sustainable viticulture, cover crops, operational groups, collaborative innovation.

Synopsis:

- The study conducted in commercial vineyards in Piemonte confirms finding of soil erosion long-term observations or prediction in the region.
- Best improvement in reducing water, soil and nutrient losses was obtained using permanent grass cover in all rows.
- Conventional tillage management leads to loss of essential nutrients and fertility, especially as consequence of intense rainfall events.
- In alternate rows management, cover crops results in a lower volume of runoff and sediment than in the rows with spontaneous grass cover.
- During more intense and erosive events, the more sustainable approaches consistently performed better than conventional ones

Introduction

Viticulture is a key agricultural activity in the Mediterranean, offering significant economic, cultural, and environmental benefits (UNESCO, 2014; Foronda-Robles, 2018). Italy ranks fourth in vineyard area, with 718,000 hectares, after Spain, France, and China (OIV, 2023). The Italian administrative region of Piedmont accounts for 11 % of Italy's grapes for PDO (Protected Designation of Origin; Italian: DOP) wines (ISTAT, 2024). However, intensified vineyard management has introduced environmental challenges, especially for soil and water conservation, biodiversity, and ecosystem service provision (Giffard et al., 2022). The increasing awareness of soil as a non-renewable resource and its key role in climate change mitigation has stimulated global efforts to adopt sustainable soil management practices in viticulture (Lazcano, 2020).

The ongoing impacts of climate change are profoundly affecting both human systems and ecosystems, with agriculture among the most affected sectors (Fraga, 2019). Rising temperatures can significantly impact crop yield and quality (Adams

et al., 1998; Parthasarathi et al., 2022). Climate change's effects strongly influence grape phenology (Kowalczyk et al., 2024) and wine quality (Mariani et al., 2009). Another consequence of a rapidly changing climate is the imbalance of the water regime, characterized by a decrease in annual rainfall and an increased frequency of extreme events such as floods and droughts (Spano et al., 2020). According to the IPCC's Sixth Assessment Report (IPCC, 2023), drought phenomena will be exacerbated in the dry summer climates of the Mediterranean region, including inland hilly areas where vines are traditionally grown (Bagagiolo et al., 2021). Vineyards in Mediterranean hilly areas are increasingly exposed to prolonged dry spells punctuated by high-intensity rainfall events, which enhance runoff generation and sediment detachment on bare or recently tilled inter-rows (Straffelini & Tarolli, 2023). Importantly, erosion and related nutrient loss are highly episodic: a small number of high-magnitude storms can account for a large share of annual runoff and soil loss (Biddoccu et al., 2014; Capello et al., 2022). Under such conditions, practices that increase soil cover and reduce disturbance (e.g., permanent grass cover or cover crops) are expected to mitigate event-scale runoff, sediment yield and nutrient losses more consistently than conventional tillage (Prosdocimi et al., 2016).

In parallel, land degradation compounds climate risk. Rainfall significantly contributes to soil erosion and nutrient loss (Panagos et al., 2015), leading to non-point source pollution of groundwater reserves and ecological degradation (Ding et al., 2024; Suciú et al., 2020). Soil erosion is closely linked to nutrient loss (García-Díaz et al., 2017), and significantly impacts soil fertility and vineyard productivity (Ruiz-Colmenero et al., 2013). Under extraordinary storms, Mediterranean vineyards can also lose substantial amounts of nutrients in a single event, reinforcing the coupling between sediment yield and nutrient losses (Ramos and Martínez-Casasnovas, 2004).

EU-wide assessments estimate 0.43 % yr⁻¹ crop productivity loss due to water erosion on severely affected agricultural areas, with Italy among the most impacted (Panagos et al., 2018). In NW Italy sloping vineyards, long-term monitoring reports one order of magnitude differences in annual erosion: roughly 10–25 t ha⁻¹ yr⁻¹ under tilled inter-rows versus 2–3 t ha⁻¹ yr⁻¹ under grass cover (Biddoccu et al., 2016). In this context, effective soil and water management practices are vital to ensure the sustainability and resilience of vineyards (Salomè et al., 2016). Water resource management is emerging as a key constraint for sustaining grape yield and quality. Accordingly, implementing soil and water conservation practices can alter hydrological conditions and water flow dynamics on hillslopes, reducing both

erosion and nutrient loss (Novara, 2011; Cárceles Rodríguez et al., 2021). These practices can significantly influence soil properties and help maintain soil health, thereby supporting long-term vineyard sustainability and productivity (Prada et al., 2024; Cataldo et al., 2020). In turn, improved soil functioning can help sustain grape yield and management outcomes under variable conditions (O'Brien et al., 2025). Good soil management can also positively influence wine quality parameters (Ramírez-Pérez et al., 2024; Cataldo et al., 2021).

In Mediterranean vineyards, especially in new plantations and dry conditions, traditional soil management typically involves multiple tillage operations each year to keep the soil bare, improve aeration, and prevent competition between weeds and the crop for nutrients and water (Ruiz-Colmenero et al., 2011; Delpuech & Metay, 2018). However, this practice can also lead to accelerated soil erosion (Gristina et al., 2022), increased vulnerability to compaction (Pessina et al., 2025; Capello et al., 2019), loss of organic matter (Payen et al., 2021) and nutrients (Telak and Bogunovic, 2020), reduced aggregate stability (Belmonte et al., 2018), decreased biodiversity (Karimi et al., 2020), lower soil water content (Horel et al., 2024), and reduced crop yield (Steponavičienė et al., 2024). To mitigate these issues, alternative management practices, such as the use of groundcover with grass cover or cover crops, have been proposed (Novara et al., 2011; Ferreira et al., 2020). These practices help to reduce soil erosion by water and enhance soil organic carbon content (Prosdocimi et al., 2016; Keesstra et al., 2016; Steenwerth & Belina, 2008). Plant covers intercept raindrops, reducing their impact and acting as physical barriers to the overland flow of water and sediment, thereby decreasing runoff and sediment delivery (Marchamalo et al., 2016; Mekonnen et al., 2015). Groundcovers contribute to the overall health of the vineyard ecosystem by promoting increased aggregate stability, improving soil structure (Virto et al., 2012; Cerdà, 2000), and favouring higher infiltration rates (Biddoccu et al., 2013). Previous studies have shown that permanent grass cover can reduce runoff by up to 65 % and soil erosion by 72 % (Capello et al., 2020). Cover crops can also improve soil fertility by increasing soil organic matter and microbiological function (Steenwerth et al., 2010; Bernaschina et al., 2023) and enhancing biodiversity (Geldenhuys et al., 2021). This also aids in preserving the landscape and cultural heritage associated with viticulture (Garcia, 2018). However, these crops, such as legumes, are usually not harvested and require additional management, such as mowing, mulching, or incorporation into the soil. In addition to these practices, organic vineyard management practices have also been explored as a means to improve soil health and vine nutrition (Abad et al., 2021).

While inter-row soil management with spontaneous grass cover is already well established in Piedmont and other northern Italian regions, growing concerns about soil and water conservation and increasingly variable weather have fostered the adoption of sown cover crops tailored to site conditions and seasonal windows. Recently, due to increasing concern about water scarcity, vine growers have also moved away from uniform/permanent grass cover, shifting instead to alternating grass cover in every second row or maintaining vegetation only during part of the year (Caffaro et al., 2026; Dugan et al., 2024).

Despite substantial evidence that sloping vineyards are highly erosion-prone and that cover crops can mitigate runoff and soil loss, most quantitative knowledge still comes from small plot or rainfall-simulation experiments, often conducted in research settings and with heterogeneous methods and spatial scales. These conditions can limit external validity and comparability across sites. Reviews repeatedly underline the methodological dispersion (plot size, devices, intensities) and the difficulty of generalising results beyond experimental stations (Prosdocimi et al., 2016; Prosdocimi et al., 2017; Neumann et al., 2022). In addition, event-scale budgets based on Gerlach troughs, central to vineyard hydrology, are sensitive to sampling layout and storm variability, raising issues of representativeness; paired-plot studies in European vineyards document large within-storm scatter and management-induced variability across rows and seasons (Pantazis & Nastos, 2025; Quiquerez et al., 2016; Brings et al., 2017). In Mediterranean viticulture, multi-site, on-farm operational trials remain scarce and even long-term work in NW Italy demonstrating the benefits of grass cover has largely been conducted in experimental plots rather than across commercial farms under growers' constraints (Biddoccu et al., 2014; Biddoccu et al., 2015). Moreover, a small number of high-intensity rainfall events often dominates annual runoff and soil and nutrient losses, yet relatively few studies explicitly stress-test management practices across contrasting hydro-climatic years within a unified design (Capello et al., 2022; Ramos, 2016). This gap is consequential given the observed and projected intensification of hydrological extremes across the Mediterranean (Heinekamp et al., 2025; Santos et al., 2020). Finally, although co-design with growers and on-farm experimentation are recognised pathways to improve adoption and external validity, agronomic studies often under-document experimental design choices and the management decision process in operational settings (Kool et al., 2020).

To address these gaps, this study aims to evaluate how alternative inter-row soil management practices modulate the hydrological and erosive response of sloping vineyards under real-world operational conditions. We conducted a two-year,

multi-site study across operational commercial vineyards in southern Piedmont, co-designed with growers within the IN-GEST SOIL Operational Group. Management decisions (e.g., tillage, mowing, sowing dates) followed real farm constraints (labour, machinery, timing, budgets) and were supported, where applicable, by technical advice and decision-support tools. Specifically, using in-field monitoring with Gerlach troughs, we quantified surface runoff, soil erosion, and associated losses of dissolved elements (micronutrients and major cations) in runoff water, as an indicator of solute export under erosion-prone conditions. Measurements were conducted at event and seasonal scales across an increasing gradient of sustainability in farmer-adopted practices (conventional tillage, CT; sown cover crops, CC; and grass cover, GC), with particular attention to intense rainfall events and performance variability among farms. This on-farm, participatory, multi-site design moves beyond single-site experimental plots and provides a real-climate stress test across years combining prolonged drought with high-intensity rainfall, thereby strengthening the evidence base for practical soil and water conservation in sloping vineyards under increasingly variable conditions (European Commission, 2021).

Within this scope, we hypothesised that vegetated practices would consistently outperform tilled bare soil for all response variables (event runoff, sediment yield, and dissolved element loads), with the expected ranking $GC \approx CC < CT$ (lower values indicating better performance). We further expected that between-practice differences would widen during intense rainfall events, when continuous cover and higher root density should enhance interception and infiltration while reducing overland-flow connectivity, whereas differences would be smaller under moderate storms. Finally, we hypothesised that dissolved element losses are primarily driven by runoff dynamics (mainly runoff volume and, to a lesser extent, concentrations), so that practices reducing runoff also reduce dissolved element export; any association with sediment yield should be weaker and event-dependent. In line with our measurement design, these hypotheses focus on runoff, erosion, and dissolved elements export and do not aim to assess broader soil-health attributes (e.g., SOC, aggregation, soil biology). Overall, the study provides operational evidence on the comparative performance and variability of sustainable soil-management practices across multiple commercial vineyards, offering actionable guidance to reduce runoff, soil loss, and dissolved element losses under rainfall regimes that are becoming more extreme and less predictable.

Materials and method

Study area

The vineyards chosen for the experiment are located in the southern Piedmont region, Italy (Figure 21). All sites are included within DOC or DOCG wine production areas (Regione Piemonte, 2024a). Three out of four vineyards (Carpeneto, Novi Ligure and Rocchetta Tanaro) are located in Alto Monferrato region, whereas Rocchetta Ligure is situated in Val Borbera. The Carpeneto vineyard is part of an experimental centre, however it is conducted according to local farming for wine production; the other vineyards belong to commercial wine-producing farms. Two of the vineyards (Novi Ligure and Rocchetta Ligure) are managed under organic farming, the remaining followed integrated pest management regional regulations.

The four study vineyards differed in soil texture, slope, soil management and mechanization (Table 12). Vine rows were planted along the maximum slope line at all sites. At the beginning of the study, composite soil samples (0–0.2 m and 0.2–0.4 m) were collected from six locations within each plot and analysed for texture and organic matter content (Table 12). Further details on site characterization and additional baseline soil properties are provided in Capello et al. (2024).

Monthly rainfall data from 2000 onwards were available for the CA site and were used to place the 2022–2023 monitoring period within the long-term climatic variability. We therefore computed the 12-month Standardized Precipitation Index (SPI; McKee et al., 1993), which summarizes precipitation anomalies at annual scale; SPI results are used only for climatic context and are not intended as an event-scale predictor of runoff.

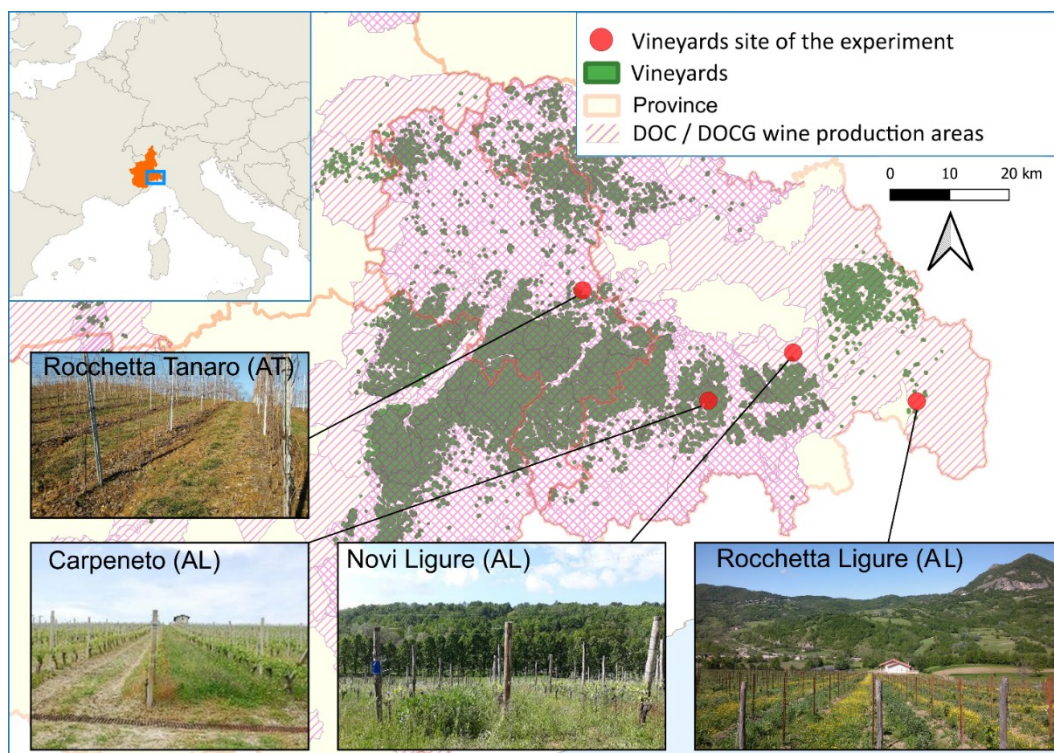


Figure 21: The map depicts the Monferrato area in the Piedmont region. DOC and/or DOCG wine production areas (Regione Piemonte, 2024a) are marked with purple hatching (cross-hatching if there are two or more DOC/DOCG). Vineyard parcels, based on the regional cadastral mosaic (Regione Piemonte, 2024b), are highlighted in green. The selected vineyards for the experiment are indicated with red dots.

Vineyard management

At each site, two adjacent plots were monitored: a baseline plot managed according to the farm's current practice and an enhanced sustainability plot (ES) implementing an alternative inter-row management (Table 13). Baseline management corresponded to low sustainability (LS) at Carpeneto (CA; Agrion Foundation "Tenuta Cannona") and to standard sustainability (SS) at Novi Ligure (NL), Rocchetta Ligure (RL) and Rocchetta Tanaro (RT).

Inter-row practices were classified as conventional tillage (CT; repeated tillage to maintain bare soil), spontaneous grass cover (GC; permanent or seasonal), or seeded cover crop (CC). Details of operations (tillage depth, mowing and under-vine management) are summarised in Table 13. ES plots adopted an innovative inter-row soil management selected jointly with the growers. The choice of practices was informed by a survey conducted among vine growers in Piedmont

(Caffaro et al., 2026) and targeted a more continuous ground cover to improve soil protection and reduce runoff, erosion and associated micro-element losses.

Table 12: Characteristics and principal information of the four vineyards site of study in the Piedmont region.

Site ID	CA		NL		RL		RT	
Municipality (province)	Carpeneto (AL)		Novi Ligure (AL)		Rocchetta Ligure (AL)		Rocchetta Tanaro (AT)	
Vineyard coordinates	44° 40' 56.42" N, 8° 37' 34.27" E		44° 44' 12.91" N, 8° 47' 23.34" 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)		269° (West)		315° (Northwest)	
Average elevation [m a.s.l.]	273.3		225.3		510.5		197	
Average slope [%]	15.3		14.2		16.8		19	
Plot area [m²]	40		39		30		30	
Inter-row width and plot length [m]	2.75 x 14.5		2.6 x 15		2.4 x 12.5		2.5 x 12	
Plant spacing in row [m]	1.0		0.9		0.9		0.9	
Grape variety	Barbera		Cortese		Timorasso		Barbera	
Climatic zone	Csa		Csb		Csa		Cfa	
	(warm temperate with hot and dry summers)		(warm temperate with warm and dry summers)		(warm temperate with hot and dry summers)		(warm temperate with hot summers and no dry season)	
USDA soil classification	Alfisols of ancient terraces / hillside Alfisols		hillside Inceptisols		Alfisols of ancient terraces / hillside Inceptisols		hillside Alfisols	
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
Sand (2.0-0.20 mm)	48.7	54.4	48	48.5	45.5	45.5	73.3	76.4
Silt (0.20-0.002 mm)	30.9	33.1	26	27	32	30.5	18.3	16.1
Clay (<0.002 mm)	20.5	12.6	26	24.5	22.5	24	8.5	7.5
Organic Matter (%)	0.95	0.44	1.35	1.05	0.89	0.66	0.53	0.55
Texture	loam	sandy loam	sandy clay loam	sandy clay loam	loam	loam	sandy loam	sandy loam

Table 13: Soil management compared in the four vineyards included in the study.

SOIL MANAGEMENT	CA	NL	RL	RT
LS management	CT, 25 cm soil tillage with ripper, all rows, in spring and autumn. Mowing in summer.			
SS management		Alternate rows with: 1) CC mixture sown in autumn with combined rotary harrow+seeder, after 40 cm vineyard subsoiler tillage and fertilization; 2) GC spontaneous grass, 5-10 cm tillage with flexible tine harrow in summer in dry conditions. Mowing of grass in spring and summer, residues on ground. After harvest each year CC rows become GC and vice versa.	Alternate rows with: 1) CC mixture sown in autumn with combined rotary harrow+seeder, after 30 cm subsoiler+disks tillage and fertilization; 2) GC spontaneous grass, 5-10 cm tillage with flexible tine harrow in summer in dry conditions. Mowing of grass in spring and summer, residues on ground. Annual rotation: each autumn the previously grassed inter-row is tilled and re-seeded as CC, while the previous CC inter-row is left to revert to spontaneous GC.	GC, permanent spontaneous grass, periodic mechanical mowing. Chemical herbicide under vines.
ES management	GC, permanent spontaneous grass, periodic mechanical mowing	Same as SS, but in GC selected grass seeds are sown with no till seeder	Same as SS, but without annual rotation: CC sown in the same inter-row every year; the GC inter-row is maintained with the aim of transitioning to permanent grass cover.	GC, permanent spontaneous grass, periodic mechanical mowing. Mechanical mowing under vines with brush cutter.
Seeded cover crop species		Mixture of typical green manure	Mixture of typical green manure	

species, including Fabaceae and Poaceae	species, consisting of Fabaceae, Poaceae, and, in smaller quantities, Brassicaceae
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Field surveys and monitoring

A monitoring system was installed at each site in autumn 2021 to cover the 2022 and 2023 seasons; at RT, equipment installation started in June 2022. Rainfall was recorded by an on-site rain gauge.

Runoff (RO) and soil loss (SL) were monitored using inter-row micro-plots (30–40 m², Table 11) equipped with a Gerlach trough (Gerlach, 1967). Micro-plot dimensions were selected to balance representativeness and field feasibility in vineyard inter-rows (Table 12; Bagarello et al., 2018). The runoff collection system from the sample area was specifically designed by CNR-STEMS for monitoring RO and SL in vineyards (SM1). At each vineyard, six micro-plots were installed (three replicates in the baseline plot and three in the ES plot; Figure 22). Collected runoff was conveyed to a tank (and, where needed, an additional container for overflow; Figure 23).

After each rainfall event producing surface runoff, the collected volume was measured and a well-mixed subsample (water + suspended sediment) was collected for laboratory analyses. During each field visit, the system was inspected to identify potential failures (e.g., clogging of outlet holes, malfunction of delimitation bars, or bypass flow beneath the borders) and to exclude external contributions (e.g., inflow from adjacent rows). Only events passing these checks were retained for subsequent analyses.

Growers and vineyard staff involved in the project were trained by the research team to perform field observations, collect runoff measurements and take water samples following a standardized protocol.

Runoff depth (RO, mm) was calculated from collected volume and contributing area. The runoff coefficient (RC, %) was computed as RO divided by event rainfall. Soil loss (SL, kg ha⁻¹) was derived from suspended sediment concentration (CES) and runoff volume. An erosion coefficient (EC, kg ha⁻¹ mm⁻¹) was calculated as SL normalized by event rainfall. For dissolved micro elements, event loads were

obtained by multiplying concentration (mg L^{-1}) by runoff volume (L) and, for cross-site comparison, were expressed per unit rainfall (mg mm^{-1}).

Runoff-water samples were analysed for dissolved elements including B, Cu, Mn and Fe, and major cations (K, Na, Mg and Ca). The analytical suite was selected to address a knowledge gap on micro-element loss from vineyards and to remain consistent with the project's scope and budget; analyses of N and P species were therefore not included. Samples were processed and preserved following standard laboratory procedures and analysed, with appropriate calibration standards and quality-control blanks/replicates.

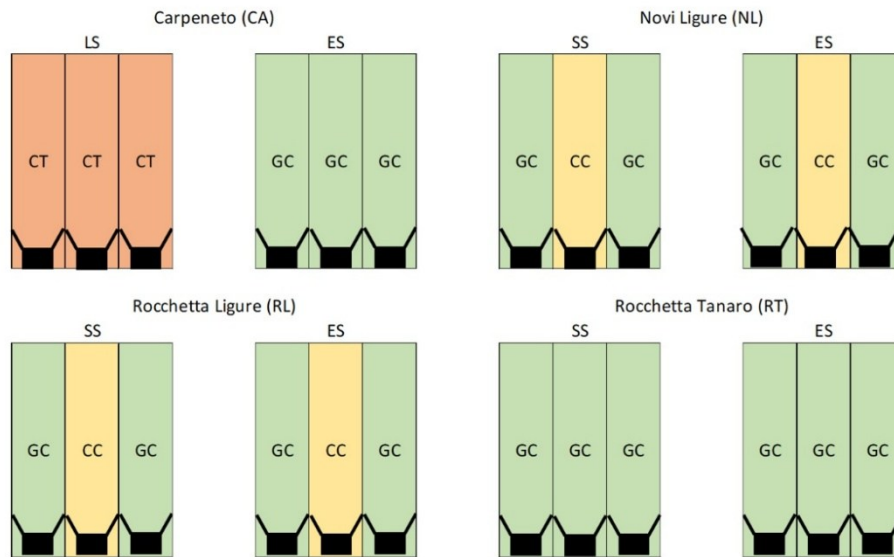


Figure 22. Layout of the six micro-plots installed at each site (three replicates per treatment). Micro-plots were located within the inter-row and labelled according to the inter-row groundcover type adjacent to the collector: CT, conventional tillage (bare soil); GC, spontaneous grass cover; CC, seeded cover crop. Baseline management was LS at CA and SS at NL, RL and RT, while ES indicates the enhanced sustainability plot (Table 13). At RT, SS and ES share the same inter-row groundcover (GC) and differ only in under-vine management. At RL, SS and ES share the same inter-row groundcover types (CC and GC), but differ in temporal management: SS alternated CC and GC between inter-rows annually, whereas ES kept CC in the same inter-row each year and maintained GC towards permanent cover.



Figure 23: On the left, the Gerlach microplots installed in the rows of the Rocchetta Ligure vineyard. On the right, the Gerlach tank after collecting runoff water and sediments.

Statistical analysis

All recorded events for each plot across all sites were carefully checked and validated. Events with incomplete data were discarded due to missing precipitation data or incomplete collection of runoff data and samples in the field. This also included cases where failures occurred, such as clogging of the holes or the delimitation bars, or where water did erode underneath and escaped without being collected. All valid runoff and soil loss events recorded over the two years of the experiment were included in the analysis.

Statistical analysis was performed on RC, CES and EC. Comparisons were first made between different treatments within the same site, comparing different sustainability level in soil management (LS vs ES or SS vs ES). Data were averaged among microplots with the same sustainability level for each event and site, and resulting datasets were checked for normality using the Shapiro–Wilk test. Since the normality test failed, statistical differences between treatments (for each site, each treatment, and overall) were assessed using the Kruskal–Wallis rank sum test. The same test was used to investigate differences in the microelements washed away. Differences among groups were assessed using the Kruskal–Wallis rank sum test, followed by pairwise Wilcoxon rank-sum tests with Bonferroni correction for multiple comparisons. Statistical significance was set at $\alpha = 0.05$. Statistical analyses were computed using R (R Core Team, 2025).

Following this analysis, individual microplot data recorded for each event and each site were used to perform Generalized Linear Mixed Models among all records, using main soil treatment (GC, CC and CT) associated to each plot, seasons, event total and maximum precipitation, 14-days antecedent precipitation as fixed effects. The models analysed the responses of vineyard's soils on runoff,

sediment concentration in runoff water and soil erosion with regression coefficients from GLMMs used to assess the strength and direction of the influence of precipitation and management on hydrological and erosion processes across sites. Microplots nested within sites and rainfall events are used as random effects, to account for spatio-temporal variability. Maximum hourly precipitation was log-transformed and, as other precipitation-related explanatory variables, was standardized (Z-scores) to assess their relative importance in the model (β coefficients). The transformation $[y * (n-1) + 0.5] / n$ (n = sample size) was applied to avoid 0 (Smithson & Verkuilen, 2006), which are not allowed by the Gamma distribution family. Significance was set at $p < .05$. GLMM was performed using R software, version 4.03 (R Core Team, 2020), with the “glmmTMB” function of “glmmTMB” package (Magnusson et al., 2017).

Results and discussion

Meteorological conditions during the monitoring period

The year 2022 was one of the warmest on record in Europe since 1950, with a temperature anomaly of $+0.85^{\circ}\text{C}$ relative to the 1991-2020 reference period average (Global Climate Highlights report 2023, 2024). Comparing the rainfall recorded during the monitored period with 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, it is evident that all four sites experienced below-average rainfall in 2022, less evident in 2023 (Table 14). In 2022, all sites recorded precipitation levels below the mean annual values, with CA registering only 52.5 % of the average annual precipitation. The following year 2023 showed higher total precipitation depths across all sites, however CA, NL, and RT still recorded precipitation levels below their respective annual averages, indicating an ongoing drought period and a continued trend of below-average rainfall. Only precipitation recorded in RL exceeded local mean annual precipitation. RT was the driest site in 2023, with only 55.4 % of the annual precipitation. Precipitation in 2023 was concentrated in spring and autumn, with some intense events occurring in summer.

Table 14: Comparison of recorded rainfall (mm) for the years 2022 and 2023 across the four sites with the mean annual precipitation (MAP) calculated over the period 1991-2020 through interpolation of the ARPA Piemonte pluviometric network (2024). The table also includes the percentage of annual precipitation relative to the mean annual values for each site. Note that the values for RT in 2022, marked with an *, are incomplete and cover the period from June onwards. The MAP from June to the end of the year is provided in parentheses.

Site	CA	NL	RL	RT
MAP (mm)	817.2	815.0	1083.4	695.7 (420.6*)
Precipitation 2022 (mm)	428.8	441.8	624.8	271.0*
2022 % of MAP	52.5 %	54.2 %	57.7 %	64.4 %*
Precipitation 2023 (mm)	527.6	624.6	1103.4	385.2
2023 % of MAP	64.6 %	76.6 %	101.8 %	55.4 %

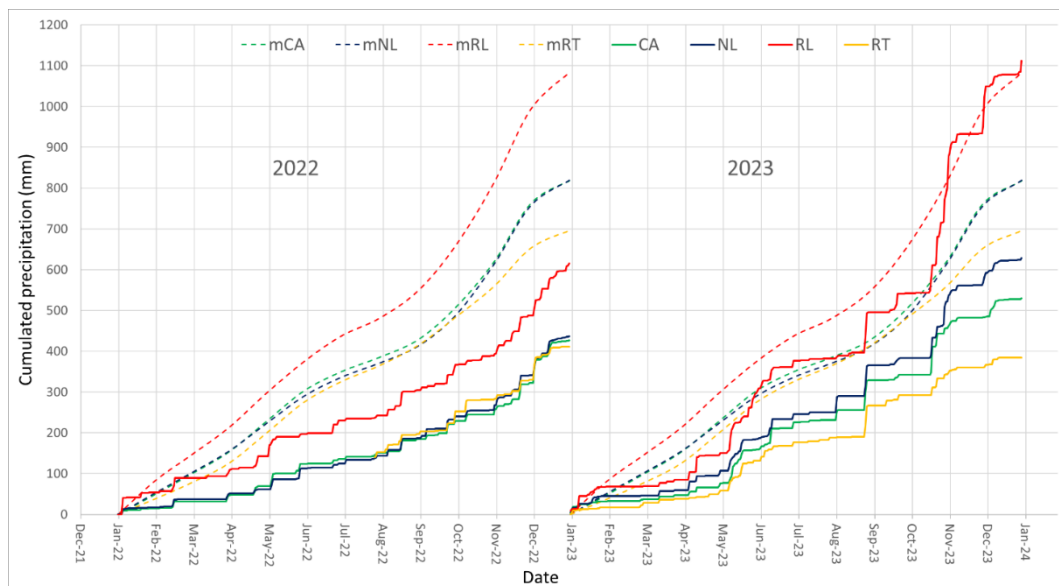


Figure 24: Comparison of recorded precipitation (mm) for the years 2022 and 2023 (solid lines) with the mean annual precipitation (dashed lines), calculated over the period 1991-2020 through interpolation of the ARPA Piemonte pluviometric network (2024) at the four experimental sites.

As observed from the cumulative precipitation graph (Figure 24), the trend was similar across the four sites, with RL receiving more precipitation during some events, although the events themselves were consistent across all sites. Across the monitoring period, runoff-generating events were generally associated with rainfall events recorded at all sites, although rainfall depth and the resulting runoff differed among sites. For CA, rainfall data from the last 25 years were available, enabling the calculation of the SPI (Figure 25). The study period was particularly dry, as indicated by the negative SPI values (with values lower than -2), which identify periods of drought and assess their severity and duration. Notably, the droughts in 2022 and 2023 were the most intense of the past 25 years. The occurrence of these particularly dry years resulted in few significant RO events. In the context of climate change, with increasingly scarce and concentrated precipitation over short periods and the intensification of drought periods, this scenario may represent a possible future situation. Consequently, data were analysed also considering values obtained during more intense rainfall events occurred during the period of observation separately from others.

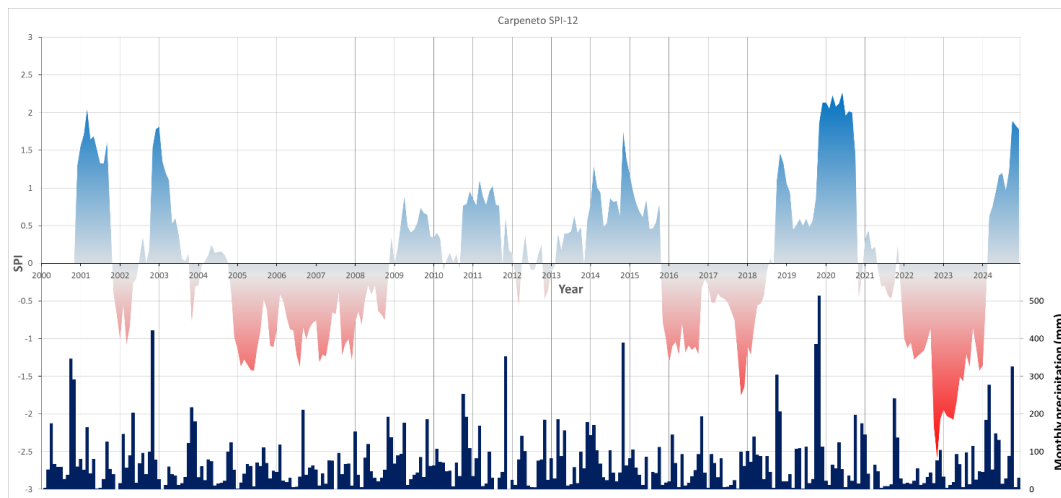


Figure 25: The 12-month SPI index calculated using monthly rainfall values (blue histograms) recorded at CA site over the 25 years from 2000 to 2024. Positive values greater than 1 indicate wet periods (light blue), or extremely wet periods if greater than 2 (blue). Negative values less than -1 indicate dry periods (pink) or extreme drought if less than -2 (red).

Study design considerations and limitations

Micro-plot dimensions were selected based on CNR-STEMS experience to match runoff volumes typically generated in vineyards with comparable soil, slope

and rainfall regimes. Larger plots are generally preferable for runoff and soil-loss monitoring, as very small plots may underestimate erosion compared with larger plot scales (Bagarello et al., 2018). This underestimation is primarily due to the limited representation of hydrological and pedological processes in small-scale plots, where the development of preferential flow paths and soil aggregation dynamics is reduced. Conversely, excessively long plots can introduce unwanted variability due to spatial heterogeneity in topography or surface cover (Bagarello et al., 2010). In this study, plot lengths were ≥ 10 m to capture both sheet and rill processes; site-specific plot dimensions are reported in Table 12. At each site, six micro-plots were installed (three replicates in the baseline LS/SS treatment and three in the ES treatment; Figure 22).

A key strength of the study is the participatory monitoring approach implemented in commercial vineyards. Growers and trained staff enabled event-based observations at multiple sites under real management conditions, enhancing practical relevance and scalability. Potential variability associated with distributed data collection was mitigated through standardized training and protocols, training, and explicit quality-control rules (including exclusion of incomplete or failed events).

A limitation of this study is that N and P losses were not quantified; therefore, conclusions refer specifically to runoff, sediment and dissolved element export (B, Cu, Mn, Fe and major cations) rather than a full macronutrient budget.

Effects of enhanced soil management on runoff and soil erosion

Against this climatic background and within the above design considerations, we next report treatment effects on runoff and soil erosion at each site: the following paragraphs presents results obtained from runoff measurements and analysis of runoff water samples collected after rainfall erosive events. The results were analysed site by site, in order to assess differences among soil managements and their level of sustainability. Finally, an evaluation of the overall effects of the adoption of enhanced soil managements spontaneous grass cover (GC) and selected cover crops (CC) in the region is carried out, considering the peculiarity of the observation period.

Novi Ligure vineyard

At the experimental sites of CA and NL, the maximum values of RO and SL were recorded following the storms occurred in August 2023. Specifically, in NL

(Table 15), the two storms on August 4 and 27, 2023 (totalling 10.8 % of the two-year total precipitation) contributed to more than 90 % of the RO recorded in the rows with SS management and 70 % in the rows with ES management, while SL exceeded 90 % in both treatments. During those events, in the GC rows, with ES management (additional sowing of grass using a no-till seeder), RO was reduced by 27 % compared to SS management, while in the CC rows the reduction was 80 %. RC was higher in both rows of the plot with SS management, with 4 % and 6 % in GC and CC, respectively. SL in GC ES management was five times greater (with a very high EC) compared to SS management. The use of CC resulted in SL lower than GC, with a third more SL in the GC ES rows compared to the GC SS ones.

Considering the entire two-year period RC was similar for the two GC managements (ES compared to SS), while in the CC rows the ES management reduced runoff similarly to the effectiveness shown during August rainfall events. Regarding SL, the GC ES rows recorded a soil loss 4.5 times greater than the SS ones, with very high EC. In the CC rows, SL was lower than in GC, but the GC ES rows experienced 30 % more SL and a higher EC than in the GC SS treatment. However, these differences were not statistically significant.

Both in the case of intense events and considering the two-year period, CC ES management proved to be the most effective in reducing RO, while CC SS management was the least effective. However, CC SS management was the most effective in reducing SL, with less than 400 kg ha⁻¹ over the two years. In fact, the RO water from CC SS management had the lowest CES average. For vineyards using an alternating row system, no-till seeding has demonstrated its potential to minimize soil disturbance and improve soil structure, which can favour water infiltration. The effect of enriched grass cover seems to extend to the CC that grows in the same row the following year. This practice can be particularly beneficial in maximizing water availability for the vines during periods of low precipitation. However, it has not shown a reduction in erosion, and this dynamic requires further investigation. The dry summer preceding the August 2023 events likely contributed to reduce ground cover. Additionally, during the summer, mowing was performed in the CC rows, with the mowed biomass left on the ground to provide a mulching effect and mitigate erosion risk. In September 2023, following the intense events of August, the ground cover was measured. It was, on average, lower in the ES rows compared with the SS rows. Consequently, despite the higher presence of preferential ways in the soil that facilitated greater infiltration, the protective effect may have been diminished, resulting in higher erosion rates. Both cover crops and grass varieties should be selected based on their ability to improve soil protection,

fertility and structure, as well as their resistance to dry periods and microenvironmental condition (Pornaro and Macolino, 2025).

Table 15: Precipitation (P) that generated runoff, runoff (RO), runoff coefficient (RC), mean concentration of eroded sediment (CES), sediment loss (SL), and erosion coefficient (EC) measured in the Novi Ligure plots during the two summer storms on August 4 and 27, 2023, and over the two-year period (TOT). The table also presents the mean values of events along with their corresponding standard deviations. Letters denote statistically significant differences between plots for the same parameter. Numbers in parentheses following the plot name indicate the number of events included in the statistical analysis.

NL		'23 summer events (2)	TOT Σ	mean		dev.st
P (mm)	GC SS (7)	115.2	273.0	39.0		18.0
	CC SS (7)	115.2	273.0	39.0		18.0
	GC ES (7)	115.2	273.0	39.0		18.0
	CC ES (7)	115.2	273.0	39.0		18.0
RO (mm)	GC SS (7)	3.8	4.2	0.6		1.1
	CC SS (7)	5.4	5.8	0.8		1.8
	GC ES (7)	2.8	4.4	0.6		0.8
	CC ES (7)	1.1	1.4	0.2		0.2
RC (%)	GC SS (7)	3.29 %	1.53 %	1.02 %	a	1.49 %
	CC SS (7)	4.65 %	2.11 %	1.33 %	a	2.27 %
	GC ES (7)	2.40 %	1.62 %	1.61 %	a	2.10 %
	CC ES (7)	0.93 %	0.50 %	0.48 %	a	0.58 %
CES mean (g l ⁻¹)	GC SS (7)	25.2		14.7	a	14.4
	CC SS (7)	5.4		7.2	a	5.4
	GC ES (7)	81.7		25.3	a	38.3
	CC ES (7)	20.1		10.5	a	8.0
SL (kg ha ⁻¹)	GC SS (7)	674.4	744.9	106.4		170.0
	CC SS (7)	360.8	389.0	55.6		125.6
	GC ES (7)	3984.2	4155.0	593.6		1355.0
	CC ES (7)	483.4	500.0	71.4		124.2
EC (kg ha ⁻¹ mm ⁻¹)	GC SS (7)	5.85	2.73	2.06	a	2.67
	CC SS (7)	3.13	1.42	0.86	a	1.62
	GC ES (7)	34.59	15.22	9.17	a	17.73
	CC ES (7)	4.20	1.83	1.29	a	1.98

Carpeneto vineyard

The vineyards of CA (Table 16), where the ES management with permanent GC was introduced over 20 years ago, experienced significant RO and SL during the storm occurred on June 12, 2023, in addition to the two storms mentioned earlier

(August 4 and 27, 2023). Summing these three summer events, which represent 13.9 % of the total precipitation over the two years, they accounted for 63 % and 77 % of the total RO measured over the two years in CT LS and GC ES management, respectively. Additionally, they accounted for 95 % and 56 % of the SL in CT LS and GC ES management, respectively.

Considering the entire monitored period in the 2022-2023 biennium, the results are similar: the GC ES treatment RO was reduced by one-third compared to the CT LS treatment. In the CT LS treatment, the RC was double than in the GC ES treatment. SL in CT LS was reduced by 97.6 % with respect to GC ES, and the difference between the two EC was statistically significant. Excluding the values recorded in the summer of 2023, the effectiveness of the grass cover in reducing soil losses decreases. Grass cover was able to protect soil from erosion especially during potentially more erosive events, with maximum hourly precipitation intensity exceeding 20 mm h⁻¹, while it was less effective during moderate intensity events, which did not generate significant erosion. Permanent GC also helps in maintaining soil structure and increasing infiltration rates. Winegrowers should consider adopting permanent grass cover in their vineyards, not only to reduce soil erosion but also to enhance soil quality by increasing organic matter and promoting biodiversity. Regular mowing should be performed to manage the grass cover effectively.

Table 16: Precipitation (P) that generated runoff, runoff (RO), runoff coefficient (RC), mean concentration of eroded sediment (CES), sediment loss (SL), and erosion coefficient (EC) measured in the Carpeneto plots during the 3 summer storms on June 12, August 4 and 27, 2023, and over the two-year period (TOT). The table also presents the mean values of events along with their corresponding standard deviations. Letters denote statistically significant differences between plots for the same parameter. Numbers in parentheses following the plot name indicate the number of events included in the statistical analysis.

CA		'23 summer events (3)	TOT Σ	mean	dev.st
P (mm)	CT LS (14)	133.2	522.2	37.3	18.8
	GC ES (23)	133.2	671.6	29.2	18.8
RO (mm)	CT LS (14)	9.3	14.8	1.06	1.47
	GC ES (23)	6.1	7.9	0.34	0.79
RC (%)	CT LS (14)	7.01 %	2.84 %	2.51 %	a 3.72 %
	GC ES (23)	4.57 %	1.18 %	0.88 %	a 2.00 %
CES mean (g l ⁻¹)	CT LS (14)	49.8		15.3	a 24.0
	GC ES (22)	1.2		5.1	b 10.2
SL (kg ha ⁻¹)	CT LS (14)	3966.9	4190.0	299.3	587.2

EC (kg ha ⁻¹ mm ⁻¹)	GC ES (23)	56.3	100.5	4.4		7.0
	CT LS (14)	29.78	8.02	7.45	a	15.08
	GC ES (23)	0.42	0.15	0.15	b	0.22

Rocchetta Ligure vineyard

At RL (Table 17), relevant amounts of RO and SL were recorded not only in the summer of 2023 but also in the winter and spring of 2023. Specifically, the storms between May and June 2023, with 8 % of the two-year precipitation, resulted in runoff that exceeded the monitoring system's capacity in some rows. Those events resulted in 83 % and 63 % of the total RO measured over the two years, for the rows managed with CC ES and those with GC SS, respectively. Lower values were recorded in the other two plots, contributing 50 % and 17 % of the total RO measured in the rows with CC SS and GC ES, respectively. In the GC rows, ES management reduced RO by 61 % compared to SS management, while in CC rows, RO was more than double in the ES rows compared to the SS ones. The Gerlach tanks collected a significant amount of suspended sediments, resulting in very high CES values, ranging from 300 to 500 g l⁻¹. Consequently, SL values were extremely high, exceeding 90 % of the SL measured over the two years in all plots. Specifically, SL exceeded 6 t ha⁻¹ (99 % of the total) in the GC SS rows, 4.5 t ha⁻¹ (93 %) in the GC ES rows, 3 t ha⁻¹ (98 %) and 1.7 t ha⁻¹ (97 %) in the CC ES and CC SS rows, respectively. In GC rows, ES management reduced SL by 25 % compared to SS, while in the CC rows, SL was 80 % higher with the ES management compared to the SS one. Similar to NL, SL was higher in the GC rows than in the CC rows.

The high values recorded during this period may be due to suboptimal soil management. Mulching of cover crop, light soil tillage using a subsoiler equipped with discs and hilling of the under-row were performed in all rows just before the onset of the wet period. The soil was soft and particularly vulnerable to erosion when the precipitation began. Runoff created rills along the rows, with depths exceeding 15 cm, resulting in significant soil loss that required the farmer to redistribute the soil along the hillside, leading also to an evident economic loss. In this case, the timing of soil-disturbing operations had a greater impact than the type of cover present. This highlights the importance of considering the timing of management practices to minimize soil disturbance and its associated effects. Perhaps no-till seeding, as practiced at NL, would have yielded different results. Due to the extreme and partially incomplete values, this event was not included in the statistical analysis.

Considering the entire monitored period in the 2022-2023 biennium, the results are different: comparing ES management with SS management, there is no reduction in water and soil loss in either the GC or CC rows. CC SS management proved to be the best, with a total RO amounting to 0.5 % of the precipitation and an average soil loss of 2.3 kg ha⁻¹ for each millimetres of rain. In contrast, the CC ES management had RC and EC values more than double, although the difference was not statistically significant. The GC SS row exhibited the highest EC, while the GC ES rows had the highest RC, which was statistically different from both the CC rows. The EC measured in the GC ES rows was statistically higher than in the CC SS.

In the ES plot, maintaining GC in the same row for a second consecutive year showed positive effects during heavy weather events. However, having CC in the same row proved to be ineffective. The CC SS practice demonstrated the best results throughout the year. Therefore, for this site, with its specific soil type and higher rainfall compared to the other sites, the current SS management practice is already optimal. Unlike observations in other vineyards in different regions of Europe (Liebhard et al., 2024), the ES management in this study was likely too extreme, highlighting more negative than positive aspects, which are only evident during heavy rainfall in GC. No-till seeding could be an interesting alternative, as experienced at the NL site.

Table 17: Precipitation (P) that generated runoff, runoff (RO), runoff coefficient (RC), mean concentration of eroded sediment (CES), sediment loss (SL), and erosion coefficient (EC) measured in the Rocchetta Ligure plots during the four spring storms in May and June 2023, and over the two-year period (TOT). The table also presents the mean values of events along with their corresponding standard deviations. Letters denote statistically significant differences between plots for the same parameter. Numbers in parentheses following the plot name indicate the number of events included in the statistical analysis.

	RL	'23 spring events (4)	TOT Σ	mean	dev.st
P (mm)	GC SS (11)	136.6	583.4	53.0	38.4
	CC SS (17)	136.6	747.4	44.0	33.1
	GC ES (17)	136.6	747.4	44.0	33.1
	CC ES (11)	136.6	583.4	53.0	38.4
RO (mm)	GC SS (11)	>4.0	>6.4	0.6	1.2
	CC SS (17)	1.9	3.7	0.2	0.4
	GC ES (17)	1.6	9.2	0.5	0.4
	CC ES (11)	>6.2	>7.4	0.7	1.8
RC (%)	GC SS (11)	2.96 %	1.09 %	0.79 %	ab 0.97 %

CES mean (g l ⁻¹)	CC SS (17)	1.38 %	0.49 %	0.39 %	b	0.41 %
	GC ES (17)	1.16 %	1.23 %	1.42 %	a	0.87 %
	CC ES (11)	4.55 %	1.27 %	0.72 %	b	1.41 %
	GC SS (8)	536.6		3.9	a	3.5
	CC SS (13)	295.0		7.8	a	9.7
	GC ES (14)	331.3		5.9	a	7.0
	CC ES (8)	441.6		13.7	a	12.4
SL (kg ha ⁻¹)	GC SS (11)	>6000.0	>6042.5	549.3		1807.8
	CC SS (16)	1666.7	1710.8	106.9		416.0
	GC ES (16)	4500.0	4818.2	301.1		1120.3
	CC ES (11)	>3000.0	>3053.1	277.6		903.0
EC (kg ha ⁻¹ mm ⁻¹)	GC SS (6)	43.92	10.36	0.18	ab	0.18
	CC SS (13)	12.20	2.29	0.09	a	0.11
	GC ES (14)	32.94	6.45	0.68	b	0.97
	CC ES (6)	21.96	5.23	0.23	ab	0.33

Rocchetta Tanaro vineyard

At RT (Table 18), three-quarters of the total RO was generated by five events occurred in autumn 2022 and summer 2023. The two events occurred on September 30 and October 8, 2022 (totalling 8.6 % of the total precipitation during the monitored period), produced more than three-quarters of the SL recorded during the study period, specifically 78 % and 76 % in the SS and ES rows, respectively. These two events also generated 38 % of the total RO in the SS plot and 32 % in the ES plot during the monitored period. During these intense events, ES management with mechanical weeding under the vines reduced the volume of water loss to RO by one-third compared to the use of chemical herbicides, while the difference in SL was minimal. Considering the entire monitored period, the reduction in RC with ES management was lower, around 20 %. Regarding the erosion, the EC was lower than 0.4 kg ha⁻¹ mm⁻¹ in both plots.

The statistical analysis did not reveal any significant difference. This minimal difference observed could be attributed to the fact that the differentiation between the two treatments only affected the under-vine area, which is a smaller portion of the soil compared to the inter-row area. Additionally, the under-vine area is less affected by compaction due to machinery passage for vineyard's management, resulting in less soil disturbance. Using mechanical weeding methods in the under-vine area is also recommended to minimize the environmental impact of herbicide use, promoting a healthier vineyard ecosystem (Gagliardi et al., 2023). It will be interesting to see in future research whether more pronounced differences emerge,

for example, in the quality and quantity of grapes produced, and the potential effects of combining under-vine management with inter-row management.

Table 18: Precipitation (P) that generated runoff, runoff (RO), runoff coefficient (RC), mean concentration of eroded sediment (CES), sediment loss (SL), and erosion coefficient (EC) measured in the Rocchetta Tanaro plots during the two autumn events on September 30 and October 8, 2022, the five events in autumn 2022 and summer 2023, and over the two-year period (TOT). The table also presents the mean values of events along with their corresponding standard deviations. Letters denote statistically significant differences between plots for the same parameter. Numbers in parentheses following the plot name indicate the number of events included in the statistical analysis.

RT		'22 autumn events (2)	'22 autumn + '23 summer events (5)	TOT Σ	mean	dev.st
P (mm)	GC SS (17)	56.4	212.6	436.8	25.7	17.8
	GC ES (17)	56.4	212.6	436.8	25.7	17.8
RO (mm)	GC SS (17)	3.26	6.19	8.56	0.50	0.56
	GC ES (17)	2.16	5.42	6.78	0.40	0.52
RC (%)	GC SS (17)	5.77 %	2.91 %	1.96 %	2.23 %	a 2.29 %
	GC ES (17)	3.83 %	2.55 %	1.55 %	1.33 %	a 1.44 %
CES mean (g l ⁻¹)	GC SS (17)	4.9	2.1		1.6	a 2.1
	GC ES (17)	4.8	2.1		3.1	a 5.5
SL (kg ha ⁻¹)	GC SS (17)	124.6	133.5	160.7	9.5	22.3
	GC ES (17)	121.8	133.1	159.6	9.4	25.5
EC (kg ha ⁻¹ mm ⁻¹)	GC SS (17)	2.21	0.63	0.37	0.42	a 0.78
	GC ES (17)	2.16	0.63	0.37	0.39	a 0.90

Effectiveness of the enhanced soil managements in reducing runoff and soil erosion

Because of the drought period, the overall RO measured was lower than 3% of precipitation, and consequently, SL was generally lower than $15 \text{ kg ha}^{-1} \text{ mm}^{-1}$ (Table 14-18). In general, across all four sites, most of the RO was measured during the spring and summer events of 2023, which, along with the autumn events of 2022, recorded the highest SL values, resulting in EC up to $43.92 \text{ kg ha}^{-1} \text{ mm}^{-1}$ (Table 14-18). Comparing the RO measured in the inter-rows with different level of sustainability across all vineyards, it is evident that ES management was not always advantageous compared to SS management. At RT and NL, RO was reduced in the GC rows but slightly increased in the CC rows, while at RL, ES management was detrimental, particularly in the CC inter-rows. Both CC ES cases performed worse, indicating that the current conventional practices are already optimal. The best results were obtained by transitioning from the LS management with bare soil and traditional tillage to the ES with permanent grass cover, as observed at CA.

When considering the summer 2023 rainfall events separately from the others, the average value of RC was lower in the rows with ES management compared to the corresponding SS or LS management, with exception of the CC rows at RL. In case of low precipitation, the differences between various types of groundcover are not so evident. Soil management practices need to be adjusted based on seasonal and climatic conditions to optimize their effectiveness in reducing runoff and erosion (Dugan et al., 2024; Telak et al., 2021).

Soil erosion measured in the micro-plots over the entire observation period (expressed as EC in $\text{kg ha}^{-1} \text{ mm}^{-1}$ to allow comparison between different sites) was considerably lower in the permanently GC rows at CA site ($0.15 \text{ kg ha}^{-1} \text{ mm}^{-1}$) and RT site ($0.63 \text{ kg ha}^{-1} \text{ mm}^{-1}$) compared to all other inter-row management types. At RL and NL site, CC management had better results than temporary GC management, although ES management was advantageous only in the GC rows at RL.

Considering the summer 2023 events separately, they were responsible for most of the SL measured over the biennium, with SL in some cases exceeding 300-400 kg ha^{-1} per mm of rain. Also, in this period, CC management performed better than other management.

As highlighted before, the results refer to mainly dry years characterized by few erosive events, occurred especially during spring and summer 2023, after long dry periods. Soil behaviour may vary significantly in wetter years, as documented in previous studies (Biddoccu et al., 2017) in one of the vineyards included in this study. Further analysis including wetter years would provide a more comprehensive understanding and facilitate the fine-tuning soil management practices for better results.

Effectiveness of different categories of soil management

The GLMM (gaussian distribution, AIC = 772.4) indicated that runoff was strongly controlled by rainfall characteristics and further modulated by soil management and seasonal conditions. Event maximum hourly precipitation (Pmax) showed a strong positive association with runoff (estimate = 0.412, $p = 0.0033$), indicating that more intense storms increase the likelihood of infiltration excess overland flow. Antecedent (14-days) precipitation (Prec14), considered as a proxy of soil wetness, showed a marginal positive effect ($p = 0.065$), suggesting that slightly wetter soils tend to generate more runoff, likely due to generation of runoff for saturation-excess. This runoff generation process is likely the one expected for large precipitation event, since total event precipitation (Prec) had a strong positive effect (estimate = 0.74, $p < 0.0001$). Inter-row soil management had a significant main effect ($\chi^2 = 24.72$, $p < 0.001$), with GC showing a marginal increase ($p = 0.081$) compared to CC. Post hoc tests indicated that CT produced significantly more runoff (Tukey $p < 0.0001$) than both CC (estimate = 0.59, $p < 0.001$) and GC. Seasonal differences were also evident ($\chi^2 = 21.07$, $p < 0.001$), driven largely by lower runoff in Winter (estimate = -0.79 , $p < 0.001$) than in other seasons. These results demonstrate that hydrological connectivity is highly variable over the year, due to temporal changes in soil hydraulic behaviour, vegetation cover, and soil moisture, as demonstrated in vineyards with different soil management by direct measurements in vineyard at plot scale (Rodrigo Comino et al., 2017).

Among analysed interactions, several were significant: $P_{max} \times \text{Treat_1}$ ($\chi^2 = 31.10$, $p < 0.001$) and $P_{max} \times \text{Season}$ ($\chi^2 = 30.78$, $p < 0.001$), indicating that the influence of peak rainfall varied by treatment and season. Under CT treatment, runoff increased steeply with rising rainfall intensity (interaction = 0.475, $p = 0.0014^*$), reflecting lower infiltration capacity, which is documented with this kind of soil management due to effect of tractor traffic (Gambarani et al., 2026; Capello et al. 2019; Biddoccu et al. 2013). Under GC, the interaction was small and non-significant, indicating that ground cover buffers the hydrological sensitivity to

storm intensity. This confirms that tilled vineyards are more vulnerable during intense rainfall, whereas grass cover confers hydrological resilience, as observed by Bagagiolo et al. (2018) in long-term observations. The interaction effect between rainfall intensity and seasons was strongly negative for winter (interaction = -0.891 , $p < 0.0001$), indicating that in winter even intense storms produce less runoff, possibly due to the increased macroporosity. During spring events, rainfall intensity increased runoff significantly less than in autumn (interaction = -0.368 , $p = 0.0024$), likely due to protective effect of grass cover and early vegetation promoting infiltration. A small but significant negative interaction emerged for $\text{Treat_1GC} \times \text{Prec}$ (estimate = -0.25 , $p = 0.037$), with respect to cover crops. Random effects showed substantial variability at the event level ($\text{SD} = 0.279$), while spatial variability effects (microplots nested within sites) were negligible. The fixed effects explained more than half of the variance, with random factors contributing moderately to total explained variation ($R^2\text{m} = 0.57$, $R^2\text{c} = 0.65$).

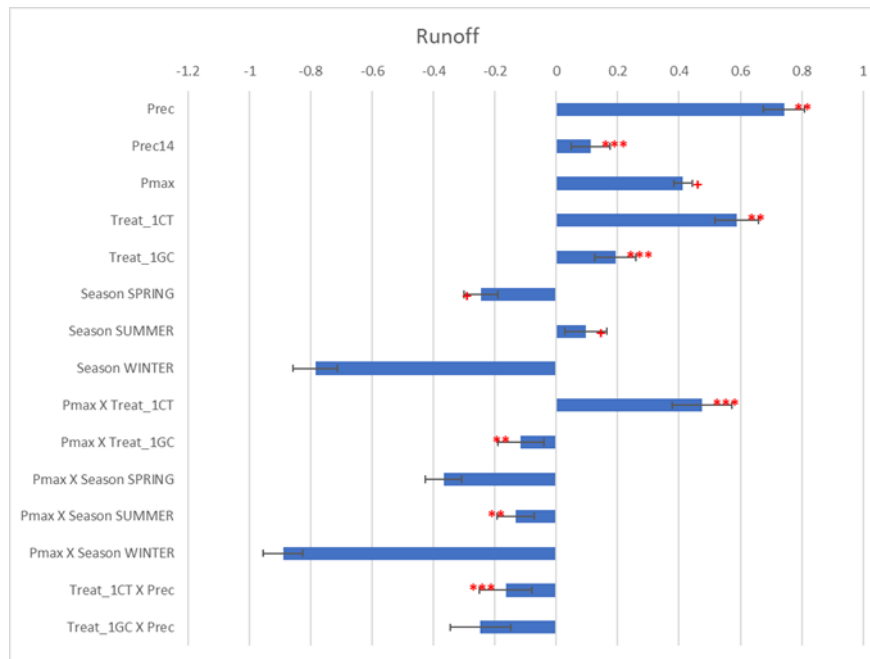


Figure 26a: GLMM regression coefficients showing the fixed effects of soil treatments (Treat), seasons (Season), event total precipitation (Prec), event maximum hourly precipitation (Pmax), 14-days antecedent precipitation (Prec14) and interactions on runoff. Significance levels are indicated as: + < 0.1 , * < 0.05 , ** < 0.01 , *** < 0.001 .

3.2.3 Effects of different categories of soil management on sediment concentration

The GLMM (Gamma distribution, AIC = 1572.3) showed that sediment concentration was strongly influenced by rainfall characteristics, season, and treatment, with additional temporal and spatial variability (attributable to event and microplots and site random effects). The model explained a substantial fraction of variability (marginal $R^2=0.35-0.36$; conditional $R^2=0.78-0.87$), indicating that fixed effects captured one third of the structure while random effects represented dominant spatial-temporal heterogeneity. Random intercepts for event (variance = 1.026; SD = 1.03) and microplots within site (variance = 1.061; SD = 1.01) were both large, reflecting substantial variability in sediment concentration associated with storm specific conditions and small scale spatial heterogeneity not explained by fixed effects. Hourly maximum rainfall intensity (Pmax) exerted a significant negative effect on sediment concentration (estimate = -0.87 , $p = 0.0085$), indicating that intense events tended to produce lower sediment concentration, due to increasing runoff volume. On the contrary, total precipitation (Prec) increased sediment concentration (estimate = 0.54 , $p = 0.028$), suggesting that larger rainfall amounts mobilized more sediment into runoff. Antecedent rainfall (Prec14) showed a marginal negative effect ($p = 0.083$), indicating a tendency for wetter soils to produce lower sediment concentrations. Season exerted a pronounced influence ($\chi^2 = 25.76$, $p < 0.001$). Winter exhibited markedly lower sediment concentrations than autumn (the reference season) (estimate = -2.22 , $p < 0.001$), whereas summer showed a moderate tendency toward higher concentrations (estimate = 1.03 , $p = 0.062$). Treatment effects were significant ($\chi^2 = 6.23$, $p = 0.044$). Compared with the reference treatment (CC), GC significantly reduced sediment concentration (estimate = -1.12 , $p = 0.019$), while CT showed no significant difference ($p = 0.65$). Interestingly, strong interaction between Pmax and treatment was detected ($\chi^2 = 15.81$, $p < 0.001$), indicating that the dilution or mobilization effect of rainfall intensity differed among treatments. Under CT conditions, rainfall intensity produced a strong increase in sediment concentration (interaction = 1.06 , $p < 0.001$), whereas GC showed a weaker, borderline significant positive interaction (interaction = 0.42 , $p = 0.068$). This pattern suggests that sediment mobilization during intense storms is most pronounced in CT plots, while GC maintains overall lower concentrations even when storms intensify. The Pmax $\times$ Season interaction was also significant ($\chi^2 = 13.12$, $p = 0.004$), indicating that the response of sediment concentration to rainfall intensity changes seasonally. In spring, intense storms sharply increased sediment concentration (interaction = 0.96 , $p = 0.0028$), whereas summer and winter showed no significant modification of the intensity-concentration relationship. This reflects seasonal differences, likely due to presence of vegetative cover.

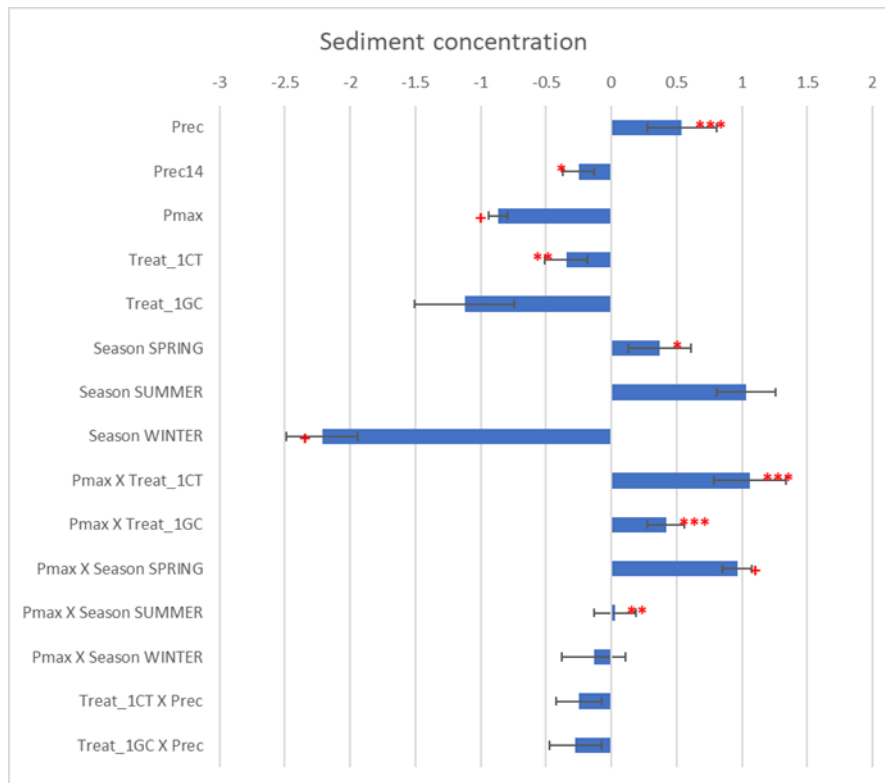


Figure 26b: GLMM regression coefficients showing the fixed effects of soil treatments (Treat), seasons (Season), event total precipitation (Prec), event maximum hourly precipitation (Pmax), 14-days antecedent precipitation (Prec14) and interactions on sediment concentration. Significance levels are indicated as: + < 0.1, * < 0.05, ** < 0.01, *** < 0.001.

Effects of different categories of soil management on soil losses

The GLMM (Gamma distribution, AIC = 1422.6) revealed that soil losses were primarily controlled by rainfall characteristics and their interactions with soil management and season, while most main effects related to treatment and season alone were not significant. The model showed substantial explanatory power, with marginal R^2 between 0.37–0.52 and conditional R^2 between 0.64–0.90, indicating that fixed effects captured about half of the variation in soil loss, and that storm and microplots level variability accounted for a large portion of the remaining heterogeneity. Total event precipitation (Prec) had a significant positive effect (estimate = 1.01, $p = 0.0197$), indicating that larger rainfall amounts consistently increased soil loss across treatments, whereas peak rainfall intensity (Pmax) showed a positive but nonsignificant trend ($p = 0.156$), consistent with the expectation that more intense rainfall increases erosivity, though this effect alone was insufficient

to explain variability in soil loss without interactions. Antecedent precipitation (Prec14) had no significant effect ($p = 0.275$), suggesting that soil wetness prior to rainfall events did not markedly influence the amount of soil losses. Seasonal effects were not significant overall ($\chi^2 = 4.87$, $p = 0.18$), although summer showed a significantly lower soil loss compared to Autumn (baseline season) (estimate = -1.69 , $p = 0.030$), reflecting reduced erosion under summer conditions. No significant differences were detected among soil managements, considering the soil treatment alone (all $p > 0.65$). Two strong interactions emerged, both involving maximum hourly precipitation. Main interaction with treatment was highly significant ($\chi^2 = 13.28$, $p = 0.0013$), showing that the erosive response to storm intensity differed among treatments, with increasing soil losses under CT treatment (interaction = 1.21 , $p = 0.0097$), indicating high vulnerability of conventionally tilled soil during intense storms. Under GC, the interaction was small and nonsignificant ($p = 0.63$), meaning ground cover management maintained stable, lower soil losses even as rainfall intensity increased. This confirms that management practices strongly regulate the sensitivity of soil erosion to extreme rainfall. Also, interaction with season was also highly significant ($\chi^2 = 18.07$, $p < 0.001$), revealing strong seasonal modulation of the intensity–soil loss relationship: summer exhibited a strong positive intensity response (interaction = 1.74 , $p = 0.0015$), confirming that intense storms in summer mobilize substantially more soil, whereas spring and winter showed no significant modification of the rainfall intensity effect (all $p > 0.17$). The high significance of interaction between Pmax and summer is related to the relevance of some soil erosion summer events, which produced very high soil losses in some vineyards (magnitude in the order of tons/ha). As the majority of summer erosion events, they were characterized by storms with high rainfall intensity, which results in large runoff and sediment concentration, but with no significant effect of the interactions on single dependent variables. The dominance, in soil erosion processes, of few events with very high magnitude was already observed both in long term monitoring and in reporting the effects of single events.

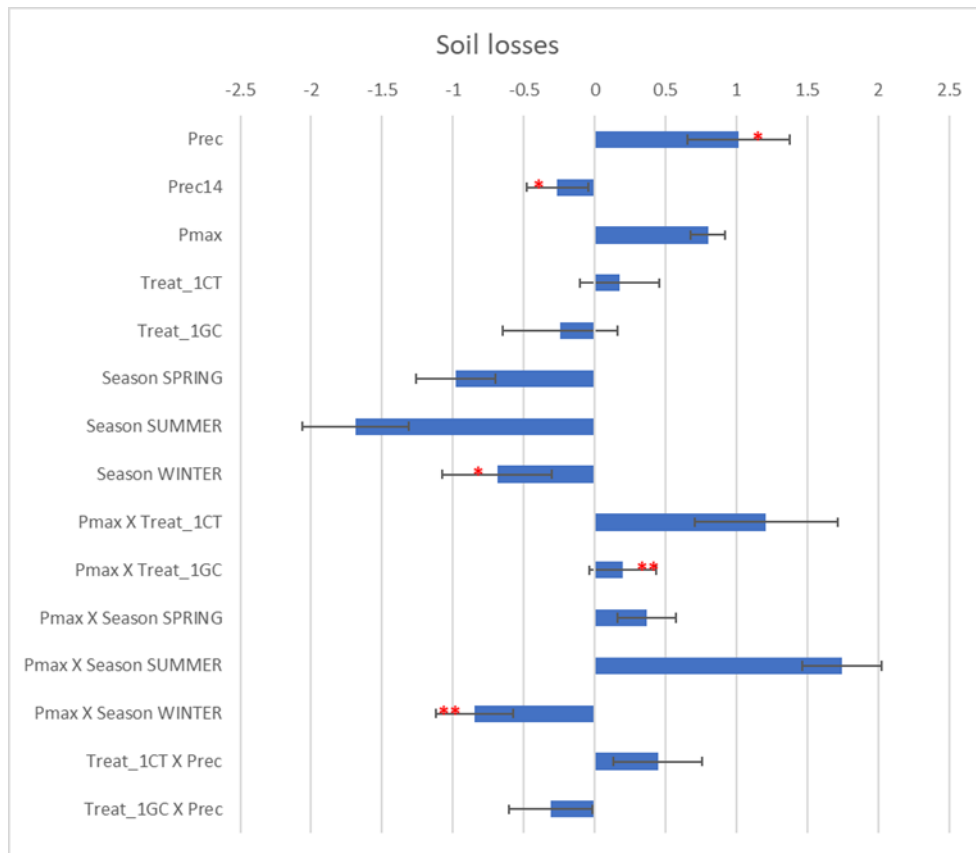


Figure 26c: GLMM regression coefficients showing the fixed effects of soil treatments (Treat), seasons (Season), event total precipitation (Prec), event maximum hourly precipitation (Pmax), 14-days antecedent precipitation (Prec14) and interactions on soil losses. Significance levels are indicated as: + < 0.1, * < 0.05, ** < 0.01, *** < 0.001.

Overall effects of sustainable soil managements on nutrient losses

Effect of soil management on nutrient removal was also analysed, considering the concentration in the runoff water samples and the amount of microelements removed in the runoff water (expressed in mg), related to the cumulative precipitation of the events to which the samples refer, resulting in removal per mm of rain (mg mm^{-1}).

Significant differences in nutrient concentrations were detected only at the CA site, where Ca in LS is four times higher than in ES. In other sites, there are no significant differences between management practices. Even when comparing all SS treatments with all ES treatments, there are no significant differences, while LS

is consistently significantly higher than other treatments for Ca, Fe, Mn, Cu, B and Al (Fig.27).

Analysing the seasonal trends, the concentration of dissolved ions is higher for bicarbonates and minimal for other ions (carbonates, chlorides, sulfates) in water collected throughout the winter season, with no evident differences between treatments. In spring, the concentration of chlorides and sulfate is higher following post-fertilization rains, generally with higher concentrations in the RO from the LS and SS plot compared to the ES one.

Generally, during winter, the microelement values remain quite stable, with minimal concentrations and no evident differences between management practices. The highest concentrations of Mg and B are usually observed following the first post-fertilization event, with higher values in the samples collected from the LS and SS plot. For the RL site, K was particularly elevated in the samples collected in the CC SS plot in spring 2023 (SM2, Fig.28a). In the same site, it is also observed that for Na, K, and B, the relationship between CES and microelement concentration is directly proportional, with a greater increase in CES and corresponding microelement in the SS rows compared to the ES ones (SM2, Fig.28b, c, d). The relationship shows a high R^2 , particularly for K and B.

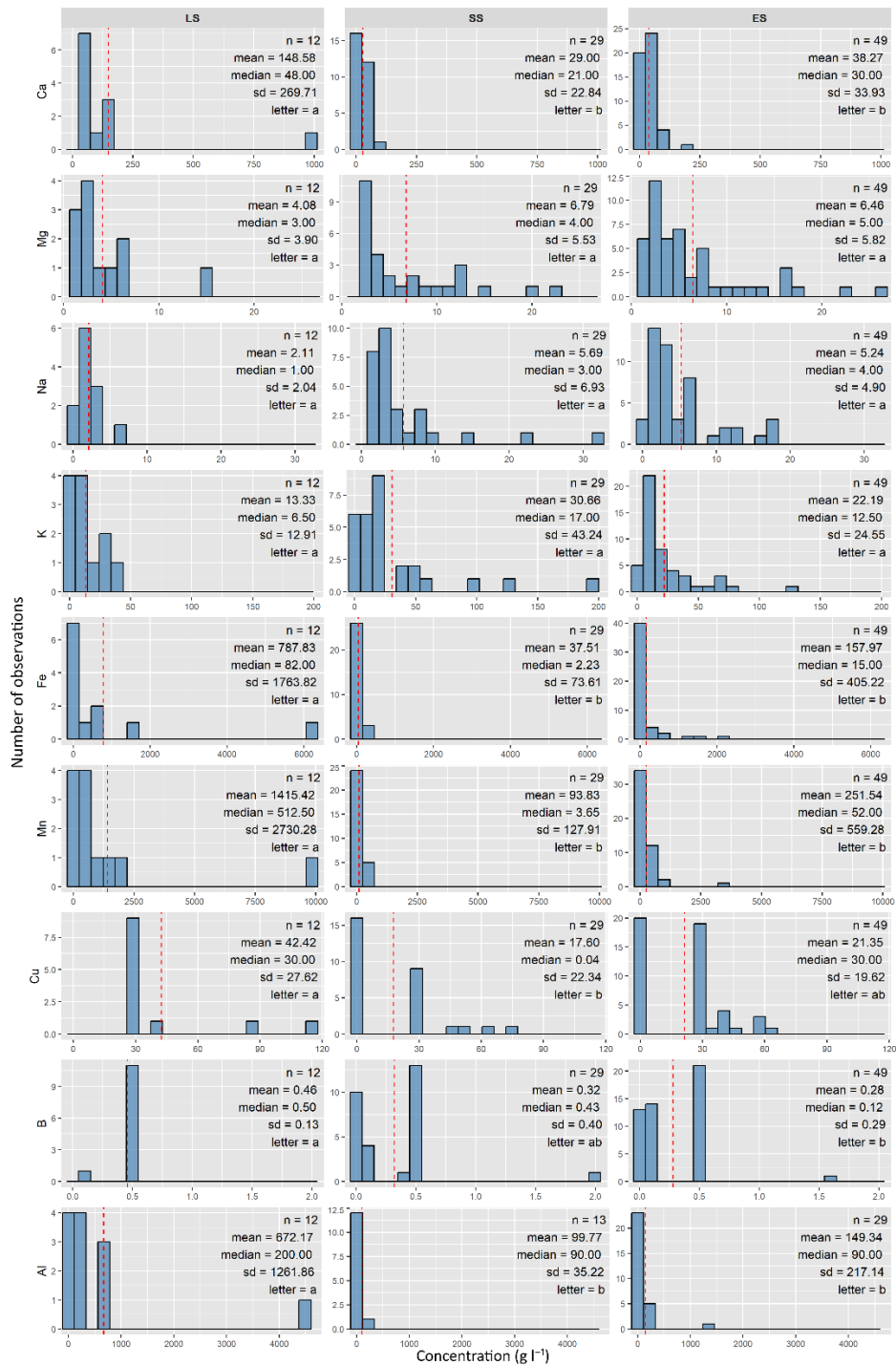


Figure 27: Distribution of microelement concentration values in runoff water (g l^{-1}) across the three treatments. Bars represent the frequency of observations (count per bin); the red dashed line indicates the mean. For each treatment, sample size (n), mean, median,

and standard deviation (SD) are reported. Letters denote homogeneous groups according to pairwise Wilcoxon rank-sum tests with Bonferroni correction ($\alpha = 0.05$).

Figure 31 (SM3) shows the amount of microelements in removal per mm of rain (mg mm^{-1}). Analysing values for all SS with all ES treatments, there are significant differences only for Al. However, LS in CA was significantly different for Na and B, with significantly lower and higher values, respectively. Again, the most significant differences were recorded in CA site, where LS plot showed higher values than ES for all elements except Na. The difference was statistically significant for Al, B, Ca, and Cu. In the RL vineyard, higher values were recorded in the ES compared to the SS management, with significant differences in Mg, Na, K, Fe, Mn, and Cu. In other vineyards, differences in nutrient removal between ES and SS management were not significant.

The results suggest that LS management may lead to greater loss of essential nutrients, which could have implications for soil fertility and the need for fertilization interventions. Other studies already highlighted the role of soil management in export of chemical elements in vineyards: exports were highly correlated with soil losses in a study by Dugan et al. (2024), with higher export in Spring and Autumn. In addition, Imfeld et al., (2023) observed that soil disturbance, particularly before a rainfall event, can be responsible of high export of dissolved Cu and Zn in runoff. The significant variability in nutrient removal across seasons indicates that soil fertilization, should be managed to minimize nutrient loss due to water erosion. The loss of nutrients through runoff can have a significant impact on aquatic ecosystems, contributing to water pollution and eutrophication (Ojha, 2021). This underscores the importance of developing soil management practices that minimize nutrient loss and protect water quality. Future studies could investigate how the type and timing of fertilization influence the presence of nutrient in the RO.

Considerations about vine-growers's engagement in the study

Even considering the limitations of this 2-years study, the outcomes of the observations in operational environments confirm results obtained from long-term monitoring in the same region (Biddoccu et al., 2016; Bagagiolo et al., 2018) and modelling results in European vineyards (Biddoccu et al., 2020). Constraints related to carrying out the study in commercial farms include the duration and number of observations, the limited number of replications, the heterogeneity of adopted soil managements. Furthermore, the use of the Gerlach systems to collect runoff and soil loss data offer some difficulties as already observed in previous studies

(Morgan, 2009; Wicharuck et al., 2023), which, in this study, resulted in the discarding of some measurements due to problems in collecting observations and samples. Nevertheless, this remains one of the most used system which allows to measure directly soil erosion by water over a variety of land uses and climatic conditions. Indeed, involvement of farmers in the study has the advantages to be based on direct measurements in a real-world context, carried out with a participatory approach in different stages of the study and resulting in increase of knowledge and awareness of soil erosion processes and impacts of soil management practices on soil and water conservation. Previous studies using Gerlach systems to monitor soil erosion directly in the fields highlighted how results obtained with this system in an operational environment allow to include the effects of soil management practices in terms of temporal and spatial variability of soil characteristics and response, which may be not so evident in experimental sites with more controlled conditions (Rodrigo-Comino et al., 2019; Antoneli et al., 2022). The perception of soil degradation processes as a threat for vine-growing and the attitude towards the adoption of sustainable soil management as viable solution are very heterogeneous across Europe (Marques et al., 2015; Cerdà & Rodrigo-Comino, 2021, Caffaro et al., 2026). In this context, the citizen engagement has potential to expand soil monitoring on larger number of sites and across different landscapes, to engage the public and final users next to scientists in obtaining and disseminate research results, and finally can increase knowledge, awareness and contribution of farmers toward more holistic resource management (Charvát et al., 2022).

Conclusions

This study has investigated the impact of vineyard management practices on runoff dynamics, soil erosion, and nutrient losses, focusing on practices with increasing levels of soil conservation used in commercial vineyards located in the Piedmont region of Italy. The study was conducted with collaboration of the farmers in the framework of activities of the IN-GEST SOIL OG project. The soil management used in the inter-rows moved from conventional tillage to use of permanent grass cover in all rows, including temporary cover in alternate rows with seeded or spontaneous vegetation, and different management of the under-vine vegetation. By comparing these different soil management practices, we have identified methods that are more effective in reducing water, soil and nutrient loss. These practices were evaluated under peculiar climatic conditions such as droughts and intense rainfall that characterized the two years of the experiment and may represent a possible recurrent future situation.

The result of the study highlights the best performance of adopted soil management practices in controlling runoff and soil erosion in the inter-rows in the region:

The occurrence of particularly dry years during the monitoring period led to a limited number of significant events where water and soil loss were concentrated: during such intense and erosive events, the more sustainable approaches consistently performed better than conventional ones.

The best improvement in terms of runoff, erosion and microelements loss was achieved by transitioning from a low sustainability management with bare soil and conventional tillage management to permanent grass cover in all rows, as observed at the Carpeneto vineyard.

Conventional tillage management may lead to loss of essential nutrients, especially during intense rainfall events, which could have implications for soil fertility and requests fertilization interventions.

The use of alternate rows managements (one row with temporary spontaneous grass cover and the second with selected annual cover crop, changed yearly) represents a trade-off between traditional soil management and more sustainable approach. However, it shows higher vulnerability to erosion during intense events compared to permanent grass cover in all rows.

In the case of alternate rows management, the currently adopted practices using cover crops in South Piedmont are already optimal, resulting in a lower volume of runoff and sediment loss even though the concentration of suspended sediment is higher than in the rows with spontaneous grass cover.

No-till seeding of cover has demonstrated its potential to minimize soil disturbance and improve soil structure, which can favour water infiltration. This practice can be particularly beneficial in maximizing water availability for the vines during periods of low precipitation.

The under-vine area, considering its small surface, influence runoff only in case of intense events. Farmers should concentrate efforts on the inter-row area, but good management of the under-vine area is also recommended to minimize the environmental impact of herbicide use, promoting a healthy vineyard ecosystem.

In all plots, the concentration of microelements in runoff is higher during rain following fertilization operations, generally with higher concentrations from the low and standard sustainability plot compared to the enhanced one. The significant variability in nutrient removal across seasons indicates that soil management practices should be optimized in order to minimize nutrient loss.

The results of this study conducted in an operational environment confirmed finding of long-term observations or prediction for vineyards in the region. This study highlights how soil management practices need to be adjusted based on local seasonal conditions to optimize their effectiveness in reducing runoff and erosion, adapting the management on the basis of meteorological conditions during the year and the productive season. Cover crops varieties or spontaneous grass should be selected based on their ability to improve soil protection, fertility, and structure, as well as their resistance to dry periods. Moreover, the timing of soil-disturbing operations has a greater impact than the type of cover present. This highlights the importance of considering the timing of management practices to minimize soil disturbance and its associated effects. All of this involves winegrowers gaining increasing knowledge and awareness of what they can do to improve soil health, starting from observing and recognising soil degradation processes, to make use of the support of viticultural technicians and monitoring and decision-making tools.

Supplementary materials

Gerlach trough for runoff and sediment collection in vineyard's inter-row.

This runoff and sediment collection system consists of a partially buried 20-liter collection tank, equipped with a sedimentation zone and a partition to retain suspended particles (leaves, grass, shredded vine shoots). The tank was designed as a Gerlach trough (Gerlach, 1967), with dimensions suitable to be placed within a vineyard inter-row (Figure 28 (SM1) a, b). Two steel delimitation bars channel the surface RO into the tank, ensuring the collection of all water flowing between the rows (Figure 28 (SM1) c). The tank and the delimitation bars were designed to allow tractor traffic in the vineyards during most of operations carried out for vineyard's management, in case of vineyards with slope up to 20% (Figure 29 (SM2)). The system was managed with collaboration of farmers properly trained, who collaborated also in measurement and sampling operations (Figure 30 (SM3) a). During minor rainfall events, any RO is collected and contained within the tank (Figure 30 (SM3) c). The tanks are designed to correctly collect even exceptional

RO events: in addition to the standard Gerlach tank, a multi-pipe divisor (with eight pipes) is installed on the downstream side of the tank (Figure 28 (SM1) b). Seven of these holes are for overflow, while one hole is connected via a flexible tube to an underground tank with a useful volume of approximately 15 litres (Figure 29 (SM2)). To prevent the eight holes from clogging with suspended particles, a mesh is installed to delimit the sedimentation zone before the holes. It is important that the tank is perfectly level to ensure proper functioning. To obtain measurements of RO, the depth of water collected in the Gerlach tank and in the second tank at the end of each event is measured manually with a precision of 1 mm. Depending on the plot size, 1 mm in the Gerlach tank corresponds to 0.005-0.006 mm of RO, and 1 mm in the second tank corresponds to 0.013-0.017 mm of RO. Before the manual measurement of the water level, potential failures are checked, such as clogging of the holes or the delimitation bars, and ensuring that water has not eroded underneath and escaped without being collected. In addition, field observations are carried out to verify that there are no evident anomalies in the microplot area, such as runoff from other external sources, like adjacent rows overtopping the delimitation, or signs of water inflow from upslope. Only in the case of positive check, the corresponding measurements and sample were considered in the following analysis. Then water in the tank is mixed to suspend the sediments, and at least 1 litre sample of water and sediment is collected (Figure 30 (SM3) d). After the measurement, the tank is completely emptied and cleaned, facilitated by a drain valve at the bottom, and it is ensured that the tank remains perfectly level. Farmer's involved in the project were trained to manage the collection system.

After each rainfall event resulting in runoff, the depth of runoff water (mm) is calculated (Eq.1) based on the volume of water collected (V_{RO} , Eq. 2) in the Gerlach trough V_1 (and the second tank, V_2), and the sampled area (A). Runoff samples are filtered, dried, and weighed in the laboratory to determine the concentration of suspended sediments (CES). The amount of SL (kg ha^{-1}) was calculated (Eq.3) by multiplying the volume of RO by the CES and then relating it to the micro-plot surface area. Runoff coefficient (RC, %) is calculated by dividing the amount of RO (mm) by the total amount of rainfall (P , mm) over a specific period (Horton, 1935).

$$RO \text{ (mm)} = \frac{V_{RO} \text{ (l)}}{A \text{ (m}^2\text{)}} \quad (\text{Eq. 1})$$

$$V_{RO} \text{ (l)} = V_1 \text{ (l)} + V_2 \text{ (l)} \times 8 \quad (\text{Eq. 2})$$

$$SL \left(\frac{kg}{ha} \right) = RO (l) \cdot CES \left(\frac{g}{l} \right) \cdot 10 \quad (\text{Eq.3})$$

$$RC (\%) = \frac{RO (mm)}{P (mm)} \quad (\text{Eq.4})$$

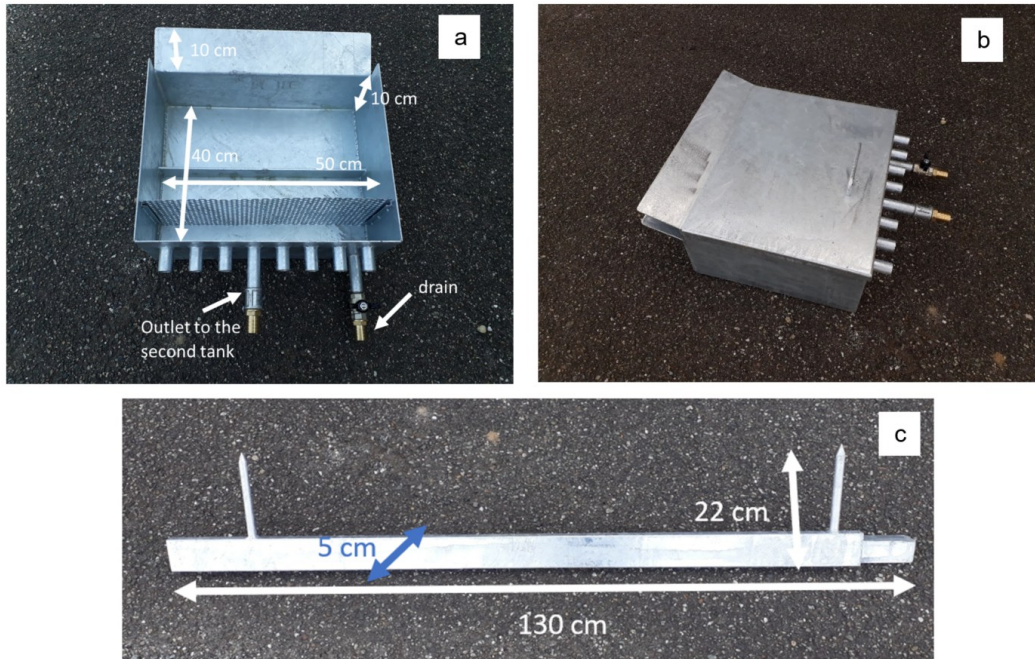


Figure 28 (SM1): a) Gerlach trough designed to be placed in the middle of a vineyard's inter-row, with sedimentation section and filter; b) Gerlach trough with cover; c) delimitation bars.

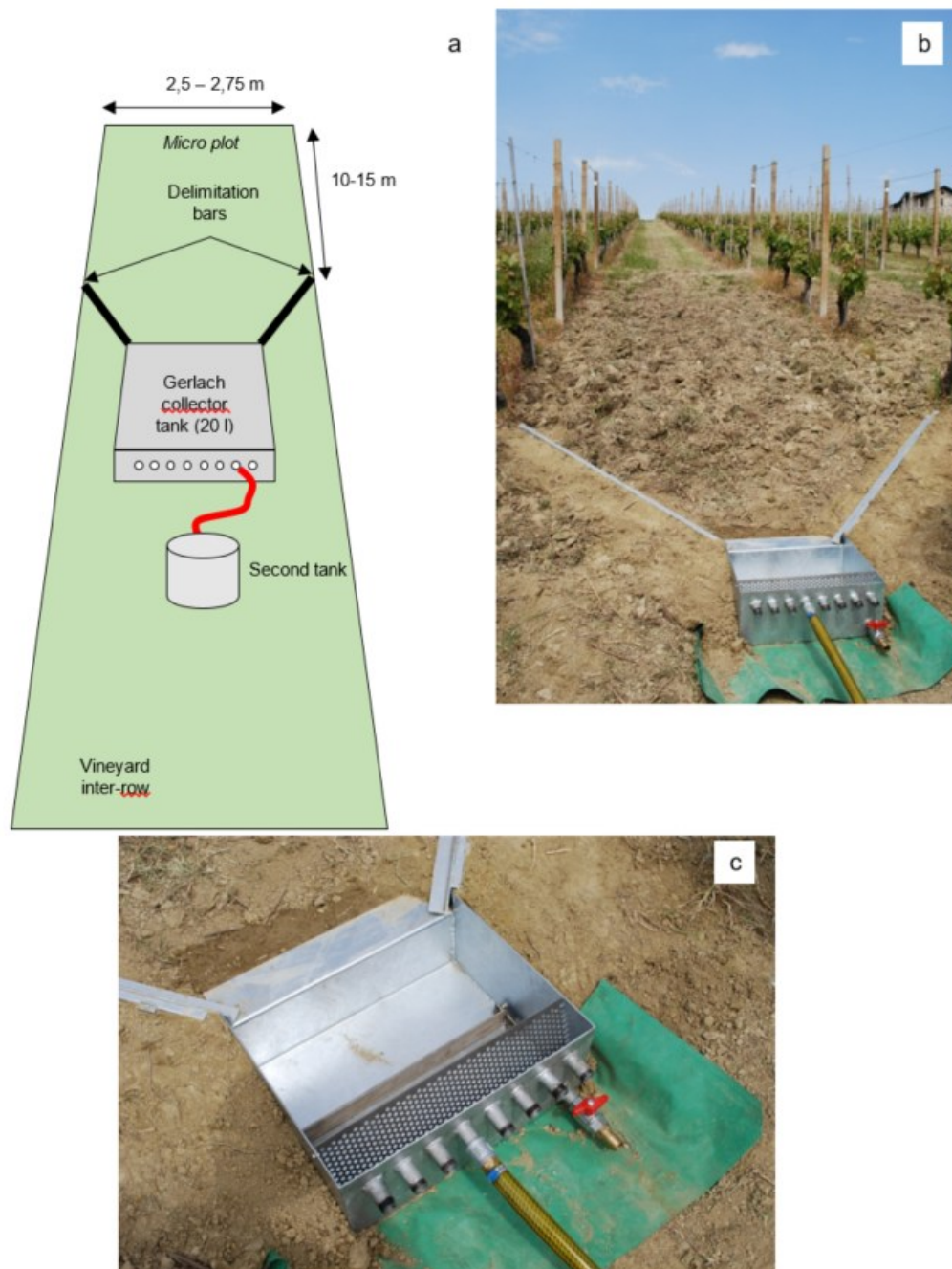


Figure 29 (SM2): a) Sketch and b) view of the system adopted to measure runoff and soil erosion in a portion of vineyard's inter-row; c) Detail of the Gerlach trough installed with delimitation bars placed to channel runoff into the collection system.

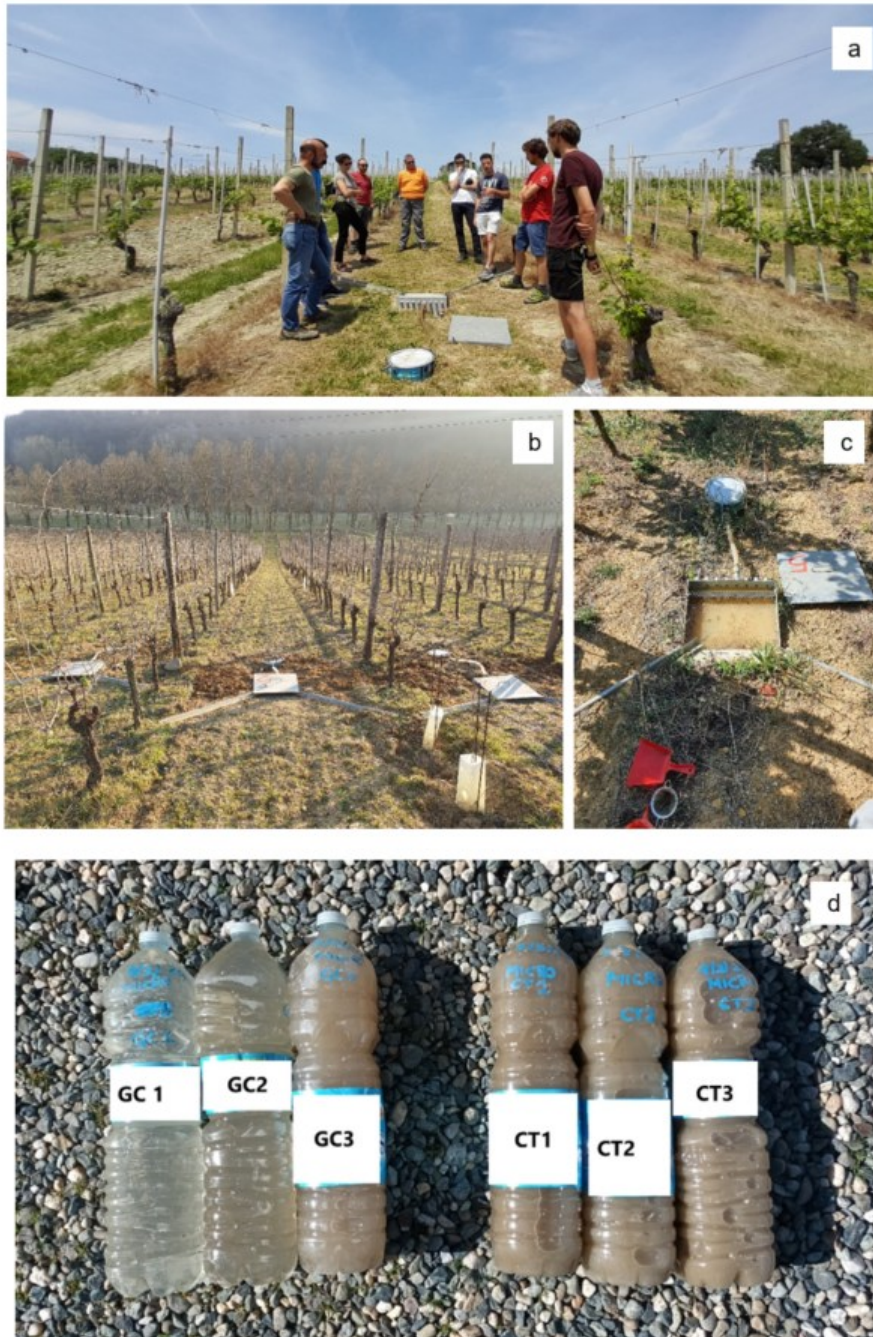
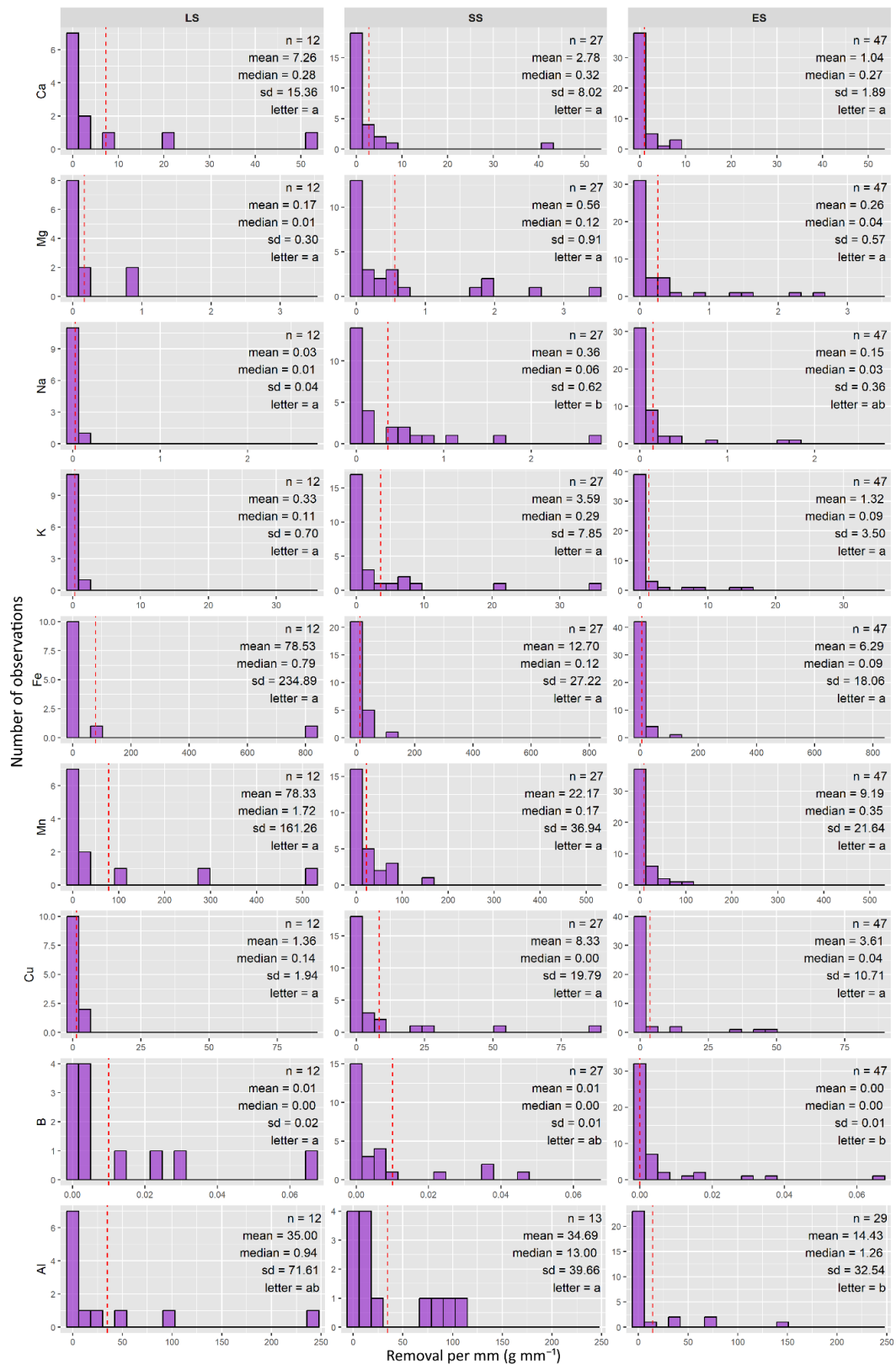


Figure 30 (SM3): a) Training with farmers and technicians participating to the IN-GEST SOIL project for correct management of the collection system and data collection; b) view of the system installed in one of the vineyards; c) Detail of the Gerlach trough filled with runoff and sediment after a rainfall event; d) samples of water-sediment mixture collected after a rainfall event from the Gerlach troughs in GC and CT treatments in one of the monitored vineyards.



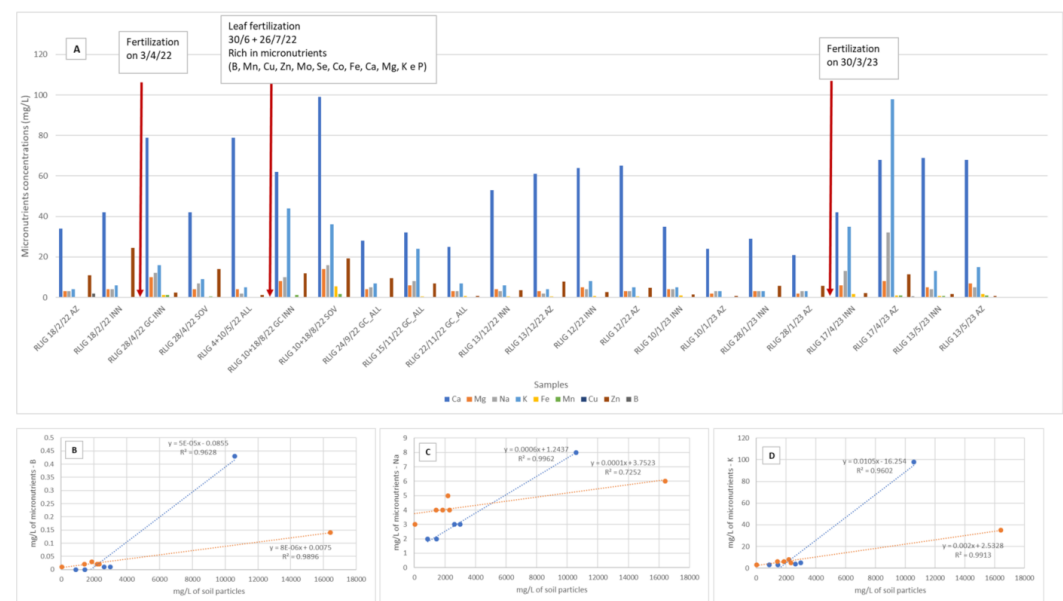


Figure 32 (SM4).a: At the Rocchetta Ligure vineyards, during winter micronutrients concentration is quite stable, with minimum values and without relevant differences between treatments. First fertilization operation occurred on 30/03/2023 with NPK: 4-3-5 + 3 Mg + B + Zn, not buried. In runoff water of the first event following this fertilization the highest concentration of Mg, Zn, B was observed in the SS treatment. Potassium and Zinc were also present in high concentration in inter-rows with CC SS in the period 17/5-19/6/2023. b, c, d: Relationships between B, Na, K concentration and soil particles concentration are directly proportional, with higher concentrations of soil sediment and micronutrient in the SS treatment than in ES treatment. The coefficient of determination R^2 is elevated especially for K and B.

Author contribution:

Giorgio Capello: Methodology; Investigation; Data curation; Formal analysis;
Writing – original draft

Stefano Ferraris: Methodology; Validation; Writing – review & editing; Supervision

Simone Bussotti: Conceptualization; Investigation; Resources.

Elisa Paravidino: Conceptualization; Investigation; Resources.

Marcella Biddoccu: Conceptualization; Investigation; Validation; Writing – review & editing; Supervision; Funding acquisition.

Competing interests:

The authors declare that they have no conflict of interest.

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References

Abad, J., Hermoso de Mendoza, I., Marín, D., Orcaray, L., and Santesteban, L. G.: Cover crops in viticulture. A systematic review (1): Implications on soil characteristics and biodiversity in vineyard, *OENO One*, 55(1), 295–312, doi:10.20870/oeno-one.2021.55.1.3599, 2021.

Adams, R. M., Hurd, B. H., Lenhart, S., and Leary, N.: Effects of Global Climate Change on Agriculture: An Interpretative Review, *Climate Research*, 11(1), 19–30, <http://www.jstor.org/stable/24865973>, 1998.

Agenzia Regionale per la Protezione Ambientale [ARPA] Piemonte: Portale sul clima in Piemonte, 2024. Retrieved from https://webgis.arpa.piemonte.it/secure_apps/portale-sul-clima-in-piemonte/, Accessed on: 8 August 2024.

Antoneli, V., Bednarz, J. A., & Thomaz, E. L.: Tobacco harvest phase is critical to runoff and soil loss in conventional tillage system. *Soil Use and Management*, 39, 249–259, doi:10.1111/sum.1282, 2023.

Bagagiolo, G., Biddoccu, M., Rabino, D., and Cavallo, E.: Effects of rows arrangement, soil management, and rainfall characteristics on water and soil losses in Italian sloping vineyards, *Environmental Research*, 166, 690–704, doi:10.1016/j.envres.2018.06.048, 2018.

Bagagiolo, G., Rabino, D., Biddoccu, M., Nigrelli, G., Cat Berro, D., Mercalli, L., Spanna, F., Capello, G., and Cavallo, E.: Effects of inter-annual climate variability on grape harvest timing in rainfed hilly vineyards of Piedmont (NW Italy), *Italian Journal of Agrometeorology*, 1, 37–49, doi:10.36253/ijam-1083, 2021.

Bagarello, V., Ferro, V., Keesstra, S., Rodrigo Comino, J., Pulido, M., and Cerdà, A.: Testing simple scaling in soil erosion processes at plot scale, *Catena*, 167, 171–180, doi:10.1016/j.catena.2018.04.035, 2018.

Bagarello, V., Di Stefano, C., Ferro, V., and Pampalone, V.: Statistical distribution of soil loss and sediment yield at Sparacia experimental area, Sicily, *Catena*, 82(1), 45–52, doi:10.1016/j.catena.2010.04.006, 2010.

Belmonte, S. A., Celi, L., Stahel, R. J., Bonifacio, E., Novello, V., Zanini, E., and Steenwerth, K. L.: Effect of Long-Term Soil Management on the Mutual Interaction Among Soil Organic Matter, Microbial Activity and Aggregate Stability in a Vineyard, *Pedosphere*, 28(2), 288–298, doi:10.1016/S1002-0160(18)60015-3, 2018.

Bernaschina, Y., Fresia, P., Garaycochea, S., and Leoni, C.: Permanent cover crop as a strategy to promote soil health and vineyard performance, *Environmental Sustainability*, 6, 243–258, doi:10.1007/s42398-023-00271-y, 2023.

Biddoccu, M., Ferraris, S., Cavallo, E., Opsi, F., Previati, M., Canone, D., 2013. Hillslope Vineyard Rainfall-Runoff Measurements in Relation to Soil Infiltration and Water Content, *Procedia Environmental Sciences*, Volume 19, 2013, Pages 351-360, ISSN 1878-0296, <https://doi.org/10.1016/j.proenv.2013.06.040>.

Biddoccu, M., Opsi, F., Cavallo, E.: Relationship between runoff and soil losses with rainfall characteristics and long-term soil management practices in a hilly vineyard (Piedmont, NW Italy). *Soil Science and Plant Nutrition*, 60(1), 92–99, doi:10.1080/00380768.2013.862488, 2014.

Biddoccu, M., Ferraris, S., Opsi, F., & Cavallo, E.: Effects of soil management on long-term runoff and soil erosion rates in sloping vineyards. In G. Lollino et al. (Eds.), *Engineering Geology for Society and Territory – Volume 1* (pp. 159–165). Springer, doi:10.1007/978-3-319-09300-0_30, 2015.

Biddoccu, M., Ferraris, S., Opsi, F., and Cavallo, E.: Long-term monitoring of soil management effects on runoff and soil erosion in sloping vineyards in Alto Monferrato (North-West Italy), *Soil Tillage Res.*, 155, 176–189, doi: 10.1016/j.still.2015.07.005, 2016.

Biddoccu, M., Ferraris, S., Pitacco, A., and Cavallo, E.: Temporal variability of soil management effects on soil hydrological properties, runoff and erosion at the field scale in a hillslope vineyard, North-West Italy, *Soil and Tillage Research*, 165, 46–58, doi:10.1016/j.still.2016.07.017, 2017.

Brings, C., Iserloh, T., Casper, M. C., Seeger, M., Senciales, J. M., Brevik, E. C., & Rodrigo-Comino, J.: Temporal changes in soil water erosion on sloping vineyards in the Ruwer–Mosel Valley: The impact of age and plantation works in young and old vines. *Journal of Hydrology and Hydromechanics*, 65(4), 362–372, doi:10.1515/johh-2017-0022, 2017.

Caffaro F, De Gregorio E, , Capello G, Vigoroso L, Bagagiolo G, Cavallo E, Biddoccu M. Winegrowers' Perceptions and Adoption of Sustainable Soil Management Practices and Technologies: A Case Study in Piedmont, Italy. *Land Degradation & Development*. 2026;0:1–18. <https://doi.org/10.1002/ldr.70621>.

Capello, G., Biddoccu, M., and Cavallo, E.: Permanent cover for soil and water conservation in mechanized vineyards: A study case in Piedmont, NW Italy, *Italian Journal of Agronomy*, 15(4), 323–331, doi:10.4081/ija.2020.1763, 2020.

Capello, G., Biddoccu, M., Ferraris, S., and Cavallo, E.: Effects of tractor passes on hydrological and soil erosion processes in tilled and grassed vineyards, *Water*, 11(10), 2118, doi:10.3390/w11102118, 2019.

Capello, G., Biddoccu, M., Bussotti, S., Paravidino, E., & Cavallo, E.: Effects of some extreme rainfall events on hydrological and soil erosion processes in tilled and grassed vineyards. In *Proceedings of the VII International Congress on Mountain and Steep Slopes Viticulture* (pp. 263–267), CERVIM/UTAD, 2022.

Capello, G., Ferraris, S., Biddoccu, M., et al. (2024). Methodological framework for characterizing vineyards subjected to soil degradation in Piedmont. *GEAM – Georesources and Mining*, 172–173. <https://doi.org/10.19199/2024.172-173.1121-9041.012>

Cárceles Rodríguez, B., Durán Zuazo, V. H., Soriano Rodríguez, M., Gálvez Ruiz, B., and García-Tejero, I. F.: Soil erosion and the efficiency of the conservation measures in Mediterranean hillslope farming (SE Spain), *Eurasian Soil Science*, 54, 792–806, doi:10.1134/S1064229321050069, 2021.

Cataldo, E., Fucile, M., and Mattii, G. B.: A Review: Soil Management, Sustainable Strategies and Approaches to Improve the Quality of Modern Viticulture, *Agronomy*, 11, 2359, doi:10.3390/agronomy11112359, 2021.

Cataldo, E., Salvi, L., Sbraci, S., Storch, P., and Mattii, G. B.: Sustainable viticulture: Effects of soil management in *Vitis vinifera*, *Agronomy*, 10, 1949, doi:10.3390/agronomy10121949, 2020.

Cerdà, A.: Aggregate stability against water forces under different climates on agriculture land and scrubland in southern Bolivia, *Soil Tillage Res.*, 57(3), 159–166, doi:10.1016/S0167-1987(00)00155-0, 2000.

Charvát K, Šmejkal J, Horák P, Kollerová M, Horáková Š, Renault P. Citizen Science for Soil Monitoring and Protection in Europe: Insights from the PREPSOIL Project Under the European Soil Mission. *Sustainability*. 2025; 17(11):5042. <https://doi.org/10.3390/su17115042>

Delpuech, X., and Metay, A.: Adapting cover crop soil coverage to soil depth to limit competition for water in a Mediterranean vineyard, *European Journal of Agronomy*, 97, 60–69, doi:10.1016/j.eja.2018.04.013, 2018.

Ding, Y., Song, Z., Hu, Y., Zhang, S., Zhang, M., Zhang, W., and Xiao, S.: A review on curbing non-point source pollution in watershed—the answer lies at the root, *Environment, Development and Sustainability*, doi:10.1007/s10668-024-05464-x, 2024.

Dugan, I., Pereira, P., Barcelo, D., and Bogunovic, I.: Vineyard management impact on soil properties, hydrological response and chemical elements transport in a Mediterranean karst environment (Croatia), *Catena*, doi:10.1016/j.catena.2024.107858, 2024.

European Commission: EU Soil Strategy for 2030: Reaping the benefits of healthy soils for people, food, nature and climate.

Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, COM (2021) 699 final, Brussels, 17 November 2021, 2021. Retrieved from <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0699> , accessed on March 8, 2026.

Ferreira, C. S., Veiga, A., Caetano, A., Gonzalez-Pelayo, O., Karine-Boulet, A., Abrantes, N., and Ferreira, A. J.: Assessment of the impact of distinct vineyard management practices on soil physico-chemical properties, *Air, Soil and Water Research*, 13, doi:10.1177/1178622120944847, 2020.

Foronda-Robles, C.: The territorial redefinition of the Vineyard Landscape in the sherry wine region (Spain), *Misc. Geogr.*, 22, 95–101, doi:10.2478/mgrsd-2018-0010, 2018.

Fraga, H.: Viticulture and Winemaking under Climate Change, *Agronomy*, 9, 783, doi:10.3390/agronomy9120783, 2019. Gagliardi, L., Fontanelli, M., Luglio, S. M., Frasconi, C., Peruzzi, A., and Raffaelli, M.: Evaluation of Sustainable Strategies for Mechanical Under-Row Weed Control in the Vineyard, *Agronomy*, 13(12), 3005, doi:10.3390/agronomy13123005, 2023.

Garcia, L., Celette, F., Gary, C., Ripoche, A., Valdés-Gómez, H., and Metay, A.: Management of service crops for the provision of ecosystem services in vineyards: A review, *Agriculture, Ecosystems & Environment*, 251, 158–170, doi:10.1016/j.agee.2017.09.030, 2018.

García-Díaz, A., Bienes, R., Sastre, B., Novara, A., Gristina, L., and Cerda, A.: Nitrogen losses in vineyards under different types of soil groundcover. A field runoff simulator approach in central Spain, *Agriculture, Ecosystems & Environment*, 236, 256–267, 2017.

Geldenhuys, M., Gaigher, R., Pryke, J., and Samways, M.: Diverse herbaceous cover crops promote vineyard arthropod diversity across different management regimes, *Agriculture, Ecosystems & Environment*, 307, 107222, doi:10.1016/j.agee.2020.107222, 2021.

Gerlach, T.: Hillslope troughs for measuring sediment movement, *Revue de Géomorphologie Dynamique*, 17(2), 173–174, 1967.

Giffard, B., Winter, S., Guidoni, S., Nicolai, A., Castaldini, M., Cluzeau, D., Coll, P., Cortet, J., Le Cadre, E., d’Errico, G., Forneck, A., Gagnarli, E., Griesser, M., Guernion, M., Lagomarsino, A., Landi, S., Le Bissonnais, Y., Mania, E., Mocali, S., and Leyer, I.: Vineyard management and its impacts on soil biodiversity, functions, and ecosystem services, *Frontiers in Ecology and Evolution*, 10, doi:10.3389/fevo.2022.850272, 2022.

Global Climate Highlights report 2023, Copernicus, 2024. Retrieved from <https://climate.copernicus.eu/global-climate-highlights-2023>, Accessed on: 7 March 2024.

Gristina, L., Novara, A., and Minacapilli, M.: Rethinking vineyard ground management to counter soil tillage erosion, *Soil and Tillage Research*, 217, 105275, doi:10.1016/j.still.2021.105275, 2022.

Heinekamp, T., Röckel, F., Herzog, K., Trapp, O., Töpfer, R., Schwander, F.: Heat waves reveal additive genetic effects leading to sunburn resilience of grapevine berries. *Front. Plant Sci.* 16:1533345, doi: 10.3389/fpls.2025.1533345, 2025.

Horel, Á., Bakacsi, Z., Vass, C., and Zsigmond, T.: Inter-row soil management affecting soil moisture in non-irrigated vineyard ecosystems: A meta-analysis, *Soil Use and Management*, doi:10.1111/sum.13159, 2024.

Horton, R. E.: *Surface Runoff Phenomena. Part 1. Analysis of the Hydrograph*, Horton Hydrologic Laboratory Publication 101, Edward Bros, Ann Arbor, MI, 1935.

Intergovernmental Panel On Climate Change (IPCC): *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 1st ed., Cambridge University Press, 2023.

Istituto Nazionale di Statistica [ISTAT]: Istat Data La banca dati dell'Istituto Nazionale di Statistica, 2024. Retrieved from <https://esploradati.istat.it/databrowser/#/it/dw>, Accessed on: 19 August 2024.

Karimi, B., Cahurel, J.-Y., Gontier, L., Charlier, L., Chovelon, M., Mahé, H., and Ranjard, L.: A meta-analysis of the ecotoxicological impact of viticultural practices on soil biodiversity, *Environmental Chemistry Letters*, 18, 1947–1966, doi:10.1007/s10311-020-01050-5, 2020.

Keesstra, S., Pereira, P., Novara, A., Brevik, E. C., Azorin-Molina, C., Parras-Alcántara, L., Jordán, A., and Cerdà, A.: Effects of soil management techniques on soil water erosion in apricot orchards, *Science of The Total Environment*, 551–552, 357–366, doi:10.1016/j.scitotenv.2016.01.182, 2016.

Kool, H., Andersson, J. A., Giller, K. E.: Reproducibility and external validity of on-farm experimental research in Africa. *Experimental Agriculture*, 56(4):587-607, doi:10.1017/S0014479720000174, 2020.

Kowalczyk, W., Nowak, J., and Zieliński, P.: The impact of climate change on the phenology of grapevines in Central Europe, *Folia Horticulturae*, 36(1), 123–134, doi:10.2478/fhort-2024-0015, 2024.

Lazcano, C., Decock, C., and Wilson, S. G.: Defining and Managing for Healthy Vineyard Soils, Intersections With the Concept of Terroir, *Frontiers in Environmental Science*, 8, 68, doi:10.3389/fenvs.2020.00068, 2020.

Liebhart, G., Guzman, G., Gomez, J. A., Winter, S., Zaller, J. G., Bauer, T., Nicolai, A., Cluzeau, D., Popescu, D., Bunea, C.-I., and Strauss, P.: Vineyard cover crop

management strategies and their effect on soil properties across Europe, *European Journal of Soil Science*, doi:10.1111/ejss.13573, 2024.

Ma, Y., Li, Z., Xu, Y., Li, C., Ding, H., Li, C., Tang, Q., Liu, M., and Hou, J.: The Development of No-Tillage Seeding Technology for Conservation Tillage—A Review, *Sustainability*, 17(5), 1808, doi:10.3390/su17051808, 2025.

Manzone, M., Demeneghi, M., Marucco, P., Grella, M., and Balsari, P.: Technical solutions for under-row weed control in vineyards: Efficacy, costs and environmental aspects analysis, *Journal of Agricultural Engineering*, 51(1), 36–42, doi:10.4081/jae.2020.991, 2020.

Marchamalo, M., Hooke, J. M., and Sandercock, P. J.: Flow and sediment connectivity in semi-arid landscapes in SE Spain: patterns and controls, *Land Degrad. Dev.*, 27(4), 1032–1044, doi:10.1002/ldr.2352, 2016.

Mariani, L., Parisi, S., Failla, O., Cola, G., Zoia, G., and Bonardi, L.: Tirano (1624–1930): A long time series of harvest dates for grapevine, *Ital. J. Agrometeorol.*, 16, 7–16, 2009. McKee, T. B., Doesken, N. J., and Kleist, J.: The Relationship of Drought Frequency and Duration to Time Scales, *Proceedings of the 8th Conference on Applied Climatology*, 17–22 January 1993, Anaheim, CA, Boston, MA, American Meteorological Society, 1993.

Mekonnen, M., Keesstra, S. D., Stroosnijder, L., Baartman, J. E. M., and Maroulis, J.: Soil conservation through sediment trapping: a review, *Land Degrad. Dev.*, 26(6), 544–556, doi:10.1002/ldr.2308, 2015.

Neumann, M., Kavka, P., Devátý, J., Stašek, J., Strouhal, L., Tejkl, A., Kubínová, R., & Rodrigo-Comino, J.: Effect of plot size and precipitation magnitudes on the activation of soil erosion processes using simulated rainfall experiments in vineyards. *Frontiers in Environmental Science*, 10, 949774, doi:10.3389/fenvs.2022.949774, 2022.

Novara, A., Gristina, L., Saladino, S. S., Santoro, A., and Cerdà, A.: Soil erosion assessment on tillage and alternative soil managements in a Sicilian vineyard, *Soil and Tillage Research*, 117, 140–147, doi:10.1016/j.still.2011.09.007, 2011.

O'Brien, F., Nesbitt, A., Sykes, R., and Kemp, B.: Regenerative viticulture and climate change resilience, *OENO One*, 59(1), doi:10.20870/oeno-one.2025.59.1.8089, 2025.

Ojha, V. K.: The effect of agricultural runoff on freshwater ecosystems, *International Journal of Applied Research*, 7(7), 287–289, doi:10.22271/allresearch.2021.v7.i7d.12097, 2021.

Organisation Internationale de la Vigne et du Vin [OIV]: State of the World Vitiviniculture Sector in 2022 – April 2023, 2023. Retrieved from

https://www.oiv.int/sites/default/files/documents/OIV_State_of_the_world_Vine_and_Wine_sector_in_2022_2.pdf, Accessed on: August 17, 2024. Panagos, P., Ballabio, C., Borrelli, P., Meusburger, K., Klik, A., Rousseva, S., Perčec Tadić, M., Michaelides, S., Hrabalíková, M., Olsen, P., Aalto, J., Lakatos, M., Rymaszewicz, A., Dumitrescu, A., Beguería, S., and Alewell, C.: Rainfall erosivity in Europe, *Science of The Total Environment*, 511, 801–814, doi:10.1016/j.scitotenv.2015.01.008, 2015.

Panagos, P., Standardi, G., Borrelli, P., Lugato, E., Montanarella, L., Bosello, F.: Cost of agricultural productivity loss due to soil erosion in the European Union: From direct cost evaluation approaches to the use of macroeconomic models, *Land Degrad Dev.* 29, 471–484, doi:10.1002/ldr.2879, 2018.

Pantazis, C., Nastos, P.: Comparing Direct Field Measurements of Soil Erosion with RUSLE Model Estimates in Mediterranean Olive Orchards, *Environ. Earth Sci. Proc.*, 35(1), 75, doi:10.3390/eesp2025035075, 2025.

Parthasarathi, T., Firdous, S., Mariya David, E., Lesharadevi, K., and Djanaguiraman, M.: Effects of High Temperature on Crops, *IntechOpen*, doi:10.5772/intechopen.105945, 2022.

Payen, F. T., Sykes, A., Aitkenhead, M., Alexander, P., Moran, D., and MacLeod, M.: Soil organic carbon sequestration rates in vineyard agroecosystems under different soil management practices: A meta-analysis, *Journal of Cleaner Production*, 290, 125736, doi:10.1016/j.jclepro.2020.125736, 2021.

Pessina, D., Tadini, V., and Galli, L. E.: Soil compaction in Northern Italian vineyards: challenges and mitigation strategies, *Journal of Agricultural Engineering*, doi:10.4081/jae.2025.1729, 2025.

Pornaro, C., and Macolino, S.: Selecting species for vineyard inter-row vegetation cover requires consideration of microenvironmental conditions, *PLoS ONE*, 20(3), e0319848, doi:10.1371/journal.pone.0319848, 2025.

Prada, J., Dinis, L. T., Soriato, E., Vandelle, E., Soletkin, O., Uysal, Ş., Dihazi, A., Santos, C., and Santos, J. A.: Climate change impact on Mediterranean viticultural regions and site-specific climate risk-reduction strategies, *Mitigation and Adaptation Strategies for Global Change*, 29, 52, doi:10.1007/s11027-024-10146-0, 2024. Prosdocimi, M., Cerdà, A., and Tarolli, P.: Soil water erosion on Mediterranean vineyards: A review, *Catena*, 141, 1–21, doi:10.1016/j.catena.2016.02.010, 2016.

Prosdocimi, M., Burguet, M., Di Prima, S., Sofia, G., Terol, E., Rodrigo-Comino, J., Cerdà, A., & Tarolli, P.: Rainfall simulation and Structure-from-Motion photogrammetry

for the analysis of soil water erosion in Mediterranean vineyards. *Science of the Total Environment*, 574, 204–215, doi:10.1016/j.scitotenv.2016.09.036, 2017.

Quiquerez, A., Follain, S., Casalí, J., Giménez, R., Cerdà, A., Keesstra, S. D., Brevik, E. C., Pereira, P., Senciales, J. M., Seeger, M., & Ruiz-Sinoga, J. D.: Soil erosion in sloping vineyards assessed by botanical indicators and sediment collectors in the Ruwer–Mosel valley. *Agriculture, Ecosystems & Environment*, 233, 158–170, doi:10.1016/j.agee.2016.09.009, 2016.

R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria, 2025. Available online: <https://www.R-project.org/> (accessed on 2/1/2025).

Ramírez-Pérez, P., López-Granados, F., León-Gutiérrez, J. M., Mesas-Carrascosa, F. J., Pérez-Porras, F., and Torres-Sánchez, J.: Influence of soil management on vegetative growth, yield, and wine quality parameters in an organic “Pedro Ximénez” vineyard: field and UAV data, *Agron. Sustain. Dev.*, 44, 10, doi:10.1007/s13593-024-00946-8, 2024.

Ramos, M. C., and Martínez-Casasnovas, J. A.: Nutrient losses from a vineyard soil in Northeastern Spain caused by an extraordinary rainfall event, *Catena*, 55, 79–90, doi:10.1016/S0341-8162(03)00074-2, 2004.

Ramos, M. C.: Soil losses in rainfed Mediterranean vineyards under climate change scenarios: The effects of drainage terraces. *AIMS Agriculture and Food*, 1(2), 124–143, doi:10.3934/agrfood.2016.2.124, 2016

Regione Piemonte: Aree di produzione dei vini a Denominazione di Origine Controllata (DOC) e a Denominazione di Origine Controllata e Garantita (DOCG), 2024a. Retrieved from https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/r_piemonte:bb722e24-ed1e-4b00-8fb0-6a205fbbda67, Accessed on: 23 September 2024.

Regione Piemonte: Vitigni su mosaicoltura catastale di riferimento regionale 2023, 2024b. Retrieved from https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/metadata/r_piemonte:95aed80b-69d3-452a-9635-bae4f498227b, Accessed on: 20 September 2024.

Rodrigo-Comino J, Senciales JM, Sillero-Medina JA, Gyasi-Agyei Y, Ruiz-Sinoga JD, Ries JB. Analysis of Weather-Type-Induced Soil Erosion in Cultivated and Poorly Managed Abandoned Sloping Vineyards in the Axarquía Region (Málaga, Spain). *Air, Soil and Water Research*. 2019;12. doi:10.1177/1178622119839403

Ruiz-Colmenero, M., Bienes, R., and Marques, M. J.: Soil and water conservation dilemmas associated with the use of green cover in steep vineyards, *Soil and Tillage Research*, 117, 211–223, doi:10.1016/j.still.2011.10.004, 2011.

Ruiz-Colmenero, M., Bienes, R., Eldridge, D. J., and Marques, M. J.: Vegetation cover reduces erosion and enhances soil organic carbon in a vineyard in central Spain, *Catena*, 104, 153–160, doi:10.1016/j.catena.2012.11.007, 2013.

Salomé, C., Coll, P., Lardo, E., Metay, A., Villenave, C., Marsden, C., Blanchart, E., Hinsinger, P., and Le Cadre, E.: The soil quality concept as a framework to assess management practices in vulnerable agroecosystems: A case study in Mediterranean vineyards, *Ecological Indicators*, 61, 456–465, doi:10.1016/j.ecolind.2015.09.047, 2016.

Santos, J. A., Fraga, H., Malheiro, A. C., Moutinho-Pereira, J., Dinis, L.-T., Correia, C., Moriondo, M., Leolini, L., Dibari, C., Costafreda-Aumedes, S., Kartschall, T., Menz, C., Molitor, D., Junk, J., Beyer, M., & Schultz, H. R.: A Review of the Potential Climate Change Impacts and Adaptation Options for European Viticulture. *Applied Sciences*, 10(9), 3092, doi:10.3390/app10093092, 2020.

Spano D., Mereu V., Bacciu V., Marras S., Trabucco A., Adinolfi M., Barbato G., Bosello F., Breil M., Chiriaco M. V., Coppini G., Essenfelder A., Galluccio G., Lovato T., Marzi S., Masina S., Mercogliano P., Mysiak J., Noce S., Pal J., Reder A., Rianna G., Rizzo A., Santini M., Sini E., Staccione A., Villani V., Zavatarelli M., 2020. “Analisi del rischio. I cambiamenti climatici in Italia”. DOI: 10.25424/CMCC/ANALISI_DEL_RISCHIO

Steenwerth, K., and Belina, K. M.: Cover crops enhance soil organic matter, carbon dynamics and microbiological function in a vineyard agroecosystem, *Appl. Soil Ecol.*, 40, 359–369, doi:10.1016/j.apsoil.2008.06.006, 2008.

Steenwerth, K. L., Pierce, D. L., Carlisle, E. A., Spencer, R. G. M., and Smart, D. R.: A vineyard agroecosystem: Disturbance and precipitation affect soil respiration under mediterranean conditions, *Soil Science Society of America Journal*, 74(1), 231–239, doi:10.2136/sssaj2008.0346, 2010.

Steponavičienė, V., Žiūraitis, G., Rudinskienė, A., Jackevičienė, K., and Bogužas, V.: Long-term effects of different tillage systems and their impact on soil properties and crop yields, *Agronomy*, 14, 870, doi:10.3390/agronomy14040870, 2024.

Straffelini, E., and Tarolli, P.: Climate change-induced aridity is affecting agriculture in Northeast Italy, *Agricultural Systems*, 208, 103647, doi:10.1016/j.agsy.2023.103647, 2023.

Suciu, C., Farolfi, F., Zambito Marsala, R., Russo, E., De Crema, M., Peroncini, E., Tomei, F., Antolini, G., Marcaccio, M., Marletto, V., Colla, R., Gallo, A., and Capri, E.: Evaluation of groundwater contamination sources by plant protection products in hilly vineyards of Northern Italy, *Sci. Total Environ.*, 749, Article 141495, doi:10.1016/j.scitotenv.2020.141495, 2020.

Telak, L. J., and Bogunovic, I.: Tillage-induced impacts on the soil properties, soil water erosion, and loss of nutrients in the vineyard (Central Croatia), *J. Cent. Eur. Agric.*, 21(3), 589–601, doi:10.5513/JCEA01/21.3.2810, 2020.

UNESCO: Vineyard Landscape of Piedmont: Langhe-Roero and Monferrato, 2014. Retrieved from <https://whc.unesco.org/uploads/nominations/1390rev.pdf>, Accessed on: September 8, 2024.

Virto, I., Imaz, M. J., Fernandez-Ugalde, O., Urrutia, I., Enrique, A., and Bescansa, P.: Soil quality evaluation following the implementation of permanent cover crops in semi-arid vineyards. Organic matter, physical and biological soil properties, *Span. J. Agric. Res.*, 10, 1121–1132, doi:10.5424/sjar/2012104-613-11, 2012.

Wang, W., Straffelini, E., Pijl, A., and Tarolli, P.: Sustainable water resource management in steep-slope agriculture, *Geography and Sustainability*, 3(3), 214–219, doi:10.1016/j.geosus.2022.07.001, 2022.

2.5 Continuous monitoring of soil water content

Soil moisture was monitored using capacitive sensors placed at different positions (track, centre of the inter-row, and under-row) at a depth of 40 cm, and in some cases at 20 cm. These sensors measure soil moisture every hour, expressed as volumetric content. They are connected to dataloggers that enable remote data transmission. However, the measurement provided is influenced by the degree of soil compaction, which varies over time, especially in the inter-row. These systems and equipment have been sized and designed, and then the various components have been acquired and assembled, and after a period of laboratory tests, installed in the vineyards (Fig. 33). Five meteorological station and systems for monitoring soil water content were installed, one in each vineyard.

Depending on the selected management practices, sensors were installed at various points within each vineyard parcel to measure and verify spatial and temporal variations related to different soil management techniques. The Capriata d'Orba vineyard, due to its lack of slope, did not require monitoring for runoff and erosion. Instead, monitoring of soil water content was intensified because of critical issues related to field access and water availability for the vines.

The sensors installed at a depth of 40 cm allowed for monitoring soil moisture trends in different plots within the inter-row (centre and track position) and under-row (Fig. 33). Observations began in late 2021 to early 2022, capturing data from two particularly critical seasons with low precipitation and consequently low soil moisture values. It was observed across various sites that the values measured by the sensors vary spatially and temporally depending on the sensor installation position. Sensors placed in the tracks of vehicle passage are significantly affected by compaction, causing an apparent increase in soil moisture, as the volumetric water content in the soil appears higher. This effect is particularly evident when sensors are placed at shallower depths and during the autumn-winter period. The values recorded in the centre of the inter-row are generally higher than those in the track are, especially in tilled soil during summer.

In spring-summer 2023, higher soil moisture values were observed in at least one of the two sensor positions in the grassed plot compared to the tilled plot in Carpeneto and Capriata (Figure 34). There was a good response to precipitation in terms of increased moisture at -40 cm. This response is not always observed in tilled soil due to poor infiltration caused by compaction. Management practices with

grassing and cover crop are characterized by a good response to precipitation and less variability related to compaction, both temporally and spatially.



Figure 33: Installation at the vineyard in Capriata D'Orba of 12 probes for continuous soil monitoring (pole, solar panel, box containing battery and Siap-Micros microDA datalogger with 3G modem remotely connected for data transmission, probes for measuring soil water content Delta OHM HD3910.1 and related protective tubes for cables) carried out on 10/02/2022.

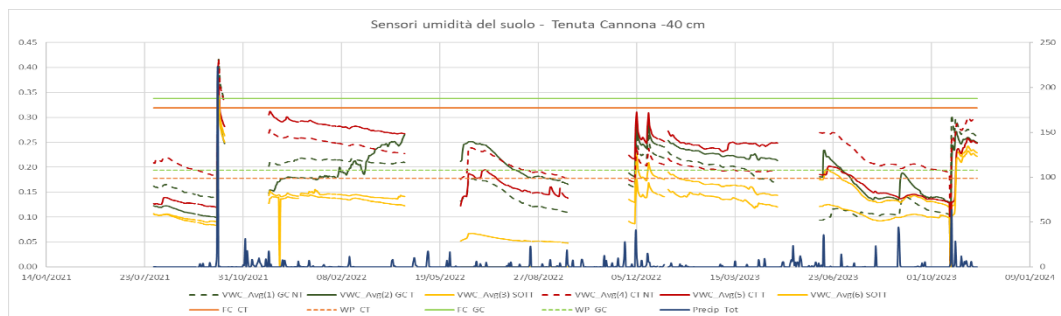


Figure 34: Soil moisture sensors at different depths at Carpeneto site, grass-covered plot.

Tenuta Cannona – Carpeneto (AL)

At the Tenuta Cannona experimental viticultural centre of Agrion in Carpeneto (AL), data on the volumetric water content of the soil (soil moisture) at various depths are available from 2016 for the plots monitored within the IN-GEST SOIL project (Figure 35). This allows us to compare the measurements made in the first period of the project with those of previous years.

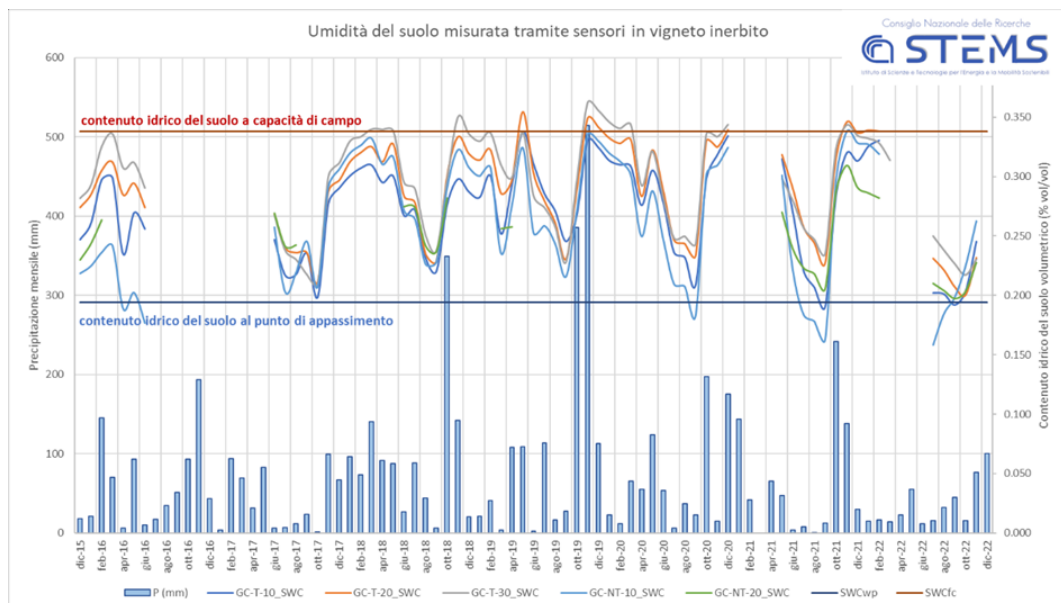


Figure 35: Soil moisture sensors at different depths at Carpeneto site, grass cover plot. The blue line indicates the wilting point threshold; the red line indicates the field capacity threshold. Histograms represent the monthly precipitation.

Looking at the average monthly values of soil moisture between 2016 and summer 2020, the water content always turned out to be higher than the soil water content at the wilting point, taken as a reference to indicate critical conditions. At the end of summer 2020, the average value of the most superficial probe placed in the centre of the inter-row turned out to be below this limit, a situation then repeated also during the summer of 2021 and 2022, for longer periods.

In order to evaluate the impact of soil moisture conditions, the Soil Moisture Index was also calculated, defined by Sridhar et al. (2008), calculated based on soil characteristics and soil moisture with the equation:

$$SMI = \left[\frac{5(SM - WP)}{(FC - WP)} - 5 \right]$$

Where SM = daily average of soil water content, WP = water content at wilting point, FC = water content at field capacity.

A value from 0 to -5 is obtained. An SMI value equal to 0 indicates non-drought conditions, -5 indicates extreme drought.

The next figure 36 shows the average monthly values of the SMI index for the grass-covered plot of Tenuta Cannona from 2016 to the end of 2022. It is observed that in summer a value corresponding to intense to severe drought (<-2) was recorded in summer 2017 and 2018, even at a depth of 30 cm. During the summers of 2020, 2021 and 2022, the SMI value fell below the limit of severe drought (<-3), with minimum values on the surface, but still lower and lower also at -20 and -30 cm. Extreme drought values were not reached.

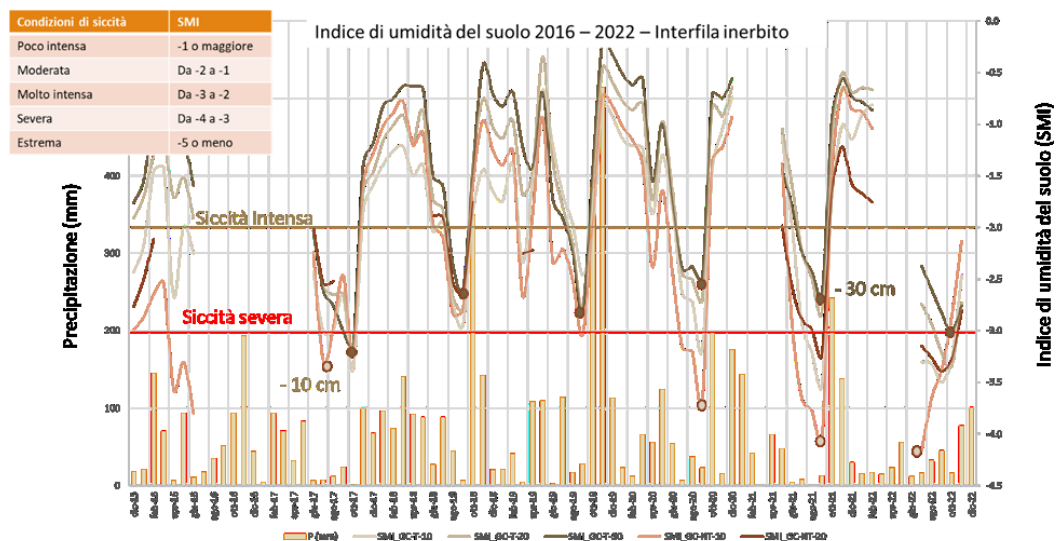


Figure 36: Average monthly values of the SMI index for the grass cover plot of Carpeneto from 2016 to the end of 2022.

Regarding the first year of monitoring, for the Carpeneto site, data are available from the start of the project in autumn 2020 until the end of 2021. Despite some interruptions due to removal of probes due to operations carried out on soil, it can be noticed how in winter humidity has generally remained high, while from May it has decreased for all summer period, when there were scarce precipitations. The soil water content returned to rise thanks to autumn rains, especially after extreme event occurred at beginning of October. Comparing two thesis, in summer tilled soil reached lower minimum values compared to grass-covered one, while during precipitations tilled soil reached saturation, recognizable in graphs by characteristic shape of lines that rise up to a limit value beyond which humidity remains constant. This did not occur so clearly in grass-covered thesis, probably thanks to greater hydraulic conductivity guaranteed by roots that deepen into soil ensuring presence of preferential paths (Fu et al., 2023).

Analysing in more detail the trend of soil moisture in the plot with grass-covered soil in the inter-row during the 2021 and 2022 seasons (Figure 37), the soil moisture at the end of May 2022 was generally significantly lower compared to the same period of 2021, due to scarce winter and spring precipitation. The most superficial probes throughout the summer of 2022 indicated a moisture value lower or close to the wilting point, and it is observed that even the sensor at a depth of 30 cm recorded decreasing values tending to this limit until the winter of 2022. It is also observed that in the autumn and winter period, the soil is characterized by such

humidity as to discourage passage with means, as ideal conditions occur to have maximum soil compaction.

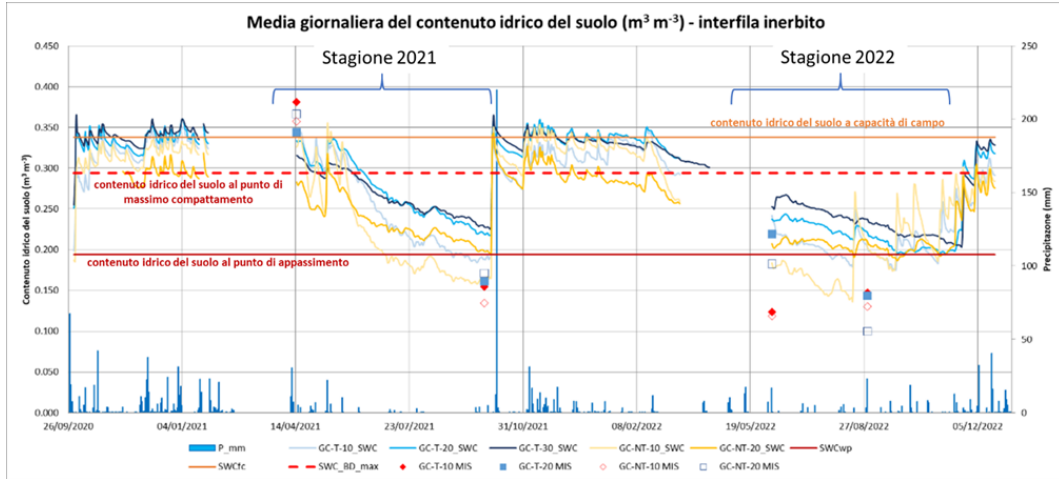


Figure 37: Soil moisture sensors at various depths at the Carpeneto site. The red line represents the wilting point threshold, while the dashed red line indicates the moisture level at which maximum compaction is achieved, as determined by the Proctor Test. The orange line denotes the field capacity threshold. The histograms illustrate daily precipitation.

At equal depth, the values of humidity expressed as volumetric content are higher in correspondence with the tractor's passage track compared to the centre of the inter-row, due to the greater density of the soil due to compaction.

It is noted that, although in the inter-row the soil is not tilled throughout the year (management is with permanent grass cover), the response to precipitation of the deeper sensor is very similar to more superficial sensors, particularly in autumn and winter. It is an index of the fact that water infiltrates easily even at greater depths.

Figure 38, relating to the tilled plot, shows the volumetric water content of the soil at different depths between autumn 2021 and spring 2022, along with indications of both precipitation and tractor passages for cultural operations. It is noted that at all depths, there is a temporary increase in soil moisture following precipitation, although minimal, as expected in recently tilled soil. The moisture measured by probes is greater than 0.300 at depths greater than 40 cm and less than this value for more superficial probes.

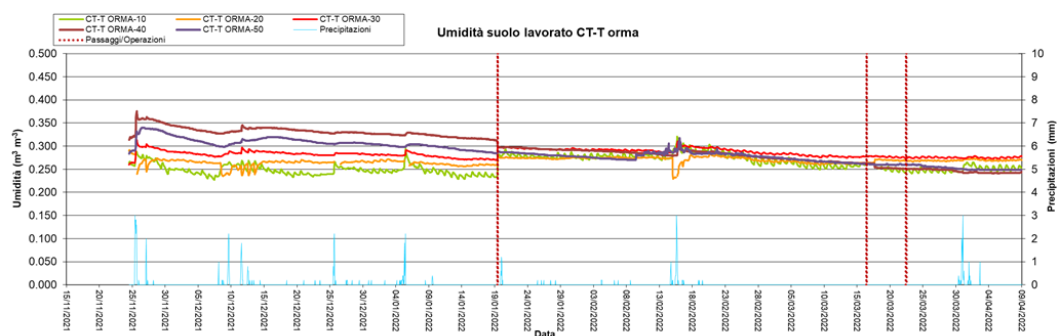


Figure 38: Volumetric water content of the soil at various depths from autumn 2021 to spring 2022 in the tilled plot at the Carpeneto site. The histograms indicate precipitation, while the red lines represent tractor passages for agricultural operations.

However, a variation in humidity values is observed following the passage that occurred on January 19, 2022: there is a sharp increase in humidity measured superficially and a slight decrease in depth. This effect is linked to soil compaction due to the passage of an agricultural vehicle on soil with humidity close to conditions of maximum compaction. By knowing the soil density before and after the vehicle passage (thanks to periodic surveys carried out during the project), it is possible to express soil humidity as a percentage of soil weight (thus independent of soil density). The next graph (Figure 39) shows how the values of surface soil humidity (up to 20 cm deep) expressed in this way are not modified by the passage on January 19, 2022.

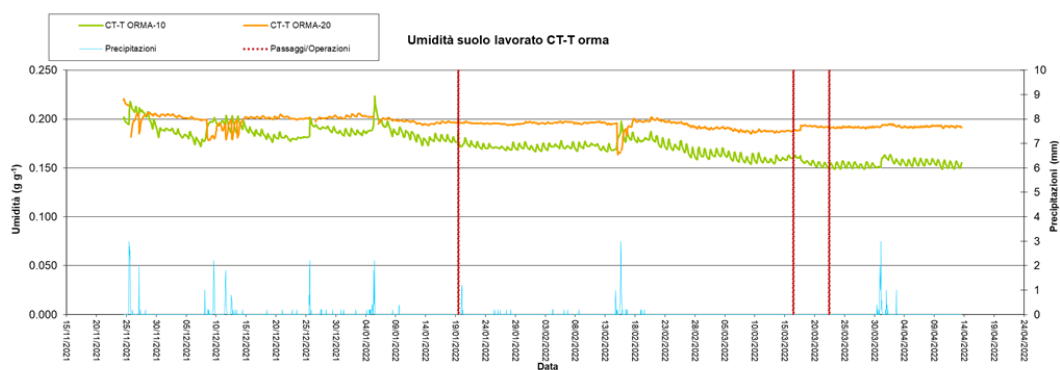


Figure 39: Gravimetric water content of the soil at various depths from autumn 2021 to spring 2022 in the tilled plot at the Carpeneto site. The histograms indicate precipitation, while the red lines represent tractor passages for agricultural operations.

Az. Torchio – San Damiano d'Asti (AT)

The monitoring of water content in the vineyard in San Damiano d'Asti was conducted from August 2021 to early May 2022 (Figure 40). It was done using sensors placed at a depth of 40 cm in the inter-rows with natural grass cover and clover, and in the two under-rows with different types of weed control, namely chemical and mechanical with a brush cutter (enhanced). During the 2021 season, soil moisture measured in the summer had values close to or less than $0.100 \text{ m}^3 \text{ m}^{-3}$. However, it was noted that in the case of the brush cutter, the increase in moisture following the first autumn rains was more evident compared to other measurement positions.

The data are interrupted during autumn tillage, but it is still interesting to observe that the humidity at 40 cm depth in both plots, before tillage, remains low and almost constant, and does not increase significantly during rains. This increase occurs instead at the two positions at 20 cm depth. This could indicate that precipitation, although exceeding 10 mm on several occasions, was not sufficient to increase soil water content in depth. The cause could be attributed to poor soil hydraulic conductivity, leading to water loss due to runoff. Following tillage and autumn rains, humidity values are significantly higher.

During winter and until May, volumetric water content was higher than $0.250 \text{ m}^3 \text{ m}^{-3}$, with a greater decrease recorded by the sensor in the grass-covered inter-row from April onwards. Following spring rains, an increase in soil moisture was recorded, again more evident in the case of the under-row managed with a brush cutter.

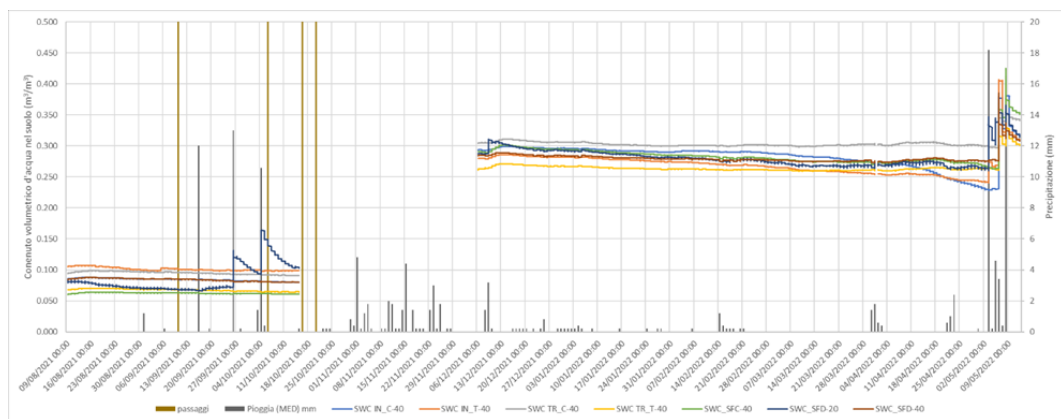


Figure 40: Volumetric water content of the soil at various depths from autumn 2021 to spring 2022 in the grass cover plot at the San Damiano site. The histograms indicate precipitation, while the brown lines represent tractor passages for agricultural operations.

Az. Porzio – Rocchetta Tanaro (AT)

The monitoring of the water content in the vineyard of Rocchetta Tanaro was operational from late June 2022 (Figure 41). However, due to a malfunction, data are available from late July 2022. This data was collected using sensors placed at a depth of 40 cm in the inter-rows with natural grass-covered soil and in the two under-rows with different types of weed control, namely chemical (conventional) and mechanical with a brush cutter (enhanced). The humidity values, expressed as volumetric water content in the soil as indicated by the probes in the under-row, are consistently higher throughout the period compared to those placed in the grass-covered inter-row, even at equal depth. In the first case, they remain above $0.200 \text{ m}^3 \text{ m}^{-3}$, and in the second case, they stay below $0.150 \text{ m}^3 \text{ m}^{-3}$ until late November. Between the two under-rows, humidity increases more noticeably in the case of weed control with a brush cutter after the first autumn rains, similar to what was observed at the vineyard of San Damiano d'Asti.

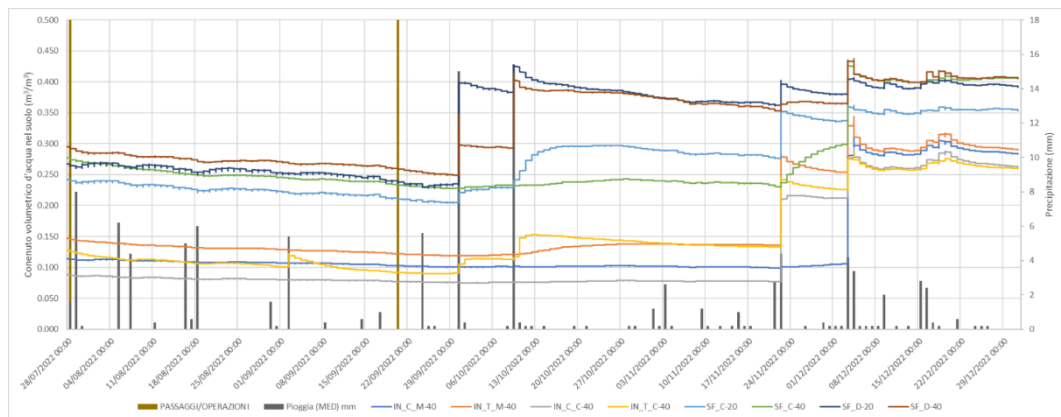


Figure 41: Volumetric water content of the soil at various depths from summer 2022 to winter 2022 in the grass cover plot at the Rocchetta Tanaro site. The histograms indicate precipitation, while the brown lines represent tractor passages for agricultural operations.

Az. Biné – Novi Ligure (AL)

The sensors for measuring soil moisture were installed in the two test plots of the Biné vineyard near Novi Ligure in early December 2021. The initial data from the end of 2021 are shown in the graphs below. It can be observed that the moisture at a depth of 40 cm, in both plots, was generally higher in the centre of the row, which was less disturbed, compared to the track position, which was subject to compaction. The lowest values were recorded in correspondence with the row, in the under-row.

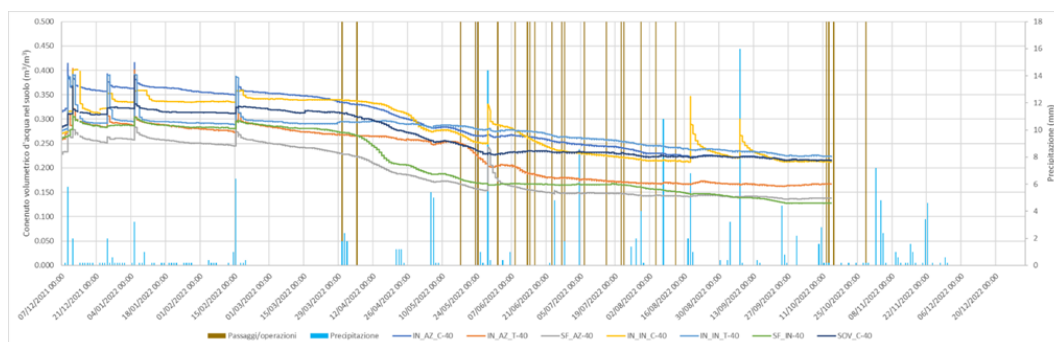


Figure 42: Volumetric water content of the soil at various depths from winter 2021 to winter 2022 in the plot at the Novi Ligure site. The histograms indicate precipitation, while the brown lines represent tractor passages for agricultural operations.

The graph (Figure 42) shows the trend of soil moisture during the first year of monitoring. All sensors are placed at a depth of 40 cm. It is clearly noticeable that during the winter period, the increase in humidity following precipitation is immediate in all measurement positions. However, from spring onwards, this does not occur, except for the sensor placed in the innovative inter-row in the centre position and in the conventional under-row. This only occurred in correspondence with the most significant precipitation at the end of May. In this row, an additional sowing on hard ground had been carried out in autumn, without first tilling the soil. It is also observed that humidity values expressed as volumetric content of soil are higher for the two sensors in the inter-row of the innovative thesis compared to the conventional one. Although it is necessary to verify that this is not due to greater soil density, the immediate response to precipitation of the sensor placed in the centre of the inter-row at 40 cm depth indicates greater ease of water infiltration, not only in the more superficial soil layer. Additionally, in the under-row of the enhanced thesis, which is less subject to compaction, greater humidity is evident compared to the conventional under-row until late summer 2022.

Az. Nebraie - Rocchetta Ligure (AL)

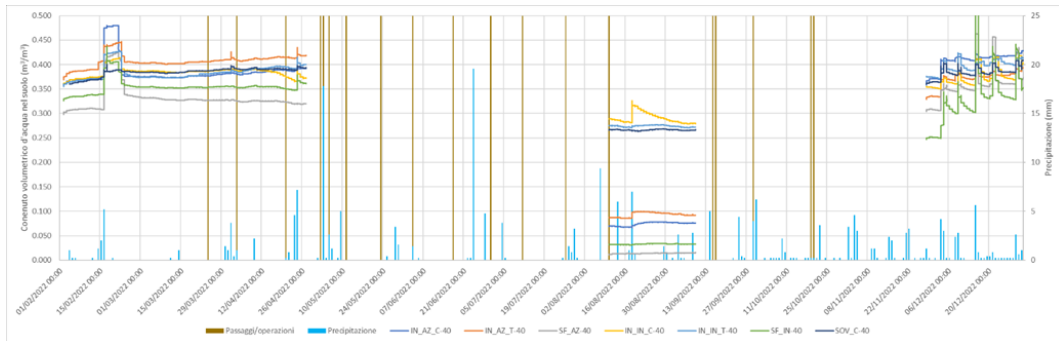


Figure 43: Volumetric water content of the soil, measured at various depths during 2022 in the plot at the Novi Ligure site. The histograms indicate precipitation, while the brown lines represent tractor passages for agricultural operations.

This graph (Figure 43) presents the trend of soil moisture in the two plots of the Nebraie vineyard (Rocchetta Ligure, AL) in 2022. The data collection was interrupted at times due to sensor malfunctions or removal for soil tillage operations. All sensors were placed at a depth of 40 cm. During the initial period of measurement, which included winter and spring, the soil moisture trend was similar across various positions. The minimum values of volumetric water content in the soil were recorded in correspondence with the under-row (lower in the conventional one), likely due to the lower soil density in that position, and higher values were observed in the inter-row with conventional management. A similar behaviour was observed at the end of 2022 after the sensors were restored.

During the summer period, measurements were available for a limited time. However, a clear differentiation between the two enhanced and conventional plots was observed. The enhanced plot showed higher values of volumetric water content ($>0.250 \text{ m}^3 \text{ m}^{-3}$), and a significant increase in humidity was detected in the central position following a rain event recorded on August 18th. The volumetric water content values measured in the conventional plot and in the two under-rows were lower than 0.100 and $0.050 \text{ m}^3 \text{ m}^{-3}$, respectively. However, it is important to consider the effect of different soil densities when making an effective comparison between plots.

Az. Cascina Gentile – Capriata d’Orba (AL)

The next graph (Figure 44) shows the trend of soil moisture in the two plots of the Cascina Gentile vineyard near Capriata d'Orba in 2022. The vineyard is located in a flat area characterized by clayey-loamy soil and was planted in 2018, which is why the conventional management involves soil tillage so as not to have cover in the inter-row. The introduced enhanced management involves sown grass cover with summer tillage if necessary.

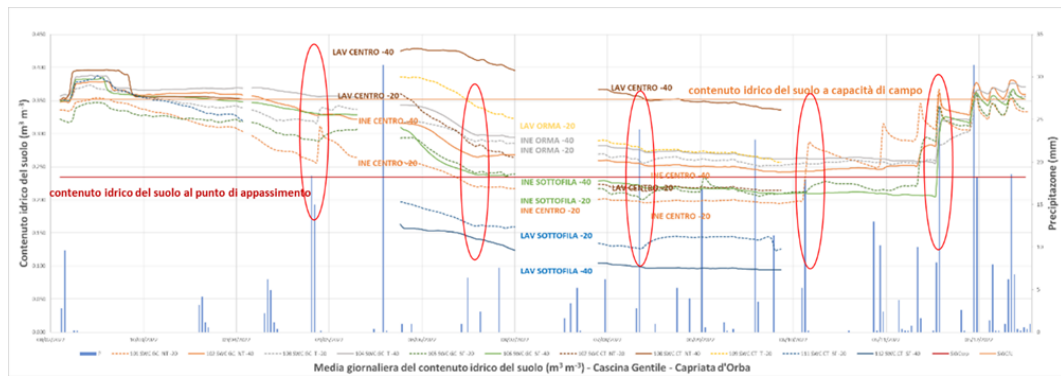


Figure 44: Volumetric water content of the soil, measured at various depths during 2022 in the plot at the Capriata d’Orba site. The histograms indicate precipitation, while the brown lines represent tractor passages for agricultural operations.

Soil moisture sensors are placed at different depths (-20 and -40 cm) in the under-row, in the centre of the inter-row, and at the tractor passage track. Observing the trend of average daily values of volumetric water content in the soil, it is generally observed that moisture is higher at greater depth, as expected. Regarding the inter-row, humidity is generally higher in the tilled inter-row compared to the grass-covered one, particularly in the central area less subject to compaction. On the other hand, the under-row of the plot with grass cover has higher humidity compared to the under-row of the tilled plot, which shows minimum values in summer 2022, below the wilting point water content. The surface humidity values at the track position are similar for both plots, while they are lower than the wilting point in the central area of the grass-covered plot. At greater depth, soil moisture is higher than this limit, much higher in tilled plot where however measured values could be affected by compaction due to passage of agricultural vehicles. The sensors at -40 cm are little or not affected by spring and summer precipitation, while an increase in deep humidity is observed in winter.

2.5.1 Information on soil moisture and soil degradation indices for winegrowers

In order not only to introduce suitable agronomic techniques, but also to equip farmers with tools that can support them in making decisions and organizing field activities, the use of an innovative DSS was introduced in the normal management of farms. After defining the monitoring of all vineyard plots involved in the project, a complete picture of the different types of soil management, pedological and topographical situations, and the configuration of the monitoring instrumentation and variables was available. This allowed for the identification of soil degradation indices and the development of additional DSS functions. This IT tool allows winegrowers to integrate all the products of the other innovations and provides information and decision support for optimal soil management (Figure 45). In collaboration with a partner company, farmers were introduced to the use of the DSS “GreenPlanet”. All data collected by weather stations and SWC probes can be viewed in real time on the DSS GreenPlanet (Figure 46). It is possible to carry out graphic and table processing and to extract the data in Excel format.



Figure 45: Schematic representation of the DSS powered by the monitoring system, which provides useful guidance to technicians and viticulturists for phytosanitary protection and field accessibility.

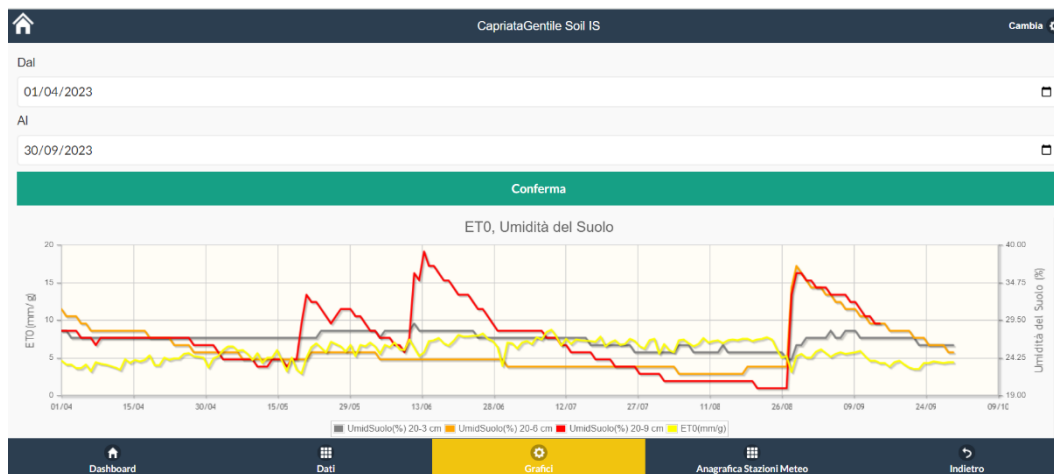


Figure 46: Representative graphs of soil moisture values and calculated Et0 provided by the Green Planet platform

Additionally, the data were used to calculate two indices provided by the soil dashboard: the soil moisture index and the field accessibility index (Figure 47). These indices evaluate field accessibility and soil degradation. They were obtained from the monitoring data acquired during the first year and validated during the second year. The intent is to define, for each site, the conditions of vulnerability to soil compaction (in terms of bulk density) as a function of soil water content. This is achieved through the Proctor test performed in the laboratory on soil samples taken from the field (2.6.2 section). These conditions were also compared with compaction measurements carried out in the field at different times of the year (2.6.1 and 2.6.3 section). This made it possible to indicate which soil moisture conditions correspond to the greatest risk of compaction due to agricultural traffic for the different parcels.

Finally, the data obtained from the soil moisture probes were used for the calibration and validation of a water balance model, which Irrigasmart uses to estimate soil water content (Figure 48), providing forecasts of soil moisture trends and field accessibility conditions (Figure 47). The estimation of soil water content is based on the most common agro-meteorological variables, in the absence of soil moisture sensors.



Figure 47: Example of the "Soil Dashboard" visualization for a vineyard plot, containing information and indices related to soil quality, water conditions, and field accessibility derived from monitoring data and subsequent analyses.

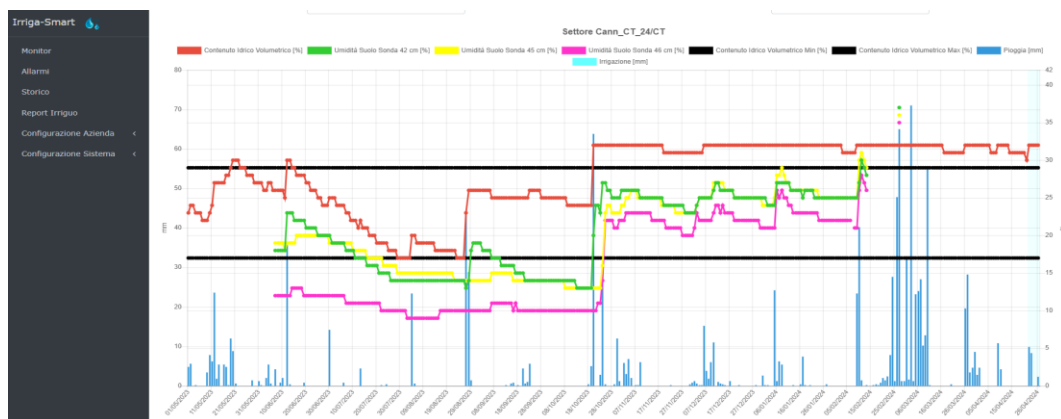


Figure 48: Representative graphs of real time and predicted soil moisture values provided by the Green Planet platform and Irrigasmart Dashboard, with estimated moisture values from the water balance model.

2.6 In field periodic monitoring of soil conditions

Periodic surveys of soil characteristics were conducted to evaluate the effect of enhanced soil management in the vineyards monitored during the project. The surveys were carried out annually at the beginning and end of the productive season (spring and autumn) regarding the soil's physical-hydrological characteristics. The comparison between the different treatments was performed using non-parametric statistical analyses.

2.6.1 Soil Bulk density (BD) and Soil water content (SWC)

Bulk density provides a measure of the void spaces (pores) in the soil and thus the degree of compaction. A healthy soil consists of more than 50% pores, while cultivation (plow pans, compaction due to agricultural traffic) can significantly affect the volume and distribution of pores. Generally, it increases with depth and is an indicator of soil compaction. Bulk density influences water infiltration, root penetration, the amount of available water, soil porosity and aeration, nutrient availability for plants, and the activity of microorganisms, which in turn affect productivity.



Figure 49: Sampling in the vineyard for measuring soil bulk density and soil water content.

Using a sharp-edged cylinder of known volume, an equivalent volume of undisturbed soil is collected (Figure 49), dried in an oven, and weighed to obtain the bulk density, or volumetric mass, as the apparent specific weight. A summary of the reference values of the ideal soil bulk density and the soil density that limits the root penetration of plant species, with reference to soil texture is reported in table 19.

Table 19: General relationship between soil bulk density and root growth, based on soil texture (USDA. 1999. Soil Quality Test Kit Guide. USDA Soil Quality Institute. Washington, D.C.)

Texture	Ideal Soil Density (g cm ⁻³)	Soil Density Limiting Root Growth (g cm ⁻³)
Sandy, sandy loam	< 1.60	> 1.80
Sandy loam, loam	< 1.40	> 1.80
Sandy clay loam, clay loam	< 1.40	> 1.75
Silty, silty loam	< 1.30	> 1.75
Silty clay loam	< 1.40	> 1.65
Sandy clay	< 1.10	> 1.58
Clay	< 1.10	> 1.47

In the monitored vineyards, soil density was measured every year both on the surface (0-20 cm deep) and at greater depth (20-40 cm), in spring and autumn in the inter-rows with different soil management, with sampling both in the centre of the inter-row and in the track position (5 repetitions per position and depth). From each sample, the volumetric water content was also obtained.

The obtained values were statistically analysed to detect significant differences between the various managements (Table 20).

Table 20: List of numbers and acronyms representing the different sites and managements that will be used in the following graphs and tables

Site	1 Carpeneto	2 Capriata d'Orba	3 Novi Ligure	4 Rocchetta Ligure	5 Rocchetta Tanaro	6 S.Damiano d'Asti
Conventional management	RMT (tilled)	RMT (tilled)	PGC1 (grass cover) RMT (cover crop)	PGC1 (grass cover) RMT1 (cover crop) Alternating annually	PGC1 (grass cover with chemical weeding)	PGC1 (grass cover with chemical weeding)
Enhanced management	PGC (grass cover)	PGC (grass cover)	PGC2 (enhanced grass cover) RMT (cover crop)	PGC2 (grass cover) RMT2 (cover crop) Not alternating	PGC2 (grass cover with mechanical weeding)	PGC2 (grass cover with mechanical weeding)

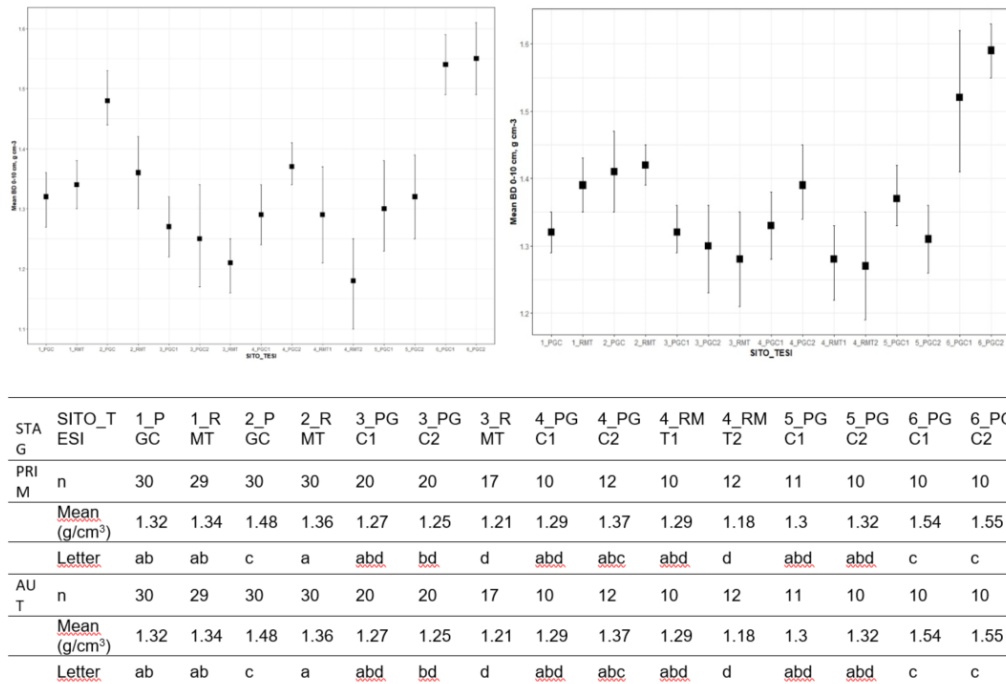


Figure 50: Average soil density values measured in spring and autumn at different sites and plots, depth 0-10 cm. Different letters indicate significant differences.

The average BD values on the surface (Figure 50) are found to be better (lower) or similar in plots with enhanced management, except in autumn in the vineyards of Capriata d'Orba and Novi Ligure. The lowest values were found in rows with grass cover or cover crop and generally fall within the range indicated as "ideal". The highest and critical values were found in the vineyard of San Damiano d'Asti.

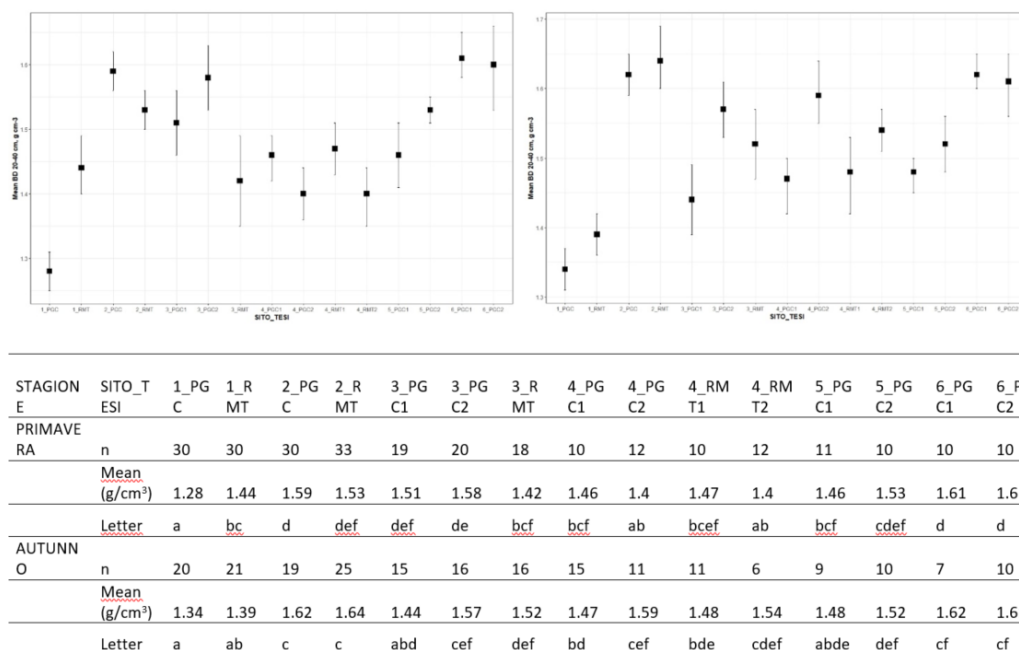


Figure 51: Average soil density values measured in spring and autumn at different sites and plots, depth 30-40 cm. Different letters indicate significant differences.

The soil bulk density at greater depth (30-40 cm, Figure 51) was significantly lower in spring in the grassed plot compared to the tilled one at Carpeneto. It is similar in two cases and in as many higher with enhanced management compared to traditional. Even at this depth, the highest values were recorded in San Damiano d'Asti, at the limit of criticality for root development ($>1.60 \text{ g/m}^3$).

Considering the BD of the soil on the surface, regardless of the site (Figure 52), management with cover crops results in significantly lower values compared to management with temporary grass cover and spring tillage (1.25 g/cm^3 versus $1.34\text{-}1.35 \text{ g/cm}^3$). In autumn, tillage management leads to significantly higher soil density compared to grass cover and cover crops (1.40 g/cm^3 versus 1.35 g/cm^3 and 1.34 g/cm^3), as illustrated in the graph below. Therefore, overall, management with cover crops results in the lowest soil density values, while grass cover management maintains a constant trend.

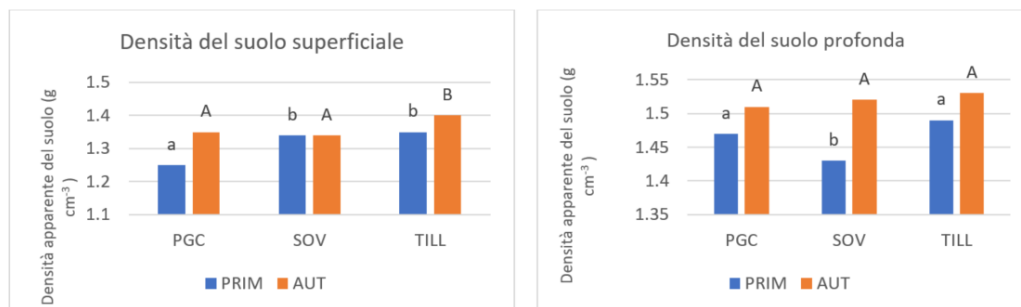
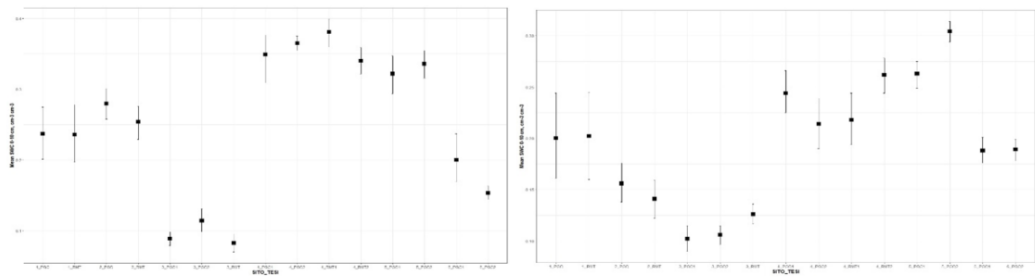


Figure 52: Average soil density values measured in plots with different soil management practices (TILL = tilled, PGC = permanent grass cover, SOV = cover crop). The graph on the left side represents 0-20 cm depth, while the graph on the right side represents 20-40 cm depth. Different letters indicate significant differences between values measured in the same season.

Also at greater depth, the management with green manure allows to have a soil density significantly lower than the management with grassing and tillage in spring (1.43 g cm^{-3} compared to $1.47\text{-}1.49 \text{ g cm}^{-3}$), while in autumn there are no significant differences and the density is higher than 1.50 g cm^{-3} in all cases. The conditions are not ideal for root growth at the end of the season, but it is seen how in spring the improvement of this condition is not guaranteed so much by traditional tillage as by the use of green manure.

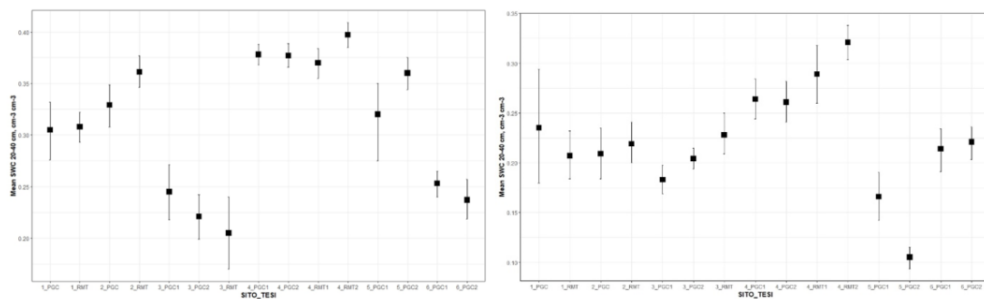
The soil moisture measured as volumetric water content in conjunction with the periodic surveys (Figure 53) was found to be, at a depth of 0-10 cm, greater or similar in plots with enhanced management compared to the conventional one, both in spring and autumn, except in the case of San Damiano d'Asti, in any case without significant differences.

Also at greater depth (30-40 cm, Figure 54) there were no significant differences in volumetric water content, with different behaviour depending on the site. The only site where in the case of enhanced management the deep soil moisture was found to be lower both in spring and in autumn is the vineyard of Capriata d'Orba.



STAGION	SITO_TE	1_PG	1_R	2_PG	2_R	3_PG	3_PG	3_R	4_PG	4_PG	4_RM	4_RM	5_PG	5_PG	6_PG	6_PG
E	SI	C	MT	C	MT	C1	C2	MT	C1	C2	T1	T2	C1	C2	C1	C2
PRIMAVERA	n	30	29	30	30	20	20	17	10	12	10	12	11	10	10	10
	Mean (cm³/cm³)	0.23	0.236	0.28	0.254	0.088	0.114	0.082	0.349	0.365	0.381	0.34	0.322	0.336	0.2	0.153
	Letter	abc	abc	abd	abc	e	ef	e	dg	g	g	dg	adg	adg	bcd	cd
AUTUNNO	n	26	20	16	13	16	16	16	14	15	16	6	9	10	10	10
	Mean (cm³/cm³)	0.2	0.202	0.15	0.141	0.102	0.106	0.126	0.244	0.214	0.218	0.262	0.263	0.304	0.188	0.189
	Letter	ab	abc	ad	ade	e	e	de	fg	bcdg	bcdg	cdg	fg	f	abcd	abcd

Figure 53: Average soil moisture values measured in spring and autumn at different sites and plots, depth 0-10 cm. Different letters indicate significant differences.



STAGIONE	SITO_TESI	1_P GC	1_R MT	2_P GC	2_R MT	3_PG C1	3_PG C2	3_R MT	4_PG C1	4_PG C2	4_RM T1	4_RM T2	5_PG C1	5_PG C2	6_PG C1	6_PG C2
PRIMAVERA	n	30	30	30	33	19	20	18	10	12	10	12	11	10	10	10
	Mean (cm³/cm³)	0.30 5	0.30 8	0.32 9	0.36 1	0.245	0.221	0.20 5	0.378	0.377	0.37	0.397	0.32	0.36	0.253	0.237
	Letter	ab	ac	abd	de	f	f	f	e	e	de	e	abcd	bde	cf	f
AUTUNNO	n	20	21	19	25	15	16	16	15	11	11	6	9	10	7	10
	Mean (cm³/cm³)	0.23 5	0.20 7	0.20 9	0.21 9	0.183	0.204	0.22 8	0.264	0.261	0.289	0.321	0.166	0.105	0.214	0.221
	Letter	abc	abc	abc	abcd	ab	abc	cde	ef	def	ef	f	ag	g	abcde	bcdef

Figure 54: Average soil moisture values measured in spring and autumn at different sites and plots, depth 20-40 cm. Different letters indicate significant differences.

Regardless of the site (Figure 55), soil moisture on the surface is higher in rows managed with green manure both in spring and in autumn. In autumn, the values measured in tilled rows are significantly lower than those recorded in inter-rows with green manure are. At a depth of 40 cm, soil moisture is higher in rows managed with tillage in spring compared to those with grassing and green manure, with the latter showing lower values. This situation reverses in autumn, with significantly higher values in rows with green manure compared to those with grassing or tillage.

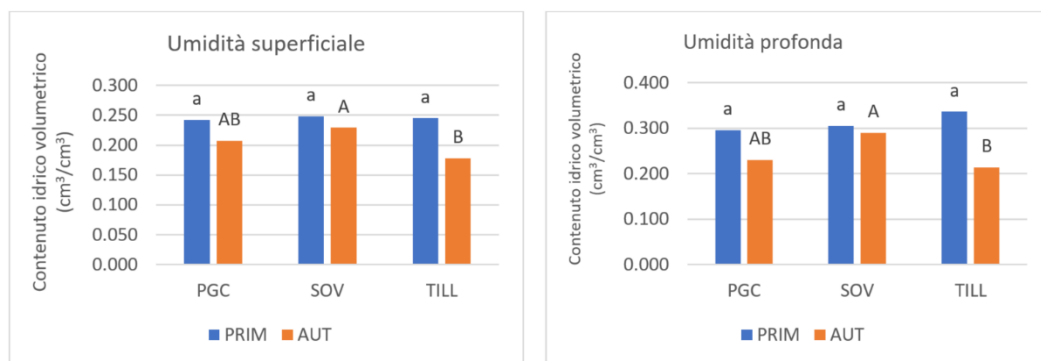


Figure 55: Average volumetric water content values measured in plots with different soil management practices (TILL = tilled, PGC = permanent grass cover, SOV = cover crop). The graph on the left side represents 0-20 cm depth, while the graph on the right side represents 20-40 cm depth. Different letters indicate significant differences between values measured in the same season.

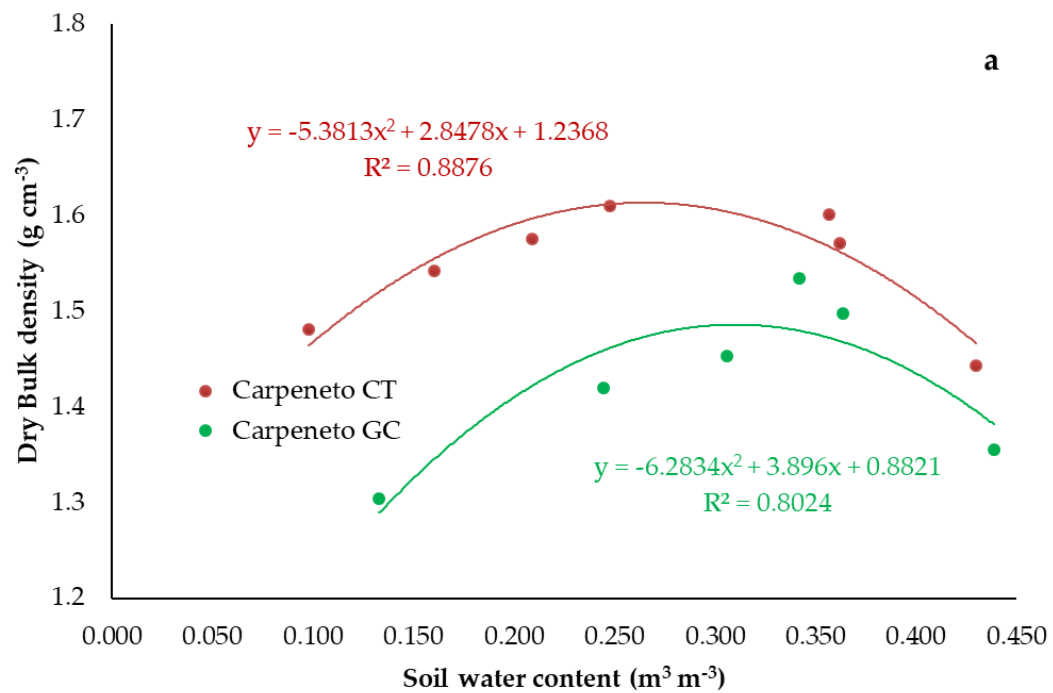
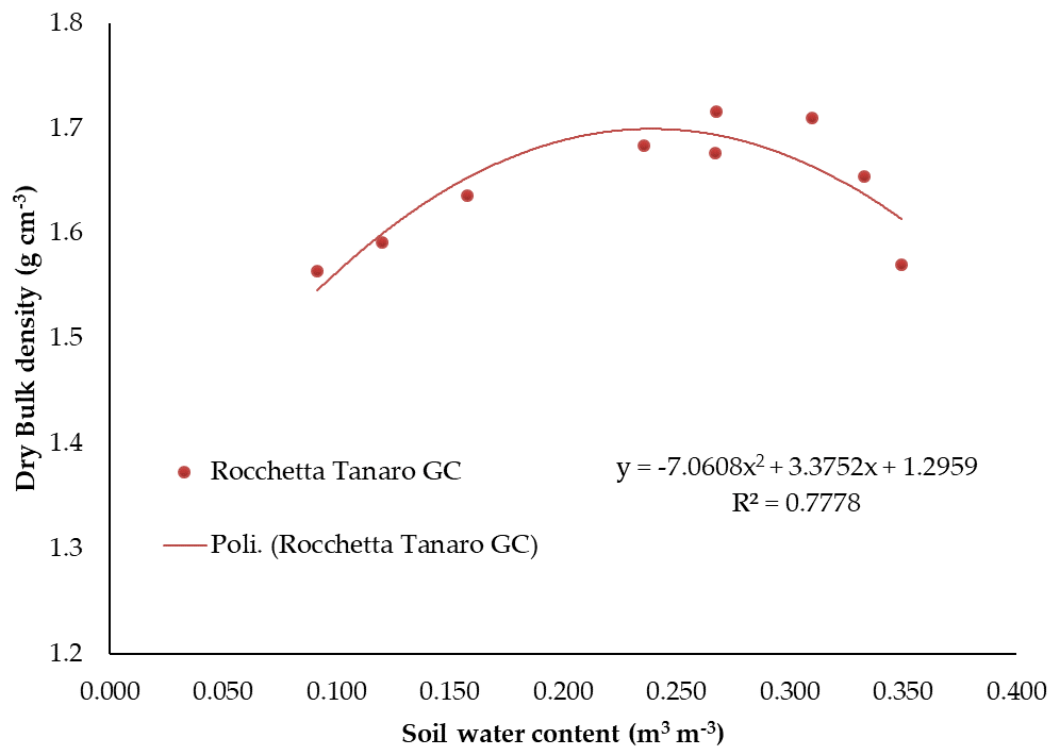
2.6.2 Proctor Test

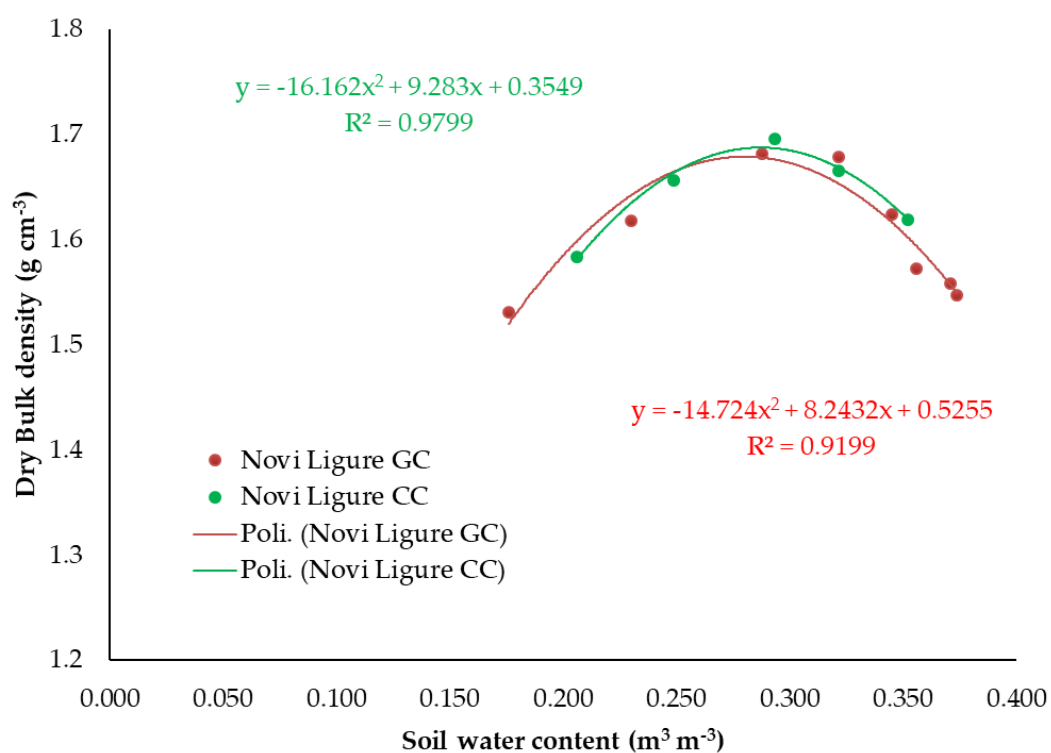
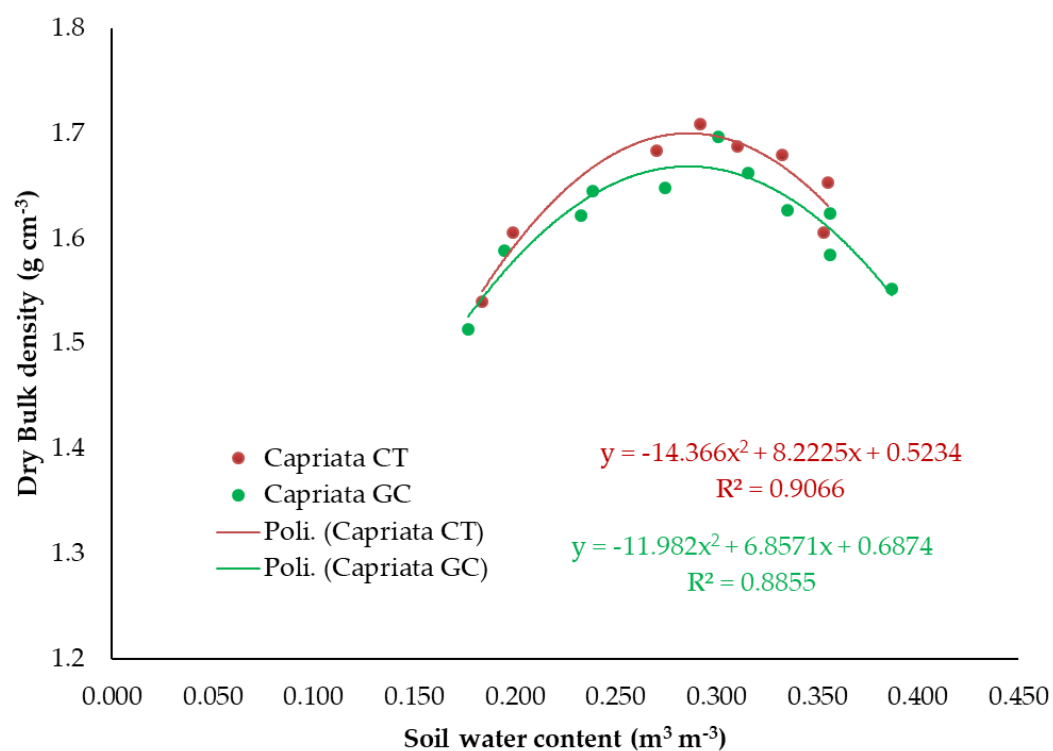
An American engineer developed the Proctor test in the early 1930s (Proctor, 1933). Its utility remains valid today and is employed in various fields such as construction, including the building of structures and dams, as well as in research. This test allows the determination of the correlation between soil compaction and the optimal water content to achieve maximum soil density. During the test, the compaction pressure and the volume of soil analysed remain constant, with moisture content being the only variable. The Proctor test involves the compaction of properly crushed soil within a cylinder of known dimensions. The soil is compacted in three overlapping layers using a 2.5 kg metal rammer, which is dropped from a height of 35 cm for 25 successive times. The test is repeated under different soil moisture conditions, and for each test, the pair of soil moisture and corresponding bulk density points are obtained after weighing and oven drying. Once a series of points with varying moisture levels is obtained, they are interpolated with a second-degree curve (parabola). It is necessary to achieve a distribution of points that allows good interpolation to accurately define the curve and thus determine the compaction achievable under specific soil moisture conditions.

The Proctor test is useful for studying soils subjected to specific compaction. Soil compaction reduces soil productivity, making it crucial to study soil susceptibility to compaction, which can be effectively assessed using the Proctor test. For instance, in vineyards, wheeled or tracked vehicles are restricted to passing between rows, consistently compacting the same soil areas in correspondence of the tracks. This results in zones that reach maximum compaction levels while others remain uncompacted. All samples from the same soil were collected from the top 10 cm at multiple points, both in the tracks (the areas compressed by the wheels or tracks of agricultural machinery) and in the centre (the area between the wheels of agricultural machinery that remains uncompressed), and then mixed.

The Proctor Test was carried out on soil samples from the two parcels of the 5 sites, to determine the maximum soil density obtainable by compaction of the soil and the corresponding level of humidity. Considering the trafficability of the vineyards, this value indicates the humidity conditions for which, by accessing the field with agricultural vehicles, greater compaction and therefore potential soil degradation is obtained. The compaction risk index indicates the moisture conditions under which maximum soil compaction is achieved for the monitored

vineyard plots. This allows for the identification of compaction risk in the event of tractor passage under these conditions.





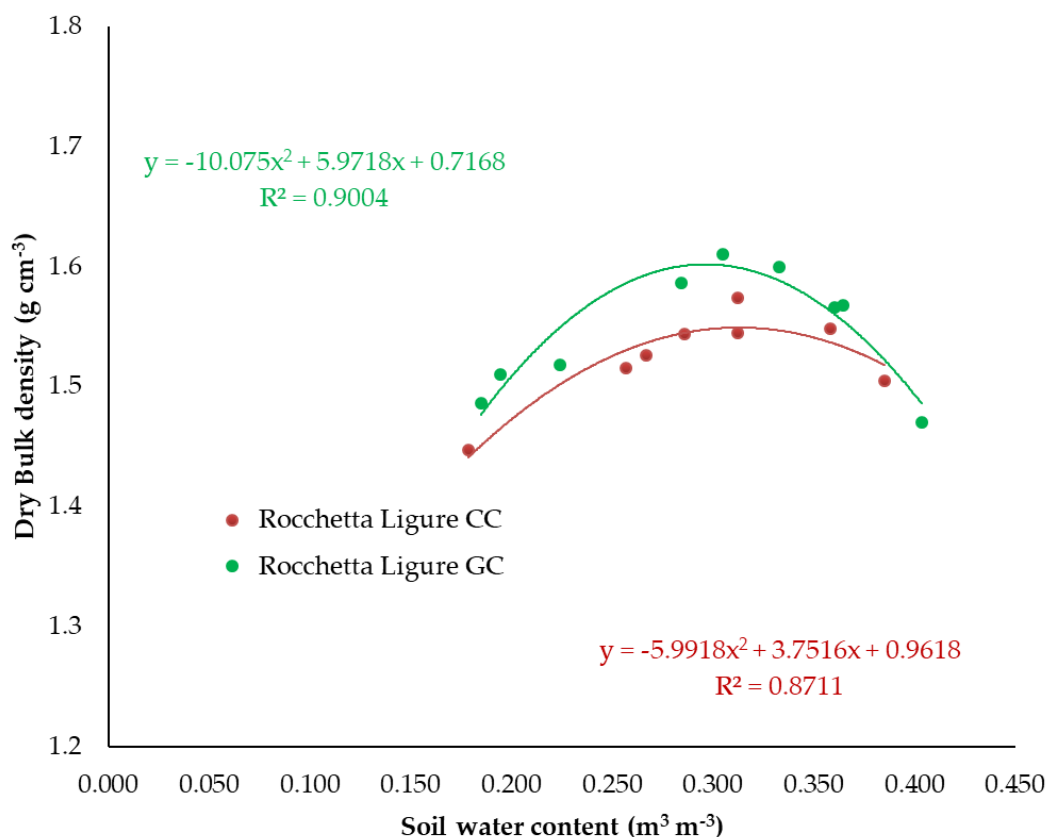


Figure 56: Proctor test curve of the different soil management practices (CT = conventional tillage, GC = grass cover, CC = cover crop) in the 5 vineyards. The maximum bulk density varies according to soil humidity conditions (soil water content).

The Proctor test (Figure 56) performed on soil samples from the vineyards of Novi Ligure and Capriata d'Orba resulted in two similar curves, as maximum compaction is achieved with practically identical soil moisture. In Capriata d'Orba, the soil density value is slightly higher in tilled soil compared to grass-covered soil. In both cases, the soil density reached is higher than that of similar management in other vineyards.

In Rocchetta Ligure and Carpeneto, the difference between the two management practices is more pronounced. In Carpeneto, the CT plot can reach a much higher maximum compaction with lower moisture compared to the GC plot. In Rocchetta Ligure, the inter-rows with cover crops can achieve lower compaction than those with grass cover, while the moisture level at which maximum compaction is reached remains the same.

Finally, in Rocchetta Tanaro, there is only one curve as there is no difference in the management of the inter-row, but only in the under-row, which is not affected by trafficking.

These characteristic curves have been used to implement a tool in the Decision Support System (DSS) that can indicate to farmers the risk of soil waterlogging and compaction based on the soil water content measured by probes.

2.6.3 Soil penetration resistance (PR)

Similar to bulk density, soil penetration resistance provides an index related to the degree of soil compaction. It was measured in each thesis at the track and the centre of the inter-row using a manually operated digital cone penetrometer (Penetrologger, Eijkelkamp, Netherlands, Figure 57). Ten repetitions of penetrometry were performed at each position, totalling 20 for each plot. These measurements aim to highlight the contrasting penetration resistance characteristics between different soil horizons.



Figure 57: Execution of a penetrometer test to determine soil penetration resistance.

The cone used for the tests has a tip with a 30° inclination and a base area of 1 cm^2 . For each measurement, the Penetrologger plate is positioned as parallel to the soil surface as possible. By applying pressure with the hands on the instrument's handles, the rod is inserted into the soil at a constant speed of 2 cm s^{-1} , to a depth of 0.8 m. The insertion is performed while maintaining an inclination of less than 3.5° from the vertical position. The instrument automatically measures the exerted force and penetration depth using an ultrasonic sensor with a resolution of 1 cm, automatically calculating the penetration resistance, considering the tip used, and associating the value in MPa with the depth. If the soil is too hard, making the test physically impossible or risking damage to the instrument, penetrometry is performed to a shallower depth or not at all. In vineyards with alternating row

management, such as alternating rows with cover crops, an additional series of penetrometry tests is conducted.

Subsequently, the data were manually validated and processed by averaging the different repetitions, divided into appropriate depth ranges, to perform a statistical analysis to identify significant differences between the various theses and positions. Statistical analysis was performed using R software to identify statistical differences ($\alpha < 0.05$) across various positions and depths, as well as different time intervals within the monitored period. The applicability of variance analysis techniques like ANOVA was assessed by checking data normality using the Shapiro-Wilk test. However, as this normality test failed, statistical differences between treatments were evaluated using the Kruskal-Wallis test. This non-parametric method substitutes data with their rank in variance analysis and is typically employed to confirm the equality of medians across different groups when a normal population distribution cannot be assumed. Essentially, it verifies whether these groups originate from the same population or from populations with identical medians.

The most evident result across all sites is the difference in soil penetration resistance between the track position, which is more compacted, and the centre of the row, which is less disturbed. In almost all sites, although an increase in value with increasing depth is normal, the presence of a plough pan was found at a variable depth between 30 and 50 cm: the soil resistance showed a sharp increase along the profile, sometimes making further measurement impossible. In the Figure 58, the presence of a thick plough pan found in the first survey carried out in Rocchetta Tanaro at a depth between 20 and 50 cm is evident, both in correspondence with the footprint and the centre. The impact of surface tillage on CT plots is noticeable only centrally; however, it is appreciable within vehicle tracks solely during spring 2021. By spring of the following year, soil compaction is already evident.

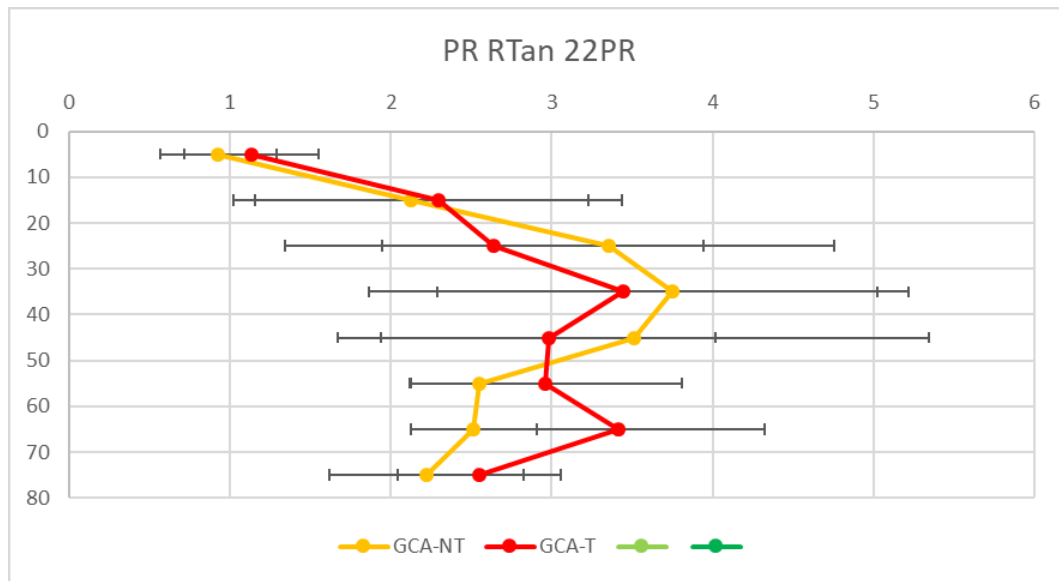


Figure 58: Penetration resistance profile varying with depth, measured at Rocchetta Tanaro during the first survey conducted (spring 2022).

In general, a higher soil penetration resistance value was observed at the end of the productive season compared to spring. For example, at the Capriata site (Figure 59 A), it is clear that the profiles obtained from the average of the values measured in autumn (AU, green and orange colours) in the four positions are significantly higher than the spring values (PR). Analysing the individual years in more detail, for example by comparing spring (Figure 59 B) with autumn (Figure 59 C) of 2023, it is clear that in spring the resting soil has low values, between 1 and 2 MPa, without significant differences between the different positions. In autumn, however, the soil is much more compact, with values that from 30 cm depth are all above the threshold value of 2 MPa. Going into even more detail, in autumn, the surface horizons have lower values, and the centre is less resistant to penetration than the track position. The grassed plot on the surface has higher values than the tilled one, but below 20 cm in the central position of the grassed rows, significantly lower values were recorded compared to the other three positions. Similar results were also found in the second site with grass cover and tilled theses compared, in Carpeneto, but with a smaller difference in surface values between the theses. The greater penetration resistance of the first centimetres of soil could be due to the presence of grass roots, which however guarantee a lower value in depth.

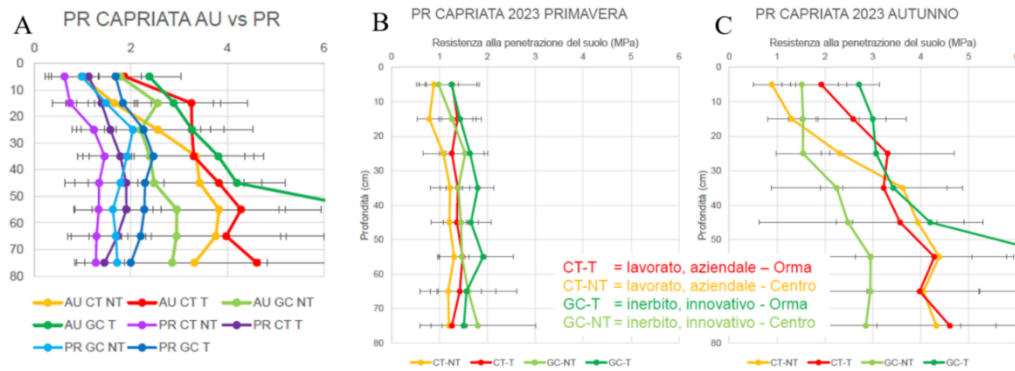


Figure 59: Average penetration resistance profiles varying with depth, measured at Capriata during the three spring and three autumn surveys (A), and detailed values measured in spring (B) and autumn (C) 2023.

Considering the entire profiles (Table 21), in Capriata d'Orba, significant differences were observed within track positions compared to central areas on grass plots during spring 2021. During this period, profiles significantly differed from all other positions. On tilled plots, differences between tracks and central areas were significant only during spring 2022; CT-NT differed significantly from all other positions due to soil tillage effects. Spring 2022 also saw significant differences between tracks across the two treatments, indicating varying degrees of compaction following agricultural vehicle passage on tilled and grassed soils. No significant differences were observed across various positions during the two autumn surveys. Comparisons across different periods reveal that for grass plots at the no-track position, initial surveys showed significant differences compared to subsequent ones. Within vehicle tracks, profiles measured across two springs were significantly different. In tilled inter-rows during both spring years, central areas differed significantly from autumn measurements. Within the track position, a significant difference was observed between spring of 2021 and both surveys conducted during 2022.

Table 21: The table illustrates the results from Kruskal-Wallis tests on penetration resistance measured in Capriata d'Orba during the years 2021 and 2022 in spring (SP) and autumn (AU), highlighting significant differences across various positions (CT = conventional tillage, GC = grass cover, T = track position, NT = no-track position). This analysis considered entire profiles rather than individual depths.

21SP_CT-NT	d	21AU_CT-NT	abc	22SP_CT-NT	d	22AU_CT-NT	abc
21SP_CT-T	d	21AU_CT-T	abcd	22SP_CT-T	a	22AU_CT-T	ab
21SP_GC-NT	d	21AU_GC-NT	ab	22SP_GC-NT	ab	22AU_GC-NT	ab
21SP_GC-T	c	21AU_GC-T	abcd	22SP_GC-T	b	22AU_GC-T	abc

Employing the same method and delving into individual survey campaigns to compare different depths at each position yields additional insights. During spring 2021, within the initial 20 cm of soil, a significant difference was observed between two tilled positions and two grassed ones; within grassed areas, differences were also noted between track and central areas but only within initial 10 cm. In CT-T areas, penetration resistance for initial 30 cm of soil was significantly lower than measurements taken at greater depths. Similar observations were made for CT-NT areas: initial 10 cm of soil exhibited significantly less penetration resistance compared to layers at depths ranging from 20 to 40 cm. This could potentially indicate presence of a tillage pan. The second survey revealed no significant differences between positions due to limited data availability caused by high soil penetration resistance; however, a significant increase in pressure values was noted between initial 30 cm and deeper layers. During spring of second year, surface soil showed significantly greater resistance in CT-T compared to GC-NT. Within central areas of grassed plots, a significant difference was observed between initial 10 cm and layers at depths ranging from 20 to 30 cm; within track areas however, initial 10 cm of soil differed from deeper layers. Lastly, during final survey period due to recorded high variability, statistically significant differences were only identifiable between initial 10 cm and subsequent 10 cm within track position of conventional rows.

In the two sites where theses were compared with equally grassed inter-rows, in San Damiano d'Asti and Rocchetta Tanaro, the different management of the under-row does not seem to have influenced soil penetration resistance, neither at the track position nor at the centre position. The increase in penetration resistance in autumn compared to spring, despite high variability, was not statistically significantly different between the theses. However, in Rocchetta Tanaro, the values for the enhanced management thesis were slightly lower than those for the chemical weeding thesis were. This could indicate that the different management

of the under-row does not significantly influence the soil penetration resistance characteristics of the inter-row.

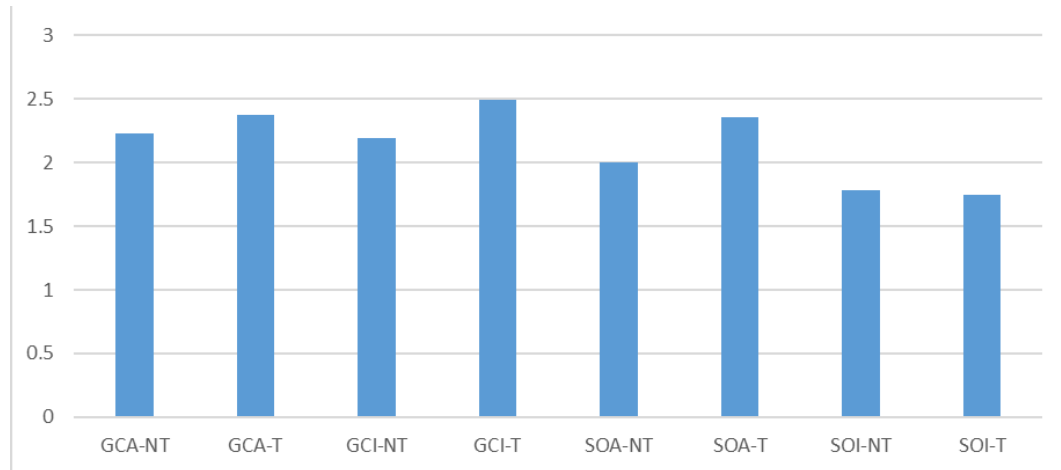


Figure 60: Average penetration resistance (MPa) measured at Rocchetta Ligure over three years in different monitored positions: grass cover (GC) and green manure (SO), for conventional (A) and enhanced (I) treatments, in the centre (NT) and track (T).

Finally, in the two vineyards with rows sown with green manure for cover crop (Novi Ligure and Rocchetta Ligure), an intermediate value of penetration resistance was recorded (Figure 60). The presence of the cover crop, combined with less frequent passage of agricultural vehicles, ensures a penetration resistance value that is on average lower than that of the rows with spontaneous grass cover, where all vehicle passages are concentrated. Analysing the values measured over three years of surveys in both sites, it is evident that soil penetration resistance is consistently lower in the rows with cover crops compared to those with grassing. Rocchetta Ligure presents the only exception, with the row with conventional cover crop showing a higher average value. Comparing the grassed rows, both positions of the one with enhanced management show a slightly higher average value compared to the conventional one, although the difference is not significant. In Rocchetta Ligure, where management was also differentiated for the cover crop, the value measured in the enhanced management is significantly lower compared to the conventional management.

2.6.4 Soil hydraulic conductivity

Saturated hydraulic conductivity is an important soil characteristic as it indicates the ease with which water can infiltrate the soil during a rainy event when the soil is saturated. To measure soil hydraulic conductivity, a series of five single-ring infiltrometers, automated with dataloggers (Concialdi et al., 2020), were used in each inter-row, both at the track of tractor passage and at the centre of the inter-row (Figure 61).



Figure 61: Execution of infiltration tests in vineyards to determine saturated hydraulic conductivity.

In all sites, the hydraulic conductivity measurements carried out in the track position, which is more compacted, have always been significantly lower than the centre of the row, which is less disturbed. This demonstrates how careful management of the passage of agricultural vehicles can strongly influence the characteristics of the soil and the availability of water resources.

The following graph in Figure 62 summarizes the results obtained from monitoring vineyards with different soil management. Soil management was considered independently of the site, grouping the managements adopted into three categories: tillage carried out at least once a year, permanent spontaneous grassing without tillage during the year, and sown green manure.

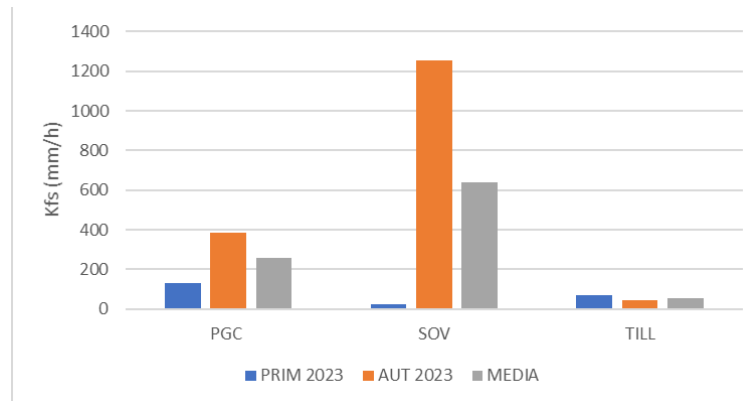


Figure 62: Average saturated hydraulic conductivity values measured in the inter-row with different soil management practices (TILL = tilled, PGC = permanent grass cover, SOV = cover crop) at various times during the productive season.

The soil's hydraulic conductivity was found to be on average higher in soils with grass cover. In particular, plots managed with permanent grassing showed a higher hydraulic conductivity compared to tilled plots. The only case where tilled plots presented a very high conductivity was immediately after tillage. However, already following the first passages of agricultural vehicles on wet soil, the resulting compaction significantly lowered the value. Plots managed with cover crop showed a greater susceptibility to compaction - and consequently lower hydraulic conductivity - in spring, following the passages also made in the sown rows. While in autumn, especially in the drier seasons, they guaranteed a higher hydraulic conductivity of the soil. This is particularly true at the Novi Ligure site (Figure 63), where the values recorded in autumn in the rows with cover crop were significantly higher than those of the rows with both types of grass cover were. Furthermore, in the autumn of the third year of experimentation, a significant difference was noted between the conventional management and the enhanced one, in favour of the latter. At the Rocchetta Ligure site, on loamy soil, the difference between the managements was less significant.

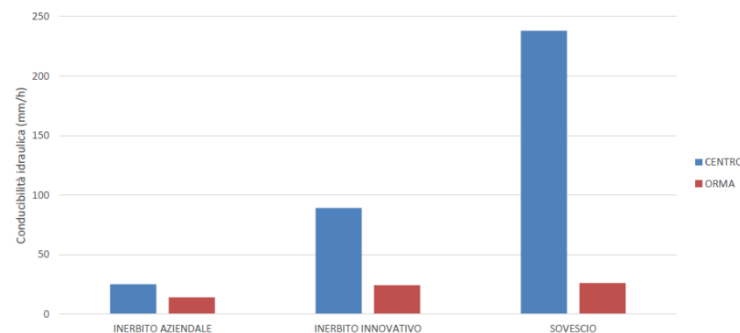


Figure 63: Average saturated hydraulic conductivity values measured in the inter-row at the track and centre, with different soil management practices in autumn 2023 at Novi Ligure.

In the sites of Rocchetta Tanaro and San Damiano d'Asti, the comparison between the two types of under-row weed control did not show significant differences, due to the high variability of the measured values. In the two sites of Carpeneto and Capriata d'Orba, where the managements compared were permanent grassing and traditional tillage, the hydraulic conductivity was found to be better in the grassed inter-row compared to the one worked at the end of the season (with double values in Carpeneto, between 5 and 10 times as much in Capriata). The difference was slightly lower in spring, following the ripping operations and the reduced number of passages of agricultural vehicles. In the tilled plots, in track position, the soil was particularly impermeable and the minimum values of hydraulic conductivity of the entire survey campaign were recorded, less than 10 mm/h. This demonstrates that the root systems of the grass cover facilitate the infiltration of water even in conditions of extremely compact surface soil.

2.6.5 Soil cover (SC)

To assess the degree of soil cover of the inter-row area by grassing or cover crops, the degree of coverage (expressed in %) was calculated using the method proposed by Agrela et al. (2003), using a 0.5x0.5 m² grid with 0.1x0.1 m² meshes that allows the evaluation of different sectors of the grid (Figure 64). The operator assigns a subjective value of the degree of coverage to each frame of the grid, on a scale ranging from 0 to 5 based on the amount of soil coverage observed, whether it is biomass of the grassing, crop residues or stones.

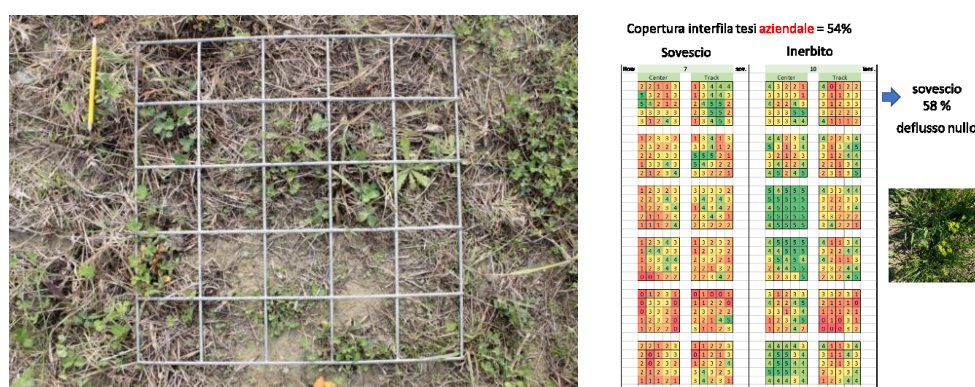


Figure 64: Grid used for assessing the degree of inter-row vegetation cover, and visual representation of a complete survey for a site

This procedure is carried out at various points in the vineyard or experimental plots, both in the centre and in the footprint, i.e., the point of the inter-row where the tractor passes and causes compaction and alteration of the surface structure of the soil.

For the Carpeneto site, the coverage and biomass surveys were more numerous (26 in total during the 3 seasons considered) and therefore allow following the trend in a more detailed way (Figure 65). In the tilled inter-rows, the maximum degree of coverage, reached before the spring or autumn tillage, is 60%, while the minimum values, less than 20% were measured after the autumn tillage of 2021 and in the following months. Values close to 20% were also measured in spring 2023, before the rainy period. The values of collected biomass generally have a trend similar to coverage, with a peak recorded in summer. The minimum values suggest that the coverage reacts to drought periods with a significant reduction. In the case of the grassed inter-row, the soil coverage was almost always between 80 and 100%, with minimum values in summer 2022 and spring 2023, always however above 60%.

The average soil coverage is significantly higher in the grassed plots compared to those tilled both in spring and in autumn (Figure 66). The average coverage, in the plots with enhanced management is generally higher than the conventional one and above 30%, up to 95%. Similarly, the aboveground biomass is usually higher in the enhanced plots compared to the conventional ones, with significant differences (Figure 67).

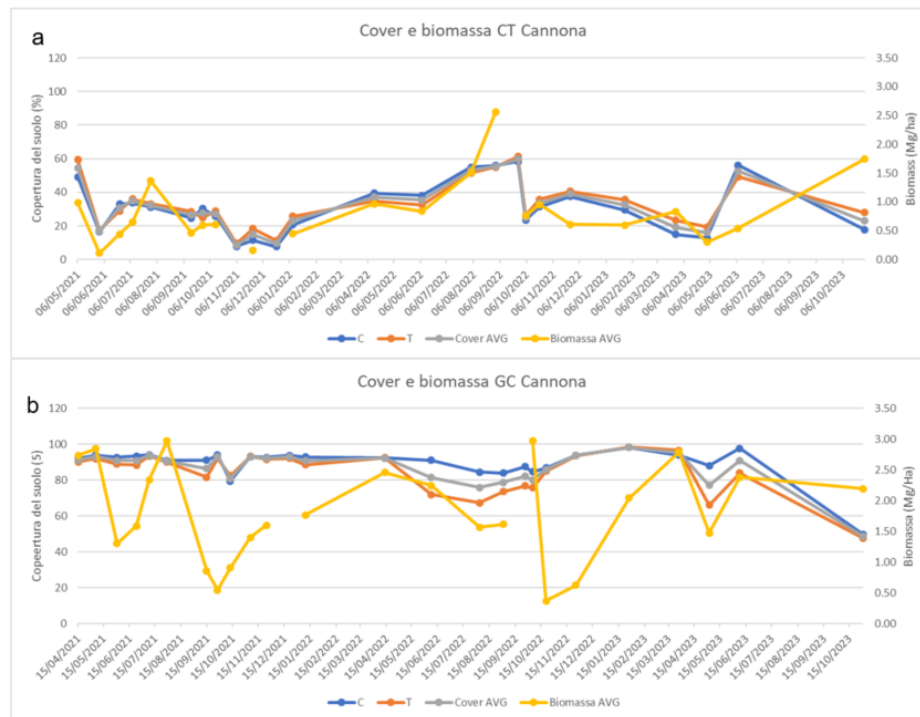


Figure 65: Trend of soil cover (a) and biomass (b) in the inter-row of the plots at Carpeneto.

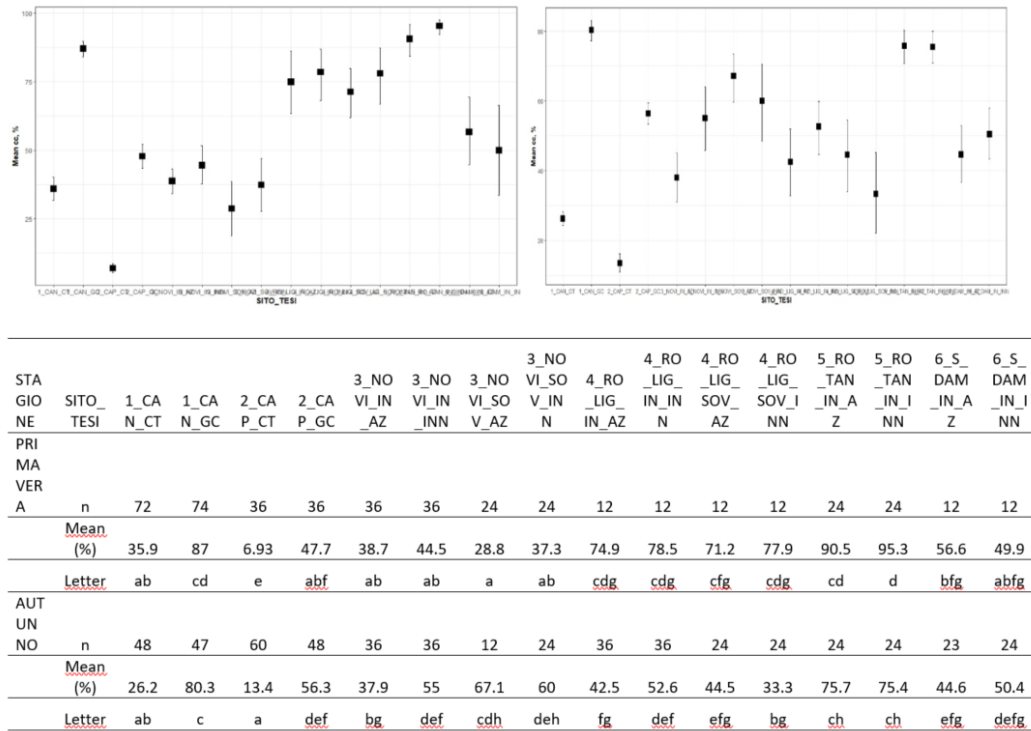


Figure 66: Average percentage values of soil cover measured in spring and autumn at different sites and plots. Different letters indicate significant differences.

Regardless of the site (Figure 68), the soil coverage by vegetation is maximum in the rows with grassing and minimum with tillage, among the different managements; both in spring and autumn, with significant differences between the different managements in spring and between management with tillage and the other two managements in autumn. The biomass of the inter-row cover, in spring, is maximum in the case of green manure and minimum with tillage, in autumn the differences are less evident, with slightly higher coverage in the case of permanent grassing compared to green manure.

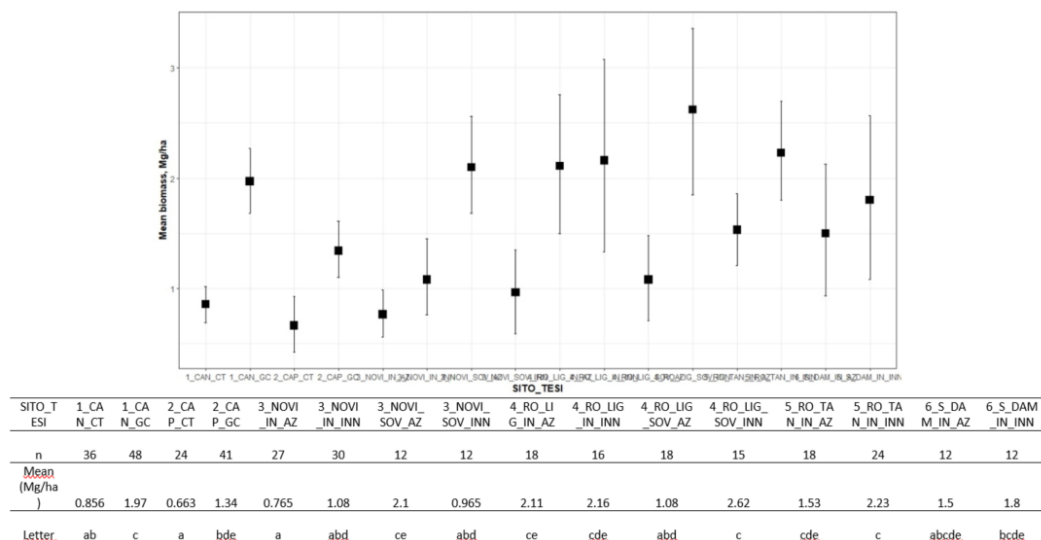


Figure 67: Average percentage values of soil cover measured at different sites and plots. Different letters indicate significant differences.

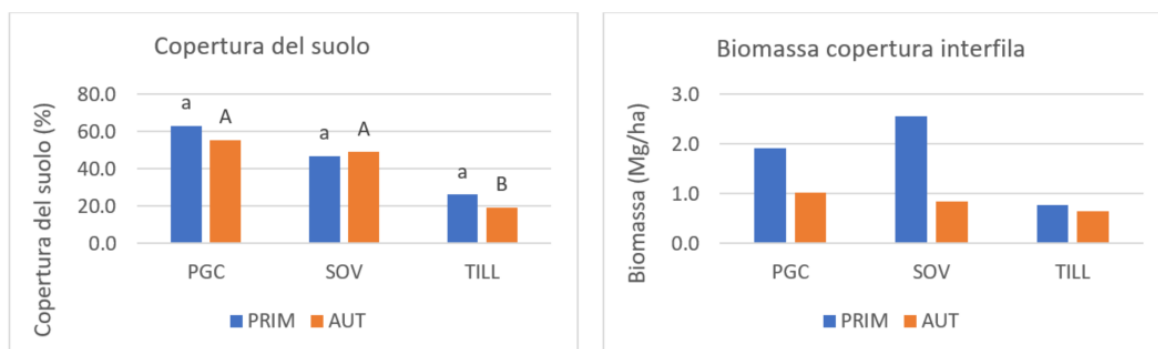


Figure 68: Average values of soil cover and biomass measured in the inter-row with different soil management practices (TILL = tilled, PGC = permanent grass cover, SOV = cover crop). The graph on the left side represents 0-20 cm depth, while the graph on the right side represents 20-40 cm depth. Different letters indicate significant differences between values measured in the same season.

2.6.6 Soil organic matter and total nitrogen content analysis

At the end of the first productive season with differentiation (autumn 2022), soil samples were collected at various depths and points in the vineyard. Differentiation occurred the previous autumn, except at Carpeneto. Additional samples were collected at the end of the monitoring period (autumn 2023), after two productive seasons with differentiation. These samples were analysed in the laboratory to obtain information on soil type (texture) and chemical characteristics.

In 2022, the organic matter content (Figure 69) was higher in the enhanced plot compared to the conventional plot (grass cover versus tillage) in samples collected at Carpeneto. At Capriata d'Orba, the behaviour was similar in 2022, while in 2023 the organic matter content was significantly lower in both plots, with slightly lower values for the superficial sample collected in the grass-covered inter-row and similar values at greater depths. At Novi Ligure and Rocchetta Tanaro in 2023, the organic matter content was consistently higher in the enhanced plot, while at Rocchetta Ligure, the trend was reversed.

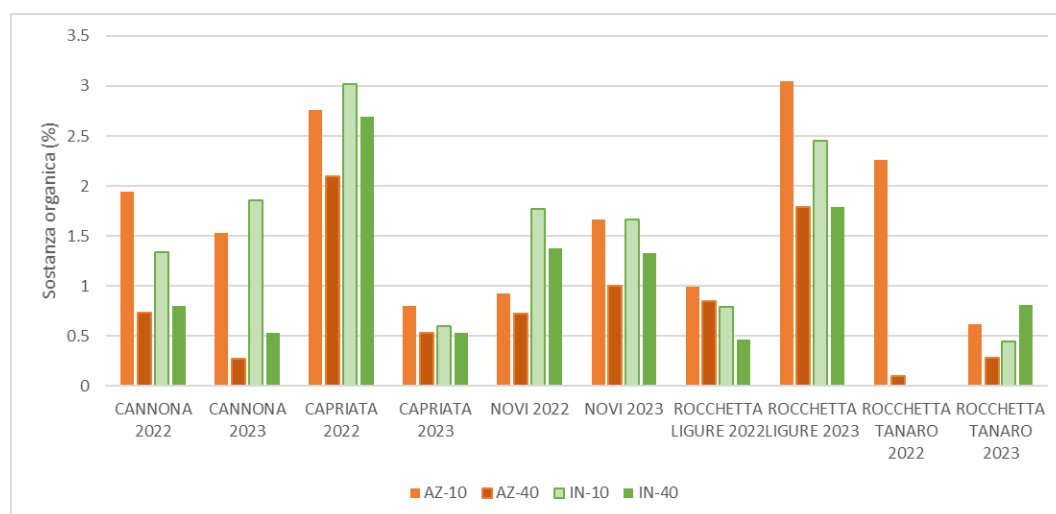


Figure 69: Soil Organic Matter measured in conventional (AZ) and enhanced (IN) plots of the vineyards under study.

Regarding total nitrogen (Figure 70), the values detected in soil samples were higher in the enhanced thesis compared to the conventional thesis at Carpeneto in 2023, Capriata d'Orba (2022 and 2023), Novi Ligure (2022 and 2023), Rocchetta Ligure (2023), and Rocchetta Tanaro (2023).

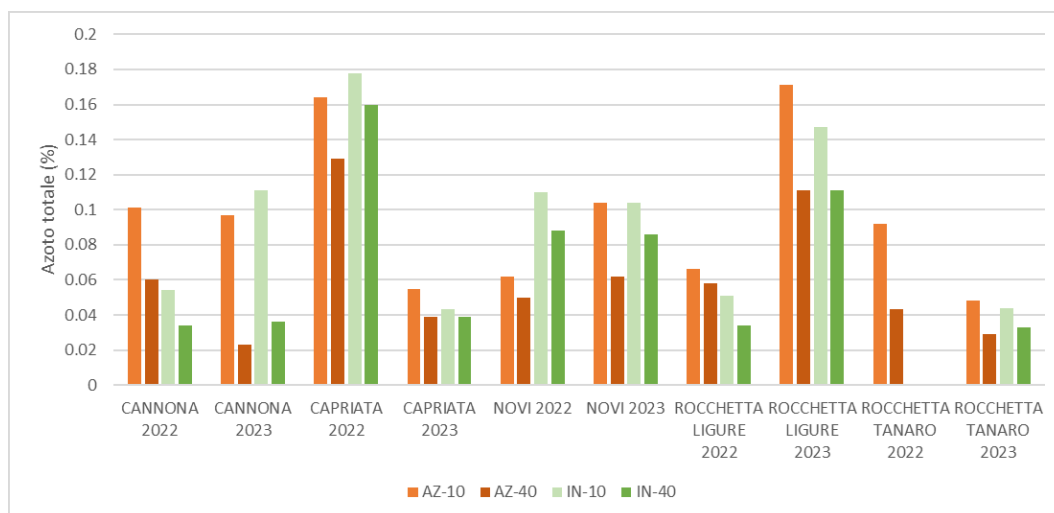


Figure 70: Total Nitrogen Content measured in conventional (AZ) and enhanced (IN) plots of the vineyards under study.

2.7 Summary of the effects of the introduced enhanced solutions and operational indications

The following Table 22 provides a summary of the results obtained through the monitoring of vineyards with different soil management. The data were analysed considering the soil management independently of the site and thus grouping the adopted managements into three categories: tillage carried out at least once a year, permanent spontaneous grassing without tillage during the year, and sown green manure for cover crop.

Table 22: Summary of the results obtained through the monitoring of vineyards with different soil management practices.

		Tilled	Grassed	Green manure
Runoff (total)	%	2.5	1.0	1.0
Runoff (summer 2023)	%	6.3	1.9	2.9
Erosion (total)	kg/ha/mm	10.0	6.7	3.2
Erosion (summer 2023)	kg/ha/mm	26.9	23.2	10.9
Soil cover (spring)	%	26.2	63.1	46.9
Soil cover (autumn)	%	19.1	55.4	49
Superficial bulk density (spring)	g/cm ³	1.35	1.34	1.25
Superficial bulk density (autumn)	g/cm ³	1.40	1.35	1.34
Deep bulk density (spring)	g/cm ³	1.49	1.47	1.43
Deep bulk density (autumn)	g/cm ³	1.53	1.51	1.52
Superficial soil water content (spring)	cm ³ /cm ³	0.245	0.242	0.248
Superficial soil water content (autumn)	cm ³ /cm ³	0.178	0.207	0.229
Deep soil water content (spring)	cm ³ /cm ³	0.336	0.296	0.305
Deep soil water content (autumn)	cm ³ /cm ³	0.214	0.230	0.290
Soil penetration resistance	Mpa	1.13	1.71	1.38
Hydraulic conductivity (spring 2023)	mm/h	70.5	129.5	26.5
Hydraulic conductivity (autumn 2023)	mm/h	43	386.5	1253.9
Biomass (spring)	Mg/ha	0.77	1.92	2.56
Biomass (autumn)	Mg/ha	0.65	1.03	0.85

		Traditional	Innovative
Soil organic matter	%	1.07	1.22
Production	kg/pianta	2.73	2.84

The results obtained from vineyards with tillage management are unfavourable for most of the considered characteristics, particularly regarding the percentage of soil coverage, the bulk density of the surface soil at the end of the productive season, and the moisture of the surface soil in autumn. However, deep moisture in spring is

higher compared to other soil managements. Grassing management allows for the best percentage of soil coverage and biomass, but the soil moisture in spring is lower compared to other managements. The best results are obtained with green manure, which allows for significantly lower soil density and significantly higher deep soil moisture in spring compared to other managements. In general, the organic matter content was found to be higher with the adoption of enhanced management.

Using green manure for cover crop allows for optimal soil density both in spring and autumn and excellent hydraulic conductivity (and therefore the possibility of rainfall infiltration) especially in autumn, limiting runoff and especially protecting the soil from erosion even in the summer months and preserving the moisture of the soil at greater depth. The loss of nutrients in runoff water is generally lower in the case of management with permanent grassing or green manure, with evident reductions especially in the case of significant removals.

The results show that even in the case of commercial vineyards, the long-term management of the soil with permanent grassing reduces erosion and runoff, especially in the case of summer events, while at the same time favouring the infiltration of rainwater into the soil throughout the year; productive surveys do not show negative effects on production.

The transition to this enhanced management is not simple, because the results are not always seen immediately; moreover, permanent grassing usually presents "negative" species due to high water and nutritional competition, little structuring effect on the soils, etc.

The Good Practices identified and disseminated through the "good practice paper" to the winegrowers allow for a smoother transition from traditional management characterized by frequent soil tillage to enhanced management, reducing the difficulties of the transition phase.

These can be summarized as follows: elimination of fine soil tillage; sporadic execution of deep tillage, possibly with a subsoiler; sowing of green manure grassing; management of grassing with mowing and shredding.

Good Practices for reducing erosion and runoff:

- if possible, maintain permanent grassing in all rows; alternatively, keep at least alternate rows grassed
- manage the grassing with mowing or shredding: this reduces surface runoff and the risk of erosion, and limits soil overheating
- avoid "fine" soil tillage: milling machine, rotary tiller, roter
- to decompact and aerate the soil, carry out deep tillage once a year
- for deep tillage, prefer the subsoiler to the ripper because it leaves the grassy crust unchanged
- sowing a green manure-grassing is useful for selecting less competitive herbaceous species with the vine
- minimize mechanical passages in situations of wet soil, especially with poor grass cover

Indications for sowing green manure:

- sowing on firm ground is very interesting because it avoids fine soil tillage
- if sowing on firm ground is not possible, good preparation of the seedbed is important (in this case "fine" tillage with the roter is necessary)
- fertilize before sowing
- sow at the right times
- prefer very varied mixtures, with a balanced presence of grasses, legumes and crucifers
- end the green manure with mowing or shredding, without burying: this improves the structuring effect of the soil.

Young vineyards:

- the adoption of grassing is possible but requires "flexibility": in case of very hot and/or dry seasons, soil tillage in summer (on alternate rows) is useful to reduce water competition.

Chapter 3

Validation and integration of innovative technological research products in real-world conditions

3.1 Introduction

Recent advancements in measurement technologies have significantly influenced hydrological modelling. Innovations in electromagnetic induction sensors have enhanced the precision and efficiency of data collection (Singh, 2018). These tools, combined with proximal and remote sensing technologies, provide more accurate and comprehensive data on water availability, soil health, and crop status. The integration of these technologies into hydrological models allows for better prediction and management of water resources in agricultural settings.

The numerical simulation of hydrological processes serves as a crucial tool for examining the movement of water and solutes within the Earth's "critical zone," which spans from the outermost vegetation layer to the groundwater storage areas (Zhang and Wang, 2022). These hydrological models are applicable at various spatial and temporal scales, addressing a wide range of environmental and economic challenges and emergencies in agriculture (Kayatz et al., 2019). Hydrological issues of great practical interest that can be addressed by simulation models include:

i) Optimizing water resource use in agriculture (McNider et al., 2015). The Water Framework Directive 2000/60/EC has set policy goals to promote sustainable water management in Europe. Given that agriculture is the primary consumer of renewable water resources, it is crucial for the scientific community to develop technologies and techniques that enhance water use efficiency in agriculture. This is especially important in light of increasing rainfall anomalies and water scarcity driven by climate change.

ii) Accelerated soil water erosion in agricultural hilly areas poses significant threats to crop yields, surface water resources, and local infrastructure (Panagos and Katsoyiannis, 2019). The EU Biodiversity Strategy for 2030, adopted by the European Commission in 2020, prioritizes reducing soil erosion through sustainable management practices. The goal is to prevent erosion on 30-50% of land with unsustainable erosion rates by 2030.

Despite the advancements, there are still challenges and limitations in hydrological modelling. One major issue is the spatial and temporal variability of soil and water properties, which can lead to inaccuracies in model predictions. Our current ability to conceptualize and simulate hydrological processes far surpasses our capacity to accurately measure the input parameters required for these models (Baroni et al., 2010). This discrepancy necessitates the calibration of nearly all hydrological models, making it an essential step in the modelling process (Teweldebrhan et al., 2018). Without proper calibration, the predictions made by these models remain uncertain to an unknown extent, limiting their practical utility.

According to the scientific literature, this limitation of hydrological models is primarily due to the persistent inability to obtain a hydrologically realistic description of soil behaviour (Moriassi et al., 2015). To address this problem, the common assumption that, at the near-point measurement scale, soil can be represented as a homogeneous, rigid, and isotropic medium must be revised. Instead, it must be considered that: i) the porous medium exhibits marked spatial and temporal variability, and ii) a hydrologically relevant soil physical and hydraulic characterization requires transitioning from the near-point measurement scale to the field scale in a practical manner.

The future of hydrological modelling lies in the development of more sophisticated and robust measurement technologies to improve the calibration process to enhance model reliability and the integration of interdisciplinary approaches (Singh, 2018). Emerging technologies such as machine learning and artificial intelligence have the potential to revolutionize data analysis and model predictions (Rozos et al., 2022). Additionally, the use of real-time data from sensors and satellites can provide continuous monitoring and improve the responsiveness of hydrological models to changing environmental conditions (Abegeja, 2024). Integrating hydrological models with other scientific disciplines, such as meteorology and ecology, can provide a more comprehensive understanding of environmental processes (Granata et al., 2025). For example, combining meteorological data with hydrological models can improve predictions of rainfall

patterns and water availability (Wang et al., 2024). Similarly, incorporating ecological data can help assess the impact of water management practices on biodiversity and ecosystem health.

Point-scale soil moisture measurements with sensors can represent the temporal variations of the variable, but each sensor is representative of a limited volume of soil, so capturing spatial variability would require several sensors within a single field. When direct measurement methods are not sustainable in terms of time and costs, satellite and proximal sensing emerge as viable alternatives (Pôças et al., 2013; Schönbrodt-Stitt et al., 2021). Satellite remote sensing offers the opportunity to obtain spatially explicit information on landscapes at regular time intervals. Among proximal sensors, Cosmic-Rays Neutron Sensing (CRNS) has emerged as a valuable technique for non-invasive soil moisture estimation at field scale, larger than the usual point-scale sensors, and at sub-daily resolution (Desilets et al., 2010; Zreda et al., 2008; Bogaen et al., 2015). Nevertheless, ground-based measurements of land surface variables, such as soil moisture, are indispensable in the process of developing, calibrating, validating, and advancing spatially contiguous data sets derived from satellites or models (Loew et al., 2017; Gruber et al., 2020).

Furthermore, modelling and investigation of hydrological and soil erosion processes require rainfall characterization in terms of temporal and energy distribution to assess interactions with soil (Ran et al., 2019). However, precipitation is currently measured and characterized at ground level mainly at point scale, using rain gauges and disdrometers. These instruments are usually considered representative for several km², despite providing information related to a small sampling area (a few cm²). Additionally, traditional instruments rarely capture the temporal variability of precipitation, and the assessment of both temporal and spatial variability is generally possible only through remote sensing, which does not refer to conditions at ground level, where precipitation interacts with soil (Sehler et al., 2019).

New field measurement approaches must be developed to make soil characterization a routine step in the application of hydrological models, while minimizing time demands. These approaches should account for the spatial and temporal variability of the measured variables. The use of innovative measurement techniques, such as automatic infiltrometers (Concialdi et al., 2020), geophysical technologies (e.g., geo-radars, electromagnetic induction sensors), and proximal and remote sensing technologies, may contribute to achieving this goal.

The general objective of this section is to introduce the use of proximal sensing technologies for characterizing the interactions between water and soil in complex real-world environments, thereby overcoming the limitations associated with near-point measurements of variables with high spatial and temporal variability.

3.2 W-Band Radar

3.2.1 Introduction

Vegetation cover significantly influences the hydrological response at the field level, consequently affecting runoff and soil erosion processes (Biddoccu et al., 2020). Maintaining bare soil in the inter-rows of vineyards through tillage, combined with tractor traffic, poses known risks of soil compaction, reduced water retention capacity, and increased runoff and erosion (Capello et al., 2019). The adoption of grass cover is one of the most widespread and effective strategies to mitigate these risks (Capello et al., 2020). Over the past decades, numerous studies have been conducted on runoff and soil loss induced by precipitation in sites with different types of cover (Bagagiolo et al., 2018). It has been found that runoff and erosion are often correlated with rainfall characteristics (Biddoccu et al., 2014). However, this correlation varies significantly between different sites and over time. In many studies, rainfall is represented only by a few parameters, such as maximum intensity and total precipitation. The size of raindrops is rarely analysed, despite being an important element for an accurate estimate of the kinetic energy of rainfall (Meshesha et al., 2019). Millimetre-wavelength polarimetric radars (W-band) are among the instruments capable of measuring raindrop size. Compared to in-situ rain sensors, these radars have a much larger sampling area and can estimate the distribution of raindrop sizes with high spatial and temporal resolution (Unal and van den Brule, 2024). Therefore, it is possible to correlate runoff and soil erosion with rainfall properties using traditional monitoring techniques integrated with radar observations. The information obtained from W-band radar monitoring allows for a more in-depth examination of the relationships between precipitation characteristics and the generation of runoff and soil erosion. To this end, the experimental vineyard of Tenuta Cannona (Agrion, Carpeneto, AL), located in the wine-growing area of Alto Monferrato (Piedmont, NW Italy), was equipped with a 94 GHz radar in June 2023. The site comprises two field-scale vineyard plots, with inter-rows managed respectively with traditional tillage (CT) and permanent grass cover (GC). Both plots are equipped with two systems for measuring and collecting runoff water at both plot and micro-plot scales. After each erosive event, a 1.5 L sample of runoff sediment mixture was collected. Sediments deposited along drains and in the sedimentation traps were also collected and weighed after being dried. An optical sensor is placed at the outlet of the channel in order to monitor the turbidity of the flow due to the sediment concentration. Rainfall data for the experiment period were obtained from an agro-meteorological station, placed at the

border of the plots. There are also probes for measuring soil moisture at different depths and positions, a complete weather station, a cosmic-ray soil moisture sensor, and a pair of scintillometers. The radar is positioned approximately 125 meters from the plots, with its elevation set at 30° to sample the rain falling on the plots at an altitude of about 100 meters. This is the first experiment using this type of fixed-position radar in a hillside vineyard.

The RPG-FMCW-94-SP/DP radar is a cloud Doppler radar operating in the W-band at 94 GHz. Developed by RPG (Radiometer Physics) for atmospheric research, it uses frequency-modulated continuous wave (FMCW) signals, providing a high range resolution from 3 to 30 meters. The RPG Polarimetric 94-GHz cloud radar has a sampling volume of 150 m^3 and an observation area of up to several square kilometres. The radar features Doppler and polarimetric capabilities, and after accurate calibration, it allows for retrievals based on spectral polarimetry of rain characteristics. These include the estimation of drop size distribution profiles, rain rate, kinetic energy, liquid water content, median diameter, and quantitative characterization of hydrometeors. Hydrometeors are atmospheric phenomena related to the condensation of moisture present in the Earth's atmosphere, such as rain, snow, hail, as well as phenomena like fog and clouds, which are formed by tiny particles of condensed water.

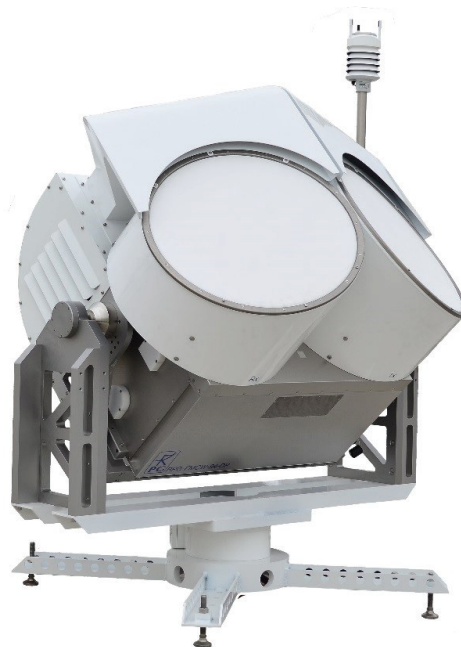


Figure 71: The radar with the scanning unit (image taken from the brochure)

The radar (Figure 71) consists of several parts, primarily the two-axis rotor that allows for sky pointing and scanning, and the radar unit mounted on it. The radar unit features a metal box containing the electronics, on which two parabolic antennas with skirts are mounted and covered with a hydrophobic material. A fan creates an air sheet over the antenna drum to prevent water or insects from settling on it. Additionally, a thermohygrometer with an ultrasonic anemometer is mounted on a bracket.

Below are some of the main characteristics:

Central frequency: 94 GHz ($\lambda=3.19$ mm) $\pm$ 30 MHz, with a bandwidth of 100 MHz.

Transmitter power: 1.5 W typical (solid-state amplifier).

Antenna type: Bistatic Cassegrain with a 500 mm aperture.

Antenna gain: 51.5 dB.

Beamwidth: 0.48° FWHM.

Polarization: V (optional V & H).

Typical dynamic range (sensitivity): from -46 dBz to +20 dBz (at an altitude of 5 km with a resolution of 30 m).

Operational range: from 100 m to 10 km (minimum 50 m, maximum 18 km).

Vertical resolution: 15-30 m (up to 4 m for limited height).

3.2.2 Installation and positioning of the radar for precipitation monitoring in vineyards:

Several site inspections were conducted to identify the optimal location for radar installation. It is crucial to ensure an adequate distance - at least 100 meters - from the plots to be monitored and an elevation of at least 30° to achieve precise precipitation measurements over the vineyard. The chosen site needed to be obstacle-free, easily accessible for transporting heavy equipment, and located near a three-phase 220V power source (5-pin connector: 3 phases, one neutral, and ground). Additionally, a PC with internet connection had to be positioned within a

50-meter radius. Various potential locations were considered, as illustrated in Figure 72.

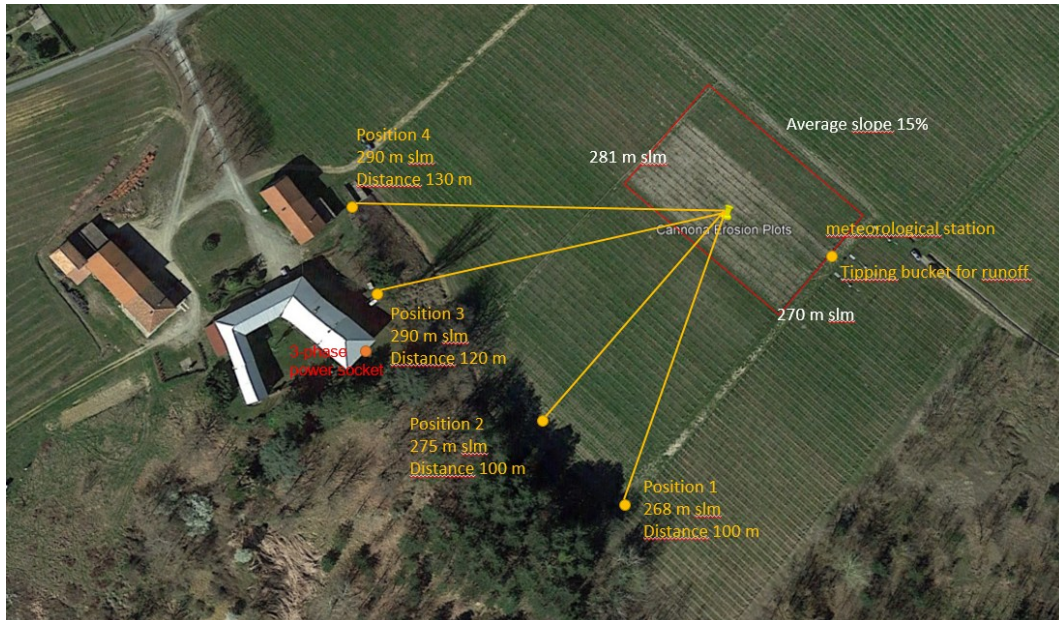


Figure 72: Vineyards at Tenuta Cannona (Agrion) with potential positions marked. The visible buildings on the left are Tenuta Cannona (image processed from Google Earth).

The first two positions were excluded as they were too far from the buildings, where the power supply is available and where the PC can be located. Instead, a position near number 3 was selected, which offers an open view of the vineyards to be monitored (Figure 73) and is less than 50 meters from the building.

For the radar installation, the necessary authorization requests and/or communications were made to the Ministry of Economic Development (MISE) and the Single Desk for Productive Activities (SUAP) by CNR-STEMS and DIST.



Figure 73: View of the vineyards at Tenuta Cannona (Agrion) from the chosen installation position. The blue arrow indicates the location of the study plots.

The equipment was delivered to Tenuta Cannona in two crates. The main body of the instrument was already mounted on the bottom of one of the crates, equipped with a platform for transport using a forklift. Therefore, it was only necessary to remove the sidewalls. The ground where the base would be positioned was prepared, aiming to level it as much as possible. With the support of Tenuta Cannona staff, the heavy instrument was moved using the forklift mounted on the back of a tracked vehicle (Figure 74) and correctly positioned. Subsequently, the base was manually levelled by lifting it with a small pallet jack and inserting spacers. Once the main body of the instrument was positioned, the other components stored in the second crate were installed: the fans were attached to the main body, and the thermohygrometer with ultrasonic anemometer was positioned. Additionally, a disdrometer was installed near the radar to provide an additional set of data for comparison with the measured data (Figure 75).



Figure 74: Moving the main body using the forklift mounted on the back of a tracked vehicle.

The next step involved installing the various cables needed to connect the radar (a three-phase power cable and a fiber optic data cable) and the disdrometer (power cable and data cable). A conduit was buried between the disdrometer and the radar to route the two disdrometer cables. To avoid obstructing vehicle passage, the cables were routed over the plants between the radar position and the building, and finally secured to a ring on the facade, above the entry point to the room where the PC was placed. To prevent potential damage to the cables from oscillations, such as those caused by wind, a rope was used as support to which the cables were attached.

The RPG technician then proceeded with connecting the equipment and installing the PC. Various calibration and testing operations were carried out, including sun pointing for optimal rotor calibration (Figure 76).

To underpin data reliability, quality control relied on systematic cross-checks with the co-located optical disdrometer installed next to the radar. These intercomparisons included event-wise and intra-event evaluations of rain rate and drop-size-related metrics retrieved from the radar's spectral/polarimetric observations against the disdrometer reference, as well as consistency checks with the adjacent agro-meteorological station for accumulated rainfall. The disdrometer therefore provided an independent benchmark to identify possible drifts or residual miscalibrations and to assess retrieval performance under different storm types and at the chosen elevation angle.

In the months following the installation, due to recorded power outages, particularly during severe thunderstorms, an uninterruptible power supply (UPS) was added to prevent data loss.

The radar remained operational from May 2023 to the end of May 2024. Subsequently, it was dismantled with the collaboration of RPG, DIST, and AGRION technicians and sent back to RPG. First results were presented at the EGU international conference and are summarized in the following two sections.



Figure 75: The disdrometer on the left and the radar on the right, installed in position.



Figure 76: View of the radar from the vineyard below.

3.2.3 The contribution of W-band radar monitoring for understanding of runoff and soil erosion response at field scale

During the summer and autumn seasons of 2023, 26 rainfall events and 13 runoff events were recorded. For each runoff event, we characterized precipitation in terms of accumulated precipitation, accumulated kinetic energy, and median diameter of raindrops. Stepwise multiple linear regression models for runoff and sediment yield predictions have been obtained considering rainfall variables both traditional and obtained from radar observations (Figure 77). In addition, intra-event analysis was performed to investigate relationships between rainfall characteristics retrieved from radar observations and sediment transport by superficial flow.

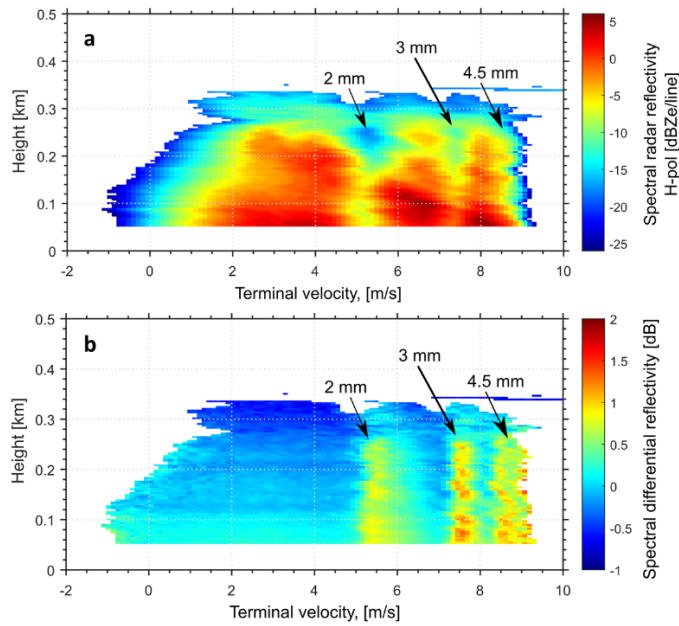


Figure 77: Spectral reflectivity (a) and spectral differential reflectivity (b) measured by a W-band cloud radar in rain. Measurements were taken at 30° elevation. Distinct polarimetric signatures agree well with the scattering model and allow for assignment of velocity bins to drop sizes even at low elevation angles.

Preliminary results from conventional analysis indicate that during this period, runoff was directly correlated with the erosivity index (EI30) for both plots managed with traditional tillage (CT) and those with permanent grass cover (GC). However, for the GC treatment only, runoff was also correlated with the maximum rainfall intensity recorded over a 10-minute interval and the rainfall that occurred in the preceding 7 days. Conversely, the maximum rainfall intensity over 30 and 60-minute intervals had an inverse correlation with runoff. Soil erosion, for both treatments, was also directly correlated with the maximum rainfall intensity over 10 minutes and the rainfall in the preceding 7 days, but showed an inverse correlation with rainfall energy.

It is important to highlight the significant role played by short-term rainfall intensity and antecedent rainfall, which lead to increased soil moisture. These relationships differ from those obtained at the same site in a previous study, reflecting the peculiarity of the summer of 2023, characterized by few rainfall events on very dry soil. Information obtained from W-Band radar monitoring allows for a deeper investigation into the relationships among rainfall characteristics and the generation of runoff and soil erosion. Specifically, kinetic

energy and kinetic energy-weighted median diameter improve the model for predicting runoff and soil erosion from the GC plot (Figure 78 and Figure 79).

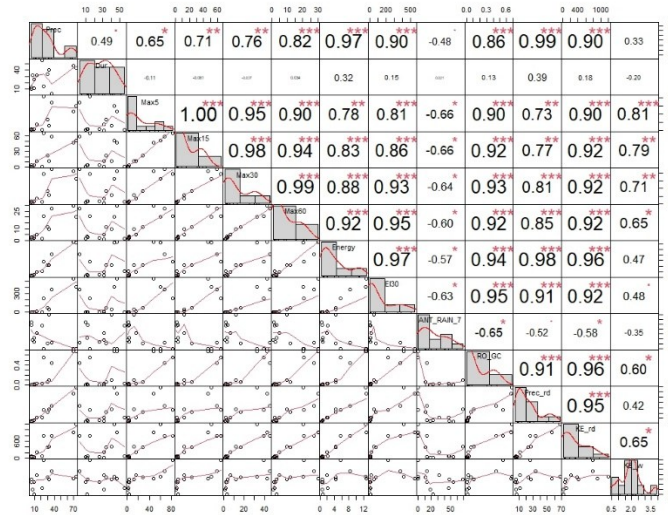


Figure 78: Pearson correlation among variables obtained from conventional and radar rainfall observations for the GC plot.

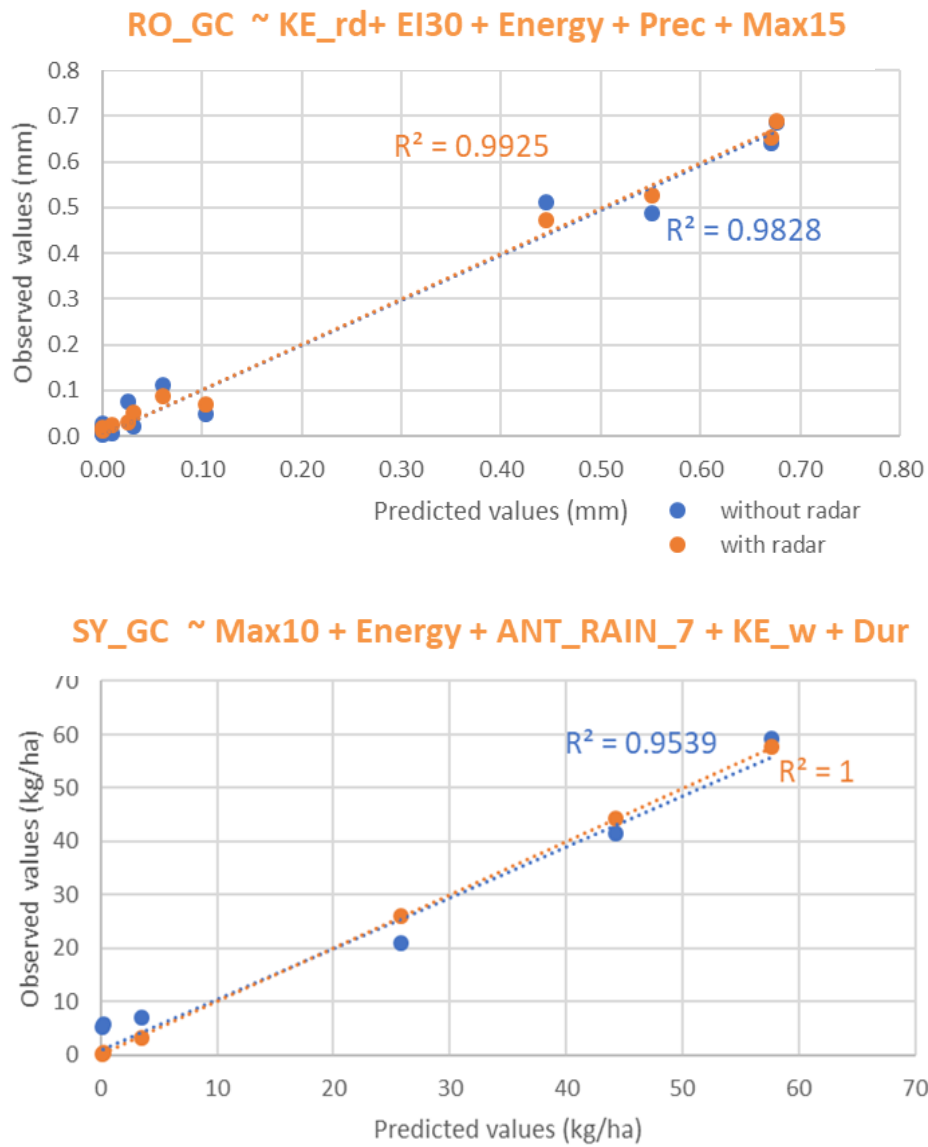


Figure 79: Prediction of runoff and soil erosion from the GC plots, based on conventional and radar-based variables.

Turbidity of the runoff flowed from the CT plot, due to sediment concentration, reflected the trend of rain rate and kinetic energy retrieved from radar observations (Figure 80, 81 and 82) in a high-erosive summer rainfall event.

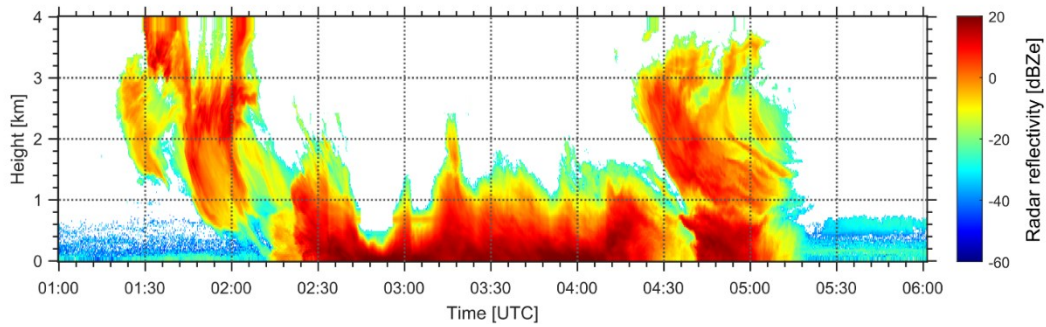


Figure 80: Example of the radar reflectivity observations during a rain event on 12 June 2023. The radar was pointed at 30° elevation. The reflectivity is proportional to amount of power scattered back by rain droplets. During intense precipitation (e.g. at 2:45 UTC) the radar signal is strongly attenuated, however first few 500 meters could be measured.

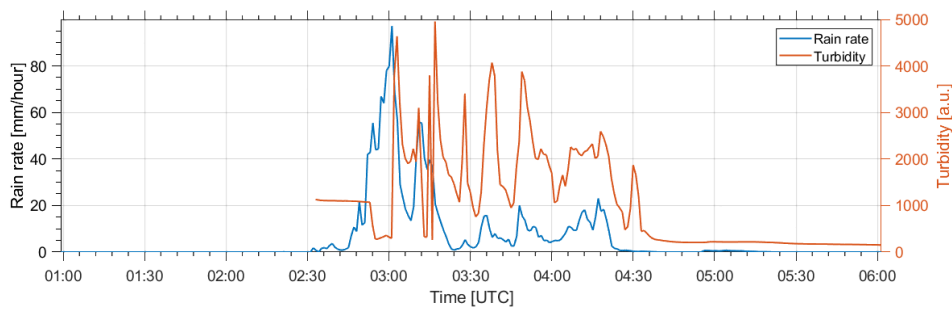


Figure 81: Rain rate retrieved from radar observations and turbidity measured in situ for the rain event on 12 June 2023.

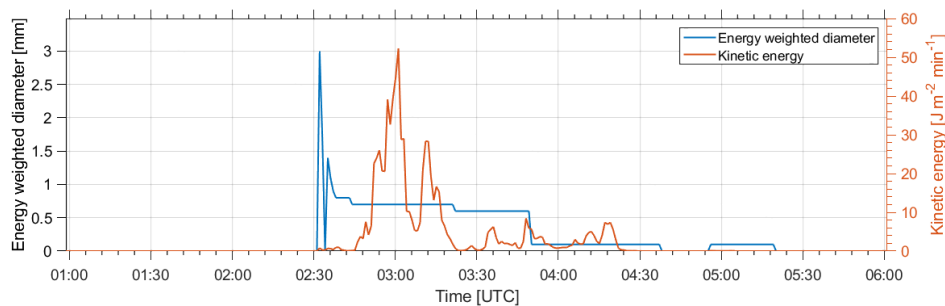


Figure 82: Energy weighted diameter and kinetic energy retrieved from radar observations for the rain event on 12 June 2023.

The preliminary results are encouraging for quantifying the runoff and soil erosion response at field/slope scale using information about rainfall energy and drop sizes retrieved from cloud radar.

3.2.4 Applicability of cloud radar observations for an intra-event analysis of runoff on a steep vineyard

Intra-event analysis of runoff may help to better understand the runoff formation, and the sensitivity of the runoff amount to rain characteristics and properties of ground. An analysis on a field scale is especially advantageous since sampling effects are mitigated. The sampling effects may result from different measurement tools and spatial homogeneity of precipitation and ground.

With respect to other instruments for characterization of precipitation, i.e. optical disdrometers and weather radar, which have small and large sampling area, the RPG Polarimetric 94-GHz cloud radar allows monitoring at field or slope scale, with sampling volume of 150 m^3 , resolution from 3 to 30 m, observation area up to few km^2 . The observed polarimetric spectra (Figure 84) allow for estimation of drop-size-distribution and rain rate with high temporal and spatial resolution, kinetic energy, liquid water content, median diameter (Figure 83).

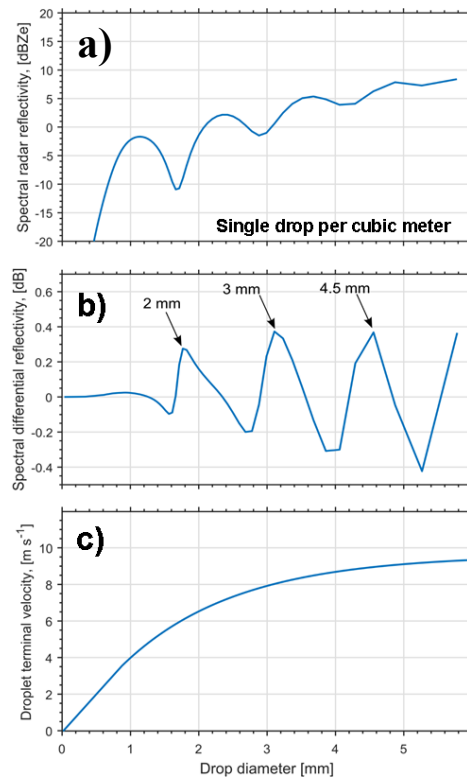


Figure 83: Modelled reflectivity (a), modelled differential reflectivity (b), and empirical terminal velocity of raindrops (c). T-matrix and spheroidal approximation are used to model the scattering properties.

We estimate soil properties (saturated water content and conductivity) by fitting modeled and measured soil moisture and accumulated runoff.

1D Richards equation is used as a forward model (Assouline, 2013):

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[D(\theta) \frac{\partial \theta}{\partial z} - K(\theta) \right]$$

Diffusivity and conductivity are parameterized following Leij et al. (2021). Rain rate from the radar and soil moisture at a depth of 40 cm are used as boundary conditions. The soil moisture profiles from moisture sensors are used as initial conditions (Figure 85). A time resolution of 1 second and a depth resolution of 1 cm are used.

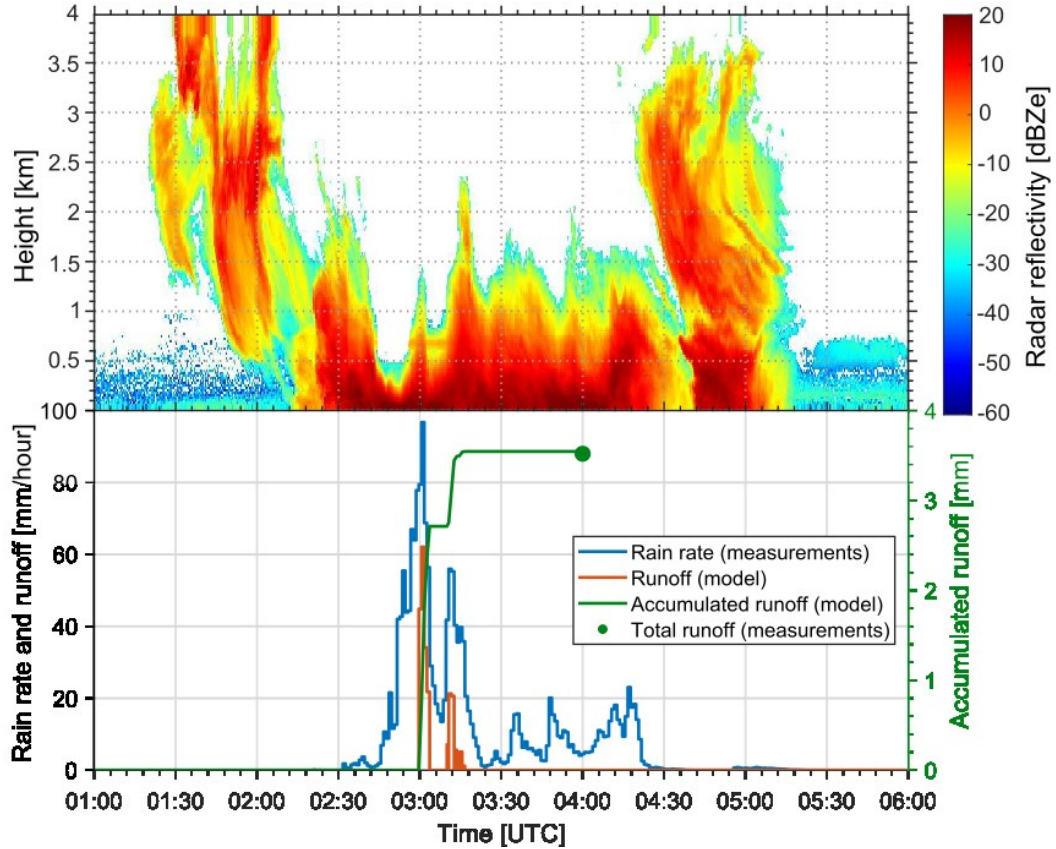


Figure 84: Radar reflectivity (a) measured by the cloud radar during the rain event on 12 June 2023. The panel (b) shows time profiles of the estimated rain rate, modelled runoff, and the accumulated runoff. The green dot indicated the value of the accumulated runoff from the tipping bucket.

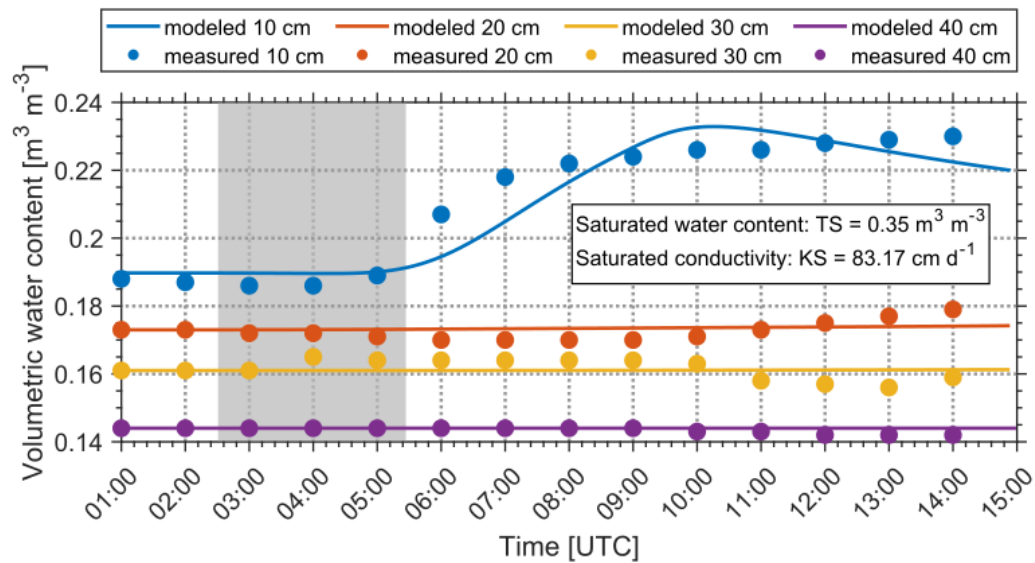


Figure 85: Fit of the simulated soil moisture (continuous lines) to hourly measurements (dots). Different colour corresponds to different depths. Grey area denotes the rain event.

The presented case study shows that rain rate from the W-band cloud radar can be used to model runoff on field-scale. Further work will include an extension of the approach to 2 dimensions to fit the time evolution of runoff.

Reference:

Assouline, S., 2013. Infiltration into soils: Conceptual approaches and solutions, Water Resour. Res.

Leij, F. J., et al., 2021. Analytical solution for field soil water content profiles. Water Resources Research.

3.2.5 Conclusions and Perspectives

The integration of fixed-position W-band polarimetric cloud radar observations with conventional field monitoring provides a substantive advance in linking rainfall microphysics to runoff generation and soil erosion at vineyard slope scale. The radar configuration enabled retrieval of rain rate and microphysical descriptors, such as drop-size distribution profiles, kinetic energy, liquid water content, and median/energy-weighted drop diameters, at spatial and temporal resolutions that are more representative of plot/slope processes than point precipitation measurements alone. Within the Tenuta Cannona experimental vineyard, preliminary event-scale analyses indicate that runoff and sediment response were not fully explained by traditional rainfall summaries, whereas radar-derived variables (notably kinetic energy and kinetic-energy-weighted diameter) improved model performance, underscoring the role of raindrop energetics in shaping erosive outcomes under mitigated surface conditions. Coupling radar-derived rain-rate estimates with soil moisture observations offers a promising route to strengthen process-based runoff modelling beyond purely empirical relationships

Looking forward, further and more comprehensive analyses of the existing dataset will be pursued to consolidate these preliminary findings and to quantify their robustness across events and management conditions. Efforts will prioritize enhanced retrieval quality control and systematic intercomparisons with the co-located disdrometer and agro-meteorological station, enabling explicit uncertainty propagation from rainfall microphysics into runoff and erosion modelling. In parallel, advancing the modeling from the current 1-D formulation toward 2-D hillslope representations is expected to improve the reconstruction of runoff timing and spatial organization on steep vineyards. . Future work will focus on exploiting this integration to better constrain soil hydraulic parameters and to disentangle the respective roles of antecedent moisture and short-term rainfall structure in controlling runoff initiation and sediment delivery, ultimately improving the transferability and predictive skill of field-scale models.

A practical consideration is that the cost and operational complexity of a W-band polarimetric cloud radar currently limit its deployment primarily to scientific research rather than agricultural applications. Nevertheless, the scientific value of such instrumentation lies precisely in its capacity to reveal and parameterize rainfall–runoff–erosion mechanisms (e.g., the role of kinetic energy and drop-size distributions) that are otherwise difficult to observe at the relevant scale. By using these insights to improve and validate physically based and

empirical models, it should become possible to transfer the gained understanding to workflows that rely on more affordable, widely accessible measurements (e.g., standard rain gauges, lower-cost optical sensors), thereby improving predictive skill and decision support without requiring widespread deployment of high-end radar systems. If monitoring could be extended across additional seasons and storm regimes, it would enable a more rigorous assessment of the generality of radar-informed predictors and help disentangle the relative influence of rainfall microphysics versus antecedent soil moisture on runoff and erosion response, thereby supporting more transferable erosion-risk frameworks for vineyards.

3.3 Optical and microwave Scintillometer

3.3.1 Introduction

The RPG-MWSC-160 microwave scintillometer, produced by Radiometer Physics GmbH (RPG) and first launched in 2014, is designed to be used in combination with a Large Aperture Scintillometer (LAS), to observe sensible and latent heat fluxes simultaneously (Figure 86). The equipment consists of two coupled units, one optical and one microwave, each with independent transmitting and receiving components.

The application of a scintillometer like the RPG-MWSC-160 in a vineyard represents an innovative approach, especially when installed alongside other water or climate monitoring technologies used in vineyards. This device has various applications, particularly for measuring evapotranspiration, which is the sum of evaporation and plant transpiration. These measurements are crucial for evaluating the hydrological cycle and calculating the water balance. They can help determine soil water availability and detect potential crop water stress, providing valuable insights into when and how much to irrigate, thus contributing to more efficient water management (Ghiat et al., 2021). Additionally, the scintillometer can measure various atmospheric parameters useful for weather forecasting. By measuring the radiant energy flux entering and leaving the Earth's surface, it can help understand the Earth's energy balance (Danodia et al., 2024).

The data and information obtained from scintillometer monitoring, combined with other innovative water monitoring technologies used in vineyards, can enable a more in-depth examination of the relationships between soil hydrological cycle characteristics, including precipitation, runoff generation and erosion, soil water availability, and evapotranspiration. To this end, the scintillometer was installed in the experimental vineyard of Tenuta Cannona (Agrion, Carpeneto, AL), located in the wine-growing area of Alto Monferrato (Piedmont, NW Italy), in June 2023. The vineyard where the scintillometer was installed comprises two field-scale plots, with inter-rows managed respectively with traditional tillage (CT) and permanent grass cover (GC). Both plots are equipped with two systems for measuring and collecting runoff water at both plot and micro-plot scales (section 2.4), and there are probes for measuring soil moisture at different depths and positions (section 2.5). Additionally, the vineyard is equipped with a complete weather station, a cosmic-ray soil moisture sensor (section 3.4), and an innovative millimetre-wavelength polarimetric radar (section 3.2).



Figure 86: The optical and microwave scintillometers (transmitting units)

Some of the main characteristics are:

Frequency: 160.8 GHz ($\lambda=1.86$ mm)

Radiated power: Maximum power: >25 mW, 50 dB attenuator

Antenna type: Cassegrain with a 300 mm aperture

Antenna gain: 52 dB

Beamwidth: 0.45° FWHM

Detection bandwidth: 10 kHz

Gain stability: $> 2.0 \times 10^{-5}$

Temperature stability: < 0.03 K (two-stage control)

Power supply: 12 V DC

Power consumption: Max. 50 W (per unit), 20 W typical (receiver), 15 W typical (transmitter)

Baseline length: From 500 m to 10 km

An analysis of the long and short term monitoring of the site was provided in the manuscript “Effects of some extreme rainfall events on Hydrological and Soil Erosion Processes in Tilled and Grassed Vineyards” presented at the 7th International Congress of Mountain and Steep Slopes Viticulture 2022, held in Vila Real (Portugal), May 12nd-14th, 2022, reported in the next section.

3.3.2 Installation and positioning of an RPG-MWSC-160 Scintillometer for Monitoring Evapotranspiration in Vineyards

Several site inspections were conducted to identify the optimal location for scintillometer installation. It is crucial to ensure an adequate distance - at least 500 meters - between the transmitting and receiving units to achieve precise evapotranspiration measurements. The chosen sites for the transmitter and receiver needed to be obstacle-free, ensuring optical line-of-sight between the two units, and located near a 220V power source. Additionally, a PC with internet connection had to be positioned within a 50-meter radius of the receiver.

For the scintillometer installation, the necessary authorization requests and communications were made to the Ministry of Economic Development (MISE) and the Single Desk for Productive Activities (SUAP) by CNR-STEMS and DIST.

Various potential positions were considered, and tests were conducted using binoculars and high-visibility materials to verify mutual visibility between the positions. Thanks to the cooperation of the Fratelli Facchino Winery, which allowed the installation of the transmitting units on their property, the two sites for the transmitter and receiver were identified. The transmitters were installed at the back of a building at the Fratelli Facchino Winery, utilizing a wall for positioning a 2-meter pole, while the receivers were installed on the balcony of a building at Tenuta Cannona. This ensured that the elevation of the transmitted beam was sufficient and free of obstacles, as illustrated in Figure 87.

The installation of the two poles was carried out on the wall at the back of the Fratelli Facchino Winery, using a special plate fixed with dowels, and on the balcony of one of the buildings at Tenuta Cannona, using the same system and U-bolts to further secure the pole to the railing. Subsequently, brackets were placed on top of each pole, and the transmitting and receiving units were installed on these brackets (Figure 90). An ultrasonic anemometer with a thermohygrometer was also placed on the receiving unit to aid in accurate data processing.

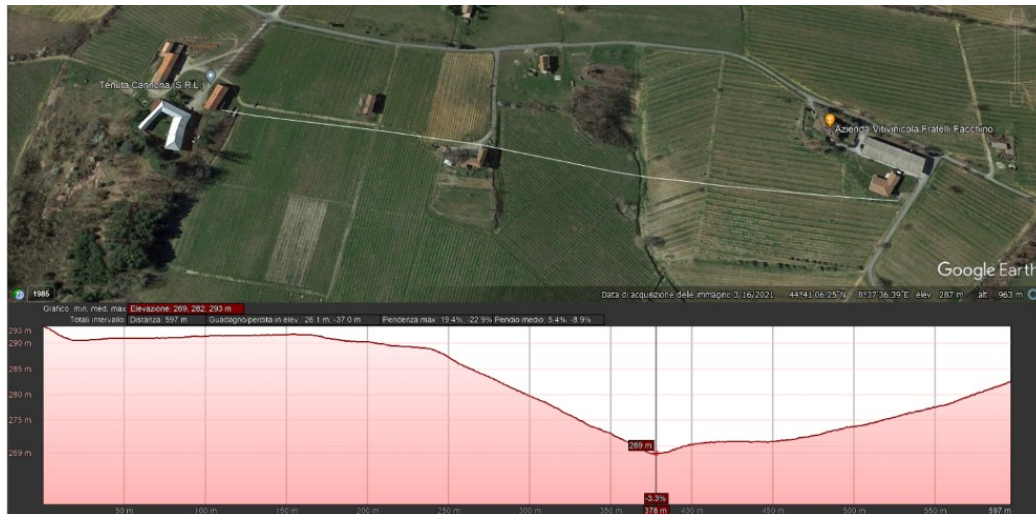


Figure 87: The white line represents the beam path between the transmitters and receivers. The buildings visible on the left are Tenuta Cannona, and those on the right are the Fratelli Facchino Winery. The graph shows the ground elevation, noting that the receiver at Tenuta Cannona is more than 5 meters above the ground (image processed from Google Earth).

The power cable installation was relatively simple for the transmitting unit, thanks to a nearby power outlet. For the receiving units, however, the distance was greater as it was necessary to reach another building, and in addition to the power cable, a data optical fiber cable also had to be routed. To avoid obstructing the passage of agricultural vehicles, the cables were routed over the plants between the balcony and the second building, and finally secured to a ring on the facade, above the entry point to the room where the PC for data collection and remote transmission was placed. To prevent potential damage to the cables from oscillations, such as those caused by wind, a rope was used as support to which the cables were attached (Figure 88).



Figure 88: Positioning of the overhead cables between the balcony and the building where the PC is located.



Figure 89: View through the telescope mounted on the transmitter towards the receiver.

The initial alignment of the four units was performed using optical telescopes (Figure 89). Subsequently, a more precise alignment was achieved by monitoring signal intensity: both the optical and microwave transmitters were set to maximum power, after which the receivers were adjusted vertically and horizontally using micrometric screws until the point of maximum signal was found. The same operation was carried out with the transmitters. Then, the power was gradually reduced, and the alignment operation was repeated multiple times on all units until optimal alignment was achieved. This allowed for a stable reception signal with reduced transmission power.



Figure 90: Positioning of the transmitters (a) and receivers (b).

Then, the technician configured the site-specific parameters in the acquisition software—notably the transmitter–receiver baseline and the beam-height profile above ground along the path—and verified the link budget; no additional absolute calibration was required for this deployment beyond geometric alignment and parameterization. Throughout operation, periodic alignment checks were carried out to confirm that pointing had not drifted and that the received signal level remained within the optimal range. The processing chain ingests wind speed, air temperature, and humidity - measured by the ultrasonic anemometer and

thermohygrometer mounted at the receiver - to account for meteorological controls in the first reduction of raw data, so that flux-relevant estimates are calculated considering these factors. Time windows exhibiting evidence of beam obstruction, anomalous volatility, or sub-optimal link budget were flagged for cautious use in subsequent analyses. Emphasis on beam geometry and clearance from near-surface obstacles reflects the pathway-dependent nature of scintillometer measurements in complex terrain and supports the expectation that higher mounting heights would further stabilize the signal in future deployments.

The scintillometer remained operational from July 2023 to the end of October 2024. Subsequently, it was dismantled and sent back to RPG.

Raw scintillometer measurements were processed according to the instrument manual using the manufacturer's software, tested across successive (updated yet still experimental) releases, to derive turbulent heat fluxes - sensible heat (H) and latent heat (LE) - and evapotranspiration (ET). In the adopted sign convention H can be positive (upward) or negative (downward), while the automatic sign evaluation for LE implemented via the Lüdi method (RTQ) constrains LE to positive values (no condensation), which is not universally valid; therefore, alongside the algorithm-selected solution, we also inspected outputs with and without the automatic atmospheric correction. Following the manufacturer's guidance, the FLX v3 file format was used to export both stable and unstable solutions for the fluxes. The resulting time series of H, LE and ET were then used for comparison with CLM simulations, whose first results were presented the EGU international conferences in 2024 and are summarized in the following section 3.3.2. Section 3.3.3 presents an early draft (in preparation; figures are provisional) of the results of site-level evaluation of Community Land Model (CLM) version 5.0 single-point simulations against energy-flux observations collected at the Cannona experimental vineyard (Piedmont, NW Italy) using an RPG-MWSC-160 optical and microwave scintillometer.

3.3.3 Eddy covariance, scintillometer, and cosmic ray 1 km scale measurements at three sites (grassland, forest, and vineyard) in North-West Italy compared with CLM simulations

The data and information obtained from scintillometer monitoring were processed in combination with those measured by the radar, the cosmic-ray soil moisture sensor, the soil moisture probes, and the systems for monitoring runoff and soil erosion, as well as other innovative monitoring technologies like eddy covariance, installed in experimental vineyards, grassland, and forest in North-West Italy. Water and energy balances have been monitored at a scale comparable to remote sensing at these sites. An essential aspect of the study involved evaluating the performance of the Community Land Model (CLM). Measurements taken at the horizontal hundreds of meters scale were also compared with vertical profiles from local soil moisture sensors. At the grassland mountain site (2600 m asl), eddy covariance data were collected over 6 years, while at the forest site, data were collected from a 25 m high mast over 3 years. The scintillometer and cosmic ray sensors in the vineyard have been installed for one year. This allowed for a more in-depth examination of the relationships between soil hydrological cycle characteristics, including precipitation, runoff generation and erosion, soil water availability, and evapotranspiration (Figure 91). The main result was the monitoring of different land covers at about a 1 km scale, showing that uncalibrated CLM simulations generally followed the data well (Figure 92). This demonstrate that it is possible to measure fluxes and soil moisture at the scale of remote sensing, and compare with uncalibrated CLM land surface model. The data will be further analyzed for the most significant periods. Future work will involve comparisons with satellite data.

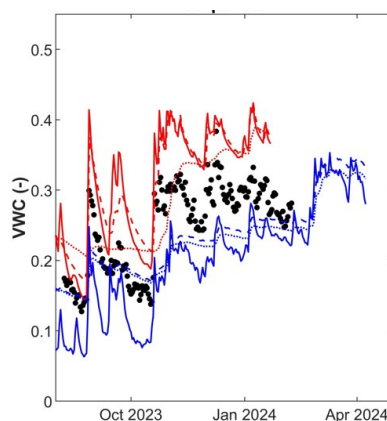


Figure 91: Soil water availability simulated by CLM land surface model

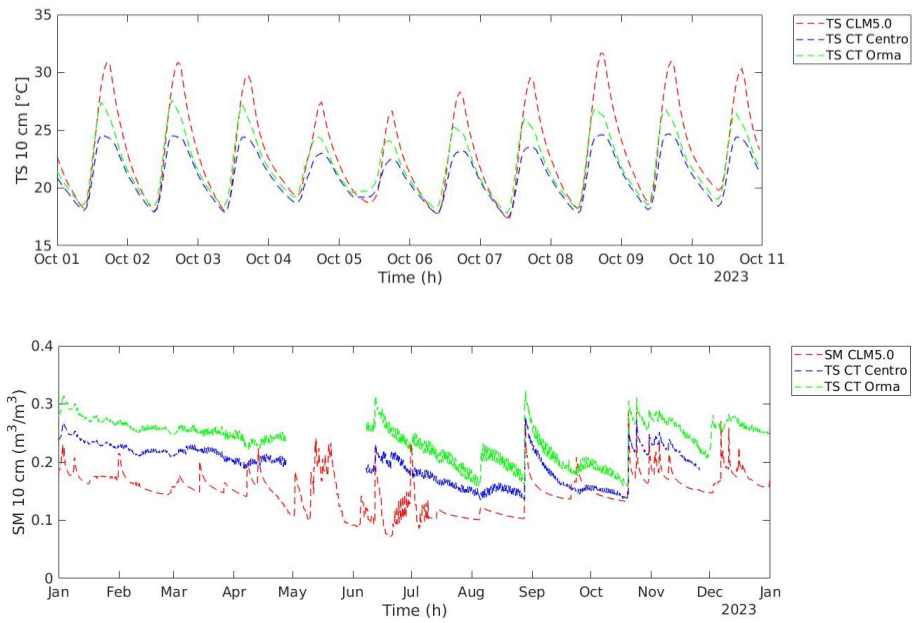


Figure 92: Temperature and soil moisture measured in track (green) and centre (blue) of the tilled plot of the vineyard compared to simulated with CLM (red).

3.3.4 Early draft (in preparation, provisional figures) — CLM5.0 Simulations and Optical/Microwave Scintillometer Observations at the Cannona Vineyard (NW Italy)

Abstract

We evaluate site-level CLM5.0 single-point simulations against dual-wavelength optical–microwave scintillometer (OMS) fluxes at the Cannona vineyard (NW Italy), focusing on net radiation (R_n), sensible heat (H), and latent heat (LE) across three quality-controlled windows (summer 2023, spring 2024, late-summer 2024). R_n is well reproduced, showing high covariance and only a modest site-level bias relative to the station estimate, while the comparison with ERA5 is nearly unbiased, placing CLM between site and reanalysis references. For H , CLM tends to underestimate OMS fluxes, with best agreement in summer 2023 and weaker performance in 2024. For LE , performance is consistently poorer and exhibits a proportional bias: CLM misses daytime peaks and the underestimation increases with flux magnitude. For both H and LE , a night time floor in OMS affects variance without explaining the daytime deficit.

Keywords: land–atmosphere exchange; Community Land Model; scintillometer; vineyard; sensible heat flux; latent heat flux; net radiation

Introduction

Accurately representing land–atmosphere interactions is essential for understanding climate and hydrological processes. Sensible heat and latent heat fluxes, which govern energy transfer through temperature gradients and water phase changes, are strongly influenced by soil moisture and soil temperature (Seneviratne et al., 2010). These variables are themselves affected by complex land surface processes, including soil hydrology, vegetation dynamics, and land management practices. Reliable modeling of these processes is critical for both site-specific studies and broader climate predictions.

The Community Land Model (CLM) is the land component of the Community Earth System Model (CESM) and is widely used in global and regional modeling systems. In this study, simulations are performed using CLM version tag 5.0.34 within the Community Terrestrial Systems Model (CTSM) framework (source code: <https://github.com/ESCOMP/CTSM/tree/release-clm5.0.34>) (Lawrence et al., 2019). CLM5 builds upon the developments of CLM4.5, incorporating

improvements in soil and plant hydrology, snow and river processes, carbon and nitrogen cycling, crop modeling, and land surface characterization. The model represents land surface heterogeneity through multiple land units, columns, and patches, allowing detailed representation of plant functional types (PFTs) and crop functional types (CFTs) (Denager et Al., 2023). Soil hydrology is treated mechanistically, with variable soil thickness, explicit soil layers, and underlying bedrock, improving the simulation of soil moisture and energy fluxes across different landscapes.

Complementary, path-integrated flux measurements from scintillometry offer an attractive bridge across the scale-mismatch between point observations (e.g., eddy covariance) and LSM tiles.

Recent advances have strengthened the methodological foundations and broadened field applications of OMS. Dual-wavelength scintillometer retrieves path-averaged H and LE by combining optical and millimetre-wave signals and exploiting MOST; the temperature–humidity correlation (RTQ) can be obtained bichromatically and used to infer the flux sign under default processing (Ludi et Al., 2005). A critical revision of the two-wavelength method shows that expressing water-vapour effects in terms of specific humidity, rather than absolute humidity, improves physical consistency and reduces systematic LE biases, with proposed density corrections where reprocessing is infeasible (Beyrich et Al., 2005).

OMS fluxes require a path-weighting treatment and an effective height consistent across wavelengths; formulations and field tests demonstrate robust derivation over slanted and structured paths. For two-wavelength systems, the microwave channel may need scaling to match the LAS effective height, simplifying flux analysis over complex terrain (Evans et Al., 2011).

In vineyards, OMS captures row-scale heterogeneity of turbulence and supports integrated flux assessment; targeted campaigns document good H agreement and spatial differences driven by irrigation and canopy structure (Perelet et Al., 2022). Dual-scale comparisons have demonstrated that large-aperture scintillometry provides path-integrated H consistent with eddy covariance while emphasizing the role of source-area location and canopy development on agreement, with best alignment observed for EC stations collocated with the LAS path center (Vendrame et Al., 2020). At kilometer scale, OMS provides area-averaged ET with a footprint comparable to $\sim 3 \times 3$ 1-km pixels, enabling scale-matched validation of satellite ET products over heterogeneous landscapes; in the Heihe River Basin, OMS-based

assessments showed strong agreement and ranked products consistently, underscoring the value of OMS as an independent reference and motivating a similar OMS–satellite cross-check (Ren et Al., 2025).

In this work, we deploy a dual-wavelength optical–microwave scintillometer (OMS), combining a LAS and a microwave channel at 160.8 GHz, at a Mediterranean vineyard site in Alto Monferrato (NW Italy), within the experimental site of Tenuta Cannona (Agrion, Carpeneto, AL, 44°40'57.12" N, 8°37'35.00" E). OMS operated continuously from July 2023 to October 2024 alongside a complete weather station. OMS leverages Monin–Obukhov Similarity Theory (MOST) to derive H and LE from structure parameters along a line-of-sight footprint, bridging the scale mismatch between point sensors and model tiles. We conduct site-level validation of CLM5 single-point (SPT) simulations, using mode one of the supported CLM5 configurations, assessing the model's representation of soil moisture, soil temperature, and the resulting sensible and latent heat fluxes. By comparing simulated values with observational data from field site, we evaluate the ability of CLM5 to reproduce local energy and water flux dynamics. This validation provides insights into both the strengths and limitations of the model's soil and surface process representations and informs confidence in CLM5 predictions at local and regional scales.

This study contributes by: (1) documenting a vineyard application of dual-wavelength scintillometer with a traceable geometry and processing chain, including LAS saturation treatment and effective-height calculation; (2) providing an independent, path-scale benchmark for CLM5 fluxes in a managed agro-ecosystem; and (3) discussing practical implications for local calibration/assimilation strategies and for the use of line-averaged fluxes to validate land-surface models over heterogeneous row crop landscapes.

Materials and Methods

Optical and Microwave Scintillometer

We used a dual-wavelength scintillometer system that combines a Large Aperture Scintillometer (LAS, near-infrared) with a microwave scintillometer operating at 160.8 GHz (model RPG-MWSC-160). The combined optical–microwave approach (hereafter OMS) enables the simultaneous estimation of sensible heat (H) and latent heat flux (LE) by exploiting the (co)variances of the intensity fluctuations at the two wavelengths together with Monin–Obukhov Similarity Theory (MOST). The instrument delivers minute-scale Level-2 flux

products after internal processing (synchronised digitization of optical and microwave signals), LAS saturation checks, and archiving of lower-level variance (Level-1) and raw (Level-0) data for post-processing.

Typical path lengths span 0.5–10 km, and the effective height is computed from path weighting functions and site topography; wind measurements from the co-located weather unit provide the cross-wind component required by the processing chain.

Study site and deployment

Deploying a scintillometer in a vineyard represents an innovative approach to quantify evapotranspiration and surface energy exchange at spatial scales relevant to remote sensing. The OMS was deployed at a Mediterranean vineyard in Alto Monferrato (NW Italy), within the experimental estate of Tenuta Cannona (Agrion, Carpeneto, AL). At the experimental vineyard, a complete weather station was operational, including a pyranometer for measuring global shortwave radiation. The transmitter–receiver line of sight was selected to satisfy the ≥ 500 m baseline requirement, maintain obstacle-free Fresnel zones, ensure stable power/data connectivity, and enable precision alignment (optical telescopes and iterative signal maximization). An ultrasonic anemometer and thermohygrometer were mounted at the receiver to support flux processing. The system operated from July 2023 through October 2024, delivering a continuous record of path-integrated turbulence and fluxes.

MOST is applied within the OMS software to convert structure parameters to H and LE, using instrument geometry and effective-height estimates. All flux data underwent quality control at minute resolution. Records were flagged as out of range when either of the following conditions held: (i) sensible heat flux $H > 500$ W m⁻², or (ii) latent heat flux $LE < -100$ W m⁻². Flagged data were excluded from skill metrics and bias/error analyses. All unflagged 1-min records were aggregated to hourly means for subsequent analyses.

Atmospheric correction & flux sign determination

For the automatic determination of flux signs, the OMS processing can infer the sign of H from the temperature–humidity correlation coefficient rTq retrieved with the Lüdi method (Lüdi et al., 2005). In the RPG implementation, rTq is used to disambiguate stability: with LE constrained to be non-negative, the sign of rTq fixes the sign of H.

In line with the instrument defaults, we restrict $LE \geq 0$ during this automatic evaluation, assuming no condensation. This assumption simplifies the sign logic but is not universally valid (e.g., dew formation can yield negative LE of small magnitude), and thus the automatically determined flux signs are not always reliable.

Hourly net radiation (Rn) computation

We computed hourly net radiation at the surface as:

$$R_n = (1 - \alpha) R_s - R_{lu}$$

where R_s is the global shortwave ($W m^{-2}$) from the pyranometer, α is surface albedo, and R_{lu} is the upward longwave emitted by the surface.

The pyranometer measures hemispheric global shortwave irradiance (direct + diffuse) in $W m^{-2}$, which we used as R_s . Albedo (α) was set to 0.23 for land-cover.

The upward longwave was parameterized via Stefan–Boltzmann:

$$R_{lu} = \epsilon \sigma T_s^4$$

with ϵ surface emissivity, $\sigma = 5.67 \times 10^{-8} W m^{-2} K^{-4}$ (Stefan–Boltzmann constant), and T_s soil surface temperature in Kelvin. Typical broadband ϵ lies near 0.95–0.98 for vegetated surfaces but can be < 0.90 over bare soils; we adopted $\epsilon = 0.95$ for our mixed vineyard–soil context (Jin & Liang, 2006). Longwave is sensitive to surface emissivity and surface temperature; without direct longwave measurements, using a surface soil temperature proxy is common practice (Jin & Liang, 2006). Direct soil surface temperature was not available; therefore we estimated T_s from air temperature at 2 m (T_a) and soil temperature at 10 cm (T_{10}) using an empirical, site-calibrated relation:

$$T_s \approx T_a + k (T_{10} - T_a)$$

Here k can range from 0.5 to 1.0 scales the near-surface thermal gradient toward the surface, higher by day (strong insolation), lower by night/weak forcing. To reflect diurnal radiative forcing, k was updated hourly from the measured R_s :

$$k = 0.5 + 0.5 \cdot R_s / 1000$$

This yields larger k under strong insolation (pushing T_s closer to T_{10}), and smaller k under weak insolation (pulling T_s toward T_a), it is capped to $[0.5, 1.0]$.

Validation datasets

Pyranometer readings were validated by comparing with RSE-SFE external reference dataset (<https://sunrise.rse-web.it/>).

We validated our hourly R_n against Copernicus/ECMWF ERA5 surface/single-level radiation variables at the nearest gridpoint of hourly series, of Copernicus ERA5 data-model (ECMWF/C3S, Copernicus, 2026). ERA5 hourly surface net solar radiation (ssr) and surface net thermal radiation (str) at the nearest grid point were combined to obtain $R_{n,ERA5}=ssr+str$, and collocated to the site time-base for comparison. Any offsets were noted and used to confirm the dynamic k calibration.

CLM5.0 Model Simulations

The simulations were conducted for a two-year period, from 2023 to 2024, with the model configured to run at an hourly time step. Hourly observational datasets from the site were used as input, consisting of five key variables required to drive the simulations which are listed in detail in Table 23. Some minor missing values in the dataset were filled using linear interpolation, and the data were subsequently cleaned and processed in MATLAB. Finally, the processed data were converted into NetCDF format to serve as input for the CLM5 single-point simulations.

Table 23: Input variables used for CLM5 single-point simulations

Input Variables	Units
Relative Humidity	%
Incoming Solar Radiation	W m^{-2}
Air Temperature	K
Wind Speed	m s^{-1}
Precipitation	mm s^{-1}

The surface dataset and domain file are generated using CTSM preprocessing tools based on the site coordinates and publicly available raw datasets distributed with CLM5 (<https://svn-ccsm-inputdata.cgd.ucar.edu/trunk/inputdata/lnd/clm2/rawdata/>). The generated grid cell has a spatial resolution of approximately 120 m in the north–south direction and 116 m in the east–west direction. The surface dataset generated was calibrated to reflect local environmental and land cover conditions. Soil texture was specified with 40% sand and 25% clay to represent site-specific soil properties. Land cover fractions were defined using plant functional types (PFTs): natural vegetation

accounted for 70% of the site, entirely dominated by C3 grasses, while crops comprised 30%, represented entirely by irrigated grapes. Topographic characteristics were also incorporated, with a slope of 8° applied to the site. These calibrated parameters were incorporated into the surface dataset and used to initialize the model, ensuring that both soil and vegetation states accurately reflected the local conditions for subsequent CLM5 simulations.

The soil pedotransfer properties are typically derived from the soil texture information provided in the surface dataset. The saturated volumetric soil moisture used in the simulations is 0.43, and the saturated hydraulic conductivity is 107 mm h⁻¹.

Simulation Phases

The CLM5 simulations at the Cannona vineyard site were conducted in three sequential phases to ensure accurate representation of soil, vegetation, and biogeochemical dynamics. In the first phase, a cold start with accelerated spin-up was performed using the I2000Clm50BgcCropGs compset configuration with site-specific surface and domain datasets. Biogeochemistry and crop modules were activated. The model was run for 12 years in single-point mode to rapidly equilibrate the soil carbon and nitrogen pools. The second phase involved a longer spin-up simulation of 24 years, starting from the accelerated spin-up output, to further stabilize ecosystem conditions and ensure near equilibrium states of soil and vegetation. Finally, the third phase consisted of the main simulation over two years (2023–2024), initialized from the restart files of the spin-up phases. This final phase generated the primary outputs for analysis, including carbon and water fluxes, soil moisture, and vegetation dynamics. Throughout all phases, site-specific meteorological forcing datasets, generated for this study, were used to drive the model, and all namelists were configured to reflect local conditions, ensuring continuity and consistency across simulations.

Data Processing, Synchronization, and Statistical Analysis

All statistical analyses and plotting were performed in R (R Core Team). Prior to all model–data comparisons, we verified the temporal synchronization between CLM outputs and OMS records; where minor misalignments were identified, a time-shift correction was applied if necessary. Analyses were carried out on quality-screened intervals only.

Statistical analyses were performed using intervals in which scintillometer products appeared valid, evaluated individually and then combined. The selected periods were: Summer 2023 (30 June 2023–19 October 2023), Spring 2024 (1 April 2024–24 May 2024), and Summer 2024 (24 July 2024–28 August 2024). A combined analysis merged these periods, excluding winter months and intervals with questionable scintillometer validity. Performance was quantified using standard goodness-of-fit metrics (bias, RMSE, correlation, and efficiency indices), and diagnostic plots (time series, scatterplots, and residual distributions) were used to identify systematic deviations and noise characteristics.

Results and discussion

Validation of pyranometer global shortwave radiation against RSE–SFE

The site pyranometer showed excellent agreement with the external RSE-SFE global shortwave radiation reference data across the full record: the correlation was $R^2 = 0.950$. The mean bias error (MBE) was -8.3 W m^{-2} (-3.15%), while the RMSE was 70.2 W m^{-2} (26.5%). Restricting the comparison to daytime conditions (reference $> 5 \text{ W m}^{-2}$; $n = 912$) yielded similarly strong performance ($R^2 = 0.920$). The MBE increased modestly in magnitude (-17.2 W m^{-2} ; -3.85%) and the RMSE to 83.5 W m^{-2} (18.7%), as expected under higher daytime irradiance. Taken together, these metrics indicate that the pyranometer tracks the external reference very closely across the dynamic range, with only a minor overall negative bias and a slight compression of high values (slope < 1).

The weak diurnal structure observed in the residuals (negative biases in the early morning, small positive biases in the afternoon) is consistent with local orographic effects: the presence of a nearby hill can partially obscure the low-elevation sun in the morning and alter the direct–diffuse partition, while late-afternoon conditions may enhance off-axis/reflected components. Together with the sensor cosine response, this can produce a slight AM/PM asymmetry without affecting the overall fidelity of the pyranometer to the external reference.

Validation of hourly net radiation (R_n) against ERA5

The locally computed hourly net radiation showed good correspondence with ERA5 at the nearest grid point across the full record ($n = 4808$): $R^2 = 0.760$, with a regression slope slightly > 1 (1.049) and a positive intercept ($+15.76 \text{ W m}^{-2}$). Accuracy metrics indicate a systematic positive bias of $\text{MBE} = +27.28 \text{ W m}^{-2}$ ($+11.57 \%$) and $\text{RMSE} = 97.48 \text{ W m}^{-2}$ (41.35%).

Taken together, these results suggest that the local Rn_CR6 is, on average, higher than ERA5 (positive MBE and intercept) and amplifies at larger values (slope > 1). This behaviour is consistent with differences in footprint and spatial representativeness—a single-site radiative budget vs a 31 km reanalysis grid—and with the methodological choices used to derive Rn locally, compared to ERA5’s model-diagnosed net radiation over a broader area. Minor diurnal structure in the residuals (small positive midday departures) is expected from sub-grid cloud variability, topographic effects (orography, horizon masking), and surface emissivity/temperature assumptions, all of which can produce site-specific departures relative to the reanalysis field. Nonetheless, the co-variance is strong ($R \approx 0.87$), confirming that the local Rn is fit for purpose as an observational benchmark for subsequent model comparisons, while the bias/scale differences should be taken into account in the interpretation of flux skill.

Path-integrated fluxes (OMS)

Across seasons, the OMS time series show well-defined diurnal cycles: net radiation estimated by meteorological station (Rn_CR6) peaks around local midday and decays toward night, with H tracking the available energy and LE reflecting evaporative demand and moisture supply. At night, a low-amplitude noise floor is visible, particularly in LE , which remains slightly positive rather than collapsing to zero. This behaviour is expected given the minute-scale processing and the sign retrieval logic: the RPG software determines the sign of H from the temperature–humidity correlation RTQ (Lüdi method), while constraining $LE \geq 0$ (no condensation) for the automatic evaluation. As a result, small positive LE values can persist under stable nocturnal conditions when true evaporation is negligible, and the path-integrated signal-to-noise ratio is reduced. Hourly aggregation mitigates, but does not entirely remove, these effects. Overall, the co-variance of Rn , H and LE is robust in clear-sky periods, while cloudy episodes produce the expected depressions and broaden the distribution of instantaneous fluxes, consistent with the integrated footprint of the OMS path (figure 93).

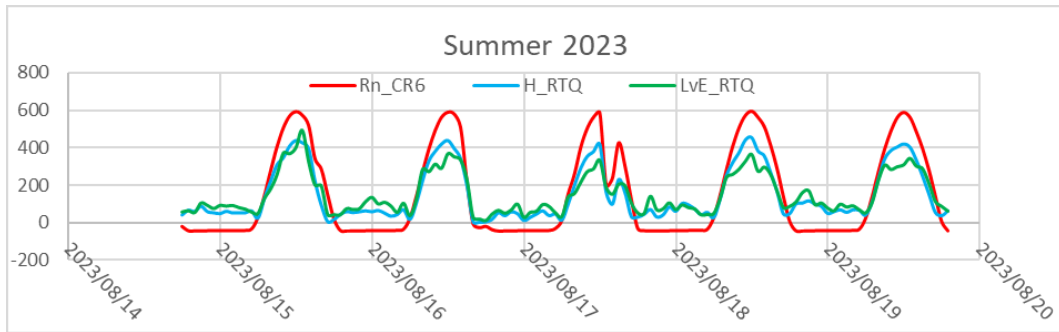


Figure 93: hourly time series of net radiation and turbulent fluxes - summer 2023 (15–20 August 2023). Clear-sky days show robust diurnal cycles with midday peaks; the cloud-affected day (17 august 2023) displays the expected depression.

In spring 2024, seasonal transition period showed moderate Rn and lower LE relative to summer; diurnal co-variance of Rn, H, and LE remains well-defined on clear days, but exhibits less robust diurnal cycles, with broader daytime variability and more frequent departures from the ideal midday peak. Notably, nighttime values of H and LE are elevated and, on several nights, reach concurrent daytime values (figure 94).

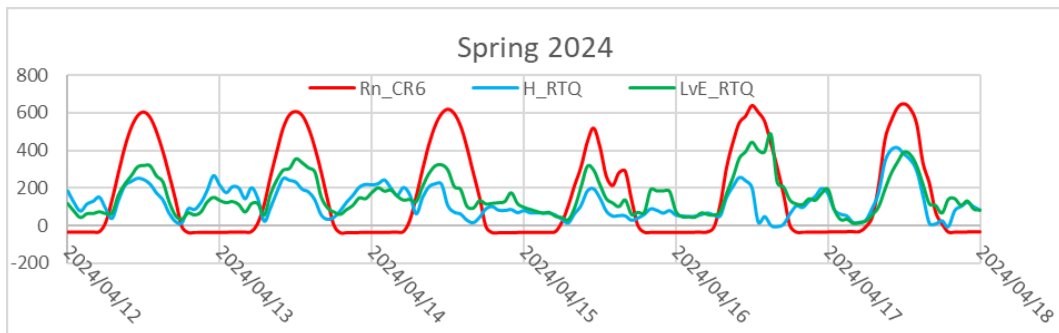


Figure 94: hourly time series of net radiation and turbulent fluxes - spring 2024 (12–18 April 2024). Clear-sky days show less robust diurnal cycles and nighttime values of H and LE are elevated compared to summer 2023.

In summer 2024, the values measured by OMS appear noisier throughout the day and night-time values of H and LE remain elevated, in several nights approaching or exceeding daytime levels.

Net Radiation (Rn)

Pooling the three analysis windows (summer 2023, spring 2024, late-summer 2024), CLM reproduces the hourly site net radiation with high

co-variance against the station estimate (CR6) but shows a moderate negative bias (Table 24). Specifically, CLM–CR6 yields $R \approx 0.93$, $RMSE \approx 86.6 \text{ W m}^{-2}$, and a mean bias $\approx -21 \text{ W m}^{-2}$, indicating that CLM tends to underestimate the locally derived R_n on average while still tracking its variability closely. As a large-scale reference, we also compared CLM with ERA5: in the pooled dataset the model is nearly unbiased relative to the reanalysis (bias $\approx -1.6 \text{ W m}^{-2}$) with $R \approx 0.91$ and $RMSE \approx 96.1 \text{ W m}^{-2}$ (Table 24), which places CLM between the site-level radiative budget and the 31-km reanalysis background.

Table 24: Hourly net radiation (Rn): summary statistics (pooled across Summer 2023, Spring 2024, Late-Summer 2024)

Pairing	Bias (W m ⁻²)	RMSE (W m ⁻²)	R	R ²	NSE	n_pairs
Rn_CLM vs Rn_CR6	-21.5	86.6	0.93	0.86	0.86	4786
Rn_CLM vs Rn_ERA5	-1.6	96.1	0.91	0.82	0.82	4795

The two scatter panels (figure 95) confirm that CLM’s net radiation is well aligned with both CR6 and ERA5 across the mid–high range, closely following the 1:1 line and supporting the high correlations reported in Table 24. At the same time, both scatters exhibit a dense vertical plume at $Rn_CLM \approx 0$ while Rn_CR6 and Rn_ERA5 remain positive (often 50–200 W m⁻²), indicating conditions in which the model clips/lingers near zero but the references still register net energy at the surface. This regime typically occurs around dawn/dusk or under overcast skies, and can be enhanced by site-specific orographic shading and horizon masking, as well as by differences in how diffuse radiation and longwave contributions are represented in CLM versus ERA5. In particular, ERA5’s single-level radiation fields (surface net solar radiation, *ssr*, and surface net thermal radiation, *str*) include diffuse all-sky components and are reported at the reanalysis grid scale (~31 km), whereas the station estimate combines the pyranometer shortwave and Stefan–Boltzmann longwave terms at site scale; both factors can keep Rn positive in the references while the model remains close to zero at transitions.

Overall, CLM tracks the diurnal/synoptic variability of site Rn well, underestimating only by ~20 W m⁻² on average. Relative to ERA5, CLM’s aggregate bias is negligible while co-variance remains robust. These differences are relevant for interpreting turbulent-flux skill, because a model underestimation of Rn typically propagates into lower H and LE and a shifted evaporative partition.

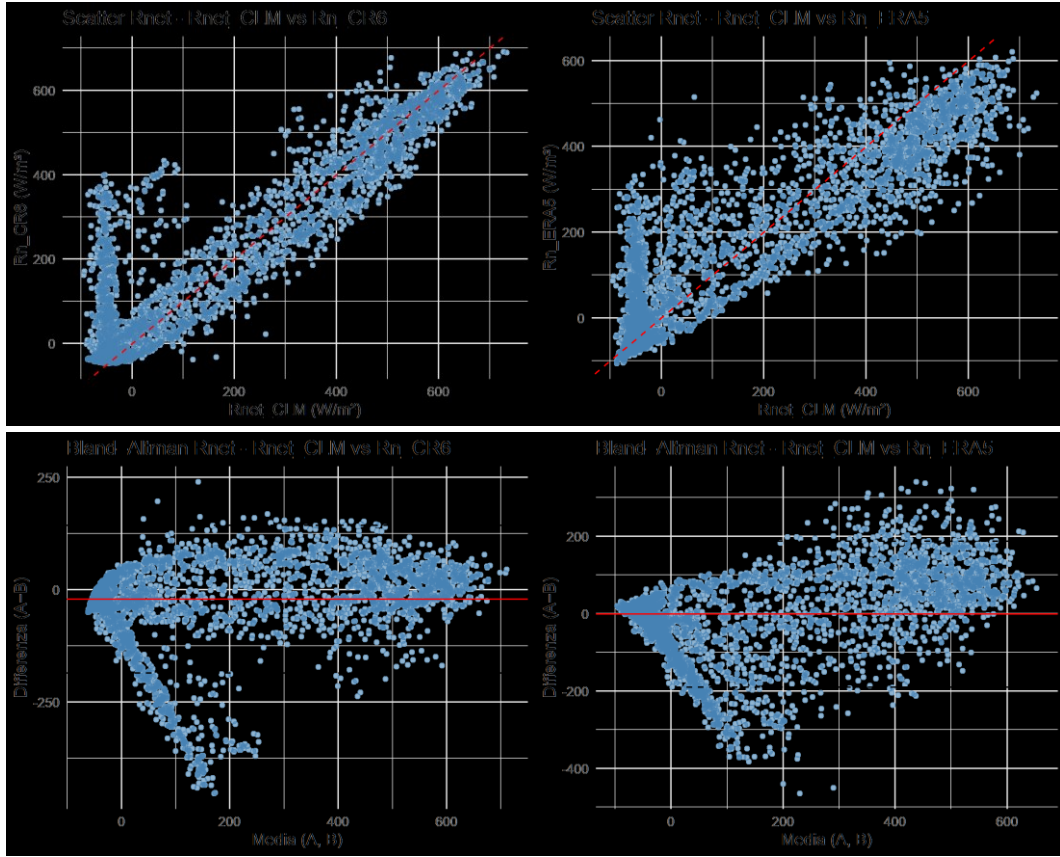


Figure 95: Pooled hourly net radiation comparisons across the three analysis windows (summer 2023, spring 2024, late-summer 2024). Top row: Scatter plots of Rn_CLM vs Rn_CR6 (left) and Rn_CLM vs Rn_ERA5 (right); the red dashed line marks the 1:1 reference. Bottom row: Bland–Altman plots for the same pairings; the red line is the mean difference, black dashed lines indicate approximate agreement limits.

Sensible Heat Flux (H)

CLM underestimates H relative to the OMS products, with the best agreement in summer 2023 and weaker performance in 2024, particularly in late summer. Pooled statistics confirm a modest covariance ($R \approx 0.71$) and a slight negative efficiency ($NSE \approx -0.03$), consistent with a negative mean bias (Table 25).

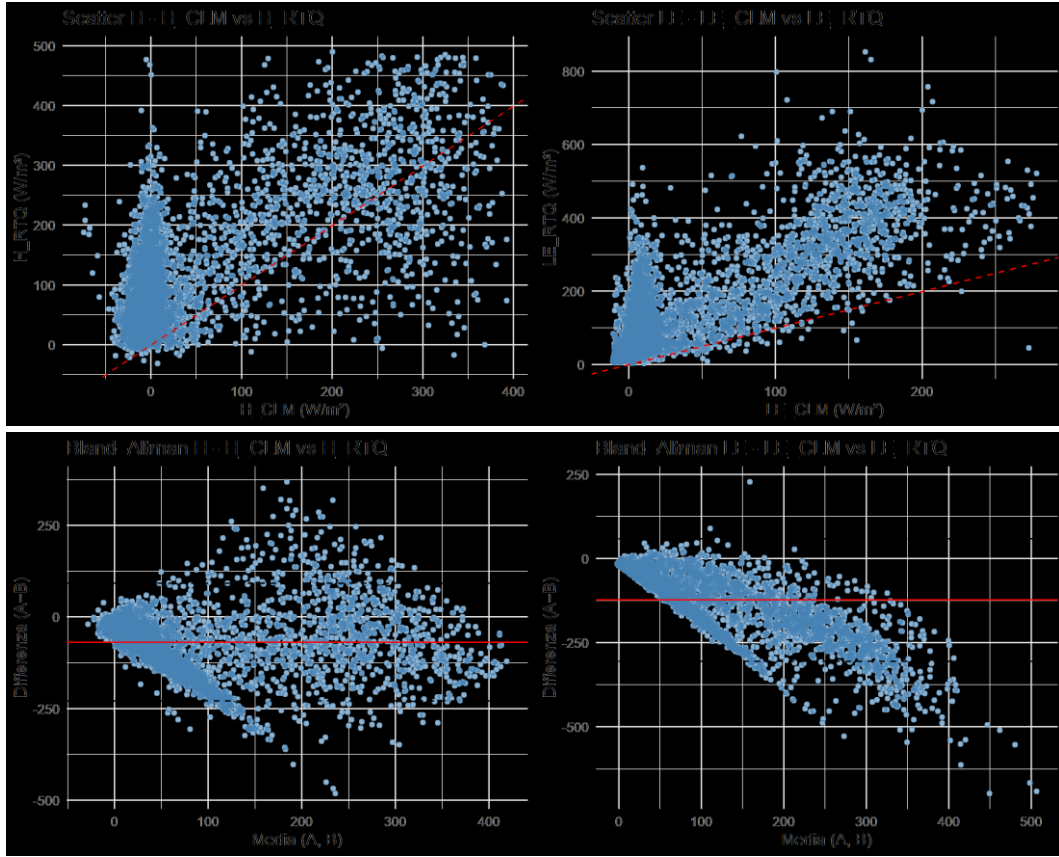


Figure 96: Pooled hourly Sensible Heat Flux (H) and Latent Heat Flux (LE) comparisons across the three analysis windows (summer 2023, spring 2024, late-summer 2024). Top row: Scatter plots of H_CLM vs H_RTQ (left) and LE_CLM vs LE_RTQ (right); the red dashed line marks the 1:1 reference. Bottom row: Bland–Altman plots for the same pairings; the red line is the mean difference, black dashed lines indicate approximate agreement limits.

As per our previous discussion and the instrument processing notes, a nocturnal background is visible in OMS H_RTQ under stable conditions (values not collapsing to zero, the scatter in figure 96 reveals a dense vertical plume at H_CLM ≈ 0), which inflates variance-based metrics while leaving daytime alignment largely intact (model and instrument show comparable peak values in summer 2023). This behavior is consistent with the RPG sign logic (use of RTQ and default $LE \geq 0$), and with the slight CLM underestimation of site net radiation relative to the station-derived budget, which can depress daytime H peaks.

Table 25: Hourly Sensible Heat Flux (H) and Latent Heat Flux (LE) estimated by CLM model and OMS (RTQ method): summary statistics (pooled across Summer 2023, Spring 2024, Late-Summer 2024).

Pairing	Bias (W m ⁻²)	RMSE (W m ⁻²)	R	R ²	NSE	n_pairs
H_CLM vs H_RTQ	-68.58	106.86	0.71	0.50	-0.025	4446
LE_CLM vs LE_RTQ	-122.83	153.96	0.79	0.62	-5.20	4446

Latent Heat Flux (LE)

LE consistently shows poorer performance across all periods. CLM underestimates LE during the warmest hours, missing daytime peaks, while the scintillometer exhibits a background signal at night when CLM estimates collapse near zero. This contrast is clearly visible in the attached figures (figure 96) and is reflected by the negative biases and strongly negative efficiencies across periods and in the pooled set (Table 25). The scatter indicates that CLM saturates around $\sim 150\text{--}250 \text{ W m}^{-2}$ and misses daytime peaks captured by the scintillometer, whereas the Bland–Altman diagram displays a pronounced negative slope of (CLM – RTQ) versus the mean, i.e., underestimation increases with magnitude. A positive nocturnal floor persists in the OMS LE (vertical plume at $\text{LE}_{\text{CLM}} \approx 0$ but $\text{LE}_{\text{RTQ}} > 0$), inflating variance-based metrics RMSE/NSE without explaining the magnitude of the daytime underestimation.

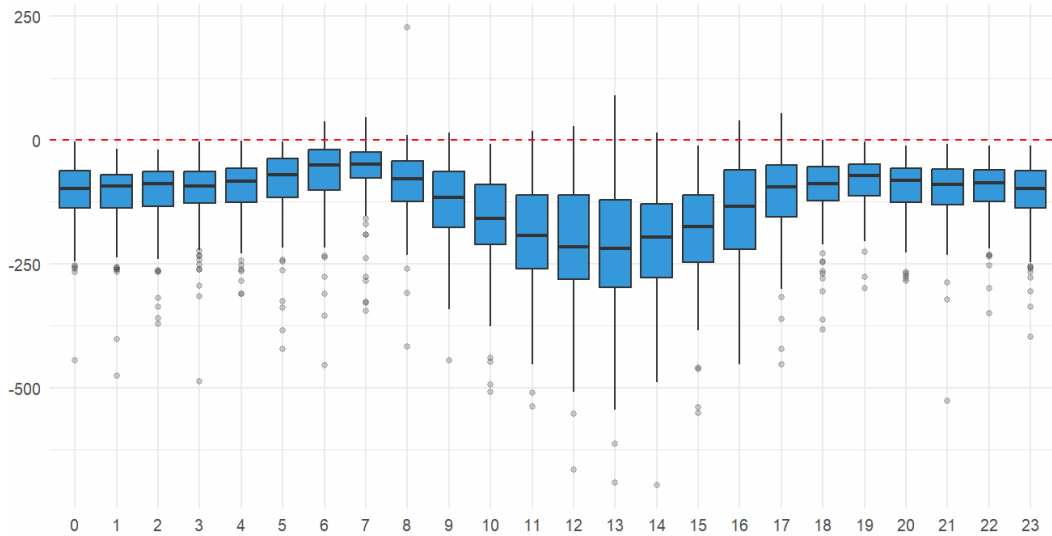


Figure 97: Hourly residuals of latent heat flux (LE) by local time. Residuals are defined as $\Delta\text{LE} = \text{LE}_{\text{CLM}} - \text{LE}_{\text{RTQ}}$ and summarized as boxplots pooling summer 2023, spring 2024, and late-summer 2024. (Sign convention: negative ΔLE means OMS exceeds CLM)

An hourly residual analysis further reveals a pronounced diurnal structure of the LE bias (figure 97). Median residuals remain near zero during the night and become increasingly negative from mid-morning, reaching a minimum around 12–14 LT (order of -200 to -250 W m^{-2}), before relaxing in late afternoon. The spread is heteroscedastic, with markedly larger dispersion during peak evaporative demand. This pattern is fully consistent with the Bland–Altman proportional bias (CLM underestimation scales with magnitude) and with the night-time positive floor in the scintillometer product (figure 96). Together, these diagnostics confirm that CLM misses daytime LE peaks while night-time differences are comparatively small.

The joint analysis highlights that both data-quality screening and accurate temporal synchronization are critical for meaningful site-level evaluation of land surface model fluxes. Remaining discrepancies, particularly for LE, may reflect limitations in model representation of canopy and soil evaporation dynamics under vineyard management, as well as noise characteristics and processing assumptions in scintillometer retrievals.

OMS path-integrated fluxes sample a heterogeneous vineyard footprint with row structure and mixed soil/vegetation patches, whereas CLM aggregates at a single point with specified PFT/CFT fractions. Under directional winds and topographic shading, LE peaks can be enhanced along the path while CLM remains limited by tile-level constraints, explaining saturation in CLM LE ($\sim 150\text{--}250 \text{ W m}^{-2}$) versus extended OMS tails ($> 400\text{--}600 \text{ W m}^{-2}$) in the scatter.

To reduce the discrepancies, small adjustments could be done to radiative and surface parameters (albedo, emissivity, near-surface temperature proxy) to alleviate Rn bias, refining crop/vegetation hydrology (stomatal conductance, soil hydraulic functions, phenology) to lift daytime LE, and revisiting aerodynamic parameters (roughness length and displacement height) to reduce resistance. Regime-filtered diagnostics (e.g., daytime only, $R_n > 50 \text{ W m}^{-2}$, wind speed $> 2 \text{ m s}^{-1}$) could help isolate the instrument nocturnal floor from the true daytime model deficit.

Consistent with recent OMS deployments in heterogeneous arid landscapes, where small but nonzero nocturnal H and LE have been reported, our findings suggest that site-adapted MOST coefficients may be warranted. Over a saline-lake site in the Atacama Desert, tuning similarity functions to local conditions substantially improved OMS–EC agreement and mitigated residual biases

(Lobos-Roco et Al., 2022); a similar hypothesis appears reasonable at Cannona and will be explored in future work.

Beyond site-adapted MOST, recent work in a semi-arid olive orchard shows that optical–microwave scintillometry (OMS) can serve as an independent benchmark for satellite energy-balance retrievals: SEBAL estimates were +3% for H and +13% for LE relative to OMS (Barguache et Al., 2025). A similar OMS–satellite cross-check at Cannona would help constrain remote-sensing flux products and strengthen scaling from path-integrated observations to field mosaics.

Conclusions

This study presented a site-level evaluation of CLM5 single-point simulations against dual-wavelength optical–microwave scintillometer (OMS) fluxes at a Mediterranean vineyard. After rigorous QC, synchronization, and restriction to reliable windows, we find that CLM reproduces hourly net radiation with high covariance but a modest negative bias relative to the station-derived budget, while sensible and latent heat fluxes are systematically underestimated, especially under strong forcing.

Net radiation is well aligned with both the local budget and ERA5, placing CLM between the site-scale and reanalysis references. This result is consistent with the footprint and methodological differences discussed for Rn and provides important context for interpreting H and LE skill.

For H and LE, model–data agreement is best in summer 2023 and weakens in 2024. A nocturnal/transition background in the OMS is evident. For LE, discrepancies are larger and display a clear proportional bias: CLM misses daytime peaks and the underestimation increases with flux magnitude.

Finally, the OMS–CLM framework used here provides a practical template for vineyard-scale flux assessment and for diagnosing model–data mismatches that depend on diurnal cycle and atmospheric regime. Extending the analysis with direct longwave measurements, refined MOST coefficients for weakly unstable conditions, and, where available, eddy-covariance snapshots would further consolidate the attribution of daytime LE deficits and improve the robustness of site-to-regional upscaling.

References

Barguache, H., Ezzahar, J., Kharrou, M. H., Khabba, S., Elfarkh, J., Laalyej, A., Er-Raki, S., & Chehbouni, A. (2025). Quantification of olive tree evapotranspiration using an optical-microwave scintillometer and SEBAL model in semi-arid region. *Acta Horticulturae*, 1422, Article 22. <https://doi.org/10.17660/ActaHortic.2025.1422.22>

Beyrich, F., Hartogensis, O. K., de Bruin, H. A. R., & Ward, H. C. (2021). Scintillometers. In T. Foken (Ed.), *Springer Handbook of Atmospheric Measurements* (pp. 969–997). Springer. https://doi.org/10.1007/978-3-030-52171-4_34

Beyrich, F., Kouznetsov, R. D., Leps, J.-P., Lüdi, A., Meijninger, W. M. L., & Weisensee, U. (2005). Structure parameters for temperature and humidity from simultaneous eddy-covariance and scintillometer measurements. *Meteorologische Zeitschrift*, 14(5), 641–649. <https://doi.org/10.1127/0941-2948/2005/0064>

Copernicus Climate Data Store (CDS)/ECMWF. (2025). ERA5 hourly data on single levels from 1940 to present. Accessed 5 Jan 2026. <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels>

Denager, T., Sonnenborg, T. O., Looms, M. C., Bogen, H., & Jensen, K. H. (2023). Point-scale multi-objective calibration of the Community Land Model (version 5.0) using in situ observations of water and energy fluxes and variables. *Hydrology and Earth System Sciences*, 27, 2827–2845. <https://doi.org/10.5194/hess-27-2827-2023>

Evans, J. G., & de Bruin, H. A. R. (2011). The effective height of a two-wavelength scintillometer system. *Boundary-Layer Meteorology*, 141(2), 165–177. <https://doi.org/10.1007/s10546-011-9634-0> [link.springer.com]

Jin, M., & Liang, S. (2006). An improved land surface emissivity parameter for land surface models using global remote sensing observations. *Journal of Climate*, 19(12), 2867–2881. <https://doi.org/10.1175/JCLI3720.1>

Lawrence, D. M., Fisher, R. A., Koven, C. D., Oleson, K. W., Swenson, S. C., Bonan, G., Collier, N., Ghimire, B., van Kampenhout, L., Kennedy, D., Kluzek, E., Lawrence, P. J., Li, F., Li, H., Lombardozzi, D., Riley, W. J., Sacks, W. J., Shi, M., Vertenstein, M., Wieder, W. R., Xu, C., Ali, A. A., Badger, A. M., Bisht, G., van den Broeke, M., Brunke, M. A., Burns, S. P., Buzan, J., Clark, M., Craig, A., Dahlin, K., Drewniak, B., Fisher, J. B., Flanner, M., Fox, A. M., Gentine, P., Hoffman, F., Keppel-Aleks, G., Knox, R., Kumar, S., Lenaerts, J., Leung, L. R., Lipscomb, W. H., Lu, Y., Pandey, A., Pelletier, J. D., Perket, J., Randerson, J. T., Ricciuto, D. M., Sanderson, B. M., Slater, A., Subin, Z. M., Tang, J., Thomas, R. Q., Val Martin, M., & Zeng, X. (2019). The Community Land Model version 5: Description of new features, benchmarking, and impact of forcing uncertainty. *Journal of Advances in Modeling Earth Systems*, 11(12), 4245–4287. <https://doi.org/10.1029/2018MS001583>

Lobos-Roco, F., Hartogensis, O., Vilà-Guerau de Arellano, J., Aguirre, F., de la Fuente, A., & Suárez, F. (2022). Optical microwave scintillometer evaporation measurements over a saline lake in a heterogeneous setting in the Atacama Desert. *Journal of Hydrometeorology*, 23(6), 909–924. <https://doi.org/10.1175/JHM-D-21-0100.1>

Lüdi, A., Beyrich, F., & Mätzler, C. (2005). Determination of the turbulent temperature–humidity correlation from scintillometric measurements. *Boundary-Layer Meteorology*, 117, 525–550. <https://doi.org/10.1007/s10546-005-1751-1>

Perelet, A. O., Ward, H. C., Stoll, R., Mahaffee, W. F., & Pardyjak, E. R. (2022). Quantifying turbulence heterogeneity in a vineyard using eddy-covariance and scintillometer measurements. *Boundary-Layer Meteorology*, 184, 479–504. <https://doi.org/10.1007/s10546-022-00714-9>

Ren, Z., Che, T., Xu, F., Zhang, Y., Tan, J., Wang, J., & Wang, W. (2025). Validation of remotely sensed evapotranspiration products using optical–microwave scintillometer flux measurements over heterogeneous surfaces. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 18, 5687–5703. <https://doi.org/10.1109/JSTARS.2025.3539224>

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., & Teuling, A. J. (2010). Investigating soil moisture–climate interactions in a changing climate: A review. *Earth-Science Reviews*, 99(3–4), 125–161. <https://doi.org/10.1016/j.earscirev.2010.02.004>

Vendrame, N., Tezza, L., & Pitacco, A. (2020). Comparison of sensible heat fluxes by large aperture scintillometry and eddy covariance over two contrasting-climate vineyards. *Agricultural and Forest Meteorology*, 288–289, 108002. <https://doi.org/10.1016/j.agrformet.2020.108002>

3.3.5 Conclusions and Perspectives

The experimental deployment of the RPG-MWSC-160 optical–microwave scintillometer in a vineyard demonstrated the feasibility and the practical challenges of monitoring surface–atmosphere exchanges at a horizontal scale that is closer to remote-sensing support than point measurements. The system enabled the collection of flux-relevant information in synergy with the broader monitoring platform and supported a first comparison with Community Land Model (CLM) simulations. In this vineyard-specific, highly innovative setup, data quality was not uniformly satisfactory: the installation was necessarily “experimental”, and several periods were affected by non-ideal or incorrect measurements, limiting continuous analyses. Nevertheless, the evaluation of the valid time windows and the comparison with CLM outputs provided encouraging indications that the measured dynamics are broadly consistent with modeled water/energy balance behavior, offering a sound basis for further exploitation.

Looking forward, priority should be given to a rigorous screening and consolidation of the existing dataset (identification of reliable periods, characterization of failure modes, and uncertainty quantification), followed by targeted analyses on the most informative episodes (e.g., peak evapotranspiration and transition periods) and extended comparisons with CLM and satellite products. A higher mounting configuration (taller poles and increased beam height above ground) would reduce near-surface obstacles and associated disturbances, and is expected to yield substantially more stable and physically consistent signals. Under such improved installation conditions, scintillometry could become a powerful component of vineyard ecohydrological monitoring - less as an operational farm tool, and more as a research-grade reference to refine model parameterizations and to upscale point observations toward remote-sensing scales.

3.4 Cosmic-ray soil moisture sensor (CRNS)

3.4.1 Introduction

Cosmic Rays Neutron Sensing (CRNS) is a well-known method in hydrology for measuring soil water content on a large scale and in depth (Bogena et al., 2022). The cosmic-ray neutron sensor is a non-invasive device that measures soil moisture levels by detecting and counting fast neutrons generated by high-energy cosmic rays from outside the solar system, which are then absorbed by water molecules in the soil (Figure 98). A single CRNS probe can measure neutron count rates sensitive to soil moisture within a volume spanning up to a dozen hectares and up to 50 cm depth in real-time, positioning itself between point measurements and satellites on a horizontal spatial scale. This sensor is noted for its speed, portability, and ability to cover larger areas compared to traditional methods. Since 2013, the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture has been testing and calibrating the sensor, including a mobile version that can be carried like a backpack. Prototypes have been installed in over 25 countries to monitor soil water content, aiding farmers in water conservation and adaptation to climate change by determining soil water availability and irrigation needs.

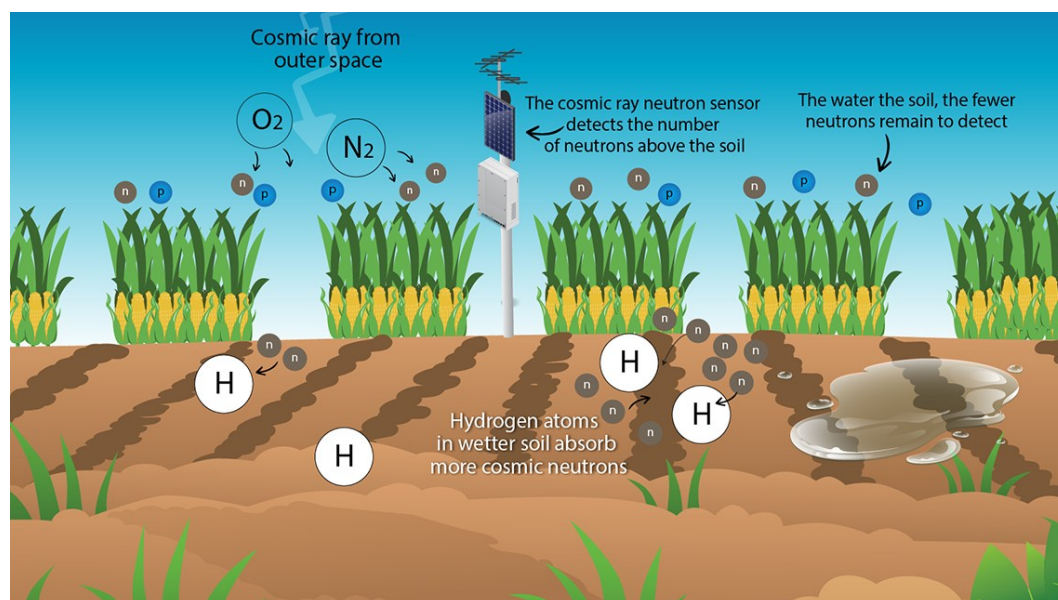


Figure 98: Scheme of operating principle of the sensor (Infographic: R. Kenn/IAEA, source <https://www.iaea.org/newscenter/news/using-cosmic-rays-to-measure-moisture-levels-in-soil>).

The objective of this study is to evaluate the effectiveness of CRNS in providing information about soil moisture in a complex agricultural system, specifically a vineyard with varying soil conditions and management practices.

3.4.2 Installation of a cosmic-ray soil moisture sensor (CRNS) at the experimental plots of Tenuta Cannona

The sensor was installed at the experimental plots of Tenuta Cannona (Agrion) in Carpeneto (AL), where several sensors are already in place to monitor the vineyard planted in rows. These include traditional soil moisture sensors at various positions and depths, a complete weather station, and a system for monitoring runoff at the plot scale. This setup allows for the comparison of data obtained from the new instrument with values measured by the existing field probes and during periodic surveys. Given the extent of the sampled area (approximately 3-10 hectares, with a minimum radius of 100 meters) and the need for a plant-free point for the installation of the pole, which should be central to a uniform area and not obstruct agricultural machinery and viticultural operations, the instrument was positioned upstream of the experimental plots. It was placed near a channel to isolate the plots from water coming from upstream, where the row is free of plants for about one meter.

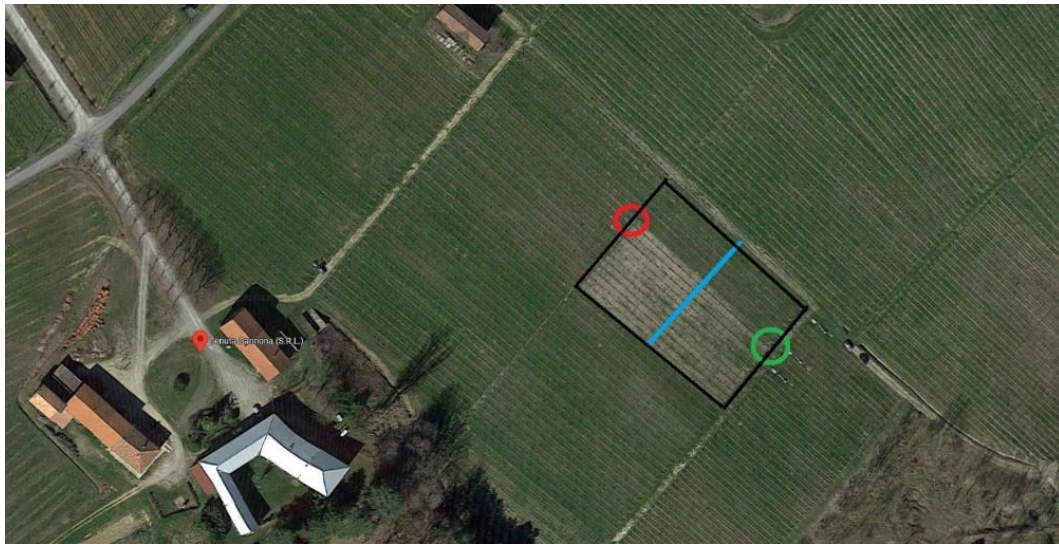


Figure 99: Vineyards at Tenuta Cannona (Agrion) where the instrumentation has been installed: the experimental plot area is marked in black, the instrument location in red, the weather station location in green, and the soil moisture sensor locations in blue. The buildings visible on the left are Tenuta Cannona (image processed from Google Earth).

Figure 99 shows the chosen location for the instrument and the positions of other sensors already present in the field. The instrument should be mounted on a pole at a height varying between 1.5 and 2 meters. The installation kit provided included the instrument and battery already housed in the protective box, brackets for attaching the box to a pole, and a solar panel with its mounting brackets and connecting cable. The installation was carried out (Figure 100 and 101) by positioning a two-part extendable pole of 2 meters, inserting the base of the pole into a stake driven into the ground. The upper part of the pole was secured with metal wire to an existing concrete pole. Subsequently, the box and solar panel were mounted using the provided brackets. Connecting the solar panel proved complex due to a connector that did not fit through the designated hole in the box. It was necessary to remove the connector, pass the cable through the hole, and reassemble everything. This issue was reported to the instrument manufacturer. The instrument was already configured, so after turning it on, it was sufficient to verify that the data were being transmitted to the dedicated server managed by DIST.



Figure 100: Instrument and solar panel installed on the pole (a) and with the protective box open (b).

Due to power issues encountered during the winter, caused by prolonged periods of lack of sunlight due to fog or persistent clouds, the solar panel was replaced with a higher power one. An external battery with greater capacity was

installed, along with a charge controller suitable for managing the increased power of the system. This controller also shuts off the instrument's power if the battery runs low, to preserve it by preventing complete discharge.



Figure 101: Position of the instrument viewed from the headland path downstream of the monitored plot.

Calibration, corrections, and quality control.

The CRNS deployment was treated as a calibration platform to ensure that raw neutron counts could be translated into spatially representative soil moisture for the vineyard footprint. Site-specific calibration followed established COSMOS/COSMOS-Europe protocols via a spatially weighted gravimetric sampling campaign across the sensor footprint, accounting for bulk density and soil water content, weights reflected the footprint sensitivity so that proximal samples contributed more strongly than peripheral ones. These steps are essential to convert corrected counts into volumetric water content with minimal bias at the field–hillslope support relevant to the vineyard.

Standard physical corrections were applied to the neutron signal prior to conversion, including barometric pressure and incoming-flux adjustments, as well as humidity effects in the air column. Together, calibration and corrections reduce systematic errors and improve comparability with in-situ probes and satellite/reanalysis products. Quality control combined automated flagging and cross-checks. Time bases were harmonized, and daily means (with a 24-h moving average) were compared against shallow sensors at 10–20 cm depth and evaluated with standard statistics, while interpretation was framed against site-specific field capacity and wilting-point thresholds to express soil water availability in agronomic terms. This calibration-and-QC framework underpins two objectives of the study: first, to clarify under which hydro-meteorological regimes the CRNS best represents near-surface versus deeper soil-water dynamics in a structurally complex vineyard; second, to provide a robust benchmark for integrating heterogeneous point measurements and bias-conditioning satellite/reanalysis soil-moisture products at decision-relevant scales. As the multi-season dataset grows, periodic recalibration or verification after major land-cover or management changes will help maintain transferability and reduce uncertainty in inter-annual comparisons.

First results were presented at some international conferences and are summarized in the following sections: EGU, section 3.4.3; IUSS, section 3.4.4; AISAM, section 3.4.5.

3.4.3 Cosmic Rays Neutron Sensing for soil moisture monitoring in vineyard with variable soil conditions

Precipitation measurements during the study period, compared with records spanning over 20 years, indicate that 2023 was very dry, with a Standardized Precipitation Index (SPI) lower than -1 for most of the year. In contrast, 2024 was increasingly wet, except for the first two months (Figure 102).

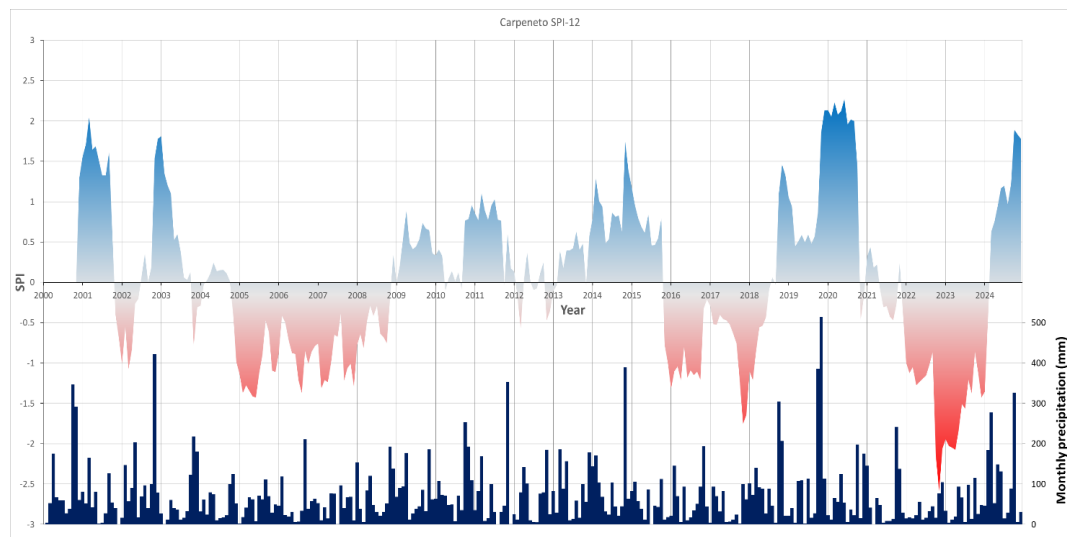


Figure 102: The 12-month SPI index calculated using monthly rainfall values (blue histograms) recorded at the Carpeneto site over the 25 years from 2000 to 2024. Positive values greater than 1 indicate wet periods (light blue) or extremely wet periods if greater than 2 (blue). Negative values less than -1 indicate dry periods (pink) or extreme drought if less than -2 (red).

Available soil moisture data from CRNS and sensors (Figure 103) were averaged daily using a 24-hour moving average and compared until autumn 2024. The comparison utilized statistical indexes such as the Nash-Sutcliffe Efficiency (NSE), Root Mean Square Error (RMSE), and the coefficient of determination (R^2) of the linear regression. The analysis was conducted separately for the two years, which were classified as dry and wet, respectively.



Figure 103: Precipitation (hourly and cumulative), hourly Soil Water Content (SWC) measured by CRNS, and superficial sensors (depth 10 cm) during the observation period.

Statistics showed that in the last 5 months of 2023 (dry period) there was a good agreement of soil moisture values measured by sensors between 10 and 20 cm of depth with both soil management practices. The best results were reported in the middle of the GC inter-row at a depth of 20 cm ($R^2=0.913$, $NSE=0.756$, $RMSE=0.25$). In contrast, the results for 2024, a wetter year, showed great variability in the values recorded by the sensors, with unsatisfactory statistics. The best values for the indexes were obtained for the sensor placed in the middle of the CT inter-row ($R^2=0.598$, $NSE=0.485$, $RMSE=0.118$).



Figure 104: Comparison of the daily average Soil Water Content (SWC) obtained from point capacitive sensors and CRNS (best performing sensors).

Thus, during the dry period, the CRNS probe provided reliable information on soil moisture conditions in the most superficial layer, regardless of the vineyard's soil management practices (Figure 104). Conversely, the difficulty in achieving good agreement in wet conditions can be attributed to the high spatial variability of soil moisture both horizontally and in-depth, soil saturation, ponding, and varying soil conditions (e.g., soil density) due to soil management and tractor traffic during the growing season. Preliminary results indicate that estimating moisture in vineyards varies with soil management and is particularly challenging when soil moisture is highly variable due to frequent rainfall and complex water dynamics. However, the results are encouraging, especially in critical conditions during dry seasons.

3.4.4 Large-scale, real-time monitoring of Soil Moisture dynamics with Cosmic Rays

Enrico Gazzola¹, Stefano Gianessi¹, Stefano Ferraris², Alessio Gentile², Francesca Ragazzi³, Silvia Obber³, Stefano Fogarin³, Giorgio Capello^{2,4}, Marcella Biddoccu⁴, Davide Gisolo², Alessandro Pirola⁵, Cinzia Alessandrini⁵

¹Finapp srl; ²DIST; ³ARPA Veneto, Unità Organizzativa Qualità del Suolo; ⁴CNR-STEMS; ⁵ARPAE Emilia-Romagna

Introduction

The availability of water resource in a soil is regulated by texture and structure of the soil itself. Establishing the expected dynamic boundaries of the water reservoir can be challenging due to the natural complexity of the soil, which can exhibit significant variability even within small areas. A solution to this issue is Cosmic-Rays Neutron Sensing (CRNS). It offers the capability to monitor the actual soil moisture dynamics of an entire field year-round, using a single non-invasive sensor. Importantly, CRNS averages over soil variability, positioning itself at a spatial scale that bridges the gap between point measurements and satellite data¹. Information obtained by CRNS can be integrated with other techniques such as point-scale measurements, sampling campaigns and satellites passes. When combined with pedological knowledge of the sites, this provides a more comprehensive and reliable picture of soil moisture dynamics at different scales. This approach enhances our understanding of soil water resources and informs better management strategies.

Finapp CNRS network

CRNS is based on the detection of neutrons, particles naturally flowing from space and strongly interacting with water molecules. The rate of neutron counts by a detector placed above ground is correlated to the water content in the soil within a volume spanning up to a dozen hectares extension and up to 50 cm depth. Finapp has developed and patented a light and compact detector suitable for CRNS applications on field. Eight Finapp probes in Northern Italy have been included in this study. They include, among others, a forest site, a mountain site and the ARPAE network of 4 probes (Figure 105).

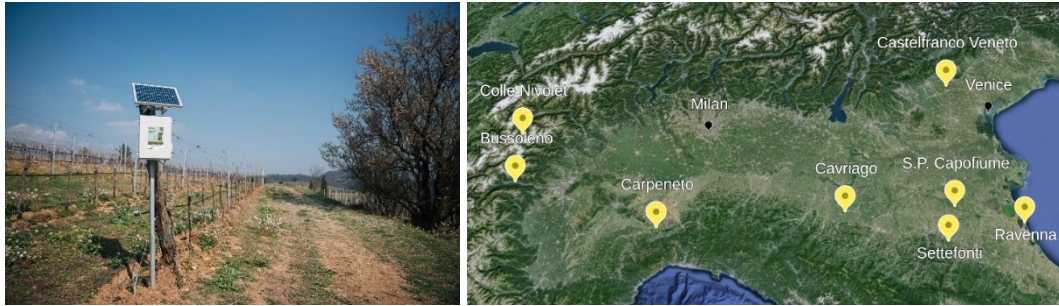


Figure 105: On the left, the CRNS applications in the field; on the right, the position of the network.

Comparison with point probes in a complex site

The Finapp CRNS probe, located at the Tenuta Cannona site (Carpeneto, AL), encompasses various plots of a vineyard within its footprint. These include a Grass Cover (GC) plot and a Conventional Tillage (CT) plot, where Volumetric Water Content (VWC) is locally monitored by sets of point-scale probes. The footprint also covers areas of Alternative Cover Crop.

The VWC trends registered by the punctual sensors shows a high variability between the plots. The areal CRNS data seems to align better with one or another point trend during different periods.

CRNS captures the VWC dynamic of a large area. This can be assessed through a distributed soil sampling campaign (represented by yellow points in the scheme of figure 106) and applying a weighted average of the VWC values of the collected known volume samples (campaign results are represented by the magenta triangle in the plot of figure 106).

The expected hydrological dynamical range for the site is reported in terms of Wilting Point and Field Capacity thresholds (dashed lines in the plot of figure 106).

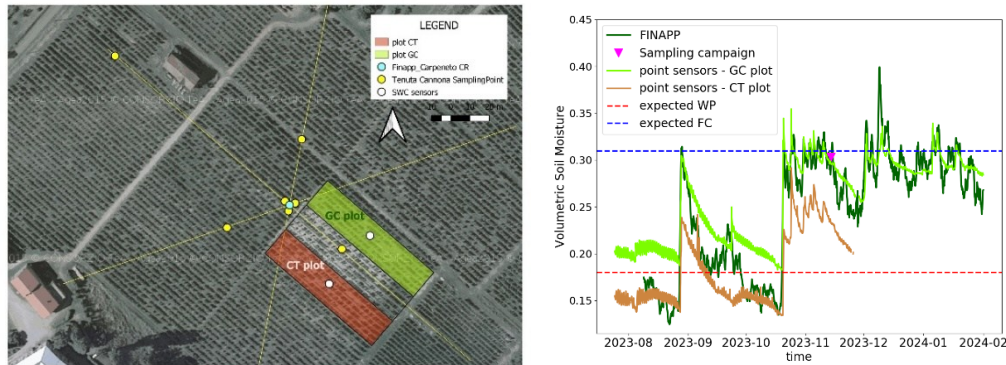


Figure 106: On the left, the Finapp CRNS probe located at the Tenuta Cannona site (Carpeneto, AL). The red area represents the tilled plot, the green area represents the permanent grass cover plot, the green dot indicates the position of the CRNS, the yellow dots are the sampling points for calibration, and the white dots are the positions of the point scale probes. On the right, comparison of the daily average Soil Water Content obtained from point capacitive sensors (light green and orange) and CRNS (dark green). The sampling campaign (purple triangle), wilting point, and field capacity thresholds (dashed lines) are also indicated.

Assessment with ERA5-Land and SMAP

The VWC measured from CNRS at all the sites is compared with estimations from satellite-based data of SMAP² and ERA5-Land³ (having spatial resolution of approximately 9 km) in order to assess how it can be representative of a wider area (Figure 107).

Finapp dynamics are generally in agreement with satellite trends suggesting that the precipitation dynamics affecting a larger area (about 80 km²) are not significantly different from those affecting the CRNS footprint (hundreds of m²). This holds especially for the agricultural sites in the plains (all presented sites, except for Bussoleno and Nivolet).

In all the agricultural sites, Finapp values are halfway between ERA5-Land and SMAP. A general overestimation of VWC by ERA5-Land with respect to SMAP was already reported by Lal et al⁴ and needs further investigation.

Two sites appear as outliers: Colle del Nivolet (high-altitude mountain site, covered with snow during winter) and Bussoleno (rugged terrain covered by forest). In both sites the VWC by Finapp CRNS is in good agreement with point-scale capacitance probes (CPS) measurements.

In the Bussoleno site, both satellite-based trends report higher VWC compared to the local measurements. A decoupling between VWC values from ERA5-Land and SMAP in forested areas was already reported by Xing et al⁵. In addition, Lal et al⁴ found that the mismatch between SMAP and ERA5-Land is greater in highly vegetated areas, such as the Bussoleno forest.

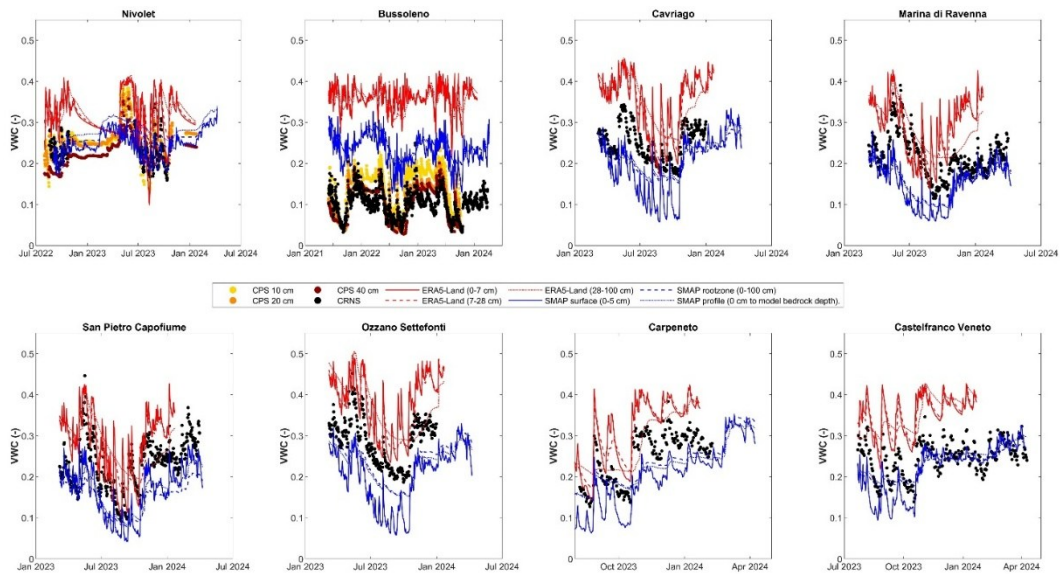


Figure 107: The VWC measured from CNRS at all the sites is compared with estimations from satellite-based data of SMAP² and ERA5-Land³.

Conclusions and perspectives

The comparison between point-scale measurements, CRNS and satellite data provides an insight into the relation between VWC measurements at different scales. Preliminary results from the Tenuta Cannona site highlight the differences between point VwC in differently managed lots and suggest that CRNS captures the prevalent dynamics. A larger scale representativity of Finapp data emerges in most sites and opens to the promising possibility of using them as ground reference to improve satellite-based products, especially in the challenging case of forestry sites.

Bibliography

1 S. Gianessi et al. (2024), Testing a novel sensor design to jointly measure cosmic-ray neutrons, muons and gamma rays for non-invasive soil moisture estimation. *Geosci. Instrum. Method. Data Syst.* 13, 9–25

2 R. Reichle et al. (2022). SMAP L4 Global 3-hourly 9 km EASE-Grid Surface and Root Zone Soil Moisture Analysis Update, Version 7 [Data Set]. <https://doi.org/10.5067/>. Date Accessed 04-15-2024

3 ERA5-Land monthly averaged data from 1950 to present. doi:10.24381/cds.68d2bb30

4 P. Lal et al. (2022), Assessment of ERA5-Land Volumetric Soil Water Layer Product Using In Situ and SMAP Soil Moisture Observations, IEEE Geosci. Remote Sens. Lett. 19: 1–5

5 Z. Xing et al. (2023), Assessment of 9 km SMAP soil moisture: Evidence of narrowing the gap between satellite retrievals and model-based reanalysis. Remote Sens. Environ. 296, 113721

3.4.5 Monitoring Soil Moisture dynamics by Cosmic Rays Neutron Sensing: a demo network in Northern Italy

Enrico Gazzola¹, Stefano Gianessi¹, Stefano Ferraris², Silvia Obber³, Francesca Ragazzi³, Stefano Fogarin³, Cinzia Alessandrini⁴, Alessandro Pirola⁴, Daniele Andreis⁵, Fabio Zotte⁵, Christian Ronchi⁶, Roberto Cremonini⁶, Secondo Barbero⁶, Giorgio Capello^{2,7}, Marcella Biddoccu⁷, Luca Stevanato¹

¹ Finapp srl; ² DIST; ³ ARPA Veneto, Unità Organizzativa Qualità del Suolo; ⁴ ARPAE Emilia-Romagna, Servizio Osservatorio Clima; ⁵ Centro di Trasferimento Tecnologico, Fondazione Edmund Mach; ⁶ ARPA Piemonte; ⁷ STEMS-CNR.

Abstract

Cosmic Rays Neutron Sensing offers the ability to obtain a continuous measurement of Soil Moisture value representative of an area of dozens of hectares through a single non-invasive sensor. Experiences from UK and other countries underscore the merits of a coordinated network of such probes, enabling the issuance of national or supranational scale bulletins with which to assess climate trends and the distribution of the impact of extreme events and improve the water resource quantification and management. We harmonized datasets from 9 Italian CRNS probes owned by different institutions to show how they can be effectively treated as a valuable network, in the first demo at this scale in Italy.

Acknowledgments

We acknowledge CMS Tres and CAVIT for the permission of using data from their probes and Agrion for the positioning of the probe in the Carpeneto experimental vineyard.

Funding declaration

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COI declaration

The authors Enrico Gazzola, Stefano Gianessi and Luca Stevanato are employed in the company manufacturing the sensors used for this research.

Data availability declaration

CRNS datasets are available from the authors upon reasonable request. ArCIS datasets are distributed under CC 4.0 license and can be retrieved from www.arcis.it with free registration. Rainfall datasets can be retrieved from ARPAE Emilia-Romagna (<https://simc.arpae.it/dext3r/>), ARPA Veneto (<https://www.ambienteveneto.it>), ARPA Piemonte, (<https://www.arpa.piemonte.it/rischinaturali/accesso-ai-dati/Richieste-dati-formato-standard/richiesta-dati/Richiesta-automatica/Dati-meteo-orari.html>) and MeteoBrowser Sud-Tirol (http://meteobrowser.eurac.edu/app_direct/meteobrowser/)

Introduction

Cosmic-Rays Neutron Sensing (CRNS) has emerged among proximal sensors as a valuable technique for non-invasive Soil Moisture (SM) estimation at a scale much larger than the usual point-scale sensors and at sub-daily resolution (Desilets et al 2010; Zreda et al 2008; Boga et al 2015). It has therefore increasingly gained importance in hydrological observations in agriculture and various kind of natural environments (Ochsner et al 2013; Rivera Villarreyes et al 2011; Coopersmith et al 2014; Zhu et al 2016; Heidbüchel et al 2016), as well as expanding its range of applications to the measurements of another key hydrological variable, snow water equivalent (Schattan et al 2017; Howat et al 2018), and possibly even biomass (Baroni and Oswald 2015; Jakobi et al 2022). The CRNS method is now widely used by research institutions and agencies around the world (Andreasen et al 2017) and some nation-wide CRNS soil moisture networks under the acronym of COSMOS have been established first in the United States and then in other nations, most notably the United Kingdom (Evans et al 2016). More recently, the community pushed for the establishment of a similar network across Europe (Boga et al 2022), while the presence of such sensors in Italy was still very limited. During the last couple of years, an increasing number of CRNS probes manufactured by Finapp have been installed in Northern Italy by the regional agencies for environmental protection (ARPA) and research institutions. We therefore explore how the sharing of data and the harmonization of a set of probes into an effective CRNS network can provide valuable information for a large-scale monitoring of SM dynamics in response to meteorological events and in relation to the characteristics of the soil.

Materials and Methods

CRNS is based on the detection of neutrons, particles naturally flowing from space and capable of penetrating the soil before being scattered back and reaching the detector. As neutrons strongly interact with the nucleus of hydrogen, their counting rate by the CRNS probe is correlated to the amount of hydrogen pools in and above the ground, like moisture, snow and organic matter. The signal detected by the probe placed above-ground is spontaneously averaged over an area of several hectares horizontally and some decimeters below ground (Schrön et al 2017) and it can record data with a temporal resolution of the order of hours. This poses it in an intermediate scale in between point-scale measurements and satellite passes, providing an averaged soil moisture data representative of heterogeneous pedological situations (Figure 108-left). The traditional technology for a CRNS detector was based on proportional gas tubes filled in with helium-3 or boron trifluoride, but nowadays new technologies are available which are based on solid scintillator materials, with the advantage to be cheaper and safer (Peerani et al 2012; Cester et al 2016). Thanks to the flexibility with which scintillator sheets can be produced and manipulated, in 2018 Finapp created a new kind of light and compact CRNS detector (Stevanato et al 2019), an example of which is shown in Figure 108-right. The Finapp detector comes with the unique feature of being able to contextually measure the flux of another particle, muons, useful to monitor the incoming cosmic rays flux (Stevanato et al 2022). During the years it was further improved and widely deployed on field (Gianessi et al 2024). We here present a demo network including 9 Finapp probes distributed across Northern Italy, mostly owned by Regional Environmental Protection Agencies (ARPA). In particular, 4 are located in monitoring sites managed by ARPAE-Emilia Romagna, one by ARPA-Piemonte, one by ARPA-Veneto, one by the CNR-STEMS Institute of Turin and two by the CMF Tres and CAVIT consortium. All probes were calibrated by gravimetric soil sampling campaign according to the standard sampling scheme and applying a weighted average of the samples SM (Schrön et al 2017). Neutrons data were processed by applying the standard pressure correction as in Bogen et al 2022 and the muons-based incoming flux correction as in Stevanato et al 2022, then the SM was calculated with the conventional formula from Desilets et al 2010:

$$SM(n) = \left(\frac{0.0808}{\frac{n}{N_0} - 0.372} - 0.115 \right) \cdot \rho_b$$

Where N_0 represents the neutron counts under dry conditions and is obtained by the calibration campaign, ρ_b the bulk density of the soil and n is neutrons counts.



Figure 108: On the left scheme of the CRNS footprint, on the right the Finapp probe installed in a vineyard.

Results and discussion

Soil water resource availability is regulated by soil features such as texture, structure, stones and organic content. It is common to define the boundaries of the available water reservoir in a soil as the amount of Volumetric Soil Moisture between a lower threshold called Wilting Point (WP) and an upper threshold called Field Capacity (FC), that can be estimated basing on clay and sand content by means of pedotransfer functions (PTF) (Dobarco et al 2019). When comparing different soils, it's therefore important to relate the measured SM to the site-specific thresholds to obtain a fair indication of a possible dry condition. For this reason, our 9 test sites were classified into three groups based on soil surface texture: Sandy Loam (SL), Loamy (L), and Clay/Silt Loam (CL). In Figure 109 the volumetric soil moisture trends registered by the 9 Finapp probes divided into the 3 groups are reported. For each group, a WP and a FC were estimated through commonly used PTF supported by an historical knowledge of the site dynamics and represented by the red and blue horizontal lines in the graphs, respectively. This way the temporal trend of the water reservoir status can be promptly appreciated for each site, capturing the dominant dynamics on a wide area.

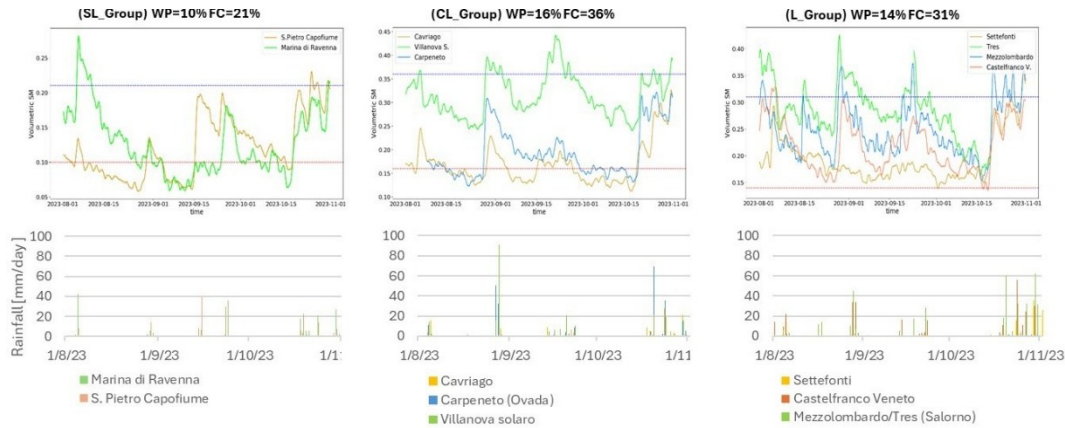


Figure 109: SM signals recorded in all sites, grouped by soil textural classes, along with daily rainfall (retrieved from ARPAE Emilia-Romagna, ARPA Veneto and ARPA Piemonte weather stations and MeteoBrowser Sud-Tirol).

Complementary to the temporal information, reported in the plots of Figure 109, is the spatial information that can be obtained by capturing the daily values from the whole network and reporting them on a map. In order to provide a significant picture of the water resource status, the nature of the reference soils need to be kept into account. Inspired by the COSMOS-UK approach, we do this by relating the measured SM to the capacity of each specific soil, defined as the difference between the FC and the WP for that soil: the reservoir is empty when $SM = WP$ and is full when $SM = FC$. We defined a 5-levels scale for the water availability status and reported in Figure 110 demo maps for two checkpoint days of choice, namely before and after a significant rain event which brought relief to soils after a dry period. Maps of the cumulative rainfalls correlated to the described situations are also reported, obtained from the ArCIS (Climatological Archive for Central–Northern Italy) as described in Pavan et al 2019. It can be seen how the first part of August 2023 was generally characterized by poor rainfalls, leading to the hydrological suffering of most of Northern Italy revealed by the SM status on the first checkpoint (August 20th). Just before the second checkpoint on August 30th, diffused rainfalls brought a significant improvement of the cumulative values and relief to the water reservoir in most sites. The two checkpoints therefore represent the transition from a generally dry condition to a generally wet condition. It can be observed how not only different regions were differently affected by the transition, but the resulting SM can have a very different significance depending on the soil type, for example a measured SM of 14% being considered a critically dry condition for a CL soil but a good reserve in a SL soil.

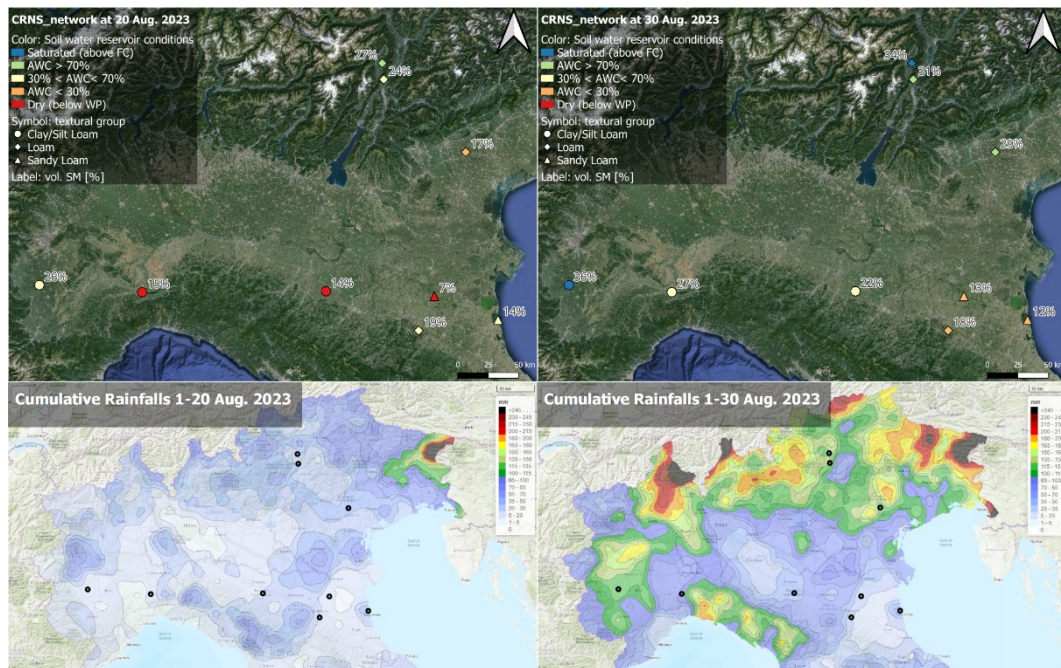


Figure 110: The upper panels report an overview of the CRNS network in two checkpoint days, Aug. 20th and Aug. 30th, 2023, representing the water reservoir status. The point shape indicates the soil textural class, the color represents soil water availability, while the label expresses the average absolute value of volumetric SM (%) recorded the CRNS probes during the specified day. The lower panels show cumulative rainfalls obtained from the ArCIS (Climatological Archive for Central–Northern Italy) for the periods of August 1st to 20th and 1st to 30th. ArCIS is a gridded precipitation dataset (5 km × 5 km) with daily temporal resolutions, obtained by validating and interpolating data from more than 1700 rain-gauges belonging to different networks, as detailed in Pavan et al 2019.

This demo highlights the added value that a CRNS network can provide to large-scale environmental monitoring. Agricultural issues such as water availability, either floods or drought risk, meteorological event effects, can be effectively managed by such a network data collection. Some similar hydrological responses among sites even at a relatively large distance suggest the effectiveness of a network with a realistically achievable number of CRNS in Northern Italy, as long as the main pedo-climatic and geomorphological differences among sites in different environments are kept into account. If sites are strategically chosen according to main soil types and main land uses, CNRS information can be spread to wider homogeneous areas. This would support the emission of bulletins which would be helpful to decision-makers concerning, for example, temporary limitations on the use of water or interventions for flood prevention. Intercalibration

and interpolation with satellite scans can assess and expand the spatial representativity over larger areas; further analyses are being done in this regard.

Summary and conclusions

The measurement of SM is strategic at various levels, from the evaluation of the need of irrigation of a single field to the assessment of the impact of climatic events at the national or even continental level. The spatial and temporal scale gap between point-scale probes and satellites can be filled by novel proximal sensors, among which CRNS is knowing a growing diffusion. In fact, CNRS allows sampling frequencies comparable with point sensors, and spatial support comparable with satellite pixels. While national networks of CRNS probes are already established in various countries, Italy is lagging behind, with a delay that recently started to be settled thanks to the installation of a significant number of Finapp probes in Northern Italy and more to come in the rest of the country. Networks of CRNS probes for the measurement of soil moisture and snow water equivalent would open to a manifold of applications, including the validation of remote sensing and computational models. On the field scale, the year-round monitoring of SM allows the observation of the real dynamics of water availability of a soil, enabling to understand its hydrological boundaries, which can be challenging to measure or model with other methods due to soil natural complexity and variability. On the wider scale, the network can highlight regional or soil-related differences in the response to meteorological events. The authors call for an expansion of such networks in Italy especially under the management of the Regional Environmental and Prevention Agencies and a harmonization of the data processing. Integration and data sharing into interregional or even international networks would be beneficial.

References

- Andreasen M, Jensen KH, Desilets D, Franz TE, Zreda M, Bogen HR, Looms MC (2017). Status and perspectives on the cosmic-ray neutron method for soil moisture estimation and other environmental science applications. *Vadose Zone J.* 16(8): 1–11. <https://doi.org/10.2136/vzj2017.04.0086>
- Baroni G, Oswald SE (2015) A scaling approach for the assessment of biomass changes and rainfall interception using cosmic-ray neutron sensing. *J. Hydrol.* 525: 264–276. <https://doi.org/10.1016/j.jhydrol.2015.03.053>
- Bogen HR, Huisman JA, Güntner A, Hübner C, Kusche J, Jonard F, Vey S, Vereecken H (2015) Emerging methods for noninvasive sensing of soil moisture dynamics

from field to catchment scale: a review. *Wiley Interdisciplinary Reviews Water* 2: 635–647. <https://doi.org/10.1002/wat2.1097>

Bogena HR, Schrön M, Jakobi J, Ney P, Zacharias S, Andreasen M, Baatz R, Boorman D, Duygu MB, Eguibar-Galán MA, Fersch B, Franke T, Geris J, González Sanchis M, Kerr Y, Korf T, Mengistu Z, Mialon A, Nasta P, Nitychoruk J, Pisinaras V, Rasche D, Rosolem R, Said H, Schattan P, Zreda M, Achleitner S, Albentosa-Hernández E, Akyürek Z, Blume T, del Campo A, Canone D, Dimitrova-Petrova K, Evans JG, Ferraris S, Frances F, Gisolo D, Güntner A, Herrmann F, Iwema J, Jensen KH, Kunstmann H, Lidón A, Looms MC, Oswald S, Panagopoulos A, Patil A, Power D, Rebmann C, Romano N, Scheiffelle L, Seneviratne S, Weltin G, Vereecken H (2022) COSMOS-Europe: a European network of cosmic-ray neutron soil moisture sensors. *Earth Syst. Sci. Data* 14: 1125–1151. <https://doi.org/10.5194/essd-14-1125-2022>

Cester D, Lunardon M, Moretto S, Nebbia G, Pino F, Sajo-Bohus L, Stevanato L, Bonesso I, Turato F (2016) A novel detector assembly for detecting thermal neutrons, fast neutrons and gamma rays. *Nucl. Instrum. Methods* 830: 191–196. <https://doi.org/10.1016/j.nima.2016.05.079>

Coopersmith EJ, Cosh MH, Daughtry CST (2014) Field-scale moisture estimates using COSMOS sensors: A validation study with temporary networks and Leaf-Area-Indices. *J. Hydrol.* 519: 637–643. <https://doi.org/10.1016/j.jhydrol.2014.07.060>

Corradini C (2014) Soil moisture in the development of hydrological processes and its determination at different spatial scales. *J. Hydrol.* 516: 1–5. <https://doi.org/10.1016/j.jhydrol.2014.02.051>

Desilets D, Zreda M, Ferré TPA (2010). Nature's neutron probe: Land surface hydrology at an elusive scale with cosmic rays. *Water Resour. Res.* 46: W11505. <https://doi.org/10.1029/2009WR008726>

Dobarco MR, Cousin I, Le Basa C, Martina MP (2019). Pedotransfer functions for predicting available water capacity in French soils, their applicability domain and associated uncertainty. *Geoderma* 336: 81–95. <https://doi.org/10.1016/j.geoderma.2018.08.022>

Evans JG, Ward HC, Blake JR, Hewitt EJ, Morrison R, Fry M, Ball LA, Doughty LC, Libre JW, Hitt OE, Rylett D, Ellis RJ, Warwick AC, Brooks M, Parkes MA, Wright GMH, Singer AC, Boorman DB, Jenkins A (2016) Soil water content in southern England derived from a cosmic-ray soil moisture observing system – COSMOS-UK. *Hydrol. Proc.* 30: 4987–4999. <https://doi.org/10.1002/hyp.10929>

Gianessi S, Polo M, Stevanato L, Lunardon M, Francke T, Oswald SE, Ahmed HS, Toloza A, Weltin G, Dercon G, Fulajtar E, Heng L, Baroni G (2024) Testing a novel sensor design to jointly measure cosmic-ray neutrons, muons and gamma rays for non-invasive soil moisture estimation. *Geosci. Instrum. Method. Data Syst.* 13: 9–25. <https://doi.org/10.5194/gi-13-9-2024>

Heidbüchel I, Güntner A, Blume T (2016) Use of cosmic-ray neutron sensors for soil moisture monitoring in forests. *Hydrol. Earth Syst. Sci.* 20: 1269–1288. <https://doi.org/10.5194/hess-20-1269-2016>

Howat IM, de la Peña S, Desilets D, Womack G (2018) Autonomous ice sheet surface mass balance measurements from cosmic rays. *Cryosphere* 12: 2099–2108. <https://doi.org/10.5194/tc-12-2099-2018>

Jakobi J, Huisman JA, Fuchs H, Vereecken H, Bogen H (2022) Potential of Thermal Neutrons to Correct Cosmic-Ray Neutron Soil Moisture Content Measurements for Dynamic Biomass Effects. *Water Resour. Res.* 58(8): e2022WR031972. <https://doi.org/10.1029/2022WR031972>

Ochsner TE, Cosh MH, Cuenca RH, Dorigo WA, Draper CS, Hagimoto Y, Kerr YH, Njoku EG, Small EE, Zreda M (2013) State of the Art in Large-Scale Soil Moisture Monitoring. *Soil Sci. Soc. Am. J.* 77: 1888. <https://doi.org/10.2136/sssaj2013.03.0093>

Pavan V, Antolini G, Barbiero R, Berni N, Brunier F, Cacciamani C, Cagnati A, Cazzuli O, Cicogna A, De Luigi C, Di Carlo E, Francioni M, Maraldo L, Marigo G, Micheletti S, Onorato L, Panettieri E, Pellegrini U, Pelosini R, Piccinini D, Ratto S, Ronchi C, Rusca L, Sofia S, Stelluti M, Tomozeiu R, Malaspina TT (2019) High resolution climate precipitation analysis for north-central Italy, 1961–2015. *Clim. Dyn.* 52: 3435–3453. <https://doi.org/10.1007/s00382-018-4337-6>

Peerani P, Tomanin A, Pozzi S, Dolan J, Miller E, Flaska M, Battaglieri M, De Vita R, Ficini L, Ottonello G, Ricco G, Dermody G, Giles C (2012) Testing on novel neutron detectors as alternative to ^3He for security applications. *Nucl. Instrum. Methods* 696: 110–120. <https://doi.org/10.1016/j.nima.2012.07.025>

Rivera Villarreyes CA, Baroni G, Oswald SE (2011) Integral quantification of seasonal soil moisture changes in farmland by cosmic-ray neutrons. *Hydrol. Earth Syst. Sci.* 15: 3843–3859. <https://doi.org/10.5194/hess-15-3843-2011>

Schattan P, Baroni G, Oswald SE, Schöber J, Fey C, Kormann C, Huttenlau M, Achleitner S (2017) Continuous monitoring of snowpack dynamics in alpine terrain by above-ground neutron sensing. *Water Resour. Res.* 53: 3615–3634. <https://doi.org/10.1002/2016WR020234>

Schrön M, Köhli M, Scheiffle L, Iwema J, Bogen HR, Lv L, Martini E, Baroni G, Rosolem R, Weimar J, Mai J, Cuntz M, Rebmann C, Oswald SE, Dietrich P, Schmidt U, Zacharias S (2017) Improving calibration and validation of cosmic-ray neutron sensors in the light of spatial sensitivity. *Hydrol. Earth Syst. Sci.* 21: 5009–5030. <https://doi.org/10.5194/hess-21-5009-2017>

Stevanato L, Baroni G, Cohen Y, Fontana CL, Gatto S, Lunardon M, Marinello F, Moretto S, Morselli L (2019) A Novel Cosmic-Ray Neutron Sensor for Soil Moisture Estimation over Large Areas. *Agriculture* 9: 202. <https://doi.org/10.3390/agriculture9090202>

Stevanato L, Baroni G, Oswald SE, Lunardon M, Mares V, Marinello F, Moretto S, Polo M, Sartori P, Schattan P, Ruehm W (2022) An Alternative Incoming Correction for Cosmic-Ray Neutron Sensing Observations Using Local Muon Measurement. *Geophys. Res. Lett.* 49: e2021GL095383. <https://doi.org/10.1029/2021GL095383>

Zhu X, Shao M, Zeng C, Jia X, Huang L, Zhang Y, Zhu J (2016) Application of cosmic-ray neutron sensing to monitor soil water content in an alpine meadow ecosystem on the northern Tibetan Plateau, J. *Hydrol.* 536: 247–254. <https://doi.org/10.1016/j.jhydrol.2016.02.038>

Zreda M, Desilets D, Ferré TPA, Scott RL (2008) Measuring soil moisture content non-invasively at intermediate spatial scale using cosmic-ray neutrons. *Geophys. Res. Lett.* 35: L21402. <https://doi.org/10.1029/2008GL035655>

3.4.6 Conclusions and Perspectives

Cosmic-Ray Neutron Sensing (CRNS) proved to be a valuable addition to the Tenuta Cannona monitoring infrastructure by providing non-invasive, near-real-time soil moisture estimates representative of an intermediate spatial support, thereby bridging the scale gap between point probes and satellite products. The installation upstream of the experimental plots enabled comparisons with existing capacitance sensors and ancillary observations, highlighting both the potential and the limitations of areal averaging in a structurally complex vineyard system characterized by heterogeneous soils and contrasting inter-row management. Initial results highlight a contrasting CRNS performance between the dry (2023) and wet (2024) periods, an aspect that warrants further investigation to clarify the roles of seasonal hydrological dynamics and spatial heterogeneity in shaping the agreement with point-scale probes. Continued monitoring is expected to provide additional events and a broader range of conditions, enabling more robust analyses and inter-annual comparisons under comparable meteorological regimes, ultimately strengthening the interpretation and transferability of CRNS-derived soil moisture signals in complex vineyard settings.

Future work will prioritize a deeper exploitation of the existing and forthcoming CRNS time series to strengthen the robustness of the current evidence, explicitly quantify uncertainty, and determine the hydro-meteorological conditions under which CRNS best represents vineyard soil water dynamics. This will be supported by improved site-specific calibration/validation (targeted gravimetric campaigns and refined corrections) and by a systematic assessment of vegetation/biomass and other hydrogen pools that may affect the neutron signal in perennial cropping systems. A central perspective is to leverage CRNS as a scale-appropriate benchmark to reconcile heterogeneous point observations and evaluate satellite/reanalysis soil-moisture products; where feasible, harmonized multi-site networks would further enhance representativeness and the value of CRNS for improving operational monitoring and modelling.

3.5 Comparative Perspectives on Proximal Sensing in Vineyards

Taken together, W-band radar, CRNS, and scintillometer provide complementary information on the Soil–Plant–Atmosphere system at spatial scale that are difficult to obtain with conventional monitoring alone, thereby improving the realism of model inputs and calibration/validation opportunities. In practice, however, their role differs markedly when judged against operational constraints of cost, maintenance, and specialist expertise, and against the type of decision support needed at farm level: given acquisition and operation costs as well as processing requirements, these sensors are only regarded as research-grade observatories rather than routine farm tools, with highest value in deriving transferable parameters, proxy indicators, and mechanistic understanding that can later be driven by more accessible measurements. This research function is relevant not only at field scale but also at hillslope scale, where their native spatial support - field/slope rainfall microphysics from W-band, multi-hectare soil-moisture footprints from CRNS, long-path sampling for energy fluxes from scintillometry - matches the scales at which runoff, erosion, and surface–atmosphere exchange heterogeneity emerge.

In our study, the W-band radar retrieved microphysical descriptors (e.g., drop-size distributions, kinetic energy) that improved the interpretation, and in preliminary models the prediction, of runoff and erosion beyond traditional rain totals and intensities, thereby offering a concrete route to parameterize process-based models at plot and slope scales.

The CRNS installation bridged the gap between point probes and satellite/reanalysis products by delivering footprint-integrated soil-moisture dynamics; despite contrasting performance across dry and wet periods that merits further investigation, its behavior and network analyses indicate strong potential as a benchmark layer for integrating heterogeneous point observations and for evaluating gridded soil-moisture products at decision-relevant scales.

The optical–microwave scintillometer targets turbulent fluxes and evapotranspiration at a horizontal scale close to remote sensing, but in a vineyard it remains technically demanding and sensitive to installation geometry; in this experimental deployment, data quality was not uniformly reliable. Nonetheless, analyses of valid periods and comparisons with CLM indicate strong potential: with adequate resources, a higher beam path (taller supports, greater clearance from

near-ground obstacles) would likely yield more stable signals, making scintillometry a valuable research-grade reference for model evaluation and scaling.

Transferring these research-grade insights into affordable operational workflows is feasible by calibrating once and operating many with low-cost networks. For rainfall, relationships established between radar-derived kinetic energy or energy-weighted drop diameters and simple gauge-based descriptors (e.g., short-window intensities, EI30) can be embedded into runoff/erosion thresholds and then driven in real time by tipping-bucket gauges complemented by weather-forecast products. For soil moisture, CRNS inferred volumetric water content can be framed in terms of available water between field capacity and wilting point and then scaled to low-cost probes to produce site-specific antecedent moisture indices. The same CRNS baseline can be used to bias-condition satellite and reanalysis soil-moisture fields (e.g., SMAP, ERA5-Land) and generate operational soil water content maps for irrigation, field accessibility, and hydrological conditioning at hillslope scale. For evapotranspiration, valid scintillometry windows can be exploited to tune crop coefficients, or CLM parameter sets, after which daily ET can be produced from a standard meteorological station (radiation, humidity, wind). Where resources allow, future research installations should prioritize higher beam paths to stabilize signals and further strengthen the calibration basis.

Beyond viticulture, these rainfall and soil-moisture-driven transfers are directly relevant to hydro-geomorphic risk: calibrated rainfall thresholds and antecedent moisture indices can be combined to flag short-lead-time windows of landslide and flash-flood susceptibility at slope or small basin scales. The same fused workflows (gauges, low-cost probes, operational radar/satellite) can inform nowcasting triggers and the conditioning of physics-based or data-driven risk models. In sum, while W-band radar, CRNS, and scintillometry are not economically suited to routine farm use, their research value at field and hillslope scales is precisely what enables robust downscaling to cost-effective, widely accessible monitoring and DSS pipelines for technicians and farmers.

Chapter 4

Conclusions

The comprehensive objectives outlined in this research have been successfully achieved, demonstrating that combining improved soil management with multi-scale monitoring and decision support leads to measurable and operationally relevant gains in the sustainability of hilly vineyards in North-West Italy. Across working farms, enhanced practices increased year-round soil cover, improved infiltration, limited machinery-induced compaction, and reduced both runoff and sediment export during high-intensity storms, thereby strengthening the resilience of vineyards to concurrent hydro-climatic stressors such as summer drought and cloudburst rainfall. The development of simple, actionable indices and their integration into an ICT platform further enabled timely scheduling of field operations under favourable soil moisture and trafficability conditions, limiting soil compaction, and ensuring operator safety, translating research outputs into everyday management decisions. The practical field demonstrations and training activities conducted have successfully transferred knowledge to winegrowers, other farms, and schools, showcasing the results and effects of good practices. The dissemination of a "Charter of Good Agricultural Practices" has provided guidelines for achieving better soil management and protection in wine-growing environments.

In light of the evidence consolidated during the research, the study recommends, as standard practice, maintaining permanent grass cover in all inter-rows, or at minimum alternating grassed and tilled rows when site constraints or vineyard age require a more adaptive approach. Permanent grassing consistently delivered the most favourable overall response, with higher soil protection, improved structural stability, and lower erosion risk under intense rainfall. When properly designed and managed, sown cover crops and green manure mixtures provide comparable protection, optimise bulk density, enhance deep soil moisture and hydraulic conductivity, and curb nutrient losses; they therefore constitute a robust, site-tunable complement to permanent grassing. Conversely, frequent and fine mechanical tillage proved detrimental, promoting surface pulverisation,

crusting, and elevated erosion, and should be avoided. Where structural remediation is strictly necessary, occasional deep loosening with implements that preserve the sod is preferable to repeated shallow operations. Under-vine management is best achieved through mechanical weeding rather than herbicides to sustain biological activity and long-term soil function, while mowing should be timed to preserve protective cover in case of high-intensity events and avoided when soils are wet to reduce compaction risk. In young plantings and in exceptionally dry seasons, temporary relaxation of cover (e.g., alternate-row strategies or drought-tolerant species mixes) can mitigate water competition without sacrificing the protective function of vegetation.

The second part of the thesis aimed to achieve concrete and measurable results by testing scientific and technological research products in real-world conditions. Through collaboration with companies experienced in agro-meteorological monitoring, innovative tools and technologies essential to bridge the gap between point measurements and field-to-landscape scale flux were introduced and validated. A key added value of this work is the integration of traditional point and field-based measurement technologies with advanced proximal sensing, which collectively improved the characterization of processes within the Soil–Plant–Atmosphere continuum. In particular, the three research-grade instruments deployed at Tenuta Cannona provided complementary information at scales that are typically not represented by standard farm monitoring. The W-band polarimetric radar enabled rainfall characterization beyond totals and intensities by retrieving microphysical descriptors (e.g., drop-size distribution, kinetic energy) at field/slope scale; these variables proved informative for interpreting runoff and erosion responses under different inter-row managements. The CRNS sensor filled the scale gap between point probes and satellite/reanalysis products by delivering footprint-integrated soil moisture dynamics; the contrasting performance observed between dry and wet periods emerged as a key research question, motivating further analyses and longer series to improve cross-year comparability under similar hydro-meteorological regimes. Finally, the optical–microwave scintillometer represented an innovative experimental installation in a vineyard, where data quality was not uniformly reliable; nevertheless, analyses of valid periods and comparisons with CLM simulations provided encouraging indications for future applications at the remote-sensing scale. Taken together, these instruments highlight a coherent pathway: although their cost and logistical demands currently restrict them to research contexts, they generate mechanistic insights and calibration/validation opportunities that can be transferred into improved models and more robust workflows relying on affordable sensors and operational products.

Overall, this thesis supports the conclusion that coupling good agronomic practices with multi-scale monitoring and decision support can improve both sustainability outcomes (soil protection and resource conservation) and operational efficiency, while simultaneously advancing scientific understanding needed to deliver reliable, widely accessible tools for precision management in complex viticultural landscapes.

I acknowledge that each strand (surveys/interviews, plot-scale measurements, sensor-based monitoring) could be expanded or further refined. However, part of the work was conducted within the framework of a larger operational project, with pre-defined guidelines, time windows, and deployment logistics that shaped the feasible methodological scope. Within these boundary conditions, the thesis prioritised robustness and triangulation: the mixed-methods social component reached thematic saturation with engaged practitioners; the physical monitoring delivered repeatable, instrumented comparisons under real farm operations; and the proximal sensing deployments established the foundation for future data releases and cross-scale integration. These choices balance depth, feasibility, and representativeness in a context of increasing stakeholder fatigue and practical constraints typical of commercial vineyard settings.

Future Work and Research Directions

Conducted under real operating conditions in commercial vineyards, this study faced practical and methodological limitations that inform the priorities for future research; accordingly, the following directions are proposed to consolidate evidence for climate-resilient, low-disturbance vineyard management by extending the temporal and spatial scope, strengthening proximal-sensing integration with process models, and validating DSS-enabled decisions under commercial constraints:

First, the temporal scope and replication across sites could be extended. Multi-year trends in soil organic matter, structural stability, and compaction relief typically emerge over longer horizons than the present monitoring period, and inter-annual climate variability (including clusters of dry years followed by high-intensity storms) can modulate treatment effects. Expanding the duration and increasing replication across contrasted textures, slopes, and climate sub-zones would improve inference power and the transferability of the recommended practices.

A second set of limitations concerns the limited instrument deployment window and event sampling: the time available to install and operate the proximal sensors was constrained, as well as the positioning, so analyses necessarily rely on the events that occurred within that window; a longer deployment would plausibly intercept more events and improve the robustness of intra-event runoff/erosion interpretation. Looking ahead, the CRNS - the only instrument still operating in the field - should undergo further calibration and systematic cross-comparison with both point-scale soil-moisture probes and satellite-derived products to refine scaling relationships and reduce bias.

Third, decision-support validation and adoption merit targeted research. While the DSS and indices developed here proved useful for scheduling operations under favourable soil moisture and access conditions, broader participatory trials are needed to test usability, alert fatigue, and integration with existing farm workflows. Comparative evaluations should quantify reductions in machine-induced compaction, avoided interventions in high-risk windows, and net economic returns under real constraints of labour, equipment, and compliance.

Fourth, agronomic and enological outcomes should be monitored in parallel with soil conditions. The results highlight that permanent grassing and well-designed cover crops are effective soil-protection strategies; future trials should quantify any yield and grape-quality trade-offs under different seasons, test drought-tolerant species mixtures, and calibrate adaptive regimes in young vineyards to manage water competition without losing protective function. Under-vine mechanical control should be benchmarked against alternative low-input options to optimise labour, energy use, and microbiome effects.

Finally, quantify broader environmental externalities and develop coupled carbon–water budgets by implementing a site-specific water balance with models that partition precipitation, evapotranspiration, soil-water storage and drainage; expanding runoff chemistry and sediment monitoring to include nutrient and pesticide export; undertaking carbon input/output accounting to resolve net sequestration under different groundcovers; and incorporating biodiversity indicators (soil fauna and flora) to capture co-benefits beyond erosion control. Coupling these measurements with policy-oriented cost–benefit analyses will support the scaling of best management practices across heterogeneous hilly landscapes.

Taken together, these steps will consolidate evidence for climate-resilient, low-disturbance vineyard management in North-West Italy and beyond by extending the temporal and spatial scope, strengthening the integration of proximal sensing with process models, and validating DSS-enabled decisions under commercial constraints.

References

- Abegeja, D. (2024). The application of satellite sensors, current state of utilization, and sources of remote sensing dataset in hydrology for water resource management. *Journal of Water and Health*, 22(7), 1162–1179. <https://doi.org/10.2166/wh.2024.102>
- Agrela, F., Gil, J. A., Giráldez, J. V., Ordóñez, R., & González, P. (2003). Obtention of reference value in the measurement of the cover fraction in conservation agriculture systems. In *II World Congress on Conservation Agriculture* (pp. 44-47). Foz de Iguazu, Brazil.
- Bagagiolo, G., Biddoccu, M., Rabino, D., & Cavallo, E. (2018). Effects of rows arrangement, soil management, and rainfall characteristics on water and soil losses in Italian sloping vineyards. *Environmental Research*, 166, 690–704. <https://doi.org/10.1016/j.envres.2018.06.048>
- Baroni, G., Facchi, A., Gandolfi, C., Ortuani, B., Horeschi, D., & van Dam, J. C. (2010). Uncertainty in the determination of soil hydraulic parameters and its influence on the performance of two hydrological models of different complexity. *Hydrology and Earth System Sciences*, 14, 251-270.
- Biddoccu, M., Guzman, G., Capello, G., Thielke, T., Strauss, P., Winter, S., Zaller, J. G., Nicolai, A., Cluzeau, D., Popescu, D., et al. (2020). Evaluation of soil erosion risk and identification of soil cover and management factor (C) for RUSLE in European vineyards with different soil management. *International Soil and Water Conservation Research*, 8, 337–353. <https://doi.org/10.1016/j.iswcr.2020.07.003>
- Biddoccu, M., Opsi, F., & Cavallo, E. (2014). Relationship between runoff and soil losses with rainfall characteristics and long-term soil management practices in a hilly vineyard (Piedmont, NW Italy). *Soil Science and Plant Nutrition*, 60, 92–99. <https://doi.org/10.1080/00380768.2013.862488>
- Bogena, H. R., Huisman, J. A., Güntner, A., Hübner, C., Kusche, J., Jonard, F., Vey, S., & Vereecken, H. (2015). Emerging methods for noninvasive sensing of soil moisture dynamics from field to catchment scale: A review. *WIREs Water*, 2, 635-647. <https://doi.org/10.1002/wat2.1097>
- Capello, G., Biddoccu, M., & Cavallo, E. (2020). Permanent cover for soil and water conservation in mechanized vineyards: A study case in Piedmont, NW Italy. *Italian Journal of Agronomy*, 15(4), 323–331. <https://doi.org/10.4081/ija.2020.1763>

Capello, G., Biddoccu, M., Ferraris, S., & Cavallo, E. (2019). Effects of tractor passes on hydrological and soil erosion processes in tilled and grassed vineyards. *Water*, 11(10), 2118.

Desilets, D., Zreda, M., & Ferré, T. P. A. (2010). Nature's neutron probe: Land surface hydrology at an elusive scale with cosmic rays. *Water Resources Research*, 46, W11505. <https://doi.org/10.1029/2009WR008726>

Fu, X., Zhang, Y., Wang, J., & Li, H. (2023). Effects of soil hydraulic properties on soil moisture estimation. *Journal of Hydrology*, 590, 125-134. <https://doi.org/10.1007/s13351-023-2049-2>

Gerlach, T. (1967). Hillslope troughs for measuring sediment movement. *Revue de Géomorphologie Dynamique*, 17(2), 173–174.

Giffard, B., Winter, S., Guidoni, S., Nicolai, A., Castaldini, M., Cluzeau, D., Coll, P., Cortet, J., Le Cadre, E., d'Errico, G., Forneck, A., Gagnarli, E., Griesser, M., Guernion, M., Lagomarsino, A., Landi, S., Le Bissonnais, Y., Mania, E., Mocali, S., Preda, C., Priori, S., Reineke, A., Rusch, A., Schroers, H.-J., Simoni, S., Steiner, M., Temneanu, E., Bacher, S., Costantini, E. A. C., Zaller, J., & Leyser, I. (2022). Vineyard management and its impacts on soil biodiversity, functions, and ecosystem services. *Frontiers in Ecology and Evolution*, 10, 850272. <https://doi.org/10.3389/fevo.2022.850272>

Granata, F., & Di Nunno, F. (2025). Pathways for hydrological resilience: Strategies for adaptation in a changing climate. *Earth Systems and Environment*. <https://doi.org/10.1007/s41748-024-00567-x>

Gruber, A., De Lannoy, G., Albergel, C., Al-Yaari, A., Brocca, L., Calvet, J.-C., Colliander, A., Cosh, M., Crow, W., Dorigo, W., Draper, C., Hirschi, M., Kerr, Y., Konings, A., Lahoz, W., McColl, K., Montzka, C., Muñoz-Sabater, J., Peng, J., Reichle, R., Richaume, P., Rüdiger, C., Scanlon, T., van der Schalie, R., Wigneron, J.-P., & Wagner, W. (2020). Validation practices for satellite soil moisture retrievals: What are (the) errors? *Remote Sensing of Environment*, 244, Article 111806. <https://doi.org/10.1016/j.rse.2020.111806>

Kayatz, B., Baroni, G., Hillier, J., Lüdtkke, S., Heathcote, R., Malin, D., van Tonder, C., Kuster, B., Freese, D., Hüttel, R., & Wattenbach, M. (2019). Cool Farm Tool Water: A global on-line tool to assess water use in crop production. *Journal of Cleaner Production*, 207, 1163-1179.

Lazcano, C., Decock, C., & Wilson, S. G. (2020). Defining and managing for healthy vineyard soils: Intersections with the concept of terroir. *Frontiers in Environmental Science*, 8, 68. <https://doi.org/10.3389/fenvs.2020.00068>

Loew, A., Bell, W., Brocca, L., Bulgin, C. E., Burdanowitz, J., Calbet, X., Donner, R. V., Ghent, D., Gruber, A., Kaminski, T., Kinzel, J., Klepp, C., Lambert, J.-C., Schaepman-Strub, G., Schröder, M., & Verhoelst, T. (2017). Validation practices for satellite-based Earth observation data across communities. *Reviews of Geophysics*, 55, 779–817. <https://doi.org/10.1002/2017RG000562>

McNider, R. T., Handyside, C., Doty, K., Ellenburg, W. L., Cruise, J. F., Christy, J. R., Moss, D., Sharda, V., Hoogenboom, G., & Caldwell, P. (2015). An integrated crop and hydrologic modeling system to estimate hydrologic impacts of crop irrigation demands. *Environmental Modelling & Software*, 72, 341-355.

Meshesha, D. T., Tsunekawa, A., & Haregeweyn, N. (2019). Influence of raindrop size on rainfall intensity, kinetic energy, and erosivity in a sub-humid tropical area: A case study in the northern highlands of Ethiopia. *Theoretical and Applied Climatology*, 136, 1221–1231. <https://doi.org/10.1007/s00704-018-2551-0>

Moriasi, D. N., Zeckoski, R. W., Arnold, J. G., Baffaut, C. B., Malone, R. W., Daggupati, P., Guzman, J. A., Saraswat, D., Yuan, Y., Wilson, B. W., Shirmohammadi, A., & Douglas-Mankin, K. R. (2015). Hydrologic and water quality models: Key calibration and validation topics. *Transactions of the ASABE*, 58(6), 1609-1618.

Panagos, P., & Katsoyiannis, A. (2019). Soil erosion modelling: The new challenges as the result of policy developments in Europe. *Environmental Research*, 172, 470-474.

Pôças, I., Cunha, M., Pereira, L. S., & Allen, R. G. (2013). Using remote sensing energy balance and evapotranspiration to characterize montane landscape vegetation with focus on grass and pasture lands. *International Journal of Applied Earth Observation and Geoinformation*, 21, 159-172. <https://doi.org/10.1016/j.jag.2012.08.017>

Proctor, R. (1933). Fundamental principles of soil compaction. *Engineering News-Record*, 111, 245–248, 286–289, 348–351.

Ran, Q., Wang, F., & Gao, J. (2019). Modelling effects of rainfall patterns on runoff generation and soil erosion processes on slopes. *Water*, 11(11), 2221. <https://doi.org/10.3390/w11112221>

Rozos, E., Dimitriadis, P., & Bellos, V. (2022). Machine learning in assessing the performance of hydrological models. *Hydrology*, 9(1), 5. <https://doi.org/10.3390/hydrology9010005>

Schönbrodt-Stitt, S., Ahmadian, N., Kurtenbach, M., Conrad, C., Romano, N., Bogen, H. R., & Nasta, P. (2021). Statistical exploration of SENTINEL-1 data, terrain parameters,

and in-situ data for estimating the near-surface soil moisture in a Mediterranean agroecosystem. *Frontiers in Water*, 3, 655837. <https://doi.org/10.3389/frwa.2021.655837>

Sehler, R., Li, J., Reager, J. T., & Ye, H. (2019). Investigating relationship between soil moisture and precipitation globally using remote sensing observations. *Journal of Contemporary Water Research & Education*, 168, 106–118. <https://doi.org/10.1111/j.1936-704X.2019.0321.x>

Singh, V. P. (2018). Hydrologic modeling: progress and future directions. *Geoscience Letters*, 5, 15. <https://doi.org/10.1186/s40562-018-0113-z>

Sridhar, V., Hubbard, K. G., You, J., & Hunt, E. D. (2008). Development of the Soil Moisture Index to quantify agricultural drought and its “user friendliness” in severity-area-duration assessment. *Journal of Hydrometeorology*, 9, 660–676. <https://doi.org/10.1175/2007JHM892.1>

Teweldebrhan, A. T., Burkhart, J. F., & Schuler, T. V. (2018). Parameter uncertainty analysis for an operational hydrological model using residual-based and limits of acceptability approaches. *Hydrology and Earth System Sciences*, 22, 5021–5039.

Unal, C., & van den Brule, Y. (2024). Exploring millimeter-wavelength radar capabilities for raindrop size distribution retrieval: Estimating mass-weighted mean diameter from the differential backscatter phase. *Journal of Atmospheric and Oceanic Technology*, 41, 583–603. <https://doi.org/10.1175/JTECH-D-23-0094.1>

Wang, H., Ma, Y., Yuan, W., Yang, H., Ye, H., Li, Y., & Guo, W. (2024). A comprehensive assessment of meteorological–hydrological indicator changes and their driving forces from a multi-temporal and spatial scale perspective. *Journal of Water and Climate Change*, 15(12), 5843–5866. <https://doi.org/10.2166/wcc.2024.412>

Zhang, Y., Li, X., & Wang, J. (2022). A review of integrated surface-subsurface numerical hydrological models. *Journal of Hydrology*, 603, 126–138. <https://doi.org/10.1007/s11430-022-1312-7>

Zreda, M., Desilets, D., Ferré, T. P. A., & Scott, R. L. (2008). Measuring soil moisture content non-invasively at intermediate spatial scale using cosmic-ray neutrons. *Geophysical Research Letters*, 35, L21402. <https://doi.org/10.1029/2008GL035655>