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

G. Capello, M. Biddoccu, S. Bussotti, E. Paravidino and E. Cavallo.
Institute of Sciences and Technologies for Sustainable Energy and Mobility (STEMS), National Research Council of Italy, 10135 Torino, Strada delle Cacce, 73, Italy;
marcella.biddoccu@cnr.it; giorgio.capello@stems.cnr.it; eugenio.cavallo@cnr.it
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 ¾ 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 m^2 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

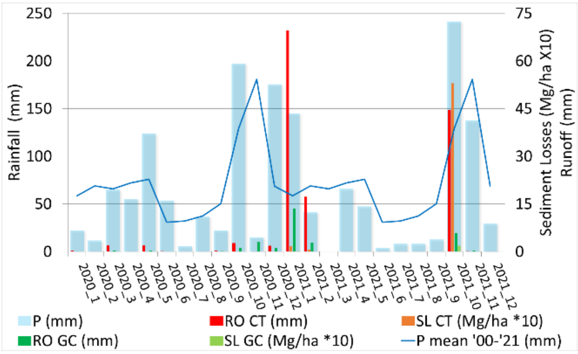

Figure 1. Monthly precipitation (P) and mean precipitation in 2000–2019 period (P mean), runoff (RO) and soil losses (SL) in CT and GC.

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 1). As consequence of low precipitations, yearly runoff was lower than in previous years (Table 1). 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.

The selected events (Table 1) 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 ¾ RO and more than 90 % of SL in the two plots.

Table 1. 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 % of 20+21	786.6 51.5%	9.62 6.8%	1.2%	0.01 0.1%
2021 % of 20+21	741.8 48.5%	131.94 93.2%	17.8%	5.54 99.9%
Sel_all % of 20+21	1256.6 82.2%	141.32 99.8%	11.2%	5.55 100.0%
Sel_normal % of sel_all	579 46.1%	31.31 22.2%	5.4%	0.07 1.3%
Sel_extreme % of sel_all	677.6 53.9%	110.01 77.8%	16.2%	5.47 98.7%

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

Moreover, most of the runoff was generated by only 2 events occurred in January and October 2021, and most of erosion (more than 85 % in CT and 95 % in GC) was due to the single extreme rainfall event occurred in October 2021. This confirms what was stated by Capello *et al*. (2020) analysing the previous 3 years: the most part of RO and SL were generated by a few extreme events that, in the sublitoranean climate that characterizes the site, are common in autumn and winter, and their frequency is increasing, due to climate change. The grass cover, compared with tilled soil, had a great efficiency in reducing water (nearly 8 times) and soil losses (nearly 30 times) during the October 2021 extreme event. This highlights the necessity to protect the soil and adopt adequate soil management to preserve water and soil in the different seasons of the year, especially considering the soil compaction due to the tractors traffication (Capello *et al*., 2019b).

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 2, 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.

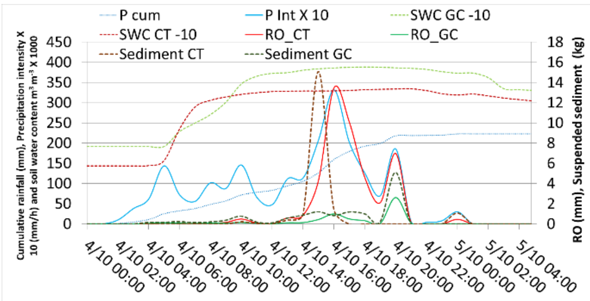

Figure 2. Cumulative precipitation (P cum, mm), Precipitation intensity (P int, X10, mm), runoff (RO, mm), soil water content (SWC, m^3 m^{-3} X1000) and suspended sediment (kg) in CT and GC.

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 traffication, are associated to relevant rainfall events. These extreme events are increasing in frequency in the context of the climate change.

Acknowledgements

The present study was partially funded by EU (FEASR) and Regione Piemonte within the project "IN-GEST SOIL (CUP J66B20006370002), PSR 2014-2020, Regione Piemonte, Operazione 16.1.1". Thanks to Francesco Palazzi and to the staff of "Centro sperimentale Vitivinicolo Tenuta Cannona" for the precious collaboration in the vineyards management and samples collection.

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.; Bogena, 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, 251,158e170. 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.; Koskiaho, 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