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Soil and management effects on aggregation and organic matter dynamics in vineyards

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ABSTRACT

Vineyards in hilly areas are often prone to erosion because of poor soil development, low soil organic matter (SOM) contents, and severe slopes. Permanent grassing, besides providing protection against erosion, can foster the soil resistance to degradation by increasing SOM that, in turn, favours the formation and limits the turnover of stable aggregates by promoting interactions between SOM and soil minerals. Although a soil's capacity to physically protect SOM is known to depend on management practices, soil properties may interact causing the soil response to vary even at relatively low spatial scales, thereby warranting site-specific sustainable soil management. The objective of this study was to evaluate how differences in soil properties within the same vineyard may modulate the effects of management practices on aggregate formation, stability as well as SOM dynamics. We exploited the spatial differences in soil types and properties in an experimental vineyard by sampling topsoil samples (0–5 cm) with contrasting texture and pH to include a non-calcareous clay loam from an Alfisol (pH 6.8, 18.6 g kg^{-1} organic C, 28% clay) and a calcareous loam from an Entisol (pH 8.0, 14.8 g kg^{-1} organic C, 14% clay), both managed for 3 years under permanent grass vs. autumn tillage. Four aggregate size fractions were separated by dry sieving, and characterized for their organic C content and distribution between functional pools by density fractionation, and their resistance to breakdown and organic C loss during wet sieving.

Soil type affected aggregate formation and stability with a greater abundance of larger aggregates richer in SOM in the clay loam with respect to the calcareous loam. Tillage enhanced aggregate breakdown and SOM loss, but the effects were highly dependent on the intrinsic soil properties that drive the different mechanisms of aggregate formation and stabilization. The largest macroaggregates were most susceptible to disruption and organic C release by tillage, but a soil-dependent effect was observed as those in the calcareous Entisol were more vulnerable than those in the Alfisol topsoil, particularly due to rapid losses resulting from slaking, swelling and dispersion. Although the aggregates in fine-textured topsoil may be relatively less vulnerable to tillage, the higher proportion of organic C in the larger macroaggregates may make them nonetheless prone to significant organic C loss (in the form of POM (particulate OM) or SOM-rich fine aggregates) unless appropriate management is adopted. Therefore, special attention should be given to the spatial variability in soil properties when planning vineyard management to reduce soil degradation.

1. Introduction

In Mediterranean and quasi-Mediterranean environments, vineyard soils are highly sensitive to degradation due to environmental conditions and soil properties (e.g. Novara et al., 2011; Prosdocimi et al., 2016; Garcia-Diaz et al., 2018). Soil conservation practices thus play an important role in limiting soil threats, particularly erosion and fertility loss. Among these, the adoption of minimum tillage, no tillage, and cover crops may contribute to increase soil organic matter (SOM) contents and aggregate stability, thus limiting soil erodibility and favouring water infiltration (e.g. Gristina et al., 2022).

SOM has been shown to be the most effective aggregating agent in

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poorly developed vineyard soils (Belmonte et al., 2016; Yilmaz et al., 2019). Organic matter inputs with fresh plant residues and root-derived materials favour the formation and stabilization of macroaggregates (> 250 μm), while more transformed organic compounds contribute to stabilize microaggregates (Denef et al., 2002). Fresh organic residues occluded in macroaggregates stimulate the production of microbial-derived binding agents that contribute to the formation of very stable microaggregates within macroaggregates, thus determining the physical protection of occluded SOM (Six et al., 2002). The effectiveness of SOM stabilization, however, varies as a function of the binding mechanisms involved in microaggregate formation, that strongly depends on soil type (Mikutta et al., 2007). Abundant Fe oxides in the soil favour ligand exchange reactions that are highly effective in stabilizing SOM (e.g. Gu et al., 1994), while in poorly developed soils the interaction of SOM molecules with clay particles through Ca^{2+}, and other cations, is more important, although less stable (e.g. von Lützow et al., 2006; Falsone et al., 2016; Rowley et al., 2018). Aggregation mechanisms can therefore be a key factor in soil conservation and may determine the resilience to soil threats.

Various studies have investigated the effects of soil type or management on aggregate stability and SOM protection in Mediterranean vineyards. The positive effects of no- or minimum tillage vs. conventional tillage in terms of carbon stocks and erosion control have been widely reviewed (e.g. Laudicina et al., 2017; Abad et al., 2021; Garcia-Diaz et al., 2018). Substantial evidence has been reported on the negative effects of tillage on aggregate formation and fragmentation (e.g. Littrell et al., 2021) and the consequent release of poorly stabilized organic components, thereby accelerating SOM decomposition and turnover (Six et al., 2002; Six and Paustian, 2014). Considering the different mechanisms responsible for aggregate stabilization, the effects of management practices on aggregate and SOM turnover in vineyards should therefore depend on soil chemical and physical properties, which can show a high spatial variability even at the farm scale (e.g. Bramley, 2022; Chapela-Oliva et al., 2022).Nonetheless, studies that evaluate the interaction between management practices and soil properties on aggregate and SOM dynamics at the farm scale are still lacking. Due consideration on the effects soil properties on these processes in vineyards under homogeneous management may, therefore, provide relevant insights that may promote the adoption of targeted soil management (e.g. Bramley, 2022).

Based on these considerations this study aims to evaluate how soil properties may modulate the effects of management practices on aggregate and SOM dynamics. We hypothesize that (i) macroaggregates in non-calcareous topsoils having a higher clay and SOM content may be less susceptible to tillage-induced breakdown with respect to calcareous soils having lower clay and SOM contents, and that (ii) the lower aggregate stability in the latter soils can be linked to a higher risk of organic C loss. To test these hypotheses, we compared the effects of two soil management practices (permanent grass vs. autumn tillage) on two topsoils with contrasting characteristics within the same vineyard situated in North-Western Italy, in terms of aggregate size, and OC distribution, aggregate stability, and their implications on OC release during aggregate breakdown. These insights are important for suggesting future approaches for sustainable soil management.

2. Materials and methods

2.1. Study area and soil sampling

The research was set-up in the "Tenuta Cannona" experimental vineyard (44°40′59.35″N, 8°37′36.85″E, Fig. 1), in the Southern part of Piemonte region, in Italy. The mean annual air temperature is 13°C and the mean cumulative annual rainfall is 711 mm (Arpa Piemonte meteo database, Arpa Piemonte, 2024). The soil thermal and moisture regimes are mesic and ustic, respectively (Soil Survey Staff, 2014). The geological setting of the area consists of the upper Miocene "Rocca Grimalda chaotic complex", a poorly consolidated marl and sandstone matrix in which coherent sandstone or mudstone blocks are suspended (ISPRA, 2018). A Typic Paleustalf fine, mixed, non-acid, mesic (hereafter defined as "ALF") occupies the summit and upper part of the hillslope, while a

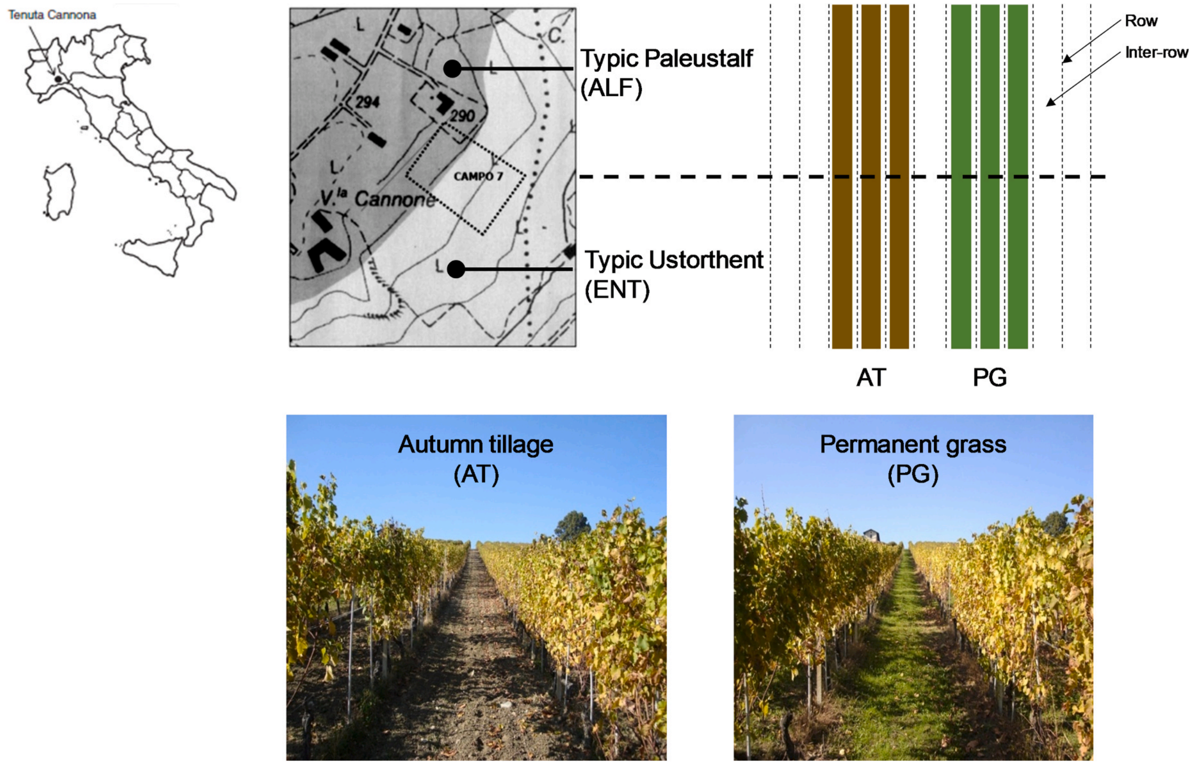

Fig. 1. Study site location showing details of the soil types and soil management treatments.

Typic Ustorthent fine-loamy, mixed, calcareous, mesic (hereafter defined as "ENT") develops at the footslope position (IPLA-Regione Piemonte, 2009; Fig. 1). The Ap horizon in the Alfisol is a clay loam (40% sand, 32% silt, 28% clay) with a pH of 6.8, a CEC of 23.9 cmol$_{(+)}$ kg^{-1}, no carbonates, 18.6 g kg^{-1} of OC and a C/N ratio of 10.3, while the Ap horizon in the Entisol is a calcareous loam (45% sand, 41% silt, 14% clay) with a pH of 8.0 due to the presence of carbonates (170 g kg^{-1} CaCO$_3$, 60 g kg $^{-1}$ active lime), a CEC of 17.5 cmol$_{(+)}$ kg^{-1}, 14.8 g kg^{-1} of OC, and a C/N ratio of 9.8.

The vineyard was deep-tilled in 1988 and planted with *Vitis vinifera* L. Chardonnay (on the Entisol) and Pinot Noir (on the Alfisol), grafted on Kober 5BB rootstock (5000 vines ha^{-1}). Details on vineyard management since 1989 are thoroughly described in Belmonte et al. (2016). Two 3-year long treatments were considered in this work: (i) permanent grass cover with autochthonous vegetation (including *Avena fatua* L., Bromus spp., *Cynodon dactylon* L., *Festuca* spp., *Hordeum* spp., and other less abundant species) in the inter-row (PG: permanent grass); (ii) rototiller passage in November every year up to a soil depth of 15 cm (AT: autumn tillage) followed by the development of a natural vegetation cover on the bare soil in spring mostly composed of Poaceae (40%) and Fabaceae (20%), and species from other families. Both treatments were mowed every year in May and July. All other viticulture practices were similar in the two treatments.

The experimental field consisted of 3 adjacent rows for each treatment (AT, PG) separated by a buffer strip. Each row had an area of 670 m^2 with 14% slope and S-E aspect, with the two contrasting soil types located as in Fig. 1. Triplicate topsoil (0–5 cm) composite samples (one per row) were collected for each row in spring 2012 by combining soil from 5 equidistant sampling points along the row. The samples were air-dried and homogenized by passing through a 5 mm sieve.

2.2. Aggregate size distribution

One kg of each soil sample was dry-sieved over nested sieves for 20 min at 250 rpm to separate four aggregate size fractions based on nominal sizes for large (F1: 5–2 mm), medium (F2: 2–0.5 mm) and small (F3: 0.5–0.25 mm) macroaggregates, and microaggregates (F4: <0.25 mm), respectively. The mass of each size fraction was used to calculate the Mean Weighted Diameter (MWD) for each soil/treatment combination as:

$$MWD = \sum_{i=1}^{n} x_i w_i \tag{1}$$

where x_i is the mean diameter (mm) of the aggregate fraction i and w_i is the proportion of the total sample weight within that fraction.

Organic C (OC) and total N concentrations in bulk soil samples (< 5 mm) and different aggregate size fractions were determined by dry combustion (NA2100, CE Instruments, Rodano, Italy) after pretreatment with HCl for the removal of inorganic C (Harris et al., 2001). The distribution of total soil OC between different aggregate size fractions was calculated as the product of each fraction mass yield and their respective organic C concentrations and expressed as a proportion of total OC.

2.3. Aggregate stability by wet sieving

The stability of aggregates (>0.25 mm) obtained by dry sieving (size fractions F1, F2, F3) was then evaluated by the wet sieving method (Kemper and Rosenau, 1986), in order to assess aggregate loss (AL) by slaking and water abrasion, which simulates the soil vulnerability to intense rainfall. Ten grams of each aggregate fraction were placed on 0.2 mm sieves and allowed to rotate at 60 rpm in deionized water for 5, 10, 15, 20, 40, and 60 minutes. Aggregate loss (%) at each sieving time was determined as:

$$\mathbf{Aggregate\ \ loss\ \ (AL,\%) = 100 - \frac{100(weight\ \ retained - weight\ \ of\ \ coarse\ \ sand)}{total\ \ sample\ \ weight - weight\ \ of\ \ coarse\ \ sand}} \tag{2}$$

where the amount of coarse sand (2–0.2 mm) within each aggregate size fraction was determined after oxidation with H$_2$O$_2$ (Gee and Bauder, 1986), and used to correct AL for primary particle contents. The aggregates resisting loss at the different wet sieving times were dried at 40°C, weighed, ground, and analyzed for organic C and total N concentrations by dry combustion as described above. The losses of OC during wet sieving were calculated as the difference between the initial C contents and the C remaining in the sample at the different sieving times. Aggregate loss kinetics were fitted with the exponential model proposed by Zanini et al. (1998) and applied in Belmonte et al. (2016).

$$\mathrm{y(t) = a + b\left(1 - e^{\frac{-t}{c}}\right)} \tag{3}$$

where y is the % aggregate loss, t is the sieving time (min), a is the aggregate loss upon water saturation (%) at time 0, i.e. the initial loss, which occurs due to slaking, swelling and clay dispersion (Le Bissonnais, 1996); b is the maximum estimated abrasion loss (%), i.e., during sieve rotation; c (min) is a parameter that links the rate of aggregate loss to wet sieving time. The a, b, c parameters were obtained by fitting the exponential model of Eq. 3 to the data obtained from the wet sieving test. The total aggregate loss was computed as (a + b). The same model was applied to OC loss during wet sieving.

From the dry- and wet- sieving data we calculated a soil stability index at specific sieving times (SSI$_t$) that takes into account both the abundance and the stability of macroaggregates (> 0.250 mm) as:

$$\mathbf{SSI}_t = \sum_{\mathbf{i}}^{\mathbf{n}} \mathbf{dw_i} \times ((\mathbf{100} - \mathbf{AL}_t) \div \mathbf{100}\quad) \tag{4}$$

Where dw is the weight fraction of the aggregates (dry sieving) in the i-th class and AL$_t$ is the loss of aggregates of the same class (g 100 g^{-1}) after t minutes of wet sieving. The index follows the approach of Nichols and Toro (2011) and ranges from 1, when the soil is totally formed by macroaggregates that are 100% stable, to 0 when no material >0.250 mm is present or complete breakdown of aggregates occurs in all classes.

2.4. Soil organic matter density fractionation

Soil organic matter in the aggregate size fractions (F1 to F4) was also separated into free and aggregate-occluded particulate organic matter (FPOM and OPOM, respectively), and mineral-associated organic matter (MOM) by density fractionation following the procedure described by Golchin et al. (1994) and modified by Cerli et al. (2012). Briefly, 25 g aliquots of each size fraction were suspended in 125 ml of sodium polytungstate (NaPT) solution having a density of 1.6 g cm^{-3} and after shaking gently by hand the light FPOM fraction was separated by centrifugation (12,800 × g, for 20 min) and filtration, rinsed with deionized water and dried. After re-suspending the soil in NaPT with the same density, aggregates were disrupted by applying 275 J ml^{-1} of ultrasonic energy (Sonoplus HD 2200, Bandelin electronic GmbH & Co. KG, Berlin, Germany) and the light OPOM fraction separated, rinsed with deionized water and dried as described above. The remaining heavy MOM fraction was repeatedly rinsed with deionized water until the washings had an electrical conductivity of <50 μS cm^{-1}, and subsequently dried. Mass yields of all fractions were recorded and OC and N (g kg^{-1}) concentrations in each fraction were determined as described above. The distribution of total aggregate OC between different density fractions was calculated as the product of each fraction mass yield and their respective OC concentrations, while the contribution to total OC was calculated by taking into account the relative contribution of each aggregate size fraction to the bulk soil**.**

2.5. *Statistical analyses*

All analyses were carried out using IBM SPSS Statistics 27. Soil type (ALF vs. ENT) and soil management (PG vs. AT) were considered as treatment factors. Because of the low number of cases, preventing the evaluation of normality, the Kruskal-Wallis test was adopted. When appropriate, differences among aggregate size fractions were also checked, using the same statistical procedure. Correlations between variables were evaluated using Spearman's coefficient. The plots were drawn using the Software Sigmaplot D. The non-linear fitting of aggregate and C loss (Eq. 3) was performed with the non-linear regression tool of SPSS.

3. Results

3.1. *Dry aggregate size distributions and organic C in size fractions*

Aggregate size distribution differed among soil types and management (Fig. 2). Whereas the largest size fraction (F1) represented more than 50% of the total mass in ALF, this fraction was less than 50% in ENT, while the relative abundance of F3 and F4 were comparable between the two soils (Fig. 2). Autumn tillage in ALF resulted in a relative decrease in the largest aggregates with a significant increase in F2 with respect to permanent grass ($p = 0.016$), while in ENT the relative decrease in F1 with tillage led to an increase in both F2 and F3 ($p = 0.05$, both cases). This effect of tillage on aggregate size was also evidenced by differences in MWD (Fig. 2) that was significantly higher in ALF ($p = 0.006$), and in the PG treatments when considering the soils separately ($p = 0.05$).

The elemental composition of the four soil fractions (Table 1) evidenced that aggregate OC concentrations (g kg^{-1}) tended to increase with decreasing aggregate size and were higher in ALF than ENT for all fractions, but these differences were only significant for F1 ($p = 0.025$). In ENT, tillage induced a significant reduction in OC in the smaller size fraction (Table 1, $p = 0.05$ for F4).

The C/N ratio ranged from 9 to 11 without any recognizable trend, except for the F4 fraction of ALF, where the C/N ratio decreased with tillage ($p = 0.05$). Inorganic C was only present in ENT, ranging from 19.1 g kg^{-1} (bulk, PG) to 22.3 g kg^{-1} (bulk, AT), without a clear trend across fractions.

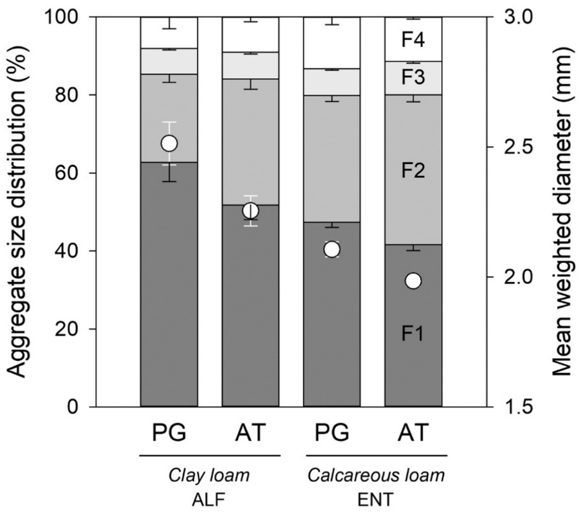

Fig. 2. Size distribution (bars) and mean weighted diameter of aggregates (circles) in soils under permanent grass (PG) and autumn tillage (AT) for both soil types. Aggregate size classes obtained by dry sieving: F1, 5–2 mm; F2, 2–0.5 mm; F3, 0.5–0.25 mm; F4 <0.25 mm. Error bars represent the standard error ($n = 3$).

3.2. *Organic C distribution and SOM fractions in the soils*

The soil OC distribution across aggregate size fractions evidenced a greater amount of OC associated with F1 in ALF than ENT ($p = 0.01$, Fig. 3), while no significant differences were observed for the finer fractions. The density fractionation of SOM in each aggregate size fraction showed that MOM always represented the greatest proportion of aggregate C and contributed the most to total OC (Fig. 4). The contribution of OPOM to total OC generally showed a decreasing trend with decreasing aggregate size from F1 to F4 across all soils without a significant effect of soil type or management. The FPOM fraction was predominantly present in the coarser aggregate-size fractions (F1 and F2) with a higher contribution to OC under AT with respect to PG for both soils. The C/N ratios of MOM and OPOM (Fig. 4) fractions were comparable across size fractions with no significant differences between soils and treatments. The FPOM fraction showed the highest C/N ratios with a clear decreasing trend with decreasing aggregate size for all soils and management types (Fig. 4).

3.3. *Aggregate and OC loss from dry aggregate fractions after wet sieving*

Aggregate loss during wet sieving did not differ significantly between the different macroaggregate fractions across both soils and managements (Table 2), although significant effects were observed between soils (at all sieving times >5 min) and managements (at all sieving times except 60 min). The tilled ENT showed the fastest aggregate loss (> 50% for all fractions after 5' of wet sieving) and the highest total aggregate losses for all fractions (Fig. 5) with the exception of the coarsest macroaggregate class (F1) for which all treatments and soils showed comparable losses (> 80%) after 60 min of wet sieving. In contrast, both tilled and grassed ALF and the grassed ENT showed visibly slower initial losses (Fig. 5). In ALF, however, the increased aggregate loss after tillage compared to permanent grass (i.e. the distance between the two loss curves) was more pronounced for F2 (Fig. 5).

The exponential model coefficients (Eq. 3), which allow subdividing the wet aggregate losses into losses upon water saturation (a) and those by abrasion (b), indicated that abrasion always contributed most to total aggregate loss, but nonetheless, the initial loss was sometimes very pronounced (Table 3) exceeding 30%. The total loss was always >78%, indicating a high vulnerability of the aggregates to wet sieving.

The global soil stability index (SSI, Fig. 6) showed a decreasing trend with time and reached very low values (≤ 0.2) after 60 min of wet sieving for all samples. Even here, the effect of management was more pronounced for the shortest sieving times (i.e. 5, 10, 15, 20 min), and a more resistant structure was observed in PG treatments (for the same soil). This was particularly evident for ENT samples, with the structure of ENT being more sensitive to tillage.

The losses of OC from each aggregate size fraction during wet sieving, normalized to the total OC content of each fraction (expressed in % in Fig. 7), followed similar trends to those observed for aggregate loss (Fig. 5). This was confirmed by a very strong and positive correlation between aggregate and OC loss when all paired data points across soils, managements, and aggregate size fractions during wet sieving were pooled ($r = 0.862$, $p < 0.001$). The extrapolated total OC % loss (initial + abrasion loss) exceeded 78% for all fractions. A significant effect of soil

Table 1

Organic and inorganic C contents (OC, IC, respectively), and C/N ratio of bulk soils and aggregate-size fractions (dry-sieving) for the different soils and treatments. Capital letters indicate differences between soils (Kruskal-Wallis test). Low-case letters indicate differences between treatments for the same soil (Kruskal-Wallis test). Significant differences for p<=0.05 are highlighted in bold. Differences between soils are not reported for the variable IC.

				OC (g kg^{-1})		IC (g kg^{-1})		C/N	
			n	mean	st. dev	mean	st. dev	mean	st. dev
Bulk (< 5 mm)	ALF	PG	3	20.0 a	6.3	nd		10.5 a	0.4
		AT	3	17.2a	1.6	nd		10.1a	0.4
		mean	6	18.6 A	4.3	nd		10.3 A	0.4
	ENT	PG	3	15.6 a	3.2	19.9a	1.4	9.6 a	1.2
		AT	3	13.9a	2.3	21.0a	2.5	10.0a	1.7
		mean	6	14.8 A	2.7	20.4	1.9	9.8 A	1.3
F1 (5–2 mm)	ALF	PG	3	19.9a	6.6	nd		10.7a	0.6
		AT	3	16.2a	0.3	nd		9.9a	0.4
		mean	6	18.1 **A**	4.6	nd		10.3 A	0.7
	ENT	PG	3	14.9a	2.7	19.6a	1.7	9.4a	0.8
		AT	3	11.8a	0.8	21.6a	1.7	9.1a	1.2
		mean	6	13.4**B**	2.5	20.6	1.8	9.3 A	0.9
F2 (2–0.5 mm)	ALF	PG	3	22.4a	8.1	nd		11.0a	0.6
		AT	3	19.5a	0.4	nd		10.4a	0.5
		mean	6	21.0 A	5.3	nd		10.7 A	0.6
	ENT	PG	3	16.2a	5.0	19.2a	1.0	9.7a	1.1
		AT	3	14.0a	0.7	21.1a	2.7	10.0a	1.2
		mean	6	15.1 A	3.3	20.2	2.1	9.9 A	1.1
F3 (0.5–0.25 mm)	ALF	PG	3	22.0a	9.8	nd		11.0a	0.4
		AT	3	18.5a	1.6	nd		10.3a	0.6
		mean	6	20.3 A	6.6	nd		10.6 A	0.6
	ENT	PG	3	18.8a	3.6	19.1a	0.5	10.0a	0.7
		AT	3	17.1a	3.9	20.8a	2.1	10.3a	1.3
		mean	6	18.0 A	3.5	19.9	1.7	10.1 A	1.0
F4 (<0.25 mm)	ALF	PG	3	24.8	9.5	nd		10.8**a**	0.2
		AT	3	20.3	0.9	nd		10.0**b**	0.3
		mean	6	22.5 A	6.5	Nd		10.4 A	0.5
	ENT	PG	3	17.7**a**	4.5	20.2**b**	0.6	9.5a	0.7
		AT	3	14.8**b**	2.4	22.3**a**	0.5	9.4a	0.5
		mean	6	16.2 A	3.6	21.2	1.2	9.4 A	0.5

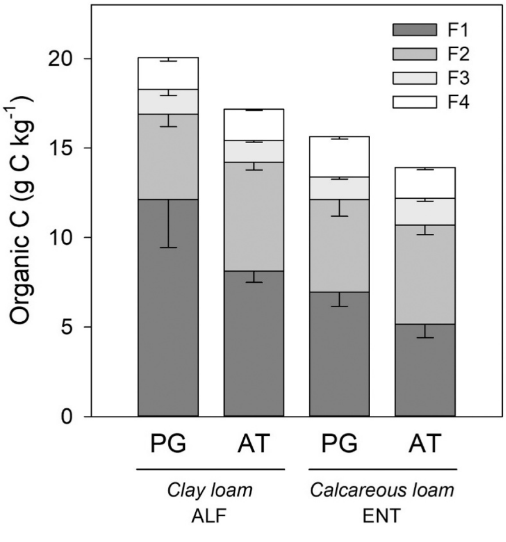

Fig. 3. OC distribution between aggregate size classes (F1, 5–2 mm; F2, 2–0.5 mm; F3, 0.5–0.25 mm; F4 <0.25 mm) in soils under permanent grass (PG) and autumn tillage (AT). Error bars represent the standard error (*n* = 3).

type (except at 5 min) on OC loss during aggregate wet sieving was observed, but no effect of the aggregate size fraction (Table 4). The effect of management was significant with the exception of 10 and 15 min (Table 4), and particularly noticeable for the coarsest aggregate fraction, F1 (Fig. 7). The ENT was generally more sensitive to AT with respect to the ALF in terms of OC losses, as evidenced by comparing the distance between AT and PG curves within each soil.

4. Discussion

In this work, we assessed the effect of a single annual autumn tillage operation vs. permanent grass on aggregate stability and organic matter dynamics in two adjacent vineyard patches with contrasting texture and pH, hence carbonate presence. We focused on the effects of differences in soil properties on dry aggregate-size and SOM distribution, as well as on the kinetics of aggregate and OC losses during wet sieving, in order to evaluate the intrinsic soil vulnerability to tillage.

4.1. *Soil properties and aggregation*

Aware of the fact that aggregate size distribution obtained by dry sieving reflects aggregate formation rather than their stabilization (e.g. Nichols and Toro, 2011), the lower proportion of coarse aggregates and lower MWD observed for the calcareous loam soil (ENT) with respect to the clay loam soil (ALF), suggests a less effective aggregation in the former. This was likely due to the lower clay and SOM contents that are known to be important constituents for macroaggregate formation. A similar finding was reported in a study by Ćirić et al. (2012), where relatively higher clay contents (as in the case of ALF herein) were associated to the presence of larger macroaggregates. Although various studies have also evidenced the importance of cementation by carbonates in contributing to aggregate formation (Fernandez-Ugalde et al., 2011; Pihlap et al., 2021) the role of these inorganic binding agents in aggregate formation in the ENT seems to suffer from the fact that carbonates in this soil were of lithogenic rather than pedogenic origin, with consequently little interaction with the other soil phases conducive to effective aggregation (Catoni et al., 2012). Moreover, it is known that the importance of different mechanisms responsible for the formation and stabilization of soil aggregates may differ across different aggregate size classes (Totsche et al., 2018, Pihlap et al., 2021). We therefore also postulate that mechanisms involving the interaction between SOM and

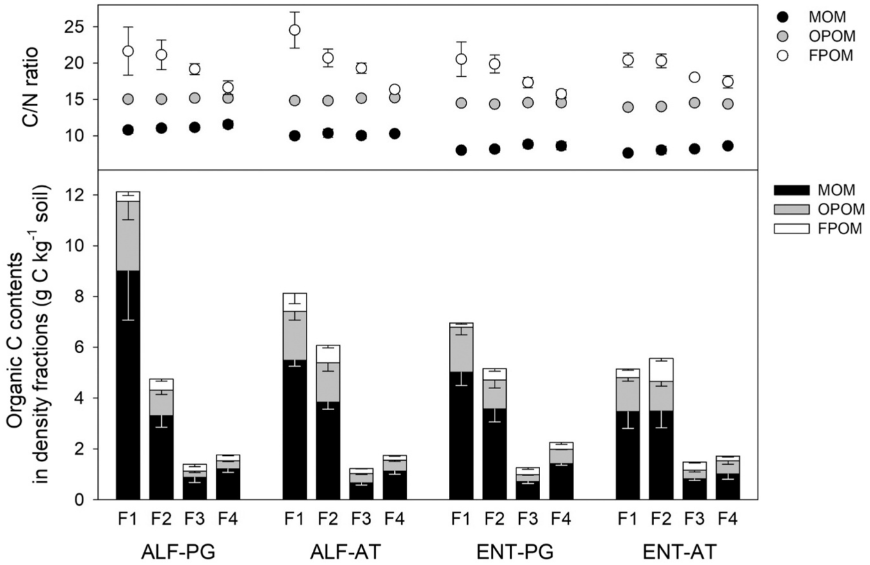

Fig. 4. Distribution of OC and C/N ratio between density fractions (FPOM, free particulate organic matter; OPOM, occluded particulate organic matter; MOM, mineral-associated organic matter) for the different aggregate size fractions (F1, 5–2 mm; F2, 2–0.5 mm; F3, 0.5–0.25 mm; F4, <0.25 mm) as a function of soil (ALF, clay loam Alfisol; ENT, calcareous loam Entisol) and management (PG, permanent grass; AT, autumn tillage). Error bars represent the standard error (n = 3). Total n=48.

Table 2
Significance (p value) of the Kruskal-Wallis test on aggregate loss data (wet sieving, different sieving times expressed in minutes), testing the effect of soil fraction, soil (ALF, clay loam Alfisol; ENT, calcareous loam Entisol), management (PG or AT). Bold is used to highlight significant ($p < 0.05$) effects of the tested factors.

Aggregate loss for sieving times	Sig. fraction	Sig. soil	Sig. management
Aggregate loss 5 min	0.242	0.150	**<0.001**
Aggregate loss 10 min	0.172	**0.013**	**0.016**
Aggregate loss 15 min	0.333	**0.002**	**0.043**
Aggregate loss 20 min	0.864	**<0.001**	**0.021**
Aggregate loss 40 min	0.502	**<0.001**	**0.017**
Aggregate loss 60 min	0.344	**0.008**	0.098

Fe (hydr)oxides or clay minerals, considered to be more important for aggregate formation in the subacidic clay loam, are more effective in the formation of the larger macroaggregates, while the role of cation bridging with the abundant Ca^{2+} in equilibrium with calcite in the calcareous loam could be more effective at smaller aggregate size classes. This could also contribute to making the larger macroaggregates resulting in the latter soil more vulnerable to breakdown as discussed below.

4.2. *Effects of soil management on aggregate and organic matter losses, and interaction with soil properties*

Soil management mainly affected the largest aggregate class that became less abundant and more fragile in both soils after tillage (Fig. 2). This is in agreement with the results obtained across a number of soil types and environments (e.g. Tivet et al., 2013; Hontoria et al., 2016; Jiang et al., 2011). Despite the general effect of tillage on soil aggregation the results evidenced differences between the two soils. Firstly, breakdown of the coarser macroaggregates with tillage led to less pronounced fragmentation in the clay loam compared to the calcareous loam (Fig. 2). In fact, in the clay loam aggregate loss with tillage seemed to be limited to the coarse macroaggregates and only affected the proportion of F1 and F2 without influencing F3 and F4. Probably, the

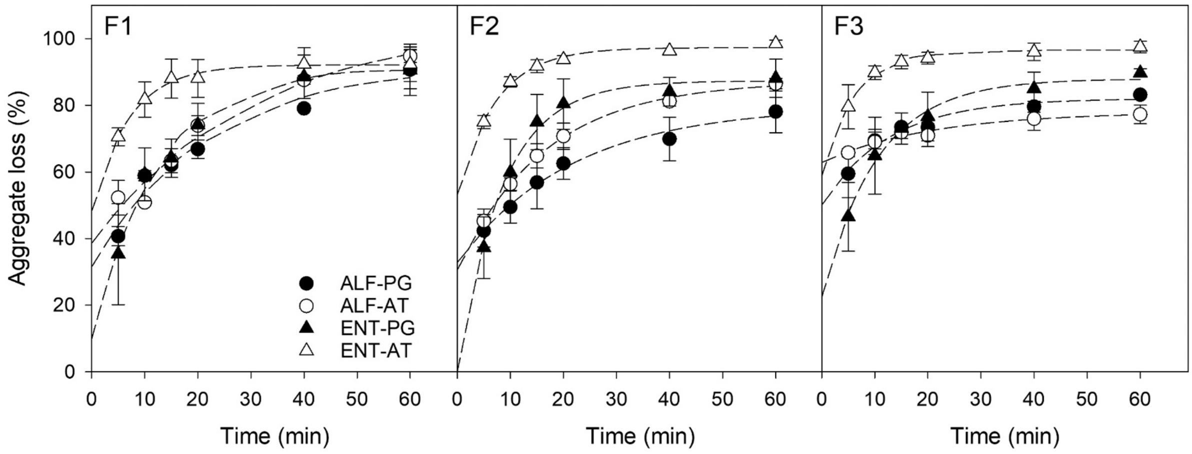

Fig. 5. Macroaggregate loss kinetics for size fractions 5–2 mm (F1), 2–0.5 mm (F2), and 0.5–0.25 mm (F3) as a function of soil (ALF, clay loam Alfisol; ENT, calcareous loam Entisol) and management (PG, permanent grass; AT, autumn tillage). Error bars represent the standard error ($n = 3$) while dashed lines represent the best fit of the exponential model (Eq. 3).

Table 3
Exponential model coefficients for initial loss (a) and total (a+b) aggregate loss, total OC loss (expressed in g OC kg-1 soil) during wet sieving for each aggregate size fraction as a function of soil type and management.

Size fraction	Soil	Management	Initial loss (%)	Abrasion loss (%)	Total loss (%)	C loss (g OC kg^{-1} soil)
F1 (5–2 mm)	ALF	PG	31.5	60.8	92.2	8.39 ± 3.48
		AT	36.7	63.3	100.0	8.42 ± 0.63
	ENT	PG	11.6	80.0	91.6	5.12 ± 1.07
		AT	48.2	43.9	92.1	4.68 ± 0.46
F2 (2–0.5 mm)	ALF	PG	32.8	46.9	79.7	2.96 ± 0.81
		AT	30.6	56.7	87.2	3.89 ± 0.33
	ENT	PG	n.d.	87.3	87.3	3.51 ± 1.16
		AT	53.2	44.1	97.3	4.26 ± 0.04
F3 (0.5–0.25 mm)	ALF	PG	50.0	32.0	82.0	0.88 ± 0.41
		AT	62.9	15.1	78.0	0.81 ± 0.13
	ENT	PG	22.3	65.6	87.9	0.80 ± 0.15
		AT	58.7	37.8	96.5	1.10 ± 0.30

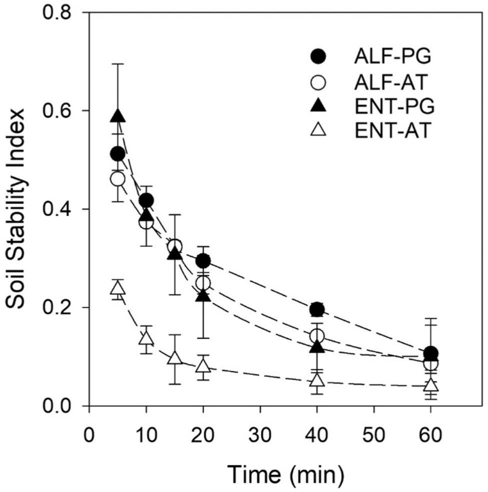

Fig. 6. Variation in the soil stability index with wet-sieving time as a function of soil (ALF, clay loam Alfisol; ENT, calcareous loam Entisol) and management (PG, permanent grass; AT, autumn tillage). Error bars represent the standard error ($n = 3$).

occluded SOM coupled with clay abundance contributed more to the stabilization of smaller macroaggregates (e.g. Šimansky et al., 2016) limiting their susceptibility to fragmentation. The results of the wet aggregate stability tests are in agreement with these findings. They evidenced that soil properties affect the stability of the finer macroaggregates (Table 2), with those in the clay loam being more resistant to breakdown irrespective of management. This result is common in vineyards (e.g. Ruiz-Colmenero et al., 2013) and has been widely motivated by the tillage-related physical disturbances incurred by the larger units during the building up of microaggregates within macroaggregates (Six et al., 2000).

Secondly, although tillage generally enhanced aggregate loss across different aggregate size classes, soil management had a stronger effect on aggregate loss during the early stages of wet sieving, particularly in the calcareous loam (Fig. 5). In fact, the disruption of the largest macroaggregates in this soil resulted in a relevant increase in the initial losses (Table 3).

This indicates an extreme susceptibility of the aggregates in the Entisol to slaking, swelling and dispersion in the absence of permanent

Table 4
Significance (p value) of the Kruskal-Wallis test in OC loss at the different times different sieving times expressed in minutes, testing the effect of soil fraction, type (ALF or ENT), management (PG or AT). Bold is used to highlight significant (p<0.05) effects of the tested factors.

OC loss for sieving times	Sig. fraction	Sig. soil	Sig. Treatment
Loss OC 5 min	0.786	0.368	**0.034**
Loss OC 10 min	0.681	**0.022**	0.231
Loss OC 15 min	0.604	**0.002**	0.063
Loss OC 20 min	0.931	**0.010**	**0.031**
Loss OC 40 min	0.552	**0.001**	**0.034**
Loss OC 60 min	0.125	**0.001**	**0.016**

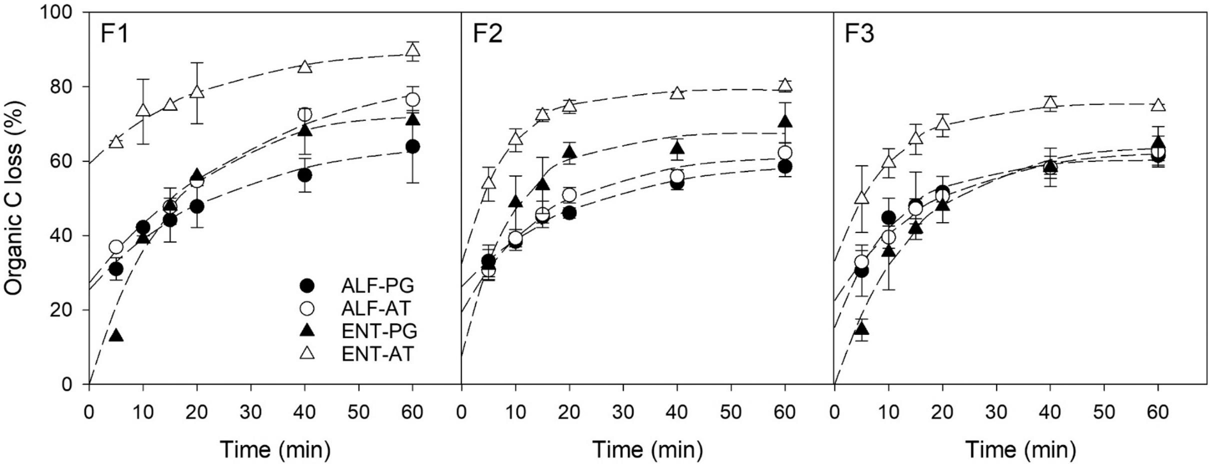

Fig. 7. OC loss during macroaggregate breakdown for size fractions 5–2 mm (F1), 2–0.5 mm (F2), and 0.5–0.25 mm (F3) as a function of soil (ALF, clay loam Alfisol; ENT, calcareous loam Entisol) and management (PG, permanent grass; AT, autumn tillage). Error bars represent the standard error ($n = 3$) while dashed lines represent the best fit of the exponential model (Eq. 3).

grass, that all act during the initial phases of aggregate breakdown (Le Bissonnais, 1996). Losses of aggregates by these three mechanisms were expected to be more pronounced in the clay-rich topsoil. However, Blanco-Moure et al. (2012) found that slaking was negatively correlated to aggregate organic C in cultivated Spanish Calcisols, and Karathanasis et al. (2014) suggested that organic coatings on mineral surfaces can create a semi-hydrophobic barrier that inhibits water penetration in small pores. The slightly higher organic C contents in aggregates of the clay loam might have thus protected them from initial breakdown. Additionally, Gargiulo et al. (2013) found that the addition of $CaCO_3$ to a Psamment in a lab wetting-drying experiment fragmented the pore space and increased the percentage of smaller pores. Because of the presence of marls in the parent material, the Entisol might therefore have a higher amount of small and blind pores that favour the collapse of aggregates upon water saturation when the contents of SOM are reduced by tillage, increasing the slaking effect. The global stability index summarized the vulnerability of the Entisol to tillage (Fig. 6). Nichols and Toro (2011) found that this index adequately represented the intensity of disturbances in cropland and rangeland Haplustolls, with lowest values under conventional tillage and highest ones under no-tillage.

Thirdly, tillage enhanced both aggregate and OC losses in the calcareous loam, whereas OC losses in the clay loam were less susceptible to soil management (see distance between the ALF curves in Fig. 7). In this study we only evaluated the release of particulate and/or mineral-associated OC (< 200 μm) during aggregate breakdown as a result of slaking (within minutes) or abrasion (within 1 hour), and not the actual loss of OC through mineralization or erosion. Nonetheless, the susceptibility of OC in macroaggregates to these processes is known to increase with aggregate breakdown, and as such OC release from these aggregates can actually represent a higher potential for SOC loss even though the wider implications on C source/sink functions in the field require wider geomorphic considerations (Xiao et al., 2018). As expected, OC losses were strongly linked to aggregate breakdown, and tended to increase with increasing aggregate size (Table 3). However, although OC losses from large macroaggregates were proportionally greater in the calcareous loam than the clay loam after tillage (Fig. 7), tillage-induced soil OC losses due to aggregate breakdown were quantitatively larger in the latter due to the greater proportion of soil OC in this fraction. This is probably also due to the larger proportion of mineral-associated and particulate organic matter occluded within the large macroaggregates compared to smaller aggregates, that are prone to be lost during aggregate breakdown. In fact, the fragmentation of soil aggregates can represent an important loss of OC from erosion sites exposing formerly encapsulated OC and C-rich fine soil particles, thus increasing their susceptibility to transport and mineralization (Xiao et al., 2018). This is in agreement with the lower amounts of MOM in larger aggregate-size classes in the tilled soils with respect to those under permanent grass (Fig. 4). These findings suggest that whereas the greater vulnerability of aggregates to tillage in the calcareous loam does not allow for substantial physical protection of OM, fine textured topsoils are nonetheless prone to significant C loss if their more stable aggregates are not preserved by appropriate soil management.

Finally, soil properties also influence the microbial turnover of organic compounds preserved by association with minerals in the soil, as evidenced by the lower C/N ratio of the MOM fraction across soil fractions in the calcareous loam with respect to the clay loam (Fig. 4). The MOM fraction is in fact considered the most stable (e.g. Baldock and Skjemstad, 2000), but the driving mechanisms for the OM-mineral interaction can be linked to aggregate stability and affect the inherent stability of SOM. Conversely to other studies (e.g. Blanco-Moure et al., 2016), tillage practices did not affect the amount or turnover of free POM fractions across aggregate-size fractions or soils. Additionally, considering the trends in C/N ratios of OM fractions, a higher C/N of FPOM was somehow expected due to the lower degree of alteration, but we observed a decreasing trend with the size fraction, i.e. the larger fractions had a less altered FPOM.

5. Conclusions

Tillage can enhance topsoil degradation through aggregate breakdown and SOM loss, but the effects are highly dependent on the intrinsic soil properties that drive the mechanisms of aggregate formation and stabilization. The largest macroaggregates (>2 mm) are most susceptible to disruption by tillage and organic C release, but a soil-dependent effect was observed as the calcareous Entisol with a coarser texture, was more vulnerable than the Alfisol topsoil having a higher clay content, particularly due to losses occurring during the early stages of wet sieving. This may lead to a great vulnerability during short but intense rainfall events that commonly affect the study area. Moreover, although the aggregates in fine-textured topsoils may be relatively less vulnerable to tillage, the higher proportion of SOC in the larger macroaggregates may make them nonetheless prone to significant OC loss in the form of particulate SOM or SOM-rich fine particles if their structure is not preserved by appropriate soil management. Sustainable soil management in vineyards is therefore of utmost importance particularly in Southern European viticulture that otherwise may experience irreversible soil and nutrients losses. Additionally, the soil variability in the same vineyard can drive the main mechanisms of soil degradation, and thus should be considered when planning sustainable soil management in viticultural agroecosystems.

CRediT authorship contribution statement

Eleonora Bonifacio: Writing – original draft, Data curation, Formal analysis, Project administration. **Daniel Said-Pullicino:** Data curation, Methodology. **Silvia Stanchi:** Formal analysis, Investigation, Methodology, Writing – review & editing. **Michele Potenza:** Data curation, Investigation, Methodology. **Sergio A. Belmonte:** Data curation, Investigation, Methodology. **Luisella Celi:** Conceptualization, Funding acquisition, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

Abad, J., Hermozo de Mendoza, I., Marin, D., Orcaray, L., 2021. Cover crops in viticulture. A systematic review (1): Implications on soil characteristics and biodiversity in vineyard. Oeno One 55, 295–312. https://doi.org/10.20870/OENO-ONE.2021.55.1.3599.

Arpa Piemonte, https://www.arpa.piemonte.it/rischinaturali/accesso-ai-dati/annali_meteoidrologici/annali-meteo-idro/banca-dati-meteorologica.htmllast visited 05/02/2024.

Baldock, J.A., Skjemstad, J.O., 2000. Role of the soil matrix and minerals in protecting natural organic materials against biological attack. Org. Geochem. 31, 697–710. https://doi.org/10.1016/S0146-6380(00)00049-8.

Belmonte, S.A., Celi, L., Stanchi, S., Said-Pullicino, D., Zanini, E., Bonifacio, E., 2016. Effects of permanent grass versus tillage on aggregation and organic matter dynamics in a poorly developed vineyard soil. Soil Res. 54, 797–808. https://doi.org/10.1071/SR15277.

Blanco-Moure, N., Moret-Fernández, D., López, M.V., 2012. Dynamics of aggregate destabilization by water in soils under long-term conservation tillage in semiarid Spain. Catena 99, 34–41. https://doi.org/10.1016/j.catena.2012.07.010.

Blanco-Moure, N., Gracia, R., Bielsa, A.C., López, M.V., 2016. Soil organic matter fractions as affected by tillage and soil texture under semiarid Mediterranean conditions. Soil Till. Res. 155, 381–389. https://doi.org/10.1016/j.still.2015.08.011.

Bramley, R.G.V., 2022. 12 - Precision Viticulture: Managing vineyard variability for improved quality outcomes. Managing Wine Quality Volume One: Viticulture and Wine Quality. Second Edition. Elsevier.

Catoni, M., Falsone, G., Bonifacio, E., 2012. Assessing the origin of carbonates in a complex soil with a suite of analytical methods. Geoderma 175–176, 47–57. https://doi.org/10.1016/j.geoderma.2012.01.022.

Cerli, C., Celi, L., Kalbitz, K., Guggenberger, G., Kaiser, K., 2012. Separation of light and heavy organic matter fractions in soil — Testing for proper density cut-off and dispersion level. Geoderma 170, 403–416. https://doi.org/10.1016/j.geoderma.2011.10.009.

Chapela-Oliva, C., Winter, S., Ochoa-Hueso, R., 2022. Edaphoclimatic drivers of the effect of extensive vegetation management on ecosystem services and biodiversity in vineyards. Agric., Ecosyst. Environ. 339, 108115 https://doi.org/10.1016/j.agee.2022.108115.

Ćirić, V., Manojlović, M., Nešić, L., Belić, M., 2012. Soil dry aggregate size distribution: Effects of soil type and land use. J. Soil Sci. Plant Nutr. 12 (4), 689–703. https://doi.org/10.4067/S0718-95162012005000025.

Denef, K., Six, J., Merckx, R., Paustian, K., 2002. Short-term effects of biological and physical forces on aggregate formation in soils with different clay mineralogy. Plant Soil 246, 185–200. https://doi.org/10.1023/A:1020668013524.

Falsone, G., Celi, L., Stanchi, S., Bonifacio, E., 2016. Relative Importance of Mineralogy and Organic Matter Characteristics on Macroaggregate and Colloid Dynamics in Mg-Silicate Dominated Soils. Land Degrad. Dev. 27, 1700–1708. https://doi.org/10.1002/ldr.2516.

Fernández-Ugalde, O., Virto, I., Barré, P., Gartzia-Bengoetxea, N., Enrique, A., Imaz, M, J., Bescansa, P., 2011. Effect of carbonates on the hierarchical model of aggregation in calcareous semi-arid Mediterranean soils. Geoderma 164, 203–214. https://doi.org/10.1016/j.geoderma.2011.06.008.

Garcia-Diaz, A., Marqués, M.J., Sastre, B., Bienes, R., 2018. Labile and stable soil organic carbon and physical improvements using groundcovers in vineyards from central Spain. Sci. Total Environ. 621, 387–397. https://doi.org/10.1016/j.scitotenv.2017.11.240.

Gargiulo, L., Mele, G., Terribile, F., 2013. Image analysis and soil micromorphology applied to study physical mechanisms of soil pore development: an experiment using iron oxides and calcium carbonate. Geoderma 197-198, 151–160. https://doi.org/10.1016/j.geoderma.2013.01.008.

Gee, G.W., Bauder, J.W., 1986. Particle-size analysis. In: Klute, A. (Ed.), Methods of Soil Analysis: Part I, 2nd Edition. America Society of Agronomy, Madison, Wi, pp. 383–409.

Golchin, A., Oades, J.M., Skjemstad, J.O., Clarke, P., 1994. Soil structure and carbon cycling. Aust. J. Soil Res 32, 1043–1068. https://doi.org/10.1071/sr9941043.

Gristina, L., Novara, A., Minacapilli, M., 2022. Rethinking vineyard ground management to counter soil tillage erosion. Soil . Res. 217 https://doi.org/10.1016/j.still.2021.105275.

Gu, B., Schmitt, J., Chen, Z., Liang, L., McCarthy, J.F., 1994. Adsorption and desorption of natural organic matter on iron oxide: mechanisms and models. Environ. Sci. Technol. 28, 38–46. https://doi.org/10.1021/es00050a007.

Harris, D., Horwath, W.R., van Kessel, C., 2001. Acid fumigation of soils to remove carbonates prior to total organic carbon or carbon-13 isotopic analysis. Soil Sci. Soc. Am. J. 65, 1853–1856. https://doi.org/10.2136/sssaj2001.1853.

Hontoria, C., Gómez-Paccard, C., Mariscal-Sancho, I., Benito, M., Pérez, J., Espejo, R., 2016. Aggregate size distribution and associated organic C and N under different tillage systems and Ca-amendment in a degraded Ultisol. Soil . Res. 160, 42–52. https://doi.org/10.1016/j.still.2016.01.003.

I.P.L.A., REGIONE PIEMONTE, 2009. - Atlante dei suoli del Piemonte. Quattro Serie di Atlanti e Note illustrative. Servizi Grafici, Bricherasio (TO).

ISPRA – Servizio Geologico d'Italia, 2018. Note illustrative della Carta Geologica d'Italia 1:50000. Fogli 194, Acqui Terme. ⟨http://www.isprambiente.gov.it/Media/carg/piemonte.html⟩. Accessed 18 June 2018.

Jiang, X., Hu, Y., Bedell, J.H., Xie, D., Wright, A.L., 2011. Soil organic carbon and nutrient content in aggregate-size fractions of a subtropical rice soil under variable tillage. Soil Use Manag. 27, 28–35. https://doi.org/10.1111/j.1475-2743.2010.00308.x.

Karathanasis, A.D., Murdock, L.W., Matocha, C.J., Grove, J., Thompson, Y.L., 2014. Fragipan horizon fragmentation in slaking experiments with amendment materials and ryegrass root tissue extracts (Article number). Sci. World J., 276892. https://doi.org/10.1155/2014/276892.

Kemper, W.D., Rosenau, R.C., 1986. Aggregate stability and size distribution. In: Klute, A. (Ed.), Methods of Soil Analysis: Part I, 2nd Edition. America Society of Agronomy, Madison, Wi, pp. 425–442.

Laudicina, V.A., Palazzolo, E., Catania, P., Vallone, M., Garcia, A.D., 2017. Soil Quality Indicators as Affected by Shallow Tillage in a Vineyard Grown in a Semiarid Mediterranean Environment. Land Degrad. Dev. 28, 1038–1046. https://doi.org/10.1002/ldr.2581.

Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. Eur. J. Soil Sci. 47, 425–437. https://doi.org/10.1111/j.1365-2389.1996.tb01843.x.

Littrell, J., Xu, S., Omondi, E., Saha, D., Lee, J., Jagadamma, S., 2021. Long-term organic management combined with conservation tillage enhanced soil organic carbon accumulation and aggregation. Soil Sci. Soc. Am. J. 85, 1741–1754. https://doi.org/10.1002/saj2.20259.

Mikutta, R., Mikutta, C., Kalbitz, K., Scheel, T., Kaiser, K., Jaln, R., 2007. Biodegradation of forest floor organic matter bound to minerals via different binding mechanisms. Geochim. Cosmochim. Acta 71, 2569–2590. https://doi.org/10.1016/j.gca.2007.03.002.

Nichols, K.A., Toro, M., 2011. A whole soil stability index (WSSI) for evaluating soil aggregation. Soil . Res. 111 (2), 99–104. https://doi.org/10.1016/j.still.2010.08.014.

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 . Res. 117, 140–147. https://doi.org/10.1016/j.still.2011.09.007.

Pihlap, E., Steffens, M., Kögel-Knabner, I., 2021. Initial soil aggregate formation and stabilisation in soils developed from calcareous loess. Geoderma 385. https://doi.org/10.1016/j.geoderma.2020.114854.

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.

Rowley, M.C., Grand, S., Verrecchia, É.P., 2018. Calcium-mediated stabilisation of soil organic carbon. Biogeochem 137, 27–49. https://doi.org/10.1007/s10533-017-0410-1.

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

Šimanský, V., Balashov, E., Horák, J., 2016. Water stability of soil aggregates and their ability to sequester carbon in soils of vineyards in Slovakia. Arch. Agr. Soil Sci. 62, 177–197. https://doi.org/10.1080/03650340.2015.1048683.

Six, J., Paustian, K., 2014. Aggregate-associated soil organic matter as an ecosystem property and a measurement tool. Soil Boil. Biochem. 68, a4–a9. https://doi.org/10.1016/j.soilbio.2013.06.014.

Six, J., Elliott, E.T., Paustian, K., 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biol. Biochem. 32, 2099–2103. https://doi.org/10.1016/s0038-0717(00)00179-6.

Six, J., Conant, R.T., Paul, E.A., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of Soils. Plant Soil 241, 155–176. https://doi.org/10.1023/A:1016125726789.

Soil Survey Staff, 2014. Keys to Soil Taxonomy. 12nd ed., NRCS.

Tivet, F., de Moraes Sa, J.,C., Lal, R., Briedis, C., Borszowskei, P.R., Burkner dos Santos, J., Farias, A., Eurich, G., da Cruz Hartman, D., Nadolny Jr, M., Bouzinac, S., Séguy, L., 2013. Aggregate C depletion by plowing and its restoration by diverse biomass-C inputs under no-till in sub-tropical and tropical regions of Brazil. Soil . Res. 126, 203–218. https://doi.org/10.1016/j.still.2012.09.004.

Totsche, K.U., Wulf, Amelung, W., Gerzabek, M.H., Guggenberger, G., Klumpp, E., Knief, C., Lehndorff, E., Mikutta, R., Peth, S., Prechtel, A., Ray, N., Kogel-Knabner, I., 2018. Microaggregates in soils. J. Plant Nutr. Soil Sci. 181, 104–136. https://doi.org/10.1002/jpln.201600451.

Von Lützow, M., Kögel-Knabner, I., Ekschmitt, K., Matzner, E., Guggenberger, G., Marschner, B., Flessa, H., 2006. Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions — a review. Eur. J. Soil Sci. 57, 426–445. https://doi.org/10.1111/j.1365-2389.2006.00809.x.

Xiao, H., Li, Z., Chang, X., Huang, B., Nie, X., Liu, C., Liu, L., Wang, D., Jiang, J., 2018. The mineralization and sequestration of organic carbon in relation to agricultural soil erosion. Geoderma 329, 73–81. https://doi.org/10.1016/j.geoderma.2018.05.018.

Yilmaz, E., Çanakcı, M., Topakci, M., Sönmez, S., Ağsaran, B., Alagöz, Z., Çıtak, S., Uras, D.S., 2019. Effect of vineyard pruning residue application on soil aggregate formation, aggregate stability and carbon content in different aggregate sizes. Catena 183, 104219. https://doi.org/10.1016/j.catena.2019.104219.

Zanini, E., Bonifacio, E., Albertson, J.D., Nielsen, D.R., 1998. Topsoil aggregate breakdown under water-saturated conditions. Soil Sci. 163, 288–298. https://doi.org/10.1097/00010694-199804000-00004.