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Cover crops in viticulture. A systematic review (1): Implications on soil characteristics and biodiversity in vineyard

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ABSTRACT

This work seeks to synthesise the knowledge on the use of cover crops in vineyards in the last 20 years, emphasising on the one hand, soil characteristics such as nutrition, organic carbon, structure or erosion and, on the other hand, environmental factors such as soil and biodiversity in vineyards, and gas emissions.

A systematic review was made using Scopus-index journals for the past 20 years (1999 - 2018). The selection was independently done by two researchers, selecting a total of 272 published papers related to cover crops in the vineyard. Each article was categorised according to its theme and metadata were created, considering all relevant information from an agro-ecological point of view.

The use of cover crops has a positive effect on the vineyard by increasing soil organic carbon (SOC), improving water infiltration and aggregate stability, and reducing erosion and greenhouse gases emission to the atmosphere. Furthermore, there is an increase in biodiversity, both in soil and the vineyard. Finally, cover crops do not constitute as a rule a major competition for nutrients to the vines except for nitrogen when grass covers are used. Contrarily, legume cover crops generally increase N in the soil, although its availability for plants is not immediate.

This review constitutes an objective tool to help growers when considering the use of cover crops in vineyards that, based in a systematic review, provides relevant information depending on the characteristics of the growing condition of the vineyard.

KEYWORDS

nutrition, soil organic carbon (SOC), erosion, water infiltration, aggregate stability, greenhouse gases

INTRODUCTION

The planting schemes commonly used in viticulture, especially trellised systems, leave a large portion of the soil surface uncultivated. The management of this part of the soil has important effects on vegetative growth, yield, plant nutrition and water status, and grape and wine quality, and also on soil characteristics (nutrition, organic carbon, structure or erosion) and environmental factors (soil and vineyard biodiversity, gas emissions)

Although the management of vineyard soils through cover crops shows a growing trend worldwide, even in areas where their use was limited in the past due to lack of rainfall, it is very convenient to set the balance between the pros and cons. This is particularly relevant since there is a great diversity in what can be considered a “cover cropping” in a vineyard. According to their origin, cover crops can be sown or spontaneous. When sown, mixtures of species, but also monocultures, are broadly used, being those in *Fabaceae* (legume) and *Poaceae* (grasses) the most widespread ones. Related to this, cover crops can be also classified as annual or permanent, according to the cover crop duration. Variation also occurs with cover crop management, sometimes including harvesting or destruction with tilling or herbicide application. There is also a certain degree of variation in the fraction of the vineyard covered with the crop, which is usually established in the alleys, sometimes covering all the vineyard, and more exceptionally established just under the vines.

Considering all the diversity mentioned above, and taking into account that some additional factors certainly affect their impact in the vineyard, such as variation in climate, soil type, rootstock and irrigation use, it is very relevant to examine in detail the balance between their potential advantages and disadvantages in every situation. Although there are some comprehensive reviews in this issue (Garcia *et al.,* 2018; Steenwerth and Guerra, 2012) that provide interesting compiled information on the effect of cover crops in viticulture, none of them approaches to all the effect of cover crops or, if it does, it is not performed following a systematic process to identify and select research on this topic.

This work aims to compile and analyse, in a systematic way, the information available in recent literature on the effect of cover crops between the rows. Given the extension of the study, this information is presented as two companion papers, this one dealing with the aspects related to soil characteristics and environment-related issues, while a second paper (Abad *et al.,* 2021) analyses the direct impact of cover crops on vineyard performance.

PUBLISHED DATA SOURCING AND SELECTION

Although a standard or consensus definition of a systematic review does not exist (Krnic Martinic *et al.,* 2019), a systematic review is a review that reports or includes: (1) a research question, (2) sources that were searched, with a reproducible search strategy (naming of databases, naming of search platforms/engines, search date and complete search strategy) (3) inclusion and exclusion criteria, (4) selection (screening) methods.

In our case, we used the Scopus database as the source for extracting publications. The following search query was constructed and applied: TITLE-ABS-KEY (“cover crop” OR “green cover” OR “ground cover” OR “tillage”) AND TITLE-ABS-KEY (“wine” OR “*vitis*” OR “vineyard” OR “grapevine” OR “grape”), between the years 1999 and 2018. A total number of 584 published papers were obtained (search day: January 20th, 2019).

To these papers, the following exclusion criteria were applied, analysing their titles and abstracts:

- Books, conferences or papers that are not based on a specific experiment.
- Publications about crops different from vines.
- When there is no mention (not even indirect) of cover crops (“nor till”).
- Publications that refer to cover crops only as examples of organically managed vineyards, but not as the main objective of the study.
- Papers presenting results of modelling exercises, without experimental ground-truthing.
- Publications about table grapes.

The selection was independently completed by two people. Those articles excluded by both selectors were directly discarded, but those excluded just by one of the selectors were re-revised. After this process, there were 272 papers remaining.

These articles were categorised according to their theme, and the following metadata were extracted:

- Location
- Vineyard: scion variety and rootstock, planting pattern, age and vine formation
- Experiment duration
- Cover crop characteristics (sown or spontaneous, monoculture or crop mixture, species, cover crop and row management)
- Climate: an illustrative classification was performed; cold (average T below 12 °C), mild (average T between 12 and 15 °C) and warm climate (average T above 15 °C)
- Cultural practices: irrigation (yes/no) and fertilisation (yes/no)
- Soil: texture, organic matter percentage (% OM) and studied horizons

Additionally, all the information regarding the effect cover crops had had on any characteristic relevant from an agro-ecological point of view was extracted and considered for global analysis. In the following sections, the information related to soil characteristics and environmental aspects is presented, whereas a companion compiled and discussed the impact of cover crops on vineyard performance.

SOIL MINERAL COMPOSITION

Grapevine is not very demanding in terms of fertilisation, among other reasons, because the main objective frequently lies in the achievement of high-quality levels more than maximising grape production. However, nitrogen (N) is considered as an important element in grape growing, due to its relevance on vegetative growth and its leaching potential in nitric form in the soil. Other nutrients, such as potassium (K), influence fermenting grape juice. In general, it is perceived that cover crops can compete with vines for soil nutrients (Celette *et al.,* 2009; Steenwerth and Belina, 2008).

1. Nitrogen

The impact of cover crops on soil N content is analysed in 14 of the articles selected (Table 1), covering 40 different management strategies. In general terms, the use of legumes as a cover crop provides an increased amount of total N (Ntot = organic + mineral N), as well as of mineral N (Nmin) in the soil due to their role in fixing air nitrogen when legume roots have *Rhizobium* (Peoples *et al.,* 2009). On the contrary, grasses act as major soil N scavengers from the soil, reducing the Ntot content to a greater extent than other families.

TABLE 1. Total nitrogen (Ntot) and mineral nitrogen (Nmin) average content of the soil, grouped according to cover crop type/soil management. Prepared from the 14 mentioned articles and Table 2.

Soil management	Ntot (g/kg)	N data	Nmin (mg/kg)	N data
Grass	0.873	4	5.475	4
Grass + legumes	1.716	7	-	
Legumes	1.555	2	17.458	5
Spontaneous vegetation	1.062	5	7.43	1
Tillage control	1.193	4	7.515	2
Herbicide control	1.053	3	1.9	1
Herbicide + tillage control	0.935	2	-	

As mentioned above, the use of grasses as cover crops leads to decreased N levels in the soil as a general rule, this diminution being, as an average, around 25 % both Ntot and Nmin. This effect was reported in Varga *et al.* (2012), analysing the role of a spontaneous cover in Hungary, where an impact on vineyard yield was also shown. Commonly used grass cover crops in France (Celette *et al.,* 2009; Gontier *et al.,* 2014), barley cover crops in Turkey (Judit *et al.,* 2011) and La Rioja, Spain (Pérez-Álvarez *et al.,* 2013), and spontaneous or *Festuca arundinacea* cover crops in Italy (Mattii *et al.,* 2005) showed a reduction in soil N content. Occasionally, the observed N reduction could affect grape juice yeast assimilable nitrogen (YAN) (Pérez-Álvarez *et al.,* 2015b). Accordingly, Rodriguez-Lovelle *et al.* (2000) identified a soil N reduction with the use of a 2-year *F. arundinacea* cover crop in Montpellier, France, linked to a 30 - 50 % reduction in leaf N content. It was also observed that other factors than N competition could explain the N reduction, such as reduced soil moisture.

Celette *et al.* (2009) demonstrated that *F. arundinacea* and a 3-year-barley cover crop in Montpellier, France, resulted in an N decrease due to a reduced soil N mineralisation caused by low soil moisture levels. The reduced soil mineralisation was more pronounced in the driest years.

The same authors observed that a *Festuca* cover crop cutting at the beginning of May caused a reduction in the cover crop N uptake. However, an increase in N mineralisation potential was detected with the use of a *F. longifolia* and an 8-year spontaneous cover crop in La Rioja (Peregrina *et al.,* 2010). For their part, Klodd *et al.* (2016) did not observe N competition in the petiole due to the presence of a grass cover crop in cooler and more humid weather conditions (Virginia, USA). However, a 63 % reduction in the length of absorptive roots at 80 cm depth was shown, as well as a thin hair-root reduction of 49 % in the first 20 cm of soil. Mycorrhizal colonisation of the grapevines was unaffected (15 - 40 % of the radicular length) by the presence of the cover crop.

Concerning legume-based cover crops, they increased soil N content, this increase being, on average, around 30 % for Ntot and nearly 100 % for Nmin. (Fourie *et al.,* 2007; Messiga *et al.,* 2015; Ovalle *et al.,* 2007; Pérez-Álvarez *et al.,* 2015a; Sulas *et al.,* 2017). However, such N increase sometimes may not modify vine behaviour directly, as observed by Sulas *et al.* (2017), who estimated that only 10 % of the total 125 kg ha^{-1} $year^{-1}$N fixed by a *Medicago polymorpha* cover was used by the vines, and hypothesised that this limited absorption could be due to a combination of physical, chemical and microbiological processes.

2. Other elements

With respect to phosphorus (P), no significant differences have been generally detected on its availability when comparing the use of cover crops and tillage practices in adult vineyards (Biddoccu *et al.,* 2016; DeVetter *et al.,* 2015; Ferreira *et al.,* 2018; Mattii *et al.,* 2005; Pérez-Álvarez *et al.,* 2015a; Ruiz-Colmenero *et al.,* 2011). Grapevine nutritional status remained unaltered concerning P content when cover cropping, according to petiole analysis (Mattii *et al.,* 2005; Pérez-Álvarez *et al.,* 2015a). However, Klodd *et al.* (2016) observed a reduced P content on cover cropped vines. This reduction could be explained by a redistribution of the vine root system towards deeper less fertile soil layers, due to the competition between cover crop and vine roots.

Regarding soil potassium (K), the general trend observed is that cover crops did not affect content (Fourie *et al.,* 2007; Mattii *et al.,* 2005; Pérez-Álvarez *et al.,* 2015a; Pou *et al.,* 2011). Vineyard soil mulching, specifically straw mulch, tended to increase P and K content in soil samples (DeVetter *et al.,* 2015). In some cases, supplemental fertiliser applications to ensure cover crop growth could account for the increased soil P and K content (Ovalle *et al.,* 2007). However, cover crops could increase P losses compared to soil tillage, in case of sloppy vineyards when the fertiliser is not covered with the soil (Napoli *et al.,* 2017). On the other hand, P, K and magnesium (Mg) losses in sloped vineyards were 70 - 95 % higher under tillage than in the presence of cover crops, due to sediment transportation by surface runoff of water (Ruiz-Colmenero *et al.,* 2011; Vrsic *et al.,* 2011).

There is much less evidence on the effect of grass cover crops on recently established vineyards, though under some conditions it can promote vine growth at the beginning of the season, probably due to the presence of organic compounds in the cover crop rhizosphere. Nevertheless, at the end of the cycle, the effect becomes negative because of the high degree of competition for nutrients and water (Brunetto *et al.,* 2017).

SOIL ORGANIC MATTER

Cover crops increased soil organic carbon (SOC) accumulation in 13 out of the 19 articles selected (see Table 2). The increase observed in SOC was variable, depending on the cover crop type and its presence, both during the season and over the years.

A total of 16 grass cover crops increased SOC by an average of 68.5 % compared to the initial conditions. When legumes were grown as a cover crop, an average increase of 39.2 % was observed (9 cases in total). Finally, the data from 8 spontaneous cover crops, mainly composed of grass species, showed the most favourable results, with a 119.5 % increment in SOC content. In contrast, one of the analysed spontaneous cover crops caused a decline of 0.5 % in the SOC levels (Mattii *et al.,* 2005).

The temporal evolution of SOC in tilled vineyards is quite variable since in the 6 articles found measuring this evolution, in 2 of them it was observed to decrease (Peregrina, 2016; Pou *et al.,* 2011), in another 2 it was not affected (Belmonte *et al.,* 2016; Mattii *et al.,* 2005), while the remaining 2 (García-Díaz *et al.,* 2017; Peregrina *et al.,* 2010) showed an increased SOC content.

As an average, in tilled vineyards, an average increase of 4.05 % per year was observed. Similarly, the evolution of SOC in soils weeded chemically was variable, since in one of the studies it was observed to decrease (Belmonte *et al.,* 2018), whereas, in the other one, it increased (Celette *et al.,* 2009), being the average change of - 0.8 % per year.

The dynamics of SOC increase in cover cropped vineyards are slow, and, for instance, García-Díaz *et al.* (2016) reported that it took 5 years for the annual incorporation of a *Vicia faba* cover crop to increase SOC. Pou *et al.* (2011) observed a decrease in the SOC content with a spontaneous cover crop under deficit irrigation for 3 years in Mallorca, Spain. According to Belmonte *et al.* (2016), the increase in SOC content is not observed until the third year when a spontaneous grass cover crop was analysed in Italy. In other cases, the use of a *Brachypodium distachylon* cover crop led to a SOC increase during the first year (Marques *et al.,* 2010), while a rye cover crop did not show the same effect. A higher increase was shown when the cover crop included grasses (Messiga *et al.,* 2015), more than when they were only composed of legume (Table 2).

SOIL STRUCTURE

Altogether with the increase in SOC reported above, soil aggregate stability was also improved by the presence of cover crops when compared to tilled soils (Table 2). Such improvement required a relatively long period to appear. Thus, Belmonte *et al.* (2016) did not observe changes in aggregate stability until the third year of a spontaneous grass cover crop establishment, whereas Ruiz-Colmenero *et al.* (2013) detected an increase in SOC and aggregate stability from the second year onwards (30 % increase in aggregate stability compared to tillage). Under some circumstances, a direct interaction between soil microbial population and the development of more stable soil structure has been observed (Virto *et al.,* 2012). Cover crops have also been reported to increase meso- and macro-porosity (Ruiz-Colmenero *et al.,* 2013), or to enhanced pore connectivity and infiltration rates, even if pore size or volume remain unaltered (García-Díaz *et al.,* 2018). Pore connectivity and infiltration rates improved through better aggregate stability, although pore size or volume remained unaltered (García-Díaz *et al.,* 2018).

SOIL EROSION

The use of cover crops is directly associated with a considerable reduction in soil erosion. A number of 12 articles, comprising 29 different soil management practices, were selected for the systematic review (Table 3). As average figures, greater soil losses were detected in herbicide-treated (12 Mg ha^{-1} $year^{-1}$) and tilled control plots (11.4 Mg ha^{-1} $year^{-1}$). Grass cover crops (1.1 Mg ha^{-1} $year^{-1}$), mixtures of grass and legume (2.3 Mg ha^{-1} $year^{-1}$), spontaneous cover crops (2.4 Mg ha^{-1} $year^{-1}$) and legume cover crops (3.4 Mg ha^{-1} $year^{-1}$) were the treatments which showed higher erosion-reducing effects. Erosion rates did not directly match with runoff coefficients, that were higher in tilled control plots (21.8 %) compared to the use of grass cover crops (11.8 %) on average values. These data are biased by the results obtained in Gontier *et al.* (2014), where both the herbicide-treated control plot and grass cover crop vineyard showed a runoff coefficient of 34 %. Leaving this outlying data aside, the average runoff coefficient for grass cover crops would be 8.2 %, more in line with the observed erosion rates. This coefficient was 1.8 % (one single data) in grass or grass-legume mixtures, and around 8.7 % in case of spontaneous cover crops. There were no available data for legume cover crops.

Most of the studies evaluating the impact of cover cropping in erosion were performed in Mediterranean climate conditions (Table 3), where strong storms occur more frequently in the summer, showing that cover crops can play an important role on soil protection during this season (Bagagiolo *et al.,* 2018; Biddoccu *et al.,* 2015; Vrsic *et al.,* 2011). Nevertheless, attention should also be paid to erosion events occurring in autumn and winter. For instance, a study performed in Portugal, in an area where 1200 mm of annual rainfall concentrates in winter, showed the highest losses to occur at this time of year (Ferreira *et al.,* 2018). Similarly, in Sicily (Italy), Novara *et al.* (2013) observed that the autumn-winter rains resulted in greater runoff and the most severe erosion of the year; and also in Carpeneto, Italy, maximum runoff occurred in winter months, while most rainfall takes place in autumn (Biddoccu *et al.,* 2016). Factors that could explain this behaviour were the reduced cover crop density when the vegetative growth stops and the increased soil compaction due to the employed mechanical tillage practices.

TABLE 2. Initial and final soil organic carbon (SOC), final nitrogen (N) content in the soil and aggregate stability from analysed publications.

N	Location	Duration	Soil management	Cover type	Initial SOC (g/kg)	Final SOC (g/kg)	ΔSOC (%)	Final soil N Ntot (g/kg) Nmin (mg/kg)	Depth (cm)	Aggregate stability
1	Kreinbacher, Turkey	3	Tillage	CT	9.28			8.72 Nmin	0 - 30	
			Spontaneous vegetation	SV				7.43 Nmin		
2	La Caple, France	4	Herbicide + tillage	CTH	6.2	6.03	- 2.74	0.60 Ntot	0 - 15	
			Permanent cover *Festuca rubra*, *Lolium perenne*	G		8.55	37.9	0.71 Ntot		
3	Agugliano, Italy	7	Tillage (depth 5 - 8 cm)	CT		7.52		1.64 Ntot	0 - 50	
			Spontaneous vegetation	SV		8.32		0.93 Ntot		
4	Tokaj, Hungary	3	Tillage (4/ seasons)	CT				6.31 Nmin	0 - 30	
			Annual cover *Hordeum vulgare*	G				3.54 Nmin		
5	Montpellier, France	5	Herbicide	CH	7.5 - 8.7	8.58	5.93	0.78 Ntot	0 - 30	
			Permanent cover *Festuca arundinacea*	G		8.41	3.83	0.82 Ntot		
			Annual cover *Hordeum vulgare*	G		8.35	3.09	0.76 Ntot		
6	Santana do Livramento, Brazil	2	Herbicide	CH	10.7			0.52 Ntot	0 - 10	
			Spontaneous vegetation *Paspalum notatun*, *L. multiflorum*, *Bromus auleticu*, *Desmodium* spp., *Vicia sativa*	SV				0.50 Ntot		
7	Western Cape, South Africa	10	Herbicide	CH	1.3	1.28	- 1.54	7.28 Nmin	0 - 15	
			Annual cover *Secale cereale*	G		2.5	92.31	6.88 Nmin		
			Annual cover *Avena sativa*	G		1.69	30.0	6.23 Nmin		
			Annual cover *A. strigosa*	G		1.92	47.69	5.25 Nmin		
			Annual cover *Medicago truncatula*	L		1.92	47.69	19.45 Nmin		
			Annual cover *Ornithopus sativus*	L		2.1	61.54	13.31 Nmin		
			Annual cover *V. dasycarpa*	L		2.39	83.85	18.53 Nmin		
8	Mallorca, Spain	3	Tillage	T	13.3	12.8	- 3.76	1.8 Ntot		
			Permanent cover *Medicago* sp., *A. sterilis*, *Lotus ornithopodioides*, *Trifolium scabrum*, *Chrysanthemum coronarium*	GL		11.0	- 17.29	1.7 Ntot		
			Annual cover *T. resupinatum*, *M. truncatula*, *T. subterraneum*, *Dactylis glomerata*	GL		13.3	0	1.9 Ntot		
9	California, U.S.A.	5	Tillage	CT		0.01			0 - 15	
			Annual cover Triticale x Triosecale	G		0.01				
			Annual cover *S. cereale*	G		0.01				
10	Región Maule, Chile	2	Herbicide	CH		8.99		1.90 Nmin	0 - 20	
			Permanent cover *T. subterraneum*, *M. polymorpha*	L		10.8		21.9 Nmin		
			Permanent cover *T. subterraneum*, *T. michelianum*	L		9.92		14.1 Nmin		
11	California, U.S.A.	3	Herbicide	CH	21.7	19.28	- 11.15	1.86 Ntot	0 - 5	+
			Permanent cover *Vulpia myuros*, *B. hordeaceus*, *T. hirtum*, *T. pratenses*	GL		26.64	22.76	2.45 Ntot		
			Annual cover *Vicia faba*, *Pisum sativum*, *Triticum aestivum* or *S. cereale*	GL		17.75	- 18.2	1.70 Ntot		
12	Ligurian Apennines, Italy	3	Tillage	CT	5.0	5.0	0		0 - 5	+
			Spontaneous vegetation	SV		11.8	136.0			
13	Brunello di Montalcino, Italy	5	Tillage (3/season, depth 20 cm)	CT	9,45	9.45	0	1.1 Ntot	0 - 15	
			Spontaneous vegetation	SV		9.40	- 0.53	1.1 Ntot		
			Annual cover *T. subterraneum*	L		9.74	3.07	1.5 Ntot		
			Permanent cover *F. arundinacea*	G		12.76	35.03	1.2 Ntot		

14	Burgundy, France	10	Herbicide	CH		13.9			0 - 5	+
			Permanent cover clover	L		25.6				
			Permanent cover *Festuca* sp.	G		32.4				
15	Badajoz, Spain	1	Tillage (3/ season, depth 10 - 15 cm)	CT		1.68		0.23 Ntot	0 - 10	+
			Spontaneous vegetation *Elytrichia repens*, *F. arundinacea*, *Portulaca oleracea*	SV		13.70		0.64 Ntot		
16	Madrid, Spain	4	Tillage (2 - 3/ season, depth 15 cm)	CT	5.20 - 8.10	≈ 11.0	≈ 65.4		0 - 5	+
			Permanent cover *Brachypodium distachyon*	G		≈ 13.0	≈ 95.5			
			Spontaneous vegetation	SV		≈ 14.5	≈ 118.0			
17	La Rioja, Spain	4	Tillage (3 - 4/ season, depth 15 cm)	CT	5.39	≈ 6.5	≈ 20.6		0 - 5	+
			Spontaneous vegetation *B. mollis*, *H. marinum*, *Diplotaxis erucoides*, *Sonchus asper*, *Sonchus oleraceus*, *Veronica latifolia*, *Coniza canadensis*, *Papaver hibridum*	SV		≈ 17.5	≈ 224.7			
			Permanent cover *Festuca glauca*	G		≈ 20.0	≈ 271.1			
18	Madrid, Spain	2	Tillage	CT		9.8			0 - 10	
			Annual cover *S. cereale*	G		10.4				
			Permanent cover *Brachypodium distachyon*	G		10.5				
19	Traisen Valley, Austria	10	Annual legumes cover with tillage (5/season, depth 5 - 10 cm)	L		27.3		1.61 Ntot	0 - 10	
			Spontaneous vegetation	SV		35.2		2.14 Ntot		
20	Nueva Escocia, Canada	2	Tillage + herbicide (depth 10 cm)	CTH		15.57		1.27 Ntot	0 - 15	
			Annual cover *A. sativa*, *Pisum sativum*, *V. villosa*	GL		15.57		1.42 Ntot		
			Annual cover *A. sativa*, *T. pratense*	GL		17.21		1.42 Ntot		
			Permanent cover *Pheum pratense* (70 %), *T. hibridum* (15 %), *T. pratense* (15 %)	GL		17.21		1.42 Ntot		
21	La Rioja, Spain	10	Tillage (3 - 4/ season, depth 15 cm)	CT	< 11.6	≈ 6.0			0 - 2.5	
			Spontaneous cover	SV		≈ 22.0				
			Permanent cover *F. longiflora* - 4 years, *B. catharticus* - 6 years	G		≈ 15.0				
22	Navarra, Spain	1 - 5	Tillage	CT		9.15			0 - 5	+
			Permanent cover *F. arundinacea*, *L. multiflorum* - 1 year	G		15.7				
			Permanent cover *F. arundinacea*, *L. multiflorum* - 5 years	G		12.5				
23	Iowa, U.S.A.	7	Tillage	CT					0 - 7.6	+
			Herbicide	CH						
			Straw mulch	M						
			Cover *Festuca rubra*	G						
24	Madrid, Spain	3	Tillage	CT						+
			Annual cover *S. cereale*	G						
			Permanent cover *Brachypodium distachyon*	G						

1: Varga *et al.* (2012); 2: Gontier *et al.* (2014); 3: Agnelli *et al.* (2014); 4: Judit *et al.* (2011); 5: Celette *et al.* (2009); 6: Brunetto *et al.* (2017); 7: Fourie *et al.* (2007); 8: Pou *et al.* (2011); 9: Steenwerth and Belina (2008); 10: Ovalle *et al.* (2007); 11: Belmonte *et al.* (2018); 12: Belmonte *et al.* (2016); 13: Mattii *et al.* (2005); 14: Bartoli and Dousset (2011); 15: López-Piñeiro *et al.* (2013); 16: García-Díaz *et al.* (2018); 17: Peregrina *et al.* (2010); 18: Marques *et al.* (2010); 19: Zehetner *et al.* (2015); 20: Messiga *et al.* (2015); 21: Peregrina (2016); 22: Virto *et al.* (2012); 23: DeVetter *et al.* (2015); 24: Ruiz-Colmenero *et al.* (2013).

N: number-author reference; Duration: years since cover crop establishment; Initial SOC: soil organic carbon at the beginning of the experiment; Final SOC: soil organic carbon at the end of the experiment; ΔSOC: variation between final SOC and initial SOC; Depth: sampling depth; Cover type: CT, tillage control; CH: herbicide control; CTH: tillage + herbicide control; G: grass; GL: grass + legume; L: legume; SV: spontaneous vegetation; M: mulch; Ntot: total N (organic N + mineral Nitrogen).

TABLE 3. Summary of runoff coefficients, soil erosion losses and vineyard description from analysed articles.

N	Location	AP (mm)	Slope (%)	Duration	Soil management	Cover type	C (%)	Annual erosion (Mg/ha-year)
1	Toscana, Italy	695	4 - 30	8	Tillage (1/ season)	CT	9.4	8.59
					Spontaneous vegetation	SV	8.3	7.78
2	La Caple, France	583	10	4	Herbicide	CH	34.0	≈ 12.0
					Permanent cover *Festuca rubra*, *Lolium perenne*	G	34.0	≈ 0.7
3	Champagne, France	757	5 - 7	7	Tillage	CT	80.0	
					Permanent cover *Lolium* sp.	G	0.4 - 77 (18.8 years average)	
4	Maribor, Slovenia	1045	34	5	Tillage alternately	CT		1.89
					Spontaneous vegetation	SV		0.09
5	Piemonte, Italy	905	15	14	Tillage (Depth 25 cm)	CT	27.1	12.3
					Permanent cover grass	G	9.6	2.2
6	Piemonte, Italy	965	15	12	Tillage (Depth 25 cm)	CT	17.4	10.4
					Tillage (Depth 15 cm)	CT	15.3	24.8
					Spontaneous vegetation	SV	10.3	2.3
7	Abruzzo, Italy		21	3	Tillage (2 - 3/ season)	CT	5.6	
					Annual cover *Hordeum vulgare* (60 %), *Vicia faba* (40 %)	GL	1.8	
8	Piemonte, Italy	849	15	14	Tillage (Depth 25 cm)	CT	18.0	7
					Tillage (Depth 15 cm)	CT	16.0	20.7
					Spontaneous vegetation	SV	10.0	1.8
9	Sicilia, Italy	589 ± 175	15.9	10	Tillage (3 - 4/season, depth 15 cm)	CT		8
					Annual cover *V. faba*	L		4.8
					Annual cover *V. faba*, *V. sativa*	L		2
					Permanent cover *Trifolium subterraneum*, *F. rubra*, *L. perenne*	GL		2.7
					Permanent cover *T. subterraneum*, *F. rubra*, *F. ovina*	GL		1.9
					Annual cover *Triticum durum*	G		3.5
					Annual cover *T. durum*, *V. sativa*	GL		2.4
10	Madrid, Spain	400	7 - 13.5	2	Tillage (3/season, depth 20 cm)	CT	28.0	
					Permanent cover *Brachypodium distachyon*	G	15.8	
					Spontaneous vegetation	SV	9.2	
11	Piemonte, Italy	850	15	10	Tillage (Depth 25 cm)	CT	21.0	11.15
					Tillage (Depth 15 cm)	CT	19.0	20.70
					Spontaneous vegetation	SV	14.0	2.60
12	Madrid, Spain	386	8 - 14	2	Tillage (3 - 4/ season)	CT	4.6	0.008
					Permanent cover *Brachypodium distachyon*	G	0.9	0.001
					Annual cover *Secale cereale*	G	1.1	0.002
					Annual cover *H. vulgare*	G	2.7	0.003
					Spontaneous vegetation	SV	0.3	0.002

1: Napoli *et al.* (2017); 2: Gontier *et al.* (2014); 3: Morvan *et al.* (2014); 4: Vrsic *et al.* (2011); 5: Bagagiolo *et al.* (2018); 6: Biddoccu *et al.* (2015); 7: Ramazzotti *et al.* (2008); 8: Biddoccu *et al.* (2016); 9: Novara *et al.* (2011); 10: García-Díaz *et al.* (2017); 11: Biddoccu *et al.* (2014); 12: Ruiz-Colmenero *et al.* (2011);

N: number-author reference; AP: average annual precipitation; Duration: in years since the beginning of the experiment; C: runoff coefficient.

Rainfall erosivity was also related to the topography of the vineyard. In Italy, Bagagiolo *et al.* (2018) observed that high-intensity rains (> 16 mm hour - 1) in 15 to 35 % sloped vineyards resulted in higher soil losses when vines were planted along contour lines. On the contrary, in vineyards disposed following the maximum slope line, long-duration rainfall events (> 50 hours) caused the highest soil loss.

The effectiveness of cover crops in the control of soil losses also depends on plant cover duration. The continuous presence of perennial cover crops showed reduced erosion rates compared to temporal plant covers that are mowed in spring (Ruiz-Colmenero *et al.,* 2011; Usón *et al.*, 1998).

Legume-based cover crops showed different effectiveness in controlling soil erodibility. A smaller erosion-reducing effect was associated with a *Vicia faba* annual cover crop in Sicily compared to a mixture of legume species or grass-legume mixtures, probably due to its lower biomass production (Novara *et al.,* 2011). Soil aggregate stability was found to be an important parameter affecting soil erosion (Ruiz-Colmenero *et al.,* 2013), but soil type could also account for reduced soil losses. In this sense, (García-Díaz *et al.,* 2016) observed that silty soils were more prone to erosion.

The effect erosion had on soil loss was accompanied by carbon and nutrient losses, dragged through soil particles. This fact was reported for K, P and N (both as ammonium and nitrates) in Biddoccu *et al.* (2016) and Ferreira *et al.* (2018), whereas García-Díaz *et al.* (2017) observed N losses occurring as nitrates while ammonium remained unaltered.

SOIL BIODIVERSITY

The use of cover crops results as a general rule in a remarkable increase in soil microbial diversity (Table 4). The enhanced soil microbial biomass and activity associated to cover crops is majorly concentrated in soil top layers (0 - 5 cm), mainly as a consequence of the increase in SOC content mentioned above. In particular, it is the particulate organic matter C which most relevantly increases nutrient availability to microorganisms (Agnelli *et al.,* 2014; Belmonte *et al.,* 2018; García-Díaz *et al.,* 2018; Peregrina *et al.,* 2010; Peregrina *et al.,* 2014).

In this regard, López-Piñeiro *et al.* (2013) observed an improvement in soil microbial amount and biodiversity after a 6-year natural vegetation management regime in Spain. Soil microbial activity, measured separately for different groups of yeasts and bacteria, was positively affected by the presence of a spontaneous cover crop during 5 years (Peregrina *et al.,* 2014). Zehetner *et al.* (2015) observed an increased SOC content with a dense grass cover compared to tillage which showed a positive influence on soil microorganisms.

The response of fungi and bacteria to the changes in soil management strategies is not the same, Likar *et al.* (2017) observing that bacteria were more sensitive to them. In a long term experiment (22 seasons), where the incorporation of the cover crop into the soil was done either every year or just mown, microbial activity was observed to be favoured by mowing (Belmonte *et al.,* 2018). Even distance between rows seemed to influence soil microorganisms. A distance of 70 cm of the grapevine row showed higher microbial activity than a 120 cm distance, regardless of the cover crop species (grasses, legumes or brassicas) (Mackie *et al.,* 2014).

Regarding earthworm populations, a three-fold increase in the number of individuals has been associated to cover crop inclusion in the management system and, conversely, a decrease is observed linked to herbicide applications (Vrsic *et al.,* 2011). Last, in a study comparing the influence of soil management on springtail species, tillage was observed not to affect their diversity, although there was a relevant decrease in the densities of the biggest species (Buchholz *et al.,* 2017).

BIODIVERSITY IN VINEYARD

The implication of cover crops on arthropods, small mammals and bird populations were analysed in 24 of the articles selected. In 72 % of the cases considered, cover crops increased the presence of species acting as natural enemies for vineyard pests. In particular, the *Hymenoptera* population increased in 86 % of cases, minute pirate bugs (*Anthocoridae*) in 80 %, spiders in 40 % and mites, as well as thrips (*Aeolothripidae*), in 100 % of cases. The diversity and density of pollinator insects, birds and small mammals also increased in all cases (Table 4).

Increasing plant biodiversity through cover crops was observed to cause a positive effect on the bee population. A study performed in California evaluated bee response to the use of different summer flowering cover crops

TABLE 4. Collection of data from articles that study the influence of cover crops in vineyards on arthropods and vertebrates. *Control treatment.

N	Location	Soil management	Cover type	Climate	Irrigation	Duration	Arthropods
1	Douro Region, Portugal	Spontaneous vegetation	SV	M		1	
2	Córdoba, Spain	*Avena sativa* (70 %), *Vicia sativa* (30 %)	GL	W		1	
3	France	Bared soil*/ Spontaneous vegetation	C/SV	M		2	
4	Douro Region, Portugal	Spontaneous vegetation	SV	M		1	
5	Barrosa, Australia	*A. sativa**/ *Austrodanthonia richardsonii*/ *Chloris truncata*/ *Atriplex* sp.	CG/G/G/O	M	Y	2	+
6	Zadar, Croatia	Tillage*/ Spontaneous vegetation	CT/SV	M		1	+
7	Modena, Italy	Grass*/ *Lobularia maritima*/ *Phacelia tanacetifolia*/ *Fagopyrum esculentum*/ *V. faba*/ *A. sativa*	CG/O/O/O/L/G	M		3	+
8	Geneva Canto, Switzerland	Herbicide*/ Spontaneous vegetation/ *Festuca rubra*, *Trifolium repens*/ *T. repens*, *Lotus corniculatus*	CH/SV/GL/GL	C		1	
9	New York County, U.S.A.	*Dactylis glomerata**/ *F. esculentum*/ *T. repens*	CG/O/L	C		2	
10	Nîmes, France	Tillage*/ Herbicide*/ Spontaneous vegetation	CT/CH/CV	M		2	
11	Zagreb, Croatia	*Agrostis alba*, *D. glomerata*, *F. rubra*, *Poa pratensis*, *L. corniculatus*, *T. repens*	GL	C		2	+
12	California, U.S.A.	Tillage*/ *F. esculentum*	CT/O	W	Y	1	
13	Valais, Switzerland			C		4	
14	California, U.S.A.	*Helianthus annuus*, *F. esculentum*	O	W		2	
15	Marche, Italy	Tillage*/ Tillage, herbicide*/ Spontaneous vegetation	CT/CTH/SV	M		2	
16	Malaga, Spain	Tillage*/ Spontaneous vegetation	CT/SV	W	Y	1	
17	California, U.S.A.	Tillage*/ *P. tanacetifolia*, *Ammi majus*, *Daucus carota*/ Spontaneous vegetation	CT/O/SV	W	Y	1	
18	California, U.S.A.	Tillage*/ *F. esculentum*	CT/O	W	Y	1	+
19	New South Wales, Australia	Tillage*/ Spontaneous vegetation/ *Brassica juncea*, *Borago officinalis*, *Coriandrum sativum*, *F. esculentum*, *L. maritima*	CT/SV/O	W		1	
20	California, U.S.A.	Untreated*/ Tillage/ Herbicide/ *Bromus carinatus*	CU/T/H/G	W	Y	2	-/=
21	California, U.S.A.	Tillage, spontaneous vegetation alternately*/ *P. tanacetifolia*, *A. majus*, *D. carota*	T, SV/O	W	Y	2	+
22	California, U.S.A.	Tillage*/ *H. annuus*, *F. esculentum*	T/O	W		2	
23	Melbourne, Australia	Adjacent vegetation	O	M		1	
24	Auckland, New Zealand	*T. subterraneum*/ *T. repens*/ *T. incarnatum*/ *T. fragiferum*	L	GH			

1: Gonçalves et al. (2017); 2: Barrio et al. (2012); 3: Vogelweith and Thiéry (2017); 4: Gonçalves et al. (2018); 5: Danne et al. (2010); 6: Franin et al. (2016); 7: Burgio et al. (2016); 8: Pétremand et al. (2017); 9: English-Loeb et al. (2003); 10: Renaud et al. (2004); 11: Barić et al. (2008); 12: Irvin et al. (2018); 13: Buehler et al. (2017); 14: Nicholls et al. (2000); 15: Minuz et al. (2013); 16: Duarte et al. (2014); 17: Wilson et al. (2018); 18: Irvin et al. (2016); 19: Begum et al. (2006); 20: Sanguankeo and León (2011); 21: Wilson et al. (2017); 22: Nicholls et al. (2008); 23: Smith et al. (2015); 24: Sandanayaka et al. (2018);

N	Hymenoptera		Anthochorini		Cicadellidae		Spiders		Mites		Thrips		Others		
1							=	NE(D)					+ / =		Ants
2													+	P	Rabbits
3					-	P			-/ +	PL, NE(D)			=	NE	*Phalangium opilio*
4													+		Predators
5											+	NE (D)	+	NE	Dermaptera, tiphiidae
6			+				=						-		Coleoptera
7	+	NE (PP)							+	NE(D)					
8													+		Syrphidae
9	+	NE (PP)													
10													+		Collembola
11															
12			+	NE			+	NE			+	NE (D)			
13													+		Woodlark
14	+	NE (PP)	+	NE (D)	-	P					-	P	+	NE (D)	Coccinellidae, *Chrysoperla*
15													=	P	Disease vectors
16													+		Passerine birds
17													+		Bees
18											+	NE (D)			
19	+	NE (PP)											+ / =	P	*Epiphyas postvittana*
20															
21	=		+	NE	=	P	+	NE							
22	+	NE (PP)	=	NE	-	P							=	NE	Coccinellidae, syrphidae
23	+	NE (PP)													
24														NE	*Pseudococcus calceolariae*, *P. longispinus*

N: number-author reference; Duration: in years since the beginning of the experiment; C: cold climate (average T > 12 °C); M: mild climate (average T 12 - 15 °C); W: warm climate (average T < 15 °C); *: Control management; GH: green house; Cover type: CT, tillage control; CH: herbicide control; CTH: tillage + herbicide control; CU: Untreated control; T: Tillage; G: grass; GL, grass + legume; L: legume; SV: spontaneous vegetation; O: other cover crop group; PE: pest; NE: pest natural enemy; (D): predatory of pests; (PP): parasitic of pests.

(*Phacelia tanacetifolia*, *Ammi majus*, *Daucus carota*) compared to tilled soils and natural vegetation (Wilson *et al.,* 2018). The study revealed that diversity and abundance of wild bees were increased with the cover crops composed of flowering species.

The presence of cover crops favoured vertebrate abundance in comparison with that in bare soils. Buehler *et al.* (2017) observed that woodlarks prefer nesting in cover cropped plots, particularly in fields with taller and denser ground covers. Besides, nest predation risk was lower in the presence of cover crops. The abundance and diversity of passerine birds were higher in vineyards with herbaceous cover crops than in those under conventional management (bare soil and soil tillage) (Duarte *et al.,* 2014). An increase in the rabbit population in vineyards due to the presence of cover crops has also been reported (Barrio *et al.,* 2012).

In general, the number of natural enemies increased with the introduction of cover crops, though this variation in the natural enemies did not have a direct effect on pests in all studies (Danne *et al.,* 2010; Irvin *et al.,* 2016). One of the best studies of natural enemy groups is *Hymenoptera*, for which there are different examples of parasitoids which increase when cover crops are used. The presence of *Anagrus*, egg parasitoids of *Cicadellidae*, increased with cover cropping (Begum *et al.,* 2006; Centinari *et al.,* 2016; English-Loeb *et al.,* 2003; Nicholls *et al.,* 2008, 2000; Smith *et al.,* 2015) and *Erythroneura* (*Cicadellidae*) population, in turn, decreased. The only exception found to this behaviour is an experiment performed in California, where the presence of cover crops did not affect *Anagrus* (Wilson *et al.,* 2017). The parasitism rate of *Epiphyas postvittana* (pest) and *Trichogramma carverae* (parasite) was also increased. In this study, the presence of a sown cover crop had the strongest effect on parasitism rate, in comparison to a spontaneous cover crop or tilled soils. However, some sown cover crops, such as *Lobularia marítima*, provided higher longevity for the pest than spontaneous cover crops or tillage, and there were no differences in *Borago officinalis* and *Fagopyrum esculentum* covers compared to control plots (Begum *et al.,* 2006).

The difference between sown cover crops and spontaneous vegetation was the presence of flowers. Some authors pointed to a link between parasitism rate increase and higher availability of floral nectar as a source of nutrition. English-Loeb *et al.* (2003) compared *Anagrus* longevity and parasitism rate of *Erythroneura* spp. in a laboratory study. Both parameters were greater when adults had access to flowering *Fagopyrum esculentum* rather than plants without flowers. Moreover, the longevity of *Anagrus* was increased when provided with honey or sugar water compared to water only.In field experiments, it was also observed that the rate of parasitism increased (Daane *et al.,* 2018; Nicholls *et al.,* 2008) or remained unaltered (Nicholls *et al.,* 2000) when cover crops were established.

Regarding arachnid populations, the effect of cover crops was highly variable. In some cases, the presence of cover crops led to a decrease in spider populations (Daane *et al.,* 2018), maintained them unaltered (Franin *et al.,* 2016; Gonçalves *et al.,* 2017), or caused an increase (Irvin *et al.,* 2018; Wilson *et al.,* 2017) in spiders known to be predators of pest insects. Cover crop management enhanced predatory mite densities (Burgio *et al.,* 2016). In France, an increase in the number of individuals of the predatory mite *Typlodromus pyri* was observed, while the number of the mycophagus mite *Orthotydeus lambi* and the pest mite *Panonychus ulmi* decreased in cover cropped vineyards (Vogelweith and Thiéry, 2017).

A positive response of predatory thrips (spiders, *Nabis* sp., *Orius* sp., *Geocoris* sp., *Coccinellidae* and *Chrysperla* sp.) to cover cropping has also been observed, while reduced densities of western flower thrips pest (*Frankliniella occidentalis*) have been reported in cover-cropped plots (Nicholls *et al.,* 2000).

The presence of natural enemies in the cover crop does not mean that they will be present in the vines themselves. Gonçalves *et al.* (2018) showed that, although predators could colonise the vineyard, it is more probable that they feed primarily on vineyard pests that spend part of their life cycle on the ground or use plants from ground cover as alternative hosts. With this regard, the abundance of grape pests has been reported to be higher on grape leaves compared to their presence on the cover crop itself, while the presence of beneficial insects was higher on cover crop (Irvin *et al.,* 2016). Concerning the impact of the presence of cover crops, it has been observed that the increase in the populations of natural enemies of a cover cropped with respect to a tilled one is greater on the ground than on the grapevine canopy (Wilson *et al.,* 2017).

Cover crop mowing could be an effective tool to increase the abundance of natural enemies on vine canopy. In California, Nicholls *et al.* (2008) showed that numbers of leafhoppers declined in vines when the cover crop was mown, while the cutting of the cover crop vegetation increased *Anagrus* densities on the vines, especially one week after mowing.

The presence of natural enemies is also influenced by cover crop types. When three native cover crops were compared to a sown *Avena sativa* control in Australia, the abundance of arthropods, predators and parasitoids as well as potential pests, was observed to be higher in all native cover crops (Danne *et al.,* 2010). The comparison of sown and spontaneous cover crops generated varied results. Regarding *Anagrus* parasitism rate, in an experiment in Italy, it was higher in sown cover crops (Muscas *et al.,* 2017) than in spontaneous covers. However, under these conditions, an increase in the abundance and biodiversity of syrphids was observed in spontaneous vegetation compared to sown cover crops (Pétremand *et al.,* 2017).

SOIL GAS EMISSIONS

Like most economic sectors, agriculture contributes to greenhouse gas (GHG) emissions. However, agriculture can also participate as a sink for gas emission storage by means of carbon sequestration in the soil. As the use of cover crops increases SOC, the installation of a cover crop can contribute to mitigating CO_2 emissions.

In a comparative study of spontaneous and *Hordeum vulgare* cover crops, the emissions were higher after tillage than in mown treatments where plant biomass was incorporated to the soil (Steenwerth *et al.,* 2010). In the same way, Bogunovic *et al.* (2017) observed that higher CO_2 emissions were found in annual tillage treatment compared to tilling the soil every two years. Lower emissions were observed under continuous no-tillage treatment, indicating that the cover crop management has more influence on CO_2 emissions than the cover crop itself. When the cover crop was annually mown and tilled, a C loss was observed, while a barley cover crop under minimum tillage (superficial tillage every two years) accumulated 1.12 Mg CO_2 ha^{-1} $year^{-1}$ (Steenwerth *et al.,* 2010). However, higher N_2O emissions were detected when leguminous cover crops were mowed and left on the soil surface, under the row or between lines, compared to the incorporation of residues into the soil via conventional tillage (Garland *et al.,* 2011), although these increased emissions relate to the nitrogen that had been previously fixed by the cover crop from the atmosphere.

The dynamics of C sequestration and emission change along the season in cover-cropped vineyards, and at some points, due to their higher biological activity, increased emissions when the soil is moist (Peregrina, 2016; Steenwerth *et al.,* 2010). Nevertheless, on a yearly or long-term basis, the presence of cover crops contributes very actively to C sequestration through the increase in SOC.

CONCLUSIONS

The systematic review performed has allowed a complete synthesis of the knowledge generated in the last two decades regarding the influence of cover crops on soil characteristics and biodiversity in vineyards. This first part is focused on soil characteristics and environment-related issues, whereas their effect on agronomic performance will be presented in the second part of this work.

As part of this wide-scope analysis, it can be concluded that using cover crops has a positive effect on increasing SOC and thus in reducing greenhouse gases in the atmosphere. Covers crops do not, in general, constitute a major competition for nutrients to the vines except for nitrogen when grass covers are used. On the contrary, legume cover crops generally increase N in the soil, although the availability of this for plants is not immediate.

Cover crops improve aggregate stability and reduce erosion. Likewise, there is an increase in biodiversity, both in soil biodiversity and activity, as well as in populations of arthropods, birds and small mammals.

Both the SOC increases in the long run and the erosion reduction are greater when the cover is formed by grasses, the results being more variable when the used cover is formed by legumes.

There are other aspects where the implication of establishing a cover crop is more variable, generally affected by soil and climate characteristics. This review constitutes a tool that can help to have a preliminary idea on what could happen under certain growing conditions, as peer-reviewed scientific literature has been revised, and some characteristics of the vineyards studied in each article are provided.

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