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Cover crops in viticulture. A systematic review (2): Implications on vineyard agronomic performance

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ABSTRACT

The present systematic review aims to provide an overview of the impact of cover crops on vegetative growth and the productive parameters of vineyards.

A systematic review was made on Scopus-index journals dating from 1999 to 2018. The selection was made at the same time by two different researchers, who selected a total of 272 published papers related to cover crops in vineyards. Each article was categorised according to its theme and a metadata database was created, considering all relevant information from an agronomic point of view for each article.

It can be concluded from the review that the use of cover crops can reduce vine vegetative growth, which in turn can help keep the incidence of fungal diseases (like grey mould) at a low level. In general, this practice does not have a clear effect on vineyard yield or grape juice parameters, like total soluble solids (TSS) or titratable acidity (TA). Cover crops can decrease vineyard pests to a certain extent, especially *Cicadellidae*. Cover crops can sometimes sporadically cause water stress in the vineyard, but only during the summer months.

This review allowed us to summarise available information on cover crops and their effects on vineyard agronomic performance in a systematic way. Such information can be used to help select the most suitable cover, based on specific vineyard objectives and growing conditions.

KEYWORDS

Vitis vinifera L., yield, water status, grape composition, pest and disease

INTRODUCTION

Cover crops are one of the most appealing options for soil management in vineyards, because- as was shown in our companion paper (Abad *et al.,* 2021) - they increase soil organic carbon, improve water infiltration and aggregate stability, reduce soil erosion and greenhouse gas emissions, and increase biodiversity in the vineyard. Nevertheless, as vines and cover crops coexist in the same space, they compete for nutrients and water at certain moments in the season, which can directly affect vineyard performance. Such competition can result in changes to shoot growth and leaf activity, which in turn can seriously affect shoot fertility, fruit set, berry development, susceptibility to pests and diseases, yield, and grape composition (Ibañez Pascual, 2013).

The intensity and implications of the aforementioned effects depend highly on many factors, such as cover crop features, soil type, climate and other vineyard characteristics. We therefore carried out a systematic review of research results obtained in recent decades to determine the main agronomic effects of cover crops in vineyards and the factors that modulate them. In this article, the second part of the review results is presented; only nutrition was included in the first part, as it was considered to be highly linked to other soil processes described therein.

PUBLISHED DATA SOURCING AND SELECTION

The methodology applied for this systematic review is detailed in the article, "Cover crops in viticulture. A systematic review (1): implications on soil characteristics and vineyard biodiversity" (Abad *et al.,* 2021). In short, a systematic review can be defined as including (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, and (4) selection (screening) methods (Krnic Martinic *et al.,* 2019). As such, the main features of the systematic review we performed on the implication of cover crops in vineyards are summarised below.

The Scopus database was used, with search query 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"). A total number of 584 published papers were obtained (search day: 20 November 2018). Two people worked independently from each other on the selection process in several steps with a final number of 272 papers being selected. The following data were extracted from the selected papers:

- Location
- Vineyard: scion variety and rootstock, planting frame, age and vine training
- 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 (annual average T^a below 12 ºC), mild (annual average T^a between 12 and 15 ºC) and warm climate (annual average T^a above 15 ºC)
- Cultural practices: irrigation (yes/no) and fertilisation (yes/no)
- Soil: texture, organic matter percentage (% OM) and studied horizons

The following sections provide information related to vineyard agronomic performance, whereas the aforementioned companion paper outlined soil characteristics and environmental aspects. Both papers together are a compilation of most of the factors that should condition the choice of soil management in a vineyard. It should be noted that other factors, such as spring frost risk, the necessity of soil amendments once the vineyard is established, or risk of excessive competition with young vines, need to be considered before choosing cover crop as the best solution; however, they were not considered in the systematic review as information on them was not available in the selected papers.

VEGETATIVE DEVELOPMENT

Ensuring optimal vegetative development is one of the key issues for successful grape growing, with a balanced number and disposition of leaves being required. Although minimum leaf development is required to guarantee carbohydrate supply to all plant organs, excessive growth can be detrimental, as it may cause reduced fruit set (Dardeniz *et al.,* 2008; Parker *et al.,* 2016), increased susceptibility to fungal diseases (Valdés-Gómez *et al.,* 2011) and delayed ripening (Smart *et al.,* 2017).

Therefore, it is of great interest to determine the ways in which cover crops can impact vine growth.

The effect of cover crops on vine vegetative growth – mostly evaluated by pruning weight measurement - was analysed in 51 of the selected articles. None of these articles reported that an increase in vegetative development was associated with the introduction of a cover crop, and only 3 studies (6 % of the cases) showed no changes in pruning weight due to its presence. Thus, the use of cover crops mostly caused a reduction in growth (Table 1). However, in 23 articles (45 %) the reduction in pruning weight was relatively small (by < 20 %), while in the remaining 25 articles (49 %) this reduction was > 20 %. When the potential impact of climate conditions was analysed (Figure 1), it was observed that vineyards in warmer regions showed a more pronounced decrease in growth than those in cooler areas.

TABLE 1. Impact of cover crop on vine vegetative growth (pruning weight) compared to tilled or to herbicide applied in the row.

				No trend				
1	Costello (2010b)	=	2	Jordan *et al.* (2016)	=	3	Wilson *et al.* (2017)	=
				Slightly negative				
4	DeVetter *et al*. (2015)	+(T)/-	12	Karl *et al.* (2016)**	=/--	20	Ingels *et al.* (2005)*	-(T)/--
5	Krohn and Ferree (2004)	+(T)/--	13	Smith *et al.* (2008)	=/-	21	Reynolds *et al.* (2006)**	-(T)/--
6	Sweet and Schreiner (2010)*	+(T)/--	14	Klodd *et al.* (2016)	- (T)	22	Ripoche *et al.* (2011)*	- (T)/--
7	Tourte *et al.* (2008)	=/-(T)	15	Steenwerth *et al.* (2016)	- (T)	23	Giese *et al.* (2016)	-
8	Lopes *et al.* (2008)	=/--	16	Coniberti *et al.* (2018a)	- (T)/-	24	Steenwerth *et al.* (2013)	-
9	Mercenaro *et al.* (2014)	=/-	17	Monteiro and Lopes (2007)	- (T)/-	25	Vrsic *et al.* (2011)	-
10	Pérez-Álvarez *et al.* (2015b)	=/-	18	Muscas *et al.* (2017)*	- (T)/-	26	Pérez *et al.* (2018)	-/--
11	Trigo-Córdoba *et al.* (2015)	=/-	19	Tomaz *et al.* (2015)	- (T)/-			
				Negative				
27	Rodriguez-Lovelle *et al.* (2000b)	+(T)/---	36	Palliotti *et al.* (2007)	--	45	Coletta *et al.* (2013)	---
28	Delpuech and Metay (2018)*	=/--	37	Pou *et al.* (2011)*	--	46	Coniberti *et al.* (2017)	---
29	Reeve *et al.* (2016)	-/---	38	Valdés-Gómez *et al.* (2011)	--	47	Gontier *et al.* (2014)	---
30	Coniberti *et al.* (2018b)	--	39	Caspari *et al.* (1997)	--/---	48	Hatch *et al.* (2011)	---
31	De Pascali *et al.* (2014)	--	40	Guilpart *et al.* (2017)	--/---	49	Olmstead *et al.* (2012)	---
32	Giese *et al.* (2015)	--	41	Mattii et al. (2005)	--/---	50	Toci *et al.* (2012)	---
33	Hickey *et al.* (2016)	--	42	Muganu *et al.* (2013)	--/---	51	Wheeler *et al.* (2005)	---
34	Linares Torres *et al.* (2018)	--	43	Rodriguez-Lovelle *et al.* (2000a)**	--/---			
35	Lopes *et al.* (2011)	--	44	Silvestre *et al.* (2012)	--/---			

= denotes does not affect, no clear trend; – (T)/+(T) denotes reduction trend/general increase; -/+ denotes difference in reduction/increase lower than 20 %; --/++ denotes difference in reduction/increase between 20 and 40 %; ---/+++ denotes difference in reduction/increase higher than 40 %; * denotes differences among treatments in one or more years; ** denotes differences among controls in one or more years.

The most drastic effect was observed in four studies, in which pruning weight reduction was shown to exceed 60 % (Coletta *et al.,* 2013; Gontier *et al.,* 2014; Olmstead *et al.,* 2012; Rodriguez-Lovelle *et al.,* 2000a). The most extreme growth diminution was observed in Olmstead *et al.* (2012): the cover crop had been established at the time of vineyard planting and the reduction was between 70 and 90 %.

Nine experiments showed reductions in pruning weight of over 40 %, and, quite remarkably, in 5 of them the rootstock was SO4 (Coletta *et al.,* 2013; Coniberti *et al.,* 2018a; Coniberti *et al.,* 2017; Toci *et al.,* 2012; Wheeler *et al.,* 2005). The predominant cover crop species in these experiments was perennial *Festuca rubra* (Coletta *et al.,* 2013; Gontier *et al.,* 2014; Toci *et al.,* 2012),

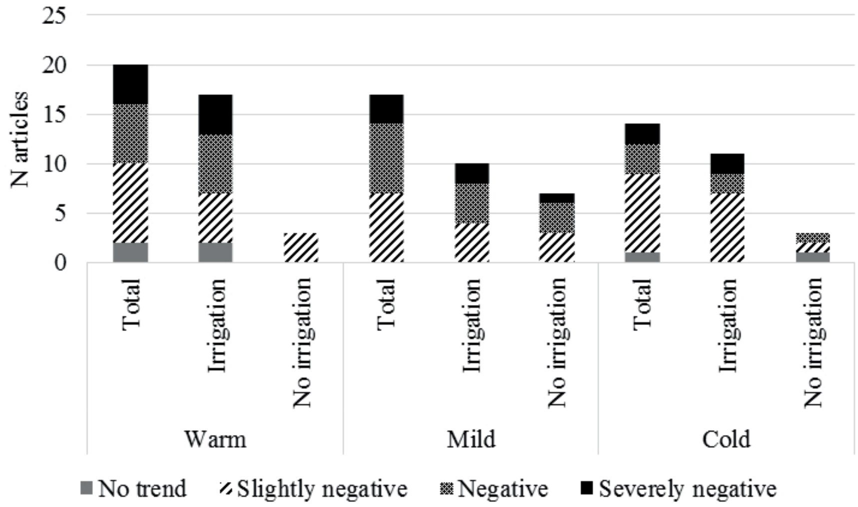

FIGURE 1. Effect of cover crop use on vine vegetative growth (pruning weight) according to climate and irrigation management.

Festuca arundinacea (Coniberti *et al.,* 2018a; Coniberti *et al.,* 2017; Hatch *et al.,* 2011; Olmstead *et al.,* 2012; Rodriguez-Lovelle *et al.,* 2000a) and *Festuca ovina* (Coletta *et al.,* 2013; Toci *et al.,* 2012). The average age of these vineyards was 5 years, but it never exceeded 8 years of age, suggesting that under some circumstances the presence of cover crops during the initial years of vineyard's life can be too limiting for proper vineyard development.

Lastly, when the influence of the cover crop on growth was found to be milder (< 20 %) or even not observed at all, most of the experiments relied on irrigation (Giese *et al.,* 2016; Jordan *et al.,* 2016; Klodd *et al.,* 2016; Mercenaro *et al.,* 2014; Monteiro *et al.,* 2008; Monteiro and Lopes, 2007; Steenwerth *et al.,* 2013; Steenwerth *et al.,* 2016; Tourte *et al.,* 2008); only in the minority of cases was irrigation not used (Pérez-Álvarez *et al.,* 2015b; Ripoche *et al.,* 2011; Vrsic *et al.,* 2011). In these cases, cover crops were mainly composed of cereals (*Triticum aestivum*, *Secale cereale* and *Avena sativa*), *Lolium* and mixtures of grass and legume. The average age of vineyards was around 12 years, which highlights that vineyard age is a key factor in the modulation of vineyard growth response.

PLANT WATER STATUS

Cover crop competition for soil water is a major constraint which needs to be considered when deciding whether to establish a cover crop in areas where a certain amount of water deficit can be expected in summer. In this review, 130 of the selected papers described at least one parameter related to water status: 40 articles measured leaf (25) or stem (15) water potential and, according to the criteria established by Carbonneau and Ojeda (2013), severe water stress was experienced in 5 % of the cases, while moderate to severe levels occurred in 45 % of the cases. Meanwhile, 40 % of the vineyards studied in the reviewed articles experienced mild to moderate water stress, and only 10 % of the vineyards experienced no water stress at all (Table 2).

In most cases, the presence of a cover crop implied a certain increase in water deficit, reaching its maximum around *veraison*, decreasing again as grape harvest approached, and fading away at the end of the grapevine cycle (Daane *et al.,* 2018; Pou *et al.,* 2011). However, it should be noted that in other cases this point of maximum stress is not so clear (Giese *et al.,* 2015; Hatch *et al.,* 2011; Jordan *et al.,* 2016).Cover-cropped treatments sometimes showed lower leaf water potential at the beginning of the cycle, while the control plots showed the most negative potential values during grape *veraison* (Steenwerth *et al.,* 2016) or after the start of irrigation (Toci *et al.,* 2012); this may be because water needs in tilled vineyards are greater at the end of the season due to their increased vigour and yield. Rainfall distribution during the grape growing seasons was found to have an extreme impact on plant stress responses; for instance, when rainfall was scarce in spring in one of the three growing seasons compared in Delpuech and Metay (2018) a 60 % cover crop soil coverage led to more negative water potential values than bare soil. Similarly, Pou *et al.* (2011) only observed significant differences between soil management treatments in the driest years.

Apart from the above-described changes in plant water status, which reduce water availability for vines (due to cover crop transpiration), the installation of cover crops can affect water status through other processes that also need to be considered, particularly increased water infiltration or reduced evaporation losses. Regarding the former, Celette and Gary (2013) showed that cover cropping successfully increases the infiltration of water into soil in Montpellier (France), whereas in terms of the latter, some authors have also reported a decrease in soil evaporation at the end of the growing cycle (Steenwerth *et al.,* 2016). Nevertheless, the potential increase in water availability that these two factors cause does not usually compensate for cover crop transpiration. In Celette and Gary (2013), although the presence of the cover crop was shown to improve winter soil water refilling, cover crop transpiration in spring led to similar water availability of grapevine compared to the control plot in the years with moderate water stress, whereas in the drier years it caused higher deficit from budbreak to flowering. As regards the reduction in transpiration, Klodd *et al.* (2016) observed that, if continuously mowed, a cover crop of *F. arundinacea* resulted in similar soil water content values than tilled soil, whereas when not mown, soil evapotranspiration increased by about 35–40 %, in both a temperate region (Virginia, USA) and a humid region (Bologna, Italy) (Centinari *et al.,* 2013).

Lastly, cover crop and vine competition for soil water can to a certain extent be compensated for by the different rooting depths of cover crops and vines (Hatch *et al.,* 2011); the compensatory growth of the grapevine root system occurs when a cover crop is established, forcing the vine roots to explore deeper soil horizons (Celette *et al.,* 2008).

PEST AND DISEASE INCIDENCE

The increase in the biodiversity of flora in the vineyard that can result from the introduction of a cover crop can increase the diversity of insects and indirectly improve the balance between insects and vineyards. Likewise, cover crop usually has the effect of reducing vine vegetative growth, and this can contribute to improved aeration in the vineyard and with it a lower incidence of fungal diseases. In general terms, pest populations in vineyards did not increase in the presence of cover crops in 95 % of the cases considered (whereas 45 % = no changes, and 50 % = decrease; Table 3). Only occasionally, at some specific moments, did *Epiphyas postvittana* and some homopters show an increase in population when cover crops were used.

The positive impact of cover crops on decreasing pest population is especially clear in the case of *Cicadellidae*. The pest reduction effect is mainly due to an increased presence of parasitoids of genus *Anagrus* (Daane *et al.,* 2018; Nicholls *et al.,* 2008). This increase in the population of *Anagrus* population was not observed in Nicholls *et al.* (2000) and, as a consequence, *Erythroneura* populations remained unaltered.

The influence of cover crop on grapevine diseases has been mainly studied for powdery mildew (*Erysiphe necator*), botrytis (*Botrytis cinerea*), downy mildew (*Uncinula necator*), black foot disease (*Ilyonectria liriodendri*) and grape black rot (*Guignardia bidwellii*). In 12 out of 18 evaluated situations (67 %), the presence of cover crops reduced disease incidence to a certain extent (Table 4).

The establishment of cover crops was found to reduce the incidence of powdery mildew in 2 out of 3 reviewed articles; no increase has ever been observed. In detail, Valdés-Gómez *et al.* (2011) compared the incidence of powdery mildew on two cover-cropped vineyards (perennial *vs.* annual) and two herbicide-treated control plots (fertilised and irrigated *vs.* not fertilised and not irrigated) in Montpellier. They observed that the powdery mildew incidence was higher in the fertilised and irrigated bare soils, but was slightly reduced in bare soils without fertilisation and irrigation practices. Both cover crop treatments showed a relevant decrease in disease incidence, being more significant in the case of a perennial cover crop in its second year of application. The differences among treatments were due to higher vegetative growth (greater number of leaves per shoot) when the cover crop competition was absent or the fertilisation rate increased. Conversely, Vogelweith and Thiéry (2017) did not observe any differences in Bordeaux (France) for powdery mildew incidence when vineyards with a spontaneous cover crop or bare soils were compared.

The evaluation of botrytis incidence on cover-cropped vineyards resulted in no change or in a reduction of this disease in 80 % of the studied cases. In a single experiment in the Tokaj wine region, where *Botrytis cinerea* is used for the production of its famous sweet wines (and thus known as noble rot), the noble-rotted berries

TABLE 2. Minimum seasonal values for leaf and stem water potential depending on the cover used – information extracted from the different articles studied.

N	Place	Variety	Soil management	Irrigation	Measure	Year 1				Year 2				Year 3			
						Rain (mm)	Ψmax (MPa)		Sig	Rain (mm)	Ψmax (MPa)		Sig	Rain (mm)	Ψmax (MPa)		Sig
1	Montpellier, France	Shiraz	Tillage	No	Ψ	-	-0.57	End August	*								
			Medicago				-0.64										
			Spontaneous cover				-0.58										
2	Nimes, France	Shiraz	Herbicide	No	Ψ	493 vc	-0.41	End August	*	321 vc	-0.8	Mid August	*ns*	301 vc	-0.51	End August	*
			Festuca rubra				-0.58				-0.89				-0.29		
3	Gallargues, France	Sauvignon blanc	Herbicide	-	Ψ	650 ay	≈ -0.17	Mid July	*ns*	650 ay	≈ -0.15	Mid August	*ns*				
			Festuca arundinacea				≈ -0.16				≈ -0.18						
4	Alentejo, Portugal	Tempranillo	Tillage	Yes	Ψ	-	≈ -0.6	Mid August	*	-	≈ -0.4	Mid August	*				
			Spontaneous cover				≈ -0.7				≈ -0.5						
5	Tokaj, Hungary	Hárslevelü	Tillage	-	Ψ	-	≈ -0.55	-	*								
			Hordeum vulgare				≈ -0.5										
			Straw				≈ -0.4										
6	Alenquer, Portugal	Cabernet-Sauvignon	Tillage	No	Ψ	942 y	≈ -0.26	Mid August	*	564 y	≈ -0.18	Mid August	*				
			Spontaneous cover				≈ -0.38				≈ -0.24						
			60 %				≈ -0.36				≈ -0.25						
7	Madrid, Spain	Shiraz	Herbicide	Yes	Ψ	142 y	-1.5	Mid August	*								
			Bromus hordeaceus				-1.25										
			Secale cereale				-1.4										
8	Sacramento County, USA	Merlot	Tillage	Yes	Ψ	-	-1.11	July	*								
			Hordeum vulgare				-1.08										
			Green manure				-1.16										
			Anual clover mix				-1.22										
			California native perennial grass				-1.14										
9	Fresno County, USA	Barbera	Tillage	Yes	-	-	≈ -0.92	August	*ns*	-	≈ -1.94	August	*ns*				
			Nassella cernua				≈ -0.92				≈ -1.72						
10	Califronia, USA	Cabernet-Sauvignon	Tillage	No	Ψ	-	≈ -1.0	Mid August	*ns*	-	≈ -1.1	Mid August	*ns*				
			50 %				≈ -0.9				≈ -1.0						
11	Bairrada, Portugal	Fernão Pires	Tillage	No	Ψ	137 vc	≈ -0.38	Mid July	*ns*	108 vc	≈ -0.55	August	*ns*				
			Spontaneous cover				≈ -0.38				≈ -0.55						

12	Tekigdar, Turkey	Cabernet-Sauvignon	Tillage	-	Ψ	175 vc	≈ -0.40	August	*ns*								
			Resilent cover				≈ -0.52										
13	Canelones, Uruguay	Tannat	*F. arundinacea*	Yes	Ψ	668 cv	≈ -1.0	Mid May	-	1019 cv	≈ -0.6	Mid May	-	1323 cv	≈ -0.8	Mid May	-
			F. arundinacea - (*F. arundinacea*				≈ -1.2				≈ -0.9				≈ -0.8		
14	Virginia County, USA	Cabernet-Sauvignon	*F. arundinacea*	Yes	Ψ	721 cv	≈ -0.65	Mid August	*ns*								
			Row				≈ -0.75										
15	Salento, Italy	Negroamaro	Tillage	Yes	Ψ	-	-1.54	Early August	*								
			F. rubra				-1.35										
16	New York County, USA	Cabernet franc	*F. arundinacea*	No	Ψ	597	-0.85	Early August	*	654	-0.29	Mid August	*				
			F. arundinacea				-1.05				-0.26						
			F. arundinacea				-0.87				-0.28						
			F. arundinacea				-0.91				-0.28						
17	Ourense, Spain	Mencía	Tillage	No	Ψ	313 cv	≈ -0.6	Early September	*	163 cv	≈ -1.0	Early September	*	185 cv	≈ -1.0	Early September	*
			Native vegetation				≈ -1.0				≈ -1.15				≈ -1.0		
			Lolium perenne				≈ -0.9				≈ -0.95				≈ -0.7		
			T. subterraneum				≈ -0.9				≈ -0.8				≈ -0.6		
18	Montevideo, Uruguay	Tannat	*F. arundinacea*	Yes	Ψ	650 ay	≈ -1	End January	-	650 ay	≈ -0.6	Mid January	-				
			F. arundinacea				≈ -1.2				≈ -0.9						
19	New York County, USA	Cabernet franc	Spontaneous vegetation - (Tillage)	No	Ψ	526 cv	≈ -0.5	Mid August	*ns*	450 cv	≈ -0.6	August	*ns*	350 cv	≈ -1.1	Early September	*ns*
			Spontaneous vegetation - (				≈ -0.7				≈ -0.8				≈ -1.2		
			Spontaneous vegetation - (				≈ -0.7				≈ -1.0				≈ -1.25		
			Spontaneous vegetation - (				≈ -0.6				≈ -0.9				≈ -1.2		
20	Oregon County, USA	Pinot noir	Tillage	No	Ψ	356 cv	-0.89	Mid September	-								
			F. rubra				-0.77										

1: Kazakou *et al.* (2016); 2: Delpuech and Metay (2018); 3: Celette *et al.* (2005); 4; Lopes *et al.* (2011); 5: Judit *et al.* (2011); 6: Lopes *et al.* (2008); 7: Linares Torres *et al.* (2018); 8: Ingels *et al.* (2005); 9: Costello (2010b); 10: Daane *et al.* (2018); 11: Cruz *et al.* (2012); 12: Bahar and Semih Yaşain (2010); 13: Coniberti *et al.* (2018a); 14: Hatch *et al.* (2011); 15: Toci *et al.* (2012); 16: Karl *et al.* (2016); 17: Trigo-Córdoba *et al.* (2015); 18: Coniberti *et al.* (2017); 19: Centinari *et al.* (2016); 20: Reeve *et al.* (2016).

() denotes under-vine soil management; Ψpd denotes predawn; Ψmd denotes middawn; * denotes significant differences; ns = no significant differences; vc = rainfall during the vine cycle (April-October); y = rainfall in a year; ay = average rainfall in a year.

TABLE 3. Main characteristics and results of the impact of cover crops on vineyard pests.

N	Place	Variety	Soil management	Cover type	Climate
1	Villenave d' Ornon, France	Merlot	Bared soil*/ Spontaneous vegetation	SV	M
2	Virginia, USA	Several	Tillage*/ Spontaneous vegetation	TC/SV	M
3	Cerdeña, Italy	Carignano	Tillage*/ *Medicago polymorpha, Trifolium yanninicum*/ *Dactylis glomerata, Lolium rigidum*	TC/L/GL	W
4	Northern Dalmatia, Croatia	-	Tillage*/ Spontaneous vegetation	TC/SV	M
5	Modena, Italy	Salamino	Tillage*/ *Lobularia maritima*/ *Phacelia tanacetifolia* / *Fagopyrum esculentum*/ *Vicia faba*/ *Vicia villosa, Avena sativa*	TC/O/O/O/L/GL	M
6	California, USA	Cabernet-Sauvignon	Tillage*/ *Elymus glaucus, Hordeum brachyantherum, Bromus carinatus*	TC/G	W
7	California, USA	Chardonnay	Tillage*/*Helianthus annuus, Fagopyrum esculentum*	TC/O	W
8	Marche, Italy	Several	Tillage*/ Spontaneous vegetation	TC/SV	M
9	New South Wales, Australia	Chardonnay	Tillage, Spontaneous vegetation*/ *Brassica juncea* / *Borago officinalis*/ *Coriandrum sativum*/ *F. esculentum* /*L.maritima*	TC, SV/O/O/O/O/O	W
10	California, USA	Zinfandel	Tillage, Spontaneous vegetation*/ *B. carinatus*	TC, SV/G	W
11	California, USA	Cabernet-Sauvignon	*P. tanacetifolia, Ammi majus, Daucus carota*		W
12	Marlborough, New Zealand	-	*Spontaneous vegetation**/ *V. faba*	SVC/L	M
13	California, USA		*H.annuus, F. esculentum*/ Flower island	O/O	W
14	California, USA	Zinfandel	Tillage*/ *Medicago sativa, A. sativa*	TC/GL	W

1: Vogelweith and Thiéry (2017); 2: Rijal *et al.* (2014); 3: Muscas *et al.* (2017); 4: Franin *et al.* (2016); 5: Burgio *et al.* (2016); 6: Daane *et al.* (2018); 7: Nicholls *et al.* (2000); 8: Minuz *et al.* (2013); 9: Begum *et al.* (2006); 10: Sanguankeo and León (2011); 11: Wilson *et al.* (2017); 12: Nboyine *et al.* (2018); 13: Nicholls *et al.* (2008); 14: Karban *et al.* (1997).

N	Duration	*Cicadelidae*		Spiders		Mites		Thrips		Others		
1	2	-	PE			-	PE, NE			=	NE	*Phalangium opilio*
2	5									=	PE	*Vitacea polistiformis*
3	3									-/=	PE	*Planoccocus ficus*
4	1			=						-		Coleoptera
5	3					+	NE(D)			+/=	PE	Homoptera
6	3	-	PE	-								
7	2	-	PE					-	PE	+	NE(D)	Coccinelidae, *Chrysoperla*
8	2									=	PE	Disease vectors
9	1									+/=	PE	*Epiphyas postvittana*
10	2											
11	2	=	PE	+	NE							
12	2									-	PE	*Hemiandrus* sp
13	2	-	PE							=	NE	Coccinelidae, Syrphidae
14	2					=	PE					

N = number-author reference; Duration: in years from the beginning of the experiment; C = cold climate (average T > 12 ºC); M = mild climate (average T 12-15 ºC); W = warm climate (average T < 15 ºC); *Control management; Cover type: CT = tillage control; G = grass; GL = grass + legume; L = legume; SV = spontaneous vegetation; O = other cover crop group; PE = pest; NE = pest natural enemy; (D) = predator of pests. Symbols: = denotes does not affect; - denotes negative effect compared to the control; + denotes positive effect compared to the control.

TABLE 4. Main characteristics and results of the impact of cover crops on grapevine diseases.

N	Place	Variety	Soil management
1	Villenave d' Ornon,France	Merlot	Bared soil*/Spontaneous vegetation
2	Sourthen, Uruguay	Tannat	Row *Festuca arundinacea**/ Full cover of *F. arundinacea*
3	Navarra, Spain	Malvasia/ Tempranillo[1]	Bared soil* /*Sinapis alba*
4	Blenheim, New Zealand	Chardonnay	Control*/ *Phacelia tanacetifolia*/ *Lolium perenne*
5	Montpellier, France	Aranel	Herbicide*/ *F. arundinacea*, *L. perenne*
6	Madrid, Spain	Shiraz	Tillage/ Herbicide/ Spontaneous vegetation
7	Sourthen, Uruguay	Tannat	Row *F. arundinacea**/ Full cover of *F. arundinacea*
8	Montpellier, France	Aranel	Herbicide*/ F. *arundinacea, Perennial ryegrass*/ *Hordeum vulgare*
9	Bairrada, Portugal	Fernão Pires	Spontaneous vegetation*/ Tillage
10	Sourthen, Uruguay	Tannat	Row *F. rubra**/ Full cover of *F. rubra*
11	Sourthen, Uruguay	Tannat	Row *F. arundinacea**/ Full cover of *F. arundinacea*
12	Montpellier, France	Shiraz	Tillage*/ *Medicago truncatula, M. rigidula, M. polymorpha*
13	British Columbia, Canada		Exotic grass: *F. trachyphylla*, *Agropyron cristatum*, *F. rubra*, *L. perenne/* Exotic grass: *Lotus corniculatus*, *M. lupulina*, *Trifolium repens* Native grass: *Bouteloua dactyloides*, *F. idahoensis*, *Pseudoroegneria spicata*, *Boteloua gracilis*/ Native grass: *Nepeta racemosa*, *Origanum vulgare*, *Artemisia frigida*, *Achillea millefolium*, *Heterotheca villosa*, *Erigonium neveum*, *Erigeron filifolius*
14	Tokaj, Hungary	Hárslevelü	Tillage*/*Hordeum vulgare*
15	Ohio, USA	Seyval blanc	Bared soil*/ *Festuca arundinacea*/ *Mazus japonicus albus*/ *Mentha pulegium*/ *Thymus serpyllum minus*/ *T. fragiferum*/ *Veronica prostratum*/ *L. perenne* (75%), *F. rubra* (25%)

[1]Nursery planting material

1: Vogelweith and Thiéry (2017); 2: Coniberti *et al.* (2018a); 3: Berlanas *et al.* (2018); 4: Jacometti *et al.* (2007); 5: Valdés-Gómez *et al.* (2008); 6: Cordero-Bueso *et al.* (2011); 7: Coniberti *et al.* (2017); 8: Valdés-Gómez *et al.* (2011); 9: Cruz *et al.* (2012); 10: Coniberti *et al.* (2018b); 11: Coniberti *et al.* (2018c); 12: Guilpart *et al.* (2017); 13: Vukicevich *et al.* (2018); 14: Judit *et al.* (2011); 15: Krohn and Ferree (2004).

N	Cover type	Climate	Duration	Powdery mildew	Downy mildew	*Botrytis*	Black rot	Black foot	*Ilyonectria liriodendri*
1	C/SV	M	2	=	=		=		
2	GC/G	M	3			-			
3	C/ O	M	2					-	
4	C/O/G	M	1			-			
5	CH/G	M	4			-			
6	CT/CH/SV	M	3						
7	GC/G	W	2			-			
8	CH/GR	M	5	-/=					
9	CSV/T	M	2			-/=			
10	GC/G	W	3			-			
11	GC/G	W	3			-			
12	TC/L	M	3	-/=		-/=			
13	G/GL/G/O	GH	1						-
14	CT/G	C	4			+			
15	C/G/O/O/O/L/O/G	GH	1			=			

N = number-author reference; Duration, in years from the beginning of the experiment; C = cold climate (average T > 12 ºC); M = mild climate (average T 12-15 ºC); W = warm climate (average T < 15 ºC); Cover type: GH = green house; C = control bared soil; CT = control tillage; CH = control herbicide; SV = spontaneous vegetation; G = grass; GL = grass + legume; L = legume; O = other crop group. Symbols: = denotes does not affect; - donates negative effect compared to the control; + donates positive effect compared to the control.

in the bunches from plots with a barley cover crop were reported to have increased by 18 % (Judit *et al.,* 2011). In France, vines with cover crop showed a reduced shoot growth, and thus a decrease in botrytis incidence (Valdés-Gómez *et al.,* 2008). The establishment of under-trellis grass cover crops in vineyards in a humid region in Uruguay also resulted in a reduction in both the incidence and the severity of this disease (Coniberti *et al.,* 2018a). The same authors observed that the extend of disease reduction depends more on the presence/ absence of the cover crop than on the planting density (0.8 m x 2.8 m *vs.* 1.5 m x 2.8 m) (Coniberti *et al.,* 2018c). Likewise, Jacometti *et al.* (2007) in New Zealand confirmed that the incidence of botrytis was higher in bare soils compared to mulched plots with mowed or tilled cover crops. This is due to the increase in soil moisture and a higher rate of soil biological activity, increased vine debris degradation, reduced *B. cinerea* primary inoculum on the debris and decreased *B. cinerea* severity at flowering and harvest. Between the two studied cover crops, the presence of *B. cinerea* in *Phacelia tanacetifolia* cover cropped vineyards tended to be higher than in *Lolium perenne*, likely due to the reduced competition of soil biota with the fungus. As already mentioned, in some experiments no differences in botrytis incidence associated with the presence of cover crops were found. For instance, in Portugal, no changes were observed between spontaneous cover and till treatments (Cruz *et al.,* 2012). Lastly, in an experiment performed in a greenhouse to compare different cover crops, no differences were found in fungus incidence on the cover crop species in most cases (Krohn and Ferree, 2004).

A study conducted in the South of France by Guilpart *et al.* (2017) concluded that reduced plant growth had a direct effect on reducing grapevine susceptibility to powdery mildew and botrytis, and that it was directly linked to the reduced plant growth by water stress at flowering in the same year. However, grapevine yield (berry number per bunch and bud fertility) was closely linked to water potential at flowering in the previous year. Thus, appropriate management of cover crops could have a positive impact by reducing fungal diseases based on the climatic variability of the growing season.

The impact of cover crops on downy mildew (*P. viticola*) incidence on vines has been reported in a single study, in which no differences were detected between treatments (Vogelweith and Thiéry, 2017). The same study revealed that the presence of cover crops did not affect the incidence of black rot (*G. bidwellii*) either. Moreover, some cover crops have been found to control soil-borne fungal diseases; for instance, *Sinapis alba* biomass residues incorporated into the soil have shown potential for improving control of black foot disease in nursery planting material (Berlanas *et al.,* 2018). Under greenhouse experimental conditions on soils from different types of groundcover management, a reduction in *Ilyonectria liriodendra* was observed with cover crop. It seems that the presence of cover crops alters the root-associated fungal communities of soil biota, thus increasing the amount of plant-protective mycoparasites, which could explain the observed reduction in black foot disease incidence (Vukicevich *et al.,* 2018).

YIELD

Another aspect that needs to be examined when considering the appropriateness of installing cover crops is their impact on yield. As a general rule, it is assumed that cover crops compete with vines for soil resources (water and nutrients; Gómez, 2017), resulting in a decrease in yield. The analysis of the published papers is mostly in line with this general assumption, but there are some exceptions.

Sixty-eight articles analysed the effect of cover crops on vineyard yield (Table 5). In 16 % of these articles, the presence of cover crops was linked to a 20 to 40 % increase in yield compared to control plots; however, this percentage was outnumbered by articles with results showing that cover crops caused no change (28 %) or a decrease in yield (56 %). Among the latter, 26 articles (38 % of total cases) reported a moderate (< 20 %) reduction in yield, whereas in the remaining 12 papers (17 %) yield loss was > 20 % when cover crops were established.

In the studies in which yield increased when using a cover crop, the species used were annual, such as *A. sativa* (Fourie *et al.,* 2007b; Messiga *et al.,* 2016; Steenwerth *et al.,* 2013; Steenwerth *et al.,* 2016; Steinmaus *et al.,* 2008), or legumes like *Trifolium* sp. (Messiga *et al.,* 2016; Ovalle *et al.,* 2010; Susaj *et al.,* 2013) and *Vicia* sp. (Fourie and Freitag, 2010; Messiga *et al.,* 2016; Nboyine *et al.,* 2018; Steenwerth *et al.,* 2013; Steenwerth *et al.,* 2016; Steinmaus *et al.,* 2008). Conversely, permanent cover crops of *F. rubra* (De Pascali *et al.,* 2014; Gontier *et al.,* 2014; Toci *et al.,* 2012)

TABLE 5. Cover crop impact on grape yield compared to tilled and inter-row herbicide-treated control plots.

Higher, slightly higher								
1	Messiga *et al*. (2016)	++	5	Fourie (2011)	=/++	9	Marques *et al*. (2018)	-(T)/+++
2	Fourie *et al*. (2007b)*	++	6	Steenwerth *et al*. (2013)***	=/+	10	Ovalle *et al*. (2010)*	-/+
3	Nboyine *et al*. (2018)	+	7	Steenwerth *et al*. (2016)*	=/+	11	Ripoche *et al*. (2011)*	-/+
4	Susaj *et al*. (2013)* **	+	8	Steinmaus *et al*. (2008)	=/+			
No trend								
12	Bettoni *et al*. (2016)	=	19	Ingels *et al*. (2005)	=	26	Rodriguez-Lovelle *et al*. (2000b)*	=
13	Coniberti *et al*. (2018a)	=	20	Lopes *et al*. (2008)	=	27	Smith *et al*. (2008)	=
14	Costello (2010a)*	=	21	Mercenaro *et al.* (2014)	=	28	Sweet and Schreiner (2010)	=
15	DeVetter *et al*. (2015)	=	22	Monteiro and Lopes (2007)	=	29	Tourte *et al*. (2008)	=
16	Donkó *et al*. (2017)	=	23	Pérez-Álvarez *et al*. (2013)	=	30	Wolff *et al*. (2018)	=
17	Giese *et al*. (2015)	=	24	Pérez-Álvarez *et al*. (2015a)	=			
18	Giese *et al*. (2016)	=	25	Pérez-Álvarez *et al*. (2015b)	=			
Slightly lower								
31	Jordan *et al*. (2016)	=/-(T)	40	Tomaz *et al*. (2015)	-(T)/-	49	Klodd *et al*. (2016)	-
32	Ruiz-Colmenero *et al*. (2011)	=/-	41	Coniberti *et al*. (2017)	-(T)/- -	50	Linares Torres *et al*. (2018)*	-
33	Muscas *et al.* (2017)*	=/- -	42	Coniberti *et al*. (2018c)	-(T)/- -	51	Lopes *et al*. (2011)	-
34	Reeve *et al*. (2016)	=/- -	43	Karl *et al*. (2016)**	-(T)/- -	52	Pérez-Bermúdez *et al*. (2016)	-
35	Bahar and Semih Yaşain (2010)	-(T)	44	Pérez *et al*. (2018)*	-(T)/- -	53	Rodriguez-Lovelle *et al.* (2000a)*	-
36	Marques *et al*. (2010)	-(T)	45	Pou *et al*. (2011)	-(T)/- -	54	Vrsic *et al*. (2011)	-
37	Trigo-Córdoba *et al*. (2015)*	-(T)	46	Varga *et al*. (2012)**	-/=	55	Nicolosi *et al*. (2016)	-/- -
38	Wheeler *et al*. (2005)	-(T)	47	Hickey *et al*. (2016)	-	56	Coletta *et al*. (2013)	- -/ -
39	Reynolds *et al*. (2006)	-(T)/-	48	Judit *et al*. (2011)	-			
Lower								
57	Cruz *et al*. (2012)	=/- - -	61	Delpuech and Metay (2018)*	- -	65	Palliotti *et al*. (2007)	- -/- - -
58	Guilpart *et al*. (2017)	-(T)/- - -	62	Kazakou *et al*. (2016)*	- -	66	Silvestre *et al*. (2012)	- -/- - -
59	Celette *et al*. (2005)	- -	63	Mattii *et al*. (2005)*	- -	67	Gontier *et al*. (2014)	- - -
60	De Pascali *et al*. (2014)	- -	64	Toci *et al*. (2012)	- -	68	Hatch *et al*. (2011)	- - -

= denotes does not affect, no clear trend; -(T)/+(T) denotes reduction trend/general increase; -/+ denotes difference in reduction/increase lower than 20 %; --/++ denotes difference in reduction/increase between 20 and 40 %; ---/+++ denotes difference in reduction/increase higher than 40 %; * denotes differences among treatments in one or more years; ** denotes differences among controls in one or more years.

and *F. arundinacea* (Celette *et al.,* 2005; Hatch *et al.,* 2011; Mattii *et al.,* 2005; Palliotti *et al.,* 2007) led to a decrease in grape yields. In other cases in which grass- and legume-based cover crops were compared, no differences were observed (Ingels *et al.,* 2005; Steinmaus *et al.,* 2008; Trigo-Córdoba *et al.,* 2015), although there were exceptions (Muscas *et al.,* 2017).

The results obtained when comparing spontaneous versus sown cover crops were inconsistent. In some cases, spontaneous cover crops led to a higher grape yield compared to that of sown cover crops (Mercenaro *et al.,* 2014; Tomaz *et al.,* 2017; Trigo-Córdoba *et al.,* 2015), while in other cases the result was the opposite (Pérez *et al.,* 2018; Susaj *et al.,* 2013).

Finally, when comparing yields of vines with cover crops on every inter-row or every second inter-row, a greater decrease in yield was observed when the plant cover took up the whole inter-row soil surface (Reeve *et al.,* 2016; Rodriguez-Lovelle *et al.,* 2000a; Rodriguez-Lovelle *et al.,* 2000b). The application of vineyard soil mulch (straw and sawdust, *etc.*), was generally found to lead to increased yields compared to living cover crops or bare soils (Fourie, 2011; Susaj *et al.,* 2013; Varga *et al.,* 2012), but not in all studied cases (Wheeler *et al.,* 2005).

The observed grapevine yield increases took place in areas of warm (average T^a above 15 ºC) and mild (average T^a between 12 and 15 ºC) climate. Only one experiment was performed in a cold climate (average T^a below 12 ºC), in which an increase in yield was found (Hatch *et al.,* 2011). The experiments showing increased yields were located in areas like California (USA) (Steenwerth *et al.,* 2013; Steenwerth *et al.,* 2016; Steinmaus *et al.,* 2008), South Africa (Fourie, 2011; Fourie *et al.,* 2007b), New Zealand (Nboyine *et al.,* 2018) or Chile (Ovalle *et al.,* 2010). However, the vineyards that suffered a loss of yield were located in the Mediterranean climate area (France, Italy and Spain), with the exception of a single experiment in Virginia (USA) (Hatch *et al.,* 2011). Although it is difficult to determine the reasons for these geographical differences, they may be related to a combination of plant water deficit and temperature: the higher these two variables, the greater the reduction in yield (Figure 2).

When climate was analysed alongside irrigation practices, it was shown that, in areas of warm climate, almost all the experiments were under irrigation and positive results were only observed when vineyards were irrigated. In the few experiments performed with irrigation in mild climate areas there was no reduction in grape yield (Figure 2).

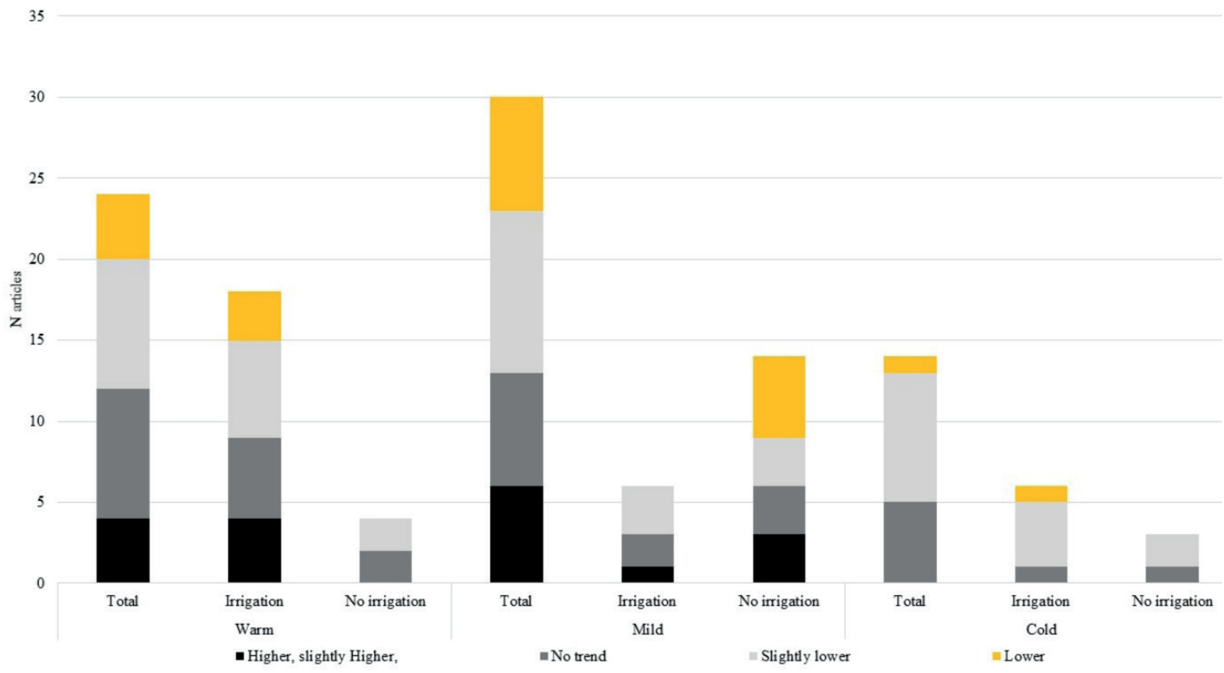

FIGURE 2. Impact of cover crops on grapevine yield according to climate conditions and irrigation practices.

Unfertilised vineyards never showed increased yields. However, vineyard fertilisation management showed higher or similar grapevine yields in cover cropped vineyards (Table 6).

TABLE 6. Comparison of cover crop impact on grape yield when the vineyard was fertilised or not.

	Fertilised	Not fertilised
Positive, slightly positive	31 % (6)	0%
No trend	42 % (8)	36 % (5)
Slightly negative	21 % (4)	36 % (5)
Negative	5 % (1)	29 % (4)

Some yield trends were also observed regarding rootstock. For instance, the use of SO4 mainly resulted in a relevant yield decrease (Celette *et al.,* 2005; Cruz *et al.,* 2012; De Pascali *et al.,* 2014; Delpuech and Metay, 2018; Palliotti *et al.,* 2007; Toci *et al.,* 2012), while increases occurred in some of the vineyards with 110R and 99R (Fourie, 2011; Marques *et al.,* 2018; Steenwerth *et al.,* 2013; Steenwerth *et al.,* 2016). When we grouped data according to rootstock tolerance to drought (Figure 3), it was possible to confirm that in the presence of cover crops yield only increased with drought tolerant rootstocks (Fercal, 110R, 140Ru, 99R and 779P). With the remaining rootstocks, (of medium resistance, such as 3309C, SO4, 1103P, 41B; or drought-sensitive, such as 101-14, 420A, 5BB, Teleki 5C), yield was observed to decrease in the presence of cover crops (Figure 3).

Classification of drought tolerance was performed according to the characteristics of the vine rootstocks published in Vivai Cooperativa Rauscedo (2013), grouped as high (Fercal, 110R, 140Ru, 99R, 779P), medium (3309C, SO4, 1103P, 41B) and low tolerance (101-14, 420A, 5BB, Teleki 5C).

GRAPE COMPOSITION

When examining the potential impact of cover crops on grape composition, it is important to take into account that it is intrinsically related to vigour, yield and canopy photosynthetic activity, which are all modified by cover crops. In addition, the presence of cover crops can affect berry size (reduced in 35 % of articles), which may also be associated with changes in berry composition.

Details of grape composition are provided in the following sub-sections. In general terms, total soluble solids (TSS) remained unaffected in 68 % of cases (30 out of 44 papers), whereas in 8 cases they showed an increase, and only 4 reported a decrease in TSS content associated with the introduction of a cover crop (Table 7). When an increase in TSS was observed (6 cases), it was mainly associated with a decrease in yield

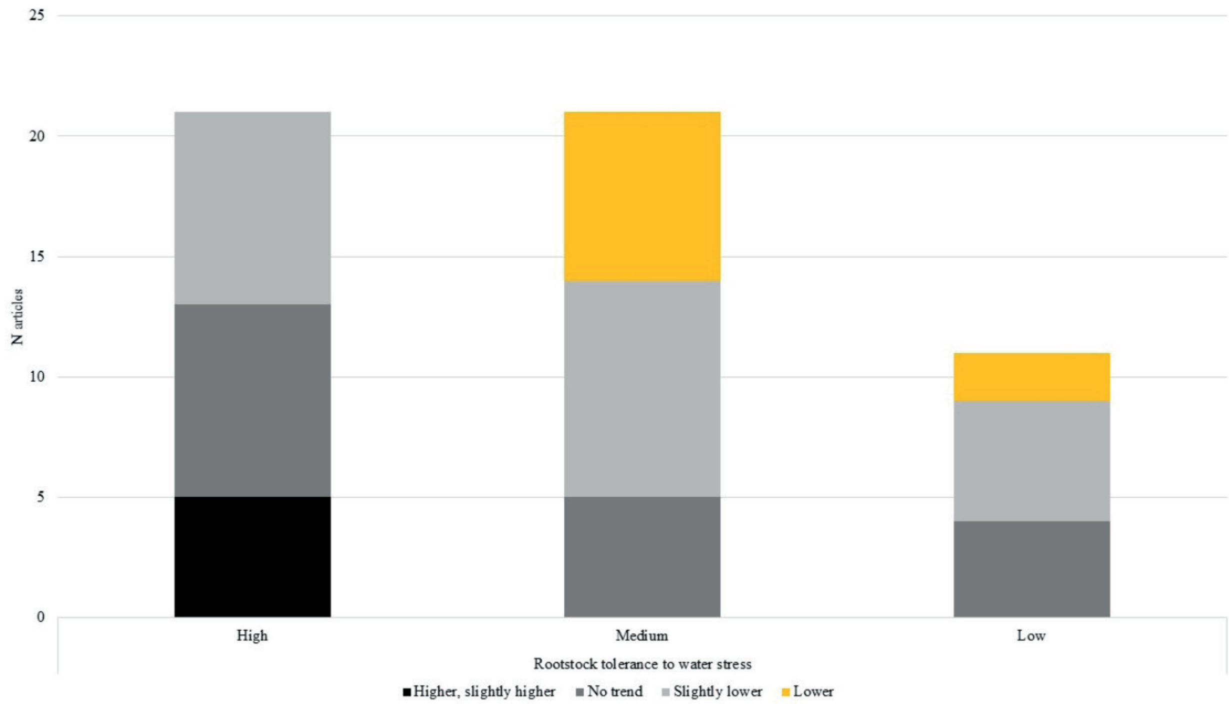

FIGURE 3. Number of reviewed papers on the impact of cover crops on grapevine yield grouped according to the rootstock resistance to water stress.

TABLE 7. Grape juice quality components.

N	Variety	Climate	Irrigation	Fertilisation	Duration	Yield	Berry weight	TSS (ºBrix)	pH	TA	YAN	Total anthocyanins	Total polyphenols
1	Cabernet-Sauvignon	W	Yes	Yes	2		=/-	=	=	=		=/+	
2	Tempranillo	W	Yes	No	2	-	-	=/+	=	-		=	=
3	Sauvignon blanc	W	Yes	Yes	10	+/=	=	-/=			+/=		
4	Cabernet-Sauvignon	W	No	Yes	3	=		=	=	-		+	+
5	Manto Negro	W	Yes		3	-		=	=			=	=
6	Pedro Ximénez	W	No		3	-	=	+	=	=	=		
7	Canaiolo nero/ Trebbiano giallo	W			2			=	=	=			=/+
8	Merlot	W	Yes	Yes/No	2/3	=		=	=	=			
9	Sangiovese	W		No	2	-	-	=	+	+			
10	Carignano	W	Yes		3	-	-	=/+				+/-	+/-
11	Negroamaro	W	Yes		1	-	=	=	=	=			
12	Cabernet-Sauvignon	W	Yes		1			-/=	-/=	+/=			-
13	Tempranillo	W	Yes		2	=/-						=(w)	
14	Negroamaro	W	Yes		1	-	=	=	=	=		+(w)	=(w)
15	Cabernet-Sauvignon	W	Yes	Yes	2						=		
16	Mazuelo	W	Yes	Yes	5	=	=	=	=	=		=/+	
17	Chardonnay	W	Yes		5	=	=	=	=	=/-			
18	Chardonnay	W	Yes	Yes	12	=/+	-/=	=	=	=	=/-/+		
19	Pinnot noir	C	No		2	=		=	=	=	=		
20	Pinnot noir	C			4			=					
21	Furmint/ Hárslevelü	C			2	=		=		=			
22	Cabernet Sauvignon	C		Yes	7	=	=	=	=	=	-		
23	Mencía	C			2							+/=(w)	=(w)
24	Gewürztraminer	C	Yes		6	-	=	-	=/-	=/+			

25	Maréchal Foch	C	Yes	Yes	7	=	=	=	=	+			
26	Pinot noir	C	No	Yes	3	=/-		=	=	-	-		
27	Shiraz	M	No	No	2						-		
28	Furmint	M			3	=		=		=			
29	Aranel	M	No	No	5/7	-	=	-/+			-		
30	Sauvignon blanc	M	Yes		4	=	=	-		-			
31	Tempranillo	M	Yes	No	3	=	=	=	=	=			=
32	Sangiovese	M			3		-	+	=	-			
33	Kallmet	M	No	Yes/No	3	-	=	=		=			
34	Merlot	M	Yes	Yes	3	=	=	=	=	=			
35	Leon Millot	M		Yes	2	+		=/+					
36	Merlot	M			2	-	-	+	=	-			
37	Mencía	M	No		3	=/-	=/-	=	=	=		=(w)	
38	Grechetto	M	No		6						=/-		
39	Merlot, Cabernet franc, Sauvignon branc	M		No	2	-					-		
40	Tempranillo	M	No		1	=	=	=	=	=			
41	Fernão Pires	M	No		2	-	-	-	=	=			
42	Tempranillo	M	No	No	4	=		=	=	=			
43	Cabernet-Sauvignon	M			1	=		=		=		=	
44	Cabermet-Sauvignon	M			2	=	=	+	=	-	-		
45	Tempranillo	M		No	1	=						+	
46	Tempranillo	M	No	No	3	=	=				=/-		

1: Lee and Steenwerth (2013); 2: Lopes *et al.* (2011); 3: Fourie *et al.* (2007b); 4: Lopes *et al.* (2008); 5: Pou *et al.* (2011); 6: Pérez *et al.* (2018); 7: Muganu *et al.* (2013); 8: Ingels *et al.* (2005); 9: Mattii *et al.* (2005); 10: Muscas *et al.* (2017); 11: Toci *et al.* (2012); 12: Nazrala (2008); 13: Silvestre *et al.* (2012); 14: Coletta *et al.* (2013); 15: Lee and Steenwerth (2011); 16: Mercenaro *et al.* (2014);17: Smith *et al.* (2008); 18: Fourie (2011); 19: Sweet and Schreiner (2010); 20: Gouthu *et al.* (2012); 21: Donkó *et al.* (2017); 22: Giese *et al.* (2015); 23: Bouzas-Cid *et al.* (2016); 24: Reynolds *et al.* (2006); 25: DeVetter *et al.* (2015); 26: Reeve *et al.* (2016); 27: Kazakou *et al.* (2016); 28: Varga *et al.* (2012); 29: Ripoche *et al.* (2011); 30: Caspari *et al.* (1997); 31: Pérez-Bermúdez *et al.* (2016); 32: Ferrini *et al.* (1996); 33: Susaj *et al.* (2013); 34: Steenwerth *et al.* (2016); 35: Messiga *et al.* (2016); 36: Rodriguez-Lovelle *et al.* (2000a); 37: Trigo-Córdoba *et al.* (2015); 38: Palliotti *et al.* (2007); 39: Rodriguez-Lovelle *et al.* (2000b); 40: Marques *et al.* (2010); 41: Cruz *et al.* (2012); 42: Pérez-Álvarez *et al.* (2015a); 43: Bahar and Semih Yaşain (2010); 44: Wheeler *et al.* (2005); 45: Pérez-Álvarez *et al.* (2013); 46: Pérez-Álvarez *et al.* (2015b).

Duration: in years since the beginning of the experiment; C = cold climate (average T > 12 ºC); M = mild climate (average T 12-15 ºC); W = warm climate (average T < 15 ºC); TSS = total soluble solids, TA = titrable acidity; YAN = Yeast assimilable nitrogen; (w) = measured in wine.

and berry size (4 cases), although in two of the studies no changes in yield or berry size were reported. Conversely, when a decrease in TSS was observed, it was associated with a reduction in yield, indicating that cover crops were the cause of strong weakening of vineyard. Concerning acidity, 90 % of studied articles (29) reported no change in the pH, whereas in 4 of them a decrease was observed, and only one showed a pH increase associated with cover crop installation. Similarly, cover crops did not alter titratable acidity (TA) in the majority of the studies (23 out of 32, 72 %), a certain decrease was observed in 8, and only 3 reported increased TA.

As regards phenolics, anthocyanins were analysed in 8 studies, out of which 3 showed an increase in anthocyanin content and 5 showed no effect. Meanwhile, for total phenolics the effects were more limited: in 4 out of 7 studies the content remained unchanged, while it increased in 2 and decreased in 1 (Table 7). Lastly, in terms of competition for nutrients, yeast assimilable nitrogen (YAN) was one of the grape composition parameters to be mostly affected by the presence of a cover crop, as it only remained unchanged in 39 % of the experiments and decreased in half of them; only 2 out of 18 studies considered it to have increased. The general implications of cover crops for nitrogen nutrition were reviewed in our companion article (Abad *et al.,* 2021).

1. Sugar content and acidity

As mentioned above, the basic grape juice parameters TSS, pH and TA did not show any variation in most of the reviewed studies. Such was the case in several Hungarian wine regions in studies which used a spontaneous cover crop and organic mulching (Varga *et al.,* 2012), or spontaneous flowering legumes and grass cover crops in Furmint vineyards (Donkó *et al.,* 2017). Similarly, no differences in grape juice parameters were found in Pinot noir vineyards when spontaneous legume or grass cover crops (monocultures or mixtures) were compared in Oregon (USA) (Sweet and Schreiner, 2010). Another experiment performed in the same region with the same variety showed no changes in these parameters with a 3-year *F. rubra* cover crop (Gouthu *et al.,* 2012). The same result was observed in Cabernet-Sauvignon in North Carolina (USA) where grassy cover crops were established (Giese *et al.,* 2015). In Iowa (USA), where the annual precipitation can reach 700 mm, no differences in TSS or pH values were detected with a *F. rubra* cover crop, although TA showed an upward trend with cv. Maréchal Foch (DeVetter *et al.,* 2015). In a trial conducted in a Merlot vineyard in California, no differences in must parameters were found when green manure, annual clover and perennial grass cover crops were used (Ingels *et al.,* 2005). For the same variety and region, similar results were reported with an oat (*A. sativa*) cover crop, or a legume/ oat cover crop mixture (Steenwerth *et al.,* 2016). The TSS content in Cabernet-Sauvignon grapes was unaffected by the presence of a native perennial grass cover crop, independently of additional irrigation, although higher irrigation levels appeared to increase yields. Native grasses led to increased tartaric acid contents, while bare soils showed higher levels of malic acid (Daane *et al.,* 2018). *S. cereale* cover crops did not alter TSS and pH values in Chardonnay vineyards in California, and neither did *Triticosecale* plant covers. However, the use of *Triticosecale* resulted in grape juices with lower TA (Smith *et al.,* 2008). The presence of a spontaneous cover crop in a Cabernet-Sauvignon vineyard in Turkey did not alter TSS, pH or TA parameters, although *veraison* onset was brought forward by 4 days (Bahar and Semih Yaşain, 2010). Cabernet-Sauvignon vineyards in Brasil, managed with *Raphanus raphanistrum*, *Avena strigosa*, *S. cereale*, *L. perenne* and two clover species showed no differences in TSS and pH values (Bettoni *et al.,* 2016). In a trial conducted in a Manto Negro vineyard in Majorca (Spain), no significant differences were found in must parameters when spontaneous and mixtures of grass and legume cover crops were established compared to tilled control plots (Pou *et al.,* 2011). Similar results were found in Valencia, in Tempranillo and Bobal vineyards with legume cover crops that were tilled at flowering and incorporated into the soil (Pérez-Bermúdez *et al.,* 2016). Similarly, a barley cover crop did not alter TSS, pH, TA, tartaric and malic acid content in Tempranillo vineyards in La Rioja (Spain) and neither did *T. resupinatu* plant covers (Pérez-Álvarez *et al.,* 2015a).

In contrast to the aforementioned studies, others have reported changes in must composition. For example, spontaneous and *A. sativa* and *Vicia sp.* mixtures led to increased TSS content in Pedro Ximenez variety in Andalucía (Spain) after 3 years, although the remaining grape composition parameters were unaltered (Pérez *et al.,* 2018). Ripoche *et al.* (2011) reported a decrease in TSS content in the first year in cv. Aranel vineyards in Montpellier managed with a permanent *F. arundinacea* cover crop. Another experiment with cv. Tempranillo in Alentejo (Portugal) showed that the presence of a spontaneous cover crop increased TSS in one of the two study years, but decreased TA in both years (Lopes *et al.,* 2011). In a Cabernet-Sauvignon vineyard located in central Portugal, a reduction in TA was observed in the third season in the presence of a spontaneous cover crop and a grass-legume mixture - probably due to a significant reduction in vegetative growth - whereas no significant differences were found for TSS and pH (Lopes *et al.,* 2008). A 10-year spontaneous cover crop study in Fernão Pires vineyards in Portugal showed a reduced TSS content, as pH and TA remained unaltered (Cruz *et al.,* 2012). The presence of natural permanent plant cover in central Italy resulted in an increased TSS content in Canaiolo nero and Trebbiano giallo grape cultivars during ripening; however, TSS was the same as that for control bare soils at the end of the cycle, whereas pH and TA parameters remained unaffected (Muganu *et al.,* 2013). A *F. arundinacea* (70 %) and *L. perenne* (30 %) cover crop resulted in a decrease in TSS content in Grechetto grapevines (Palliotti *et al.,* 2007). The use of natural grass, ground cover with *T. subterraneum* or with *F. arundinacea* resulted in higher TSS content while pH and TA tended to decrease in Sangiovese vineyards. Moreover, tall fescue gave an earlier harvest date due to the increased TSS (Ferrini *et al.,* 1996). However, the aforementioned cover crops also in Italy showed an increase in pH and TA parameters while TSS content remained unaltered in the same grape variety (Mattii *et al.,* 2005). Reynolds *et al.* (2006) observed a delayed grape ripening in Gewürztraminer vineyards in Canada due to the presence of *Agropyum cristatum* and *F. ovina* mixture cover crop, accompanied by a decrease in TSS, while TA was unaffected. Furthermore, a trial conducted in Leon Millot vineyards in Canada managed using different cover crop mixtures of legume and grass did not show significant differences in TSS, or were slightly higher in some cases, but those differences were still smaller in the second growing season (Messiga *et al.,* 2016). In a vineyard planted with Merlot variety in France, bloom and *veraison* occurred earlier in *F. arundinacea* cover-cropped vines, as berries showed no change in pH and had lower TA and higher TSS content compared to untilled plots (Rodriguez-Lovelle *et al.,* 2000a). Higher TSS content and lower TA were detected in Sauvignon blanc grape juices from *L. perenne* and *Cichorium intybus* cover cropped vineyards in New Zealand (Caspari *et al.,* 1997). More examples of changes in those parameters have been reported in Sauvignon blanc vineyards in South Africa, where TSS content increased and acidity decreased in the presence of a cover crop; this effect was more intense when the cover crop was maintained for a longer period of time during the season (Fourie *et al.,* 2007b). In Uruguay, a full *F. rubra* cover in a Tannat vineyard also resulted in higher TSS content (Coniberti *et al.,* 2018b).

2. Yeast assimilable nitrogen (YAN)

The impact of cover crops on nitrogen nutrition has already been reviewed in Abad *et al.* (2021). However due to the impact of YAN on must fermentation and wine characteristics (Bell and Henschke, 2005), we present here the results reported in the articles analysed in the systematic review. As a general rule, legume cover crops usually increase soil N content (Fourie *et al.,* 2007c; Messiga *et al.,* 2015; Ovalle *et al.,* 2007; Pérez-Álvarez *et al.,* 2015b; Sulas *et al.,* 2017), but this increment does not always result in a change in N content in grape juice (Sulas *et al.,* 2017). For instance, a legume cover crop did not cause any increase in YAN in Shiraz grapes, probably as a consequence of the water stress in the soil created by the cover crop that limited N fixation and was managed without irrigation (Kazakou *et al.,* 2016). Conversely, Fourie *et al.* (2007b) observed an increase in N in grape juice of Sauvignon blanc with the use of *Ornithopus sativus* and *Vicia dasycarpa* cover crops, but not in the first years of the study. In this same study, the chemical removal of cover crop before budbreak resulted in a clear increase in must N content.

The general trend for grassy cover crops is the opposite of legume cover regarding nitrogen, as the presence of the crop results in competition for this. In this regard, YAN was observed to decrease in the presence of the following types of cover crops: permanent grass in Cabernet-Sauvignon vineyards in North Carolina (Giese *et al.,* 2015), a mixture of *F. arundinacea* (70 %) and *L. perenne* (30 %) in Grechetto vineyards located in central Italy (Palliotti *et al.,* 2007), *F. arundinacea* in Merlot vineyards in Bordeaux (Rodriguez-Lovelle *et al.,* 2000b), and *Chicorium intybus* var. *sativum* in Cabernet-Sauvignon vineyards in New Zealand (Wheeler *et al.,* 2005). These differences between YAN in cove vineyard and nake soil sometimes appear during the first years of the cover crop, as reported for *F. arundinacea* in Montpellier (Ripoche *et al.,* 2011), and then these get smaller, or can remain unnoticed until the cover crop has been established for several years, as reported with *H. vulgare* in Tempranillo (Pérez-Álvarez *et al.,* 2015a).

In California, YAN in Cabernet-Sauvignon berries was unaffected by cover crop management (a spontaneous cover crop followed by tillage, or a barley cover mowed and then tilled) (Lee and Steenwerth, 2011). However, in Pinot noir in Oregon, differences in YAN were observed depending on whether the cover crop comprised legume, winter annuals or permanent grass and legume cover crops, although the effect of each cover crop also differed depending on the year (Sweet and Schreiner, 2010). Gouthu *et al.* (2012), focused their study on the amino acid content of Pinot noir berries in the Finger Lakes region, reporting that the ratio of YAN increased with cover cropping (*F. rubra*); however, the free amino acid content was 40-45 % lower in berries from cover crop treatments compared to that of berries from control plots. In the cold and humid climate of the Finger Lakes region, where excess levels of N can be a problem, this implies that a competitive cover crop can be an appropriate means of alternative managing vineyard soils.

3. Phenolic compound content

There is also a diversity of results in the influence of the presence of a cover crop on phenolic composition of grapes, although the general trend is for observations of an increase in their content associated with yield reductions. For example, an *H. vulgare* mown cover crop resulted in higher anthocyanin content than tillage management with Cabernet-Sauvignon in California (Lee and Steenwerth, 2013); this could be linked to decreased berry size. In several experiments conducted in Portugal, phenolics generally increased for at least one of the phenolic compounds measured for Cabernet-Sauvignon (Lopes *et al.,* 2008) and Tempranillo (Silvestre *et al.,* 2012; Tomaz *et al.,* 2017), but no changes were reported in other experiments with Tempranillo (Lopes *et al.,* 2011).

Research performed in a cv. Carignano vineyard in the northwest of Italy revealed that only the presence of a *Dactilys glomerate* cover crop increased anthocyanins, but this was not the case for different permanent grass-legume mixtures (Mercenaro *et al.,* 2014). In central Italy, the presence of a spontaneous cover crop in cv. Canailo nero, resulted in increased total polyphenol content, while identical management did not obtain the same result in cv. Trebbiano Giallo (Muganu *et al.,* 2013). A *F. arundinacea* (70 %) and *L. perenne* (39 %) cover crop caused an increase in polyphenols and colour in the Grechetto white wine grape variety in central Italy (Palliotti *et al.,* 2007), whereas cover cropping with a mix made by 20 % *F. rubra*, 20 % *F. ovina* and 60 % *T. subterraneum* decreased the concentration of flavonoids and anthocyanins in southern Italy. In Sardinia the concentration of total polyphenols and anthocyanins in cv. Carginano increased with *D. glomerata* (80 %) and *Lolium rigidum* (20 %), while the spontaneous (*Bromus hordeaceus*, *Avena sterilis* and *Vulpia myuros*) and legume mixture (50 % *Medicago polymorpha* and 50 % *Trifolium yanninicum*) cover crops showed reduced values compared to tillage (Muscas *et al.,* 2017).

In Spain, native vegetation and *L. perenne* cover crops increased anthocyanin concentrations to a greater extent than *T. subterraneum* for cv. Mencía in Galicia (Bouzas-Cid *et al.,* 2016; Trigo-Córdoba *et al.,* 2015). In a trial conducted in La Rioja, an *H. vulgare* cover crop resulted in higher levels of polyphenols and colour intensity in Tempranillo, whereas this effect was not observed with a *T. resupinatum* cover crop (Pérez-Álvarez *et al.,* 2015a). In central Spain, no differences were observed in Tempranillo when tillage and *Brachypodium distachyon* and *S. cereale* cover crops were compared (Marques *et al.,* 2010). Similarly, in an experiment carried out in Majorca, the use of spontaneous or grass and legume mixture cover crops did not alter the concentration of total phenolics (Pou *et al.,* 2011).

There are also some reports of research carried out in other countries with varying results depending on the experimental conditions. For instance, a spontaneous cover crop led to reduced tannin and flavonol content, while increased amounts of anthocyanins were observed in Cabernet-Sauvignon vineyards in Mendoza, Argentina (Nazrala, 2008). In New Zealand, a *C. intibys* var. *sativum* cover crop resulted in an increased anthocyanin content of Cabernet-Sauvignon berries (Wheeler *et al.,* 2005). Phenolic compounds were also increased by the presence of a natural grass cover in Cabernet-Sauvignon musts from Turkish vineyards (Bahar and Semih Yaşain, 2010), although anthocyanin content decreased. Cover crops in Cabernet-Sauvignon vineyards in China increased total phenols, the highest increase being observed for *F. arundinacea*, followed by *T. repens* and *M. sativa*, while soil tillage providing the lowest values (Xi *et al.,* 2010).

4. Aromas

Comparatively little research has evaluated the impacts of using a cover crop on aromatic compounds. As previously highlighted for the other effects on grape composition, it is important to take into account the fact that the reported effects can vary greatly depending on the research conditions, and that they can frequently be an indirect consequence of changes in yield and vegetative growth.

In a commercial Riesling vineyard in the Finger Lakes region, the use of under-vine cover crops of resident vegetation, buckwheat or *L. multiflorum* resulted in different perceived aroma in wines compared to when herbicide was used, despite vegetative growth or yield having been unaffected (Jordan *et al.,* 2016). A cover crop treatment consisting in a full cover of the vineyard soil with *F. rubra* increased fruit aroma and overall aroma intensity of cv. Tannat in Uruguay (Coniberti *et al.,* 2018b). Conversely, in Canada, the use of a mixture of *A. cristatum* and *F. ovina* resulted in a Gewürztraminer wine with lower quantities of free volatile terpenes, but higher concentrations of potentially volatile terpenes (Reynolds *et al.,* 2006). Meanwhile, no effect was observed in Sauvignon blanc vineyards in South Africa (Fourie *et al.,* 2007b). In New Zealand, a *C. intibys* cover crop resulted in an increase in ripe fruit aroma (Wheeler *et al.,* 2005), and a higher glycerol content and lower 2,3-butanediol content were reported in wines produced from vines subjected to cover-cropped treatments in Italy (Coletta *et al.,* 2013; De Pascali *et al.,* 2014; Toci *et al.,* 2012). Furthermore, in the Shaanxi Province, north west China, Xi *et al.* (2011) detected higher levels of volatile components in Cabernet-Sauvignon when using cover crops, especially those comprising *M. sativa* and *F. arundinacea*.

5. Yeast populations

It is also possible for cover crops to have an indirect influence on wild yeast populations, which can in turn affect wine characteristics when fermentation is conducted without the inoculation of commercial yeasts. In this regard, Cordero-Bueso *et al.* (2011) observed changes in the *Saccharomyces* populations in spontaneous fermentations during three seasons in Syrah, depended on whether the vines were grown in the presence of a cover crop or of bare soil. The authors hypothesised that the presence of a cover crop in vineyards reduces *Saccharomyces* populations due to a competitive effect on fungi and grape yeasts populations, reducing yeast quantity and biodiversity in the vineyard, mainly when fermentative strains are used.

CONCLUSIONS

The present systematic bibliographic review shows that cover crops tend to result in a reduced vineyard vegetative growth, which can commonly be associated with a reduced incidence of the main fungal diseases. Cover crops generally also reduce the incidence of pests, especially *Cicadellidae* and mite species, as their presence results in an increase in natural enemies.

In general, cover crops result in an increase in water deficit, although this effect is highly variable as it depends on soil and climate characteristics, and on the period of the year in which the covers are active. The increased competition for water that occurs when cover crops are used can be, to some extent, modulated by the fact that cover crops increase water infiltration into the soil, may reduce soil evaporation or can indirectly lead to lower water needs through leaf area and yield reduction.

The impact of cover crop on vineyard yield is relatively variable. In warmer climates, the observed yield reduction is greater, though irrigation practices tend to compensate for these losses. Apart of soil and climate characteristics, rootstock characteristics also appear to influence the effect of cover crops on grape yield: yield was reported to decrease less with increased rootstock tolerance to drought. Berry size is less affected by the presence of cover crops. Similarly, must quality parameters, like TSS or TA tend to stabilise change, whereas anthocyanins and polyphenols are usually the compounds most favoured by using cover crops. Type of cover crop determines the effect on YAN content, which can decrease, except when the cover crop is comprised of legumes, which usually cause an increase that is generally observed once the cover crop has been established for several seasons.

As a final remark, we consider it worth the effort to carry out the intensive work required to perform a systematic review, as it is the best way to minimise the omission of relevant research and biases in the article selection process. Our two companion papers are an example of how such review methodology can be successfully applied to broad agronomic topics on the variety of impacts that can occur when implementing a growing practice.

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