Agriculture, Ecosystems and Environment 338 (2022) 108073

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

General trends of different inter-row vegetation management affecting vine vigor and grape quality across European vineyards

Michaela Griesser [a,*], Magdalena Steiner [b], Martin Pingel [c], Deniz Uzman [d], Cristina Preda [e], Brice Giffard [f], Pauline Tolle [f], Daniyar Memedemin [e], Astrid Forneck [a], Annette Reineke [d], Ilona Leyer [c], Sven Bacher [b]

[a] *University of Natural Resources and Life Sciences, Vienna, Department of Crop Sciences, Institute of Viticulture and Pomology, Konrad Lorenz Straße 24, 3430 Tulln, Austria*

[b] *University of Fribourg, Department of Biology, Ecology & Evolution Unit, Ch. du Musee 15, 1700 Fribourg, Switzerland*

[c] *Hochschule Geisenheim University, Department of Applied Ecology, Von-Lade-Straße 1, 65366 Geisenheim, Germany*

[d] *Hochschule Geisenheim University, Department of Crop Protection, Von-Lade-Straße 1, 65366 Geisenheim, Germany*

[e] *Ovidius University of Constanta, Department of Natural Sciences, Aleea Universitatii, nr.1, Corp B, 900470 Constanta, Romania*

[f] *Bordeaux Sciences Agro, UMR 1065 SAVE Santé et Agroécologie du Vignoble, INRAE, ISVV, F-33170 Gradignan, France*

A R T I C L E I N F O

Keywords:
Cover crops
Viticulture
Soil functions
Grape quality

A B S T R A C T

Cover crops in vineyards do provide many important ecosystem functions, however wine growers are often reluctant to incorporate cover crops into their vineyard management as they are concerned about competition regarding water and nutrient availability. The objective of this study was to define the effects of three standard inter-row vegetation management strategies on vine growth and grape quality in different European regions. We hypothesize that general patterns of responses to different inter-row management can be identified across European vine growing regions independent of local climate and soil conditions. Data were collected in 2016 and 2017 in commercial vineyards located in five European temperate wine growing regions directly comparing standard inter-row vegetation management strategies in parallel in vineyards ranging from cover crops to bare ground through tillage or herbicide application. Vegetation management strongly influenced leaf chlorophyll content, shoot pruning weight and yeast assimilable nitrogen (YAN) in grape juice. Across countries, grape varieties and varying soil conditions, YAN consistently showed higher values in grapes separated by bare ground inter-rows as compared to inter-rows with a permanent vegetation cover. Other grape quality parameters, total soluble solids, total titratable acidity and berry weight were not or inconsistently affected across countries, preventing the prediction of generalized trends. We also observed higher values of soil organic matter in complete vegetation inter-rows. In conclusion, we identified general effects of inter-row vegetation management on vine vigor and grape quality across countries and grape varieties in different pedo-climatic conditions. Our study provides general response patterns as a basis for functional studies to develop local inter-row vegetation management strategies.

1. Introduction

Viticulture is of high economic value, with approximately 7 million hectares of grapevines planted worldwide, of which 50% are located in Europe (OIV, 2020). Although vineyards are intensively managed agro-ecosystems, they can host a large biodiversity (Bruggisser et al., 2010; Fernandez-Mena et al., 2021; Geldenhuys et al., 2021), can provide a range of ecosystem services due to their perennial nature, and form landscapes rich in high quality natural and semi-natural areas and special habitat structures (Winkler et al., 2017; Garcia et al., 2018). Vineyard inter-rows can support sustainability in viticulture by allowing a management system which supports a permanent or temporary vegetation cover with non-crop plant species, either as sown cover crop mixture or spontaneous vegetation. The positive effect of cover crops on different biodiversity levels and the associated ecosystem services has been demonstrated by many studies (Burns et al., 2016; Guzman et al.,

* Correspondence to: Institute of Viticulture and Pomology, Department of Crop Sciences, University of Natural Resources and Life Sciences, Vienna, Konrad Lorenz Straße 24, 3430 Tulln, Austria.

E-mail address: michaela.griesser@boku.ac.at (M. Griesser).

https://doi.org/10.1016/j.agee.2022.108073
Received 9 February 2022; Received in revised form 13 June 2022; Accepted 19 June 2022
Available online 24 June 2022

2019; Saenz-Romo et al., 2019; Hall et al., 2020; Paiola et al., 2020; Geldenhuys et al., 2021; Zanettin et al., 2021). Additionally, cover crops stabilize soil aggregates by enhancing root networks in soils and thereby allow a higher soil porosity and connectivity supporting a better water infiltration, retention and refilling of soil water reservoirs (Garcia et al., 2019, 2020; Abad et al., 2021a; Novara et al., 2021). The establishment of cover crops is one of the inter-row management options, frequent herbicide applications or soil tillage being others (Guerra and Steenwerth, 2012). Farmers decisions for these different soil management strategies in inter-rows largely depend on viticulture traditions, pedo-climatic conditions, vineyard inclination, available machinery and very often personal preferences (Steenwerth and Belina, 2008). Soil erosion is the major drawback of soil tillage which is amplified by gravel soils, low soil organic matter contents and the usage of hillslopes as vineyards (Gaudin et al., 2010; Ruiz-Colmenero et al., 2011; Biddoccu et al., 2016; Garcia et al., 2018). The application of herbicides is on the one hand cost-effective and efficient for weed control, but on the other hand the toxicity of the products and the negative effects on the environment and vines led to a controversy of this management strategy (Donnini et al., 2016; Chou et al., 2018; Zaller et al., 2018). Therefore, the use of cover crops in inter-rows became more popular, however wine growers are often reluctant to incorporate cover crops as they are concerned regarding a competition for water and nutrients resulting in reduced vegetative vine growth, a reduced grape yield and altered fruit composition (Monteiro and Lopes, 2007; Pou et al., 2011; Ruiz-Colmenero et al., 2011; Coniberti et al., 2018c; Garcia et al., 2018). Indeed, the effect of cover cropping on vine growth and grape quality might vary with the intensity of vegetation cover, plant species composition and their seasonality in growth, pedo-climatic conditions and the timing of disturbance by mulching or tillage (Guerra and Steenwerth, 2012; Garcia et al., 2019, 2020; Blanco-Canqui and Wortmann, 2020). The direct ecosystem service farmers receive is grape yield and quality, which itself depends on grape varieties and management decision by the wine growers but also on environmental factors, such as temperature, precipitation and soil types, a concept often named as the influence of "terroir" (Poni et al., 2018; van Leeuwen et al., 2018). In summary, many factors influence grape yield, grape quality and wine styles worldwide and therefore vineyard management decisions may be different depending on the local conditions. In humid-cool climates, cover crops in inter-rows could reduce the vegetative growth of vines, enhance water infiltration and drain wet soils leading to a modified microclimate in the canopy reducing pathogen infections as well as optimizing grape yield and biochemical aroma compounds in grapes (Gaudin et al., 2014; Messiga et al., 2016; Chou and Vanden Heuvel, 2019; de Oliveira et al., 2021). In arid and semi-arid climates, e.g. the Mediterranean region, vines may suffer a temporal water deficiency due to extended drought periods with high temperatures (Martinez et al., 2021), which hampers the implementation of cover crops in vineyard inter-rows in these regions. A systematic review confirmed the inconsistent impacts of cover crops on grape yield due to its strong dependency on pedo-climatic conditions and general conclusions should consider this aspect (Abad et al., 2021b).

The current knowledge on vineyard inter-row vegetation management and its consequences on soils, vines and biodiversity underlines the complex interactions in agro-ecosystems. Considering variation in all these environmental and agricultural factors, there is a need to know if there are general effects of vegetation management on vine growth and grape quality beyond pedo-climatic conditions and grape varieties that can guide farmers' decisions to allow or suppress cover crops or spontaneous vegetation in vineyard inter-rows. Here, we studied the effects of three inter-row vegetation management strategies on leaf chlorophyll content, shoot pruning weight and grape quality in parallel in vineyards in five European regions in temperate climate and hypothesize that generalized pattern of grapevine responses independent of grape variety and environmental factors can be extracted. On the basis of the current knowledge, we expected that a permanent vegetation cover will affect measurements on vine growth negatively due to competition with water and nutrients, while grape berry ripening and grape quality will show indifferent responses. By analyzing results obtained from our transnational study and the ability to directly compare bare ground, alternating vegetation cover and complete vegetation cover in vineyards, we highlight the most conserved responses of grapevine to different inter-row management and add this novel aspect to the current knowledge.

2. Materials and methods

2.1. Study areas, vineyard characteristics and experimental setup

The experiment was established in 2015 in five European temperate wine growing regions: Lower Austria and Burgenland in Austria (AT), Valais in Switzerland (CH), Rheinhessen in Germany (GE), Libournais near Bordeaux in France (FR) and Dobrogea in Romania (RO). Three inter-row vegetation management treatments were established in parallel in 36 replicated vineyards (GE, FR, AT, RO), with an additional 29 vineyards with individual inter-row management which were selected in Switzerland due to the small-scale vineyard typology. Each inter-row treatment was established in four inter-rows of the vineyards while the two-middle inter-rows were used for measurements and sampling. A detailed description of the three treatments is given in Table 1 and is summarized as: complete and permanent vegetation cover in all vineyard inter-rows (complete vegetation cover, CC), a partial spatial or temporal disturbance in the inter-row (alternating vegetation cover, AC) and the removal of plants in inter-rows by tillage or herbicide application (bare ground, BG). Vineyards had a Vertical Shoot Positioned Trellis (VSP) training system and were pruned either as one or two-sided spurs or canes according to regional preferences. Location, vineyard and viticulture parameters are given in Table S1. All vineyards were managed by wine growers and grapes were commercially used for vinification. Local management strategies for plant protection and nutrition were applied.

2.2. Soil characteristics of experimental vineyards and plant survey

Soil physico-chemical parameters of all vineyards were determined in 2016 and 2017 from 250 g dry soil according to standardized procedures (Schaller, 2000). Soil samples were collected in June during flowering. Briefly, soil pH was measured in a soil suspension with 0.01 M $CaCl_2$-solution (1:1.5). The soil total carbon and nitrogen contents were determined following the Dumas combustion method and using a "Vario MAX CNS" analyzer (Elementar Analysensysteme GmbH, Langenselbold, Germany). The inorganic carbon fraction was determined, by measuring the calcium-carbonate fraction using the HCl reaction and measuring the volume of released CO_2, organic carbon and soil organic matter (SOM) was calculated from the amount of total and inorganic carbon. Plant available potassium, phosphor and magnesium were determined with an atomic absorption spectrometer (AAS) after calcium acetate lactate (CAL) or $CaCl_2$ (0.025 M) extraction. Soil texture was determined according to standard procedures using a *Köhn* hydrometer and classified to soil types.

A principal component analyses (PCA) of the within country standardized soil variables (Table S2) was performed to evaluate the factors "country" and "soil type" as suitable inputs for follow-up analyses. The PCA shown in Fig. 1 was performed with PAST 4.05 (Hammer et al., 2001) and revealed that the category "country" (Fig. 1 A) could better separate the soil variables as the category "soil type" (Fig. 1 B). On the basis of these results as well as on our reasoning, that country best represents the pedo-climatic conditions as well as the viticulture practices, this factor was used in general linear mixed models.

The vegetation cover in each inter-row and the plant species composition was determined in spring 2016 and 2017 in all experimental plots. We determined the percentage cover with grasses, herbaceous species and legumes in two 1 m^2 squares per treatment inter-

Table 1
Description of the inter-row vegetation management treatments (CC, AC, BG) established in vineyards in AT, FR, GE, CH and RO. The alternating vegetation cover (AC) differed between countries in order to consider local strategies in our experimental setup. All treatments were established in four inter-rows per vineyard and samples were collected from two plots per treatment.

		Local implementation of experimental plots				
Treatment	**Vegetation disturbance intensity**	**Austria (AT)**	**France (FR)**	**Germany (GE)**	**Romania (RO)**	**Switzerland (CH)**
Complete vegetation cover (CC)	low	inter-row vegetation mulching several times per seasons				
Alternating vegetation cover (AC)	intermediate	Spatial - mechanical disturbance of vegetation in every second inter-row by tillage 2–3 times per season; mowing of the vegetation in remaining inter-rows	Temporal - green manure (winter): sown seed mixture of winter crops after harvest and tillage in spring, followed by frequent mowing throughout the season	Spatial - mechanical disturbance of vegetation in every second inter-row by tillage 2–3 times per season; mowing of the vegetation in remaining inter-rows	Temporal - green manure (spring): sown *Medicago sativa* seed mixtures in spring, mowing during the season and tillage after harvest	Spatial - chemical disturbance of vegetation growth in every second inter-row by herbicide application 1–4 times per season; mowing of the vegetation in the remaining inter-rows
No vegetation cover/ bare ground (BG)	high	disturbance of vegetation growth by tillage 2–4 times per season				disturbance of vegetation growth by herbicide application 1–4 times per season

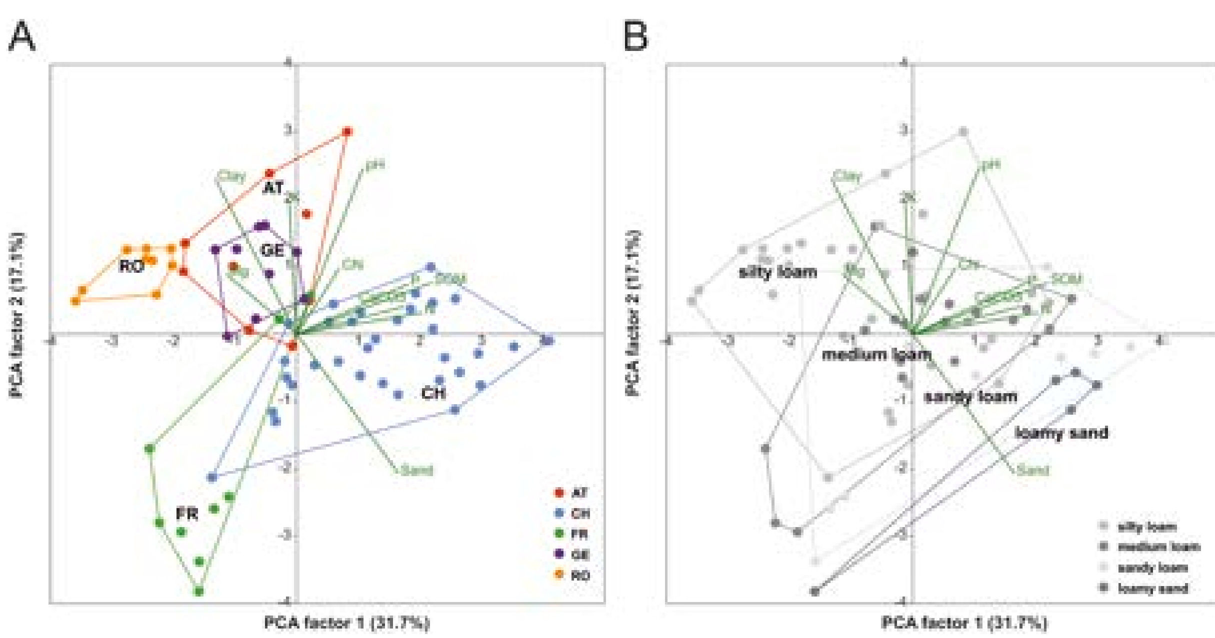

Fig. 1. Results of a principal component analyses (PCA) of the determined physico-chemical soil parameters in the experimental vineyards in AT (Austria), CH (Switzerland), FR (France), GE (Germany) and RO (Romania). Analyses were performed in PAST 4.05 with the soil variables as mean values of measurements from 2016 and 2017 (soil texture as percentage sand and clay content, soil organic matter, potassium content, nitrogen content, phosphorus content, magnesium content, C/N ratio, carbonate content, soil pH). A) Biplot of PCA analyses with country as grouping factor. B) Biplot of PCA analyses with soil type as grouping factor.

row. Results of four observations are given as mean values and standard deviation for treatments complete vegetation cover (CC) and alternating vegetation cover (AC) in Table S2.

2.3. *Non-destructive measurement of leaf nitrogen content*

Non-destructive measurements were used to assess the chlorophyll content of leaves, which also serves as proxy of leaf nitrogen content (Romero et al., 2013). Measurements were performed on at least ten healthy leaves above the grape growing zone per treatment and vineyard. Instruments used were hand-held devices (SPAD-502Plus Chlorophyll Meter (Konica Minolta Europe Langenhagen, Germany, giving SPAD values) in AT, FR, GE and RO; CCM-200plus (Opti-Sciences, Hudson NH, USA, giving CCI values) in CH)). Measurement were performed at three phenological stages, namely during flowering (BBCH65, SPAD1), at veraison (BBCH81) and at harvest (BBCH89). Results obtained at veraison and harvest were similar, therefore these measurements were combined to one dataset and named SPAD2 in the following result section. Both instruments used give dimensionless numbers, but on a different scale, which made a standardization of the data within each country necessary to compare treatment effects.

2.4. *Assessment of grape quality and vine pruning weight*

Frequently used parameters to assess grape ripening and determine harvesting dates are total soluble solids (TSS) and total titratable acidity (TA) (Poni et al., 2018). Grape berry samples (200–250 berries per treatment and vineyard) were collected from different grape clusters in plastic bags in all treatments in each vineyard before harvest (BBCH89) in 2016 and 2017. Grape juice was obtained by squeezing berries within the plastic bag manually. Further on, the juice was filtered (Whatman filter 520 A 1/2) and centrifuged for 5 min at 3500 rpm in a 50 ml Falcon tube. The clarified juice was analyzed via Fourier-Transformation-IR-Spectroscopy (FTIR, OneoFOSS, FOSS GmbH, Hamburg, Germany) to obtain the values total soluble solids (TSS, °Brix), total titratable acidity (TA, g L^{-1}) and yeast assimilable nitrogen (YAN, mg L^{-1}) as alpha-amino nitrogen and ammonia in AT, FR, RO and CH. Results for nitrogen in grape must obtained in Germany were expressed as primary amino acids determined by o-phthaldialdehyde assay (NOPA). Additionally, the weight of 100 berries was determined to estimate the treatment effects on berry growth. The pruning weight per vine was determined after the growing season 2016 (December 2016 and January 2017) by on site weighing with a hanging scale (HS-10 L, Voltcraft, Germany, 0.01 kg) of the annual shoots of 20–30 vines per treatment and vineyard in Austria, France and Germany.

2.5. Statistical analyses

Data evaluation, data exploration and correlation analyses were performed using the software SPSS 27 (IBM SPSS Statistics 27). Extreme outliers were visualized via boxplots and removed from the dataset according to standard settings (quartile ± 3 *interquartile range). PCA analyses of soil variables was performed using PAST 4.05 (Hammer et al., 2001). General linear mixed effect models (LMM) were performed in R version 4.0.3 (R Core Team, 2020) with the package "lme4" (Bates et al., 2015) using restricted maximum likelihood (REML) to investigate the effect of the treatments on grape quality, pruning weight, SPAD values and soil functions. The treatments were transformed into a numerical disturbance gradient for statistical testing (Table 1): CC, low (1); AC, intermediate (2), BG, high (3). The main interest of our study was to assess a generalized response of vine and grape parameters due to the establishment of different inter-row vegetation management strategies independent from pedo-climatic conditions, grape variety or viticulture practices. To account for the hierarchical structure of the experimental design, we selected year nested within vineyard (1|vineyard/year) if data from both years were used or vineyard (1|vineyard) as random factor. Additionally, we included country as fixed factor to account for differences in environmental conditions between countries and other variables which could not be specified in the frame of the study. Assumptions of LMM were graphically evaluated with the package's "performance" and "DHARMa" (Lüdecke et al., 2021; Hartig, 2021).

Table 2
Summary results of the Type III Analysis of Variance (ANOVA) of the general linear mixed models fitted by restriction maximum likelihood (REML) for the response variables: soil organic matter (SOM, %), total nitrogen content (N, %), plant available K (mg g^{-1}), Mg (mg g^{-1}), P (mg g^{-1}), soil texture sand (sand, %), soil texture clay (clay, %), chlorophyll content flowering (SPAD1), chlorophyll content veraison-harvest (SPAD2), shoot pruning weight (kg), total soluble solids (TSS, °Brix), total titratable acidity (TA, mg L^{-1}), 100-berry weight (g) and yeast assimilable nitrogen (YAN, mg L^{-1}). Mixed models included the nested random factor (1|vineyard/year) or (1|vineyard) and analyzed the fixed factors treatments (as factor plot disturbance with factor levels 1 (CC), 2 (AC), 3 (BG)) and country (AT, Austria; CH, Switzerland, FR, France; GE, Germany; RO, Romania). ANOVA results from the best-fit model representing the response variables are shown (summary of model selection see Table S3). Significance represents: '* ** ' p < 0.001; '* *' p < 0.01; '* ' p < 0.05; '.' p < 0.1.

		Sum Sq	Mean Sq	NumDF	DenDF	F value	P (Pr>F)	sig	η^2
log(SOM)	treatment	0.170	0.085	2	128.6	4.903	0.0089	* *	0.07
	country	1.534	0.383	4	59.0	22.086	$3.51e^{-11}$	* **	0.60
	treatment*country	0.213	0.027	8	129.3	1.535	0.1514		0.09
log(N)	treatment	0.173	0.086	2	155.6	3.563	0.0307	*	0.04
	country	2.377	0.594	4	56.5	24.534	$8.39e^{-12}$	* **	0.63
	treatment*country	0.341	0.043	8	120.1	1.761	0.0915	.	0.10
log(K)	treatment	0.035	0.017	2	151.4	2.245	0.1095		0.03
	country	0.397	0.099	4	59.9	12.907	$1.22e^{-07}$	* **	0.46
	treatment*country	0.114	0.014	8	127.8	1.853	0.0730	.	0.10
log(Mg)	treatment	0.013	0.006	2	120.2	2.246	0.1102		0.04
	country	0.076	0.019	4	59.8	6.662	0.0002	* **	0.31
	treatment*country	0.018	0.002	8	151.1	0.764	0.6349		0.04
sqrt(P)	treatment	0.842	0.421	2	162.5	1.046	0.3536		0.01
	country	23.119	5.780	4	59.2	14.360	$2.97e^{-08}$	* **	0.49
	treatment*country	2.818	0.352	8	167.9	0.875	0.5386		0.04
log(sand)	treatment	0.041	0.020	2	164.4	0.453	0.6366		0.00
	country	13.063	3.266	4	61.1	72.391	$2.00e^{-16}$	* **	0.83
	treatment*country	0.876	0.110	8	170.3	2.427	0.0165		0.10
log(clay)	treatment	0.041	0.020	2	164.4	0.453	0.6366		0.00
	country	13.063	3.266	4	61.1	72.391	$2.00e^{-16}$	* **	0.83
	treatment*country	0.876	0.110	8	170.3	2.427	0.0165	*	0.10
SPAD1 (z-sc.)	treatment	26.368	13.184	2	110.5	22.454	$6.57e^{-09}$	* **	0.29
	country	0.118	0.030	4	56.7	0.050	0.9951		0.07
	treatment*country	45.516	5.690	8	392.1	9.690	$2.75e^{-12}$	* **	0.11
SPAD2 (z-sc.)	treatment	33.976	16.988	2	98.0	28.223	$2.09e^{-10}$	* **	0.37
	country	0.039	0.010	4	57.9	0.016	0.9995		0.01
	treatment*country	56.875	7.109	8	317.2	11.811	$9.78e^{-15}$	* **	0.23
Pruning weight (sqrt-trans)	treatment	0.075	0.037	2	957.4	28.492	$9.56e^{-13}$	* **	0.06
	country	0.015	0.007	2	23.0	5.662	$1.00e^{-02}$	*	0.33
Total soluble solids	treatment	0.818	0.409	2	173.2	0.464	0.6296		0.00
	country	26.739	6.684	4	57.3	7.580	$5.66e^{-05}$	* **	0.35
	treatment*country	7.701	0.963	8	148.8	1.091	0.3723		0.06
Total titratable acidity	treatment	2.585	1.292	2	148.4	4.290	0.0154	*	0.05
	country	26.488	6.622	4	60.7	21.980	0.0000	* **	0.59
100-berry weight (log-tranformed)	treatment	0.002	0.001	2	78.6	0.339	0.7138		0.00
	country	0.054	0.013	4	59.1	3.826	0.0078	* *	0.21
	treatment*country	0.040	0.005	8	103.0	1.437	0.1901		0.10
Yeast assimilable nitrogen	treatment	10,878.000	5439.200	2	75.0	13.674	$8.64e^{-06}$	* **	0.27
	country	30,477.000	7619.200	4	67.0	19.154	$1.53e^{-10}$	* **	0.53

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Response variables were log-transformed or square-root-transformed if necessary to achieve normal distribution of residuals (Table 2). In case of heteroscedasticity we estimated robust standard errors with the functions vocv.fun = "CR" and vcov.type = "CR1" with the packages "sjPlot" (Lüdecke, 2021) and "clubSandwich" (Pustejovsky, 2021). Different models were fit to the data in order to obtain the most influencing factors explaining our results (Table S3). Model selection was performed with the package "performance" (Lüdecke et al., 2021) following the provided performance scores. Effect plots of the LMM were obtained using "ggplot2" (Wickham, 2016) and trend lines were calculated using the package "effects" (Fox and Weisberg, 2019) and the effect size partial Eta^2 (η^2) was calculated with R package "effectsize" (Ben-Shachar et al., 2020). Within country pairwise comparisons of the treatment levels in the LMM were performed with the package "emmeans" (Lenth, 2021) and we applied a Bonferroni correction for multiple testing.

3. Results

3.1. *Minor effects on soil functions due to different inter-row management*

Soil variables, obtained from treatment plots within each vineyard, differed among countries (Table 2), as has already been suggested by the PCA (Fig. 1 A). Significant results for the factor country were obtained for soil organic matter (SOM, %), total nitrogen content (N, %), plant available K (mg g^{-1}), Mg (mg g^{-1}), P (mg g^{-1}), percentage sand and percentage clay. The effect sizes of countries (η^2 = 0.31–0.83) were much higher as the comparable effect sizes of the factor inter-row management treatments (η^2 = 0.01–0.07). Among the tested soil variables, only the soil organic matter content (F (2, 128.56) = 4.90, $p = 0.009$) and total soil nitrogen content (F (2, 170.97) = 3.52, $p = 0.032$) were affected by the inter-row vegetation treatments without an interaction with the factor country (Table 2). The soil organic matter content (SOM) was lower with an increase in soil disturbance from treatment complete vegetation cover (CC) towards bare ground (BG) by tillage or herbicide application (BG estimates: −0.12, $p = 0.019$; Table S4). Pairwise comparisons of treatments within each country and the effects plots of the LMM (Fig. 2 A) confirm the significant lower values of soil organic matter for complete vegetation cover (CC) compared to bare ground (BG) for Austria (mean CC = 6.20 ± 0.6, mean BG = 5.48 ± 0.5, $p < 0.001$) and France (mean CC = 3.27 ± 0.4, mean BG = 2.68 ± 0.3, $p = 0.005$). A similar trend was observed in Switzerland and Germany. Additional to the above-mentioned results, the within country comparisons showed significant lower SOM of the green manure (AC) in France compared to the permanent vegetation cover (CC) (mean CC = 3.27 ± 0.4, mean AC = 2.76 ± 0.3, $p = 0.021$).

Similarly, to the SOM, we determined lower values in total soil nitrogen content with an increase in vegetation cover (CC estimates: −1.63, $p < 0.001$, Table S4). As shown in the effect plot of the LMM (Fig. 2 B) and confirmed by pairwise comparisons within countries, the total soil nitrogen content decreased from complete vegetation cover towards bare ground in Austria (mean CC = 0.21 ± 0.01, mean BG = 0.17 ± 0.01, $p < 0.001$) and partly in Switzerland (mean CC = 0.38 ± 0.03, mean BG = 0.31 ± 0.03, $p = 0.1868$). Additionally, in Austria the soil total N content was higher in the treatment with the alternating vegetation cover in every second row (AC) as compared to the bare ground (BG) (mean AC = 0.20 ± 0.01, mean BG = 0.17 ± 0.01, $p = 0.001$).

3.2. *Bare ground promotes leaf chlorophyll content and shoot pruning weight of vines*

The inter-row vegetation management had a strong influence on the leaf chlorophyll content at flowering (BBCH65; SPAD1; F (2, 110.45) = 22.4537, $p < 0.001$) as well as in the period from veraison until harvest (BBCH65-BBCH89; SPAD2; F (2, 98.02) = 28.2226, $p < 0.001$) (Table 2, Table S5). In detail across countries, bare ground (BG) by soil tillage or herbicide application did promote higher leaf chlorophyll contents as compared to complete vegetation cover (CC) of about 2.66 ($p = 0.005$) units (SPAD, CCI) at flowering and 2.19 ($p = 0.149$) units between veraison to harvest (Table S5). At flowering, the chlorophyll content differed between CC and BG in France (mean CC = 33.2 ± 0.5, mean BG = 36.3 ± 0.3, $p < 0.001$), Austria (mean CC = 36.6 ± 0.3, mean BG = 39.2 ± 0.4, $p < 0.001$) and Germany (mean CC = 32.9 ± 0.3, mean BG = 35.1 ± 0.2, $p < 0.001$), while in Switzerland and Romania, the obtained results in both treatments were comparable (Fig. 3 A). In Romania the lowest SPAD values were determined with the

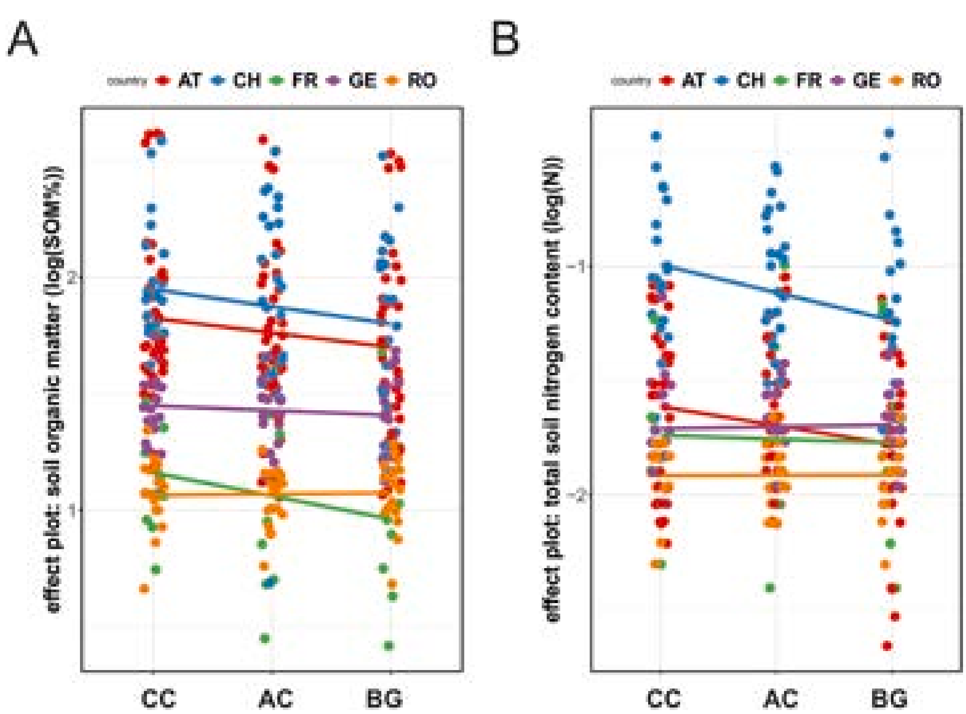

Fig. 2. Effect plots of a general linear mixed model including treatment as numerical value for plot disturbance (CC, complete vegetation cover; AC, alternating vegetation cover; BG, bare ground by tillage or herbicide application) and country (AT, Austria; CH, Switzerland, FR, France; GE, Germany; RO, Romania) as fixed factors with interactions and the nested random factor (1|vineyard/year). A) Results for soil organic matter content (SOM, %) in each country (filled circles) on a log scale and the result of the LMM as trend line for the interaction between treatment and country. B) Results for total soil nitrogen content (N, %) in each country (filled circles) on a log scale and the result of the LMM as trend line for the interaction between treatment and country.

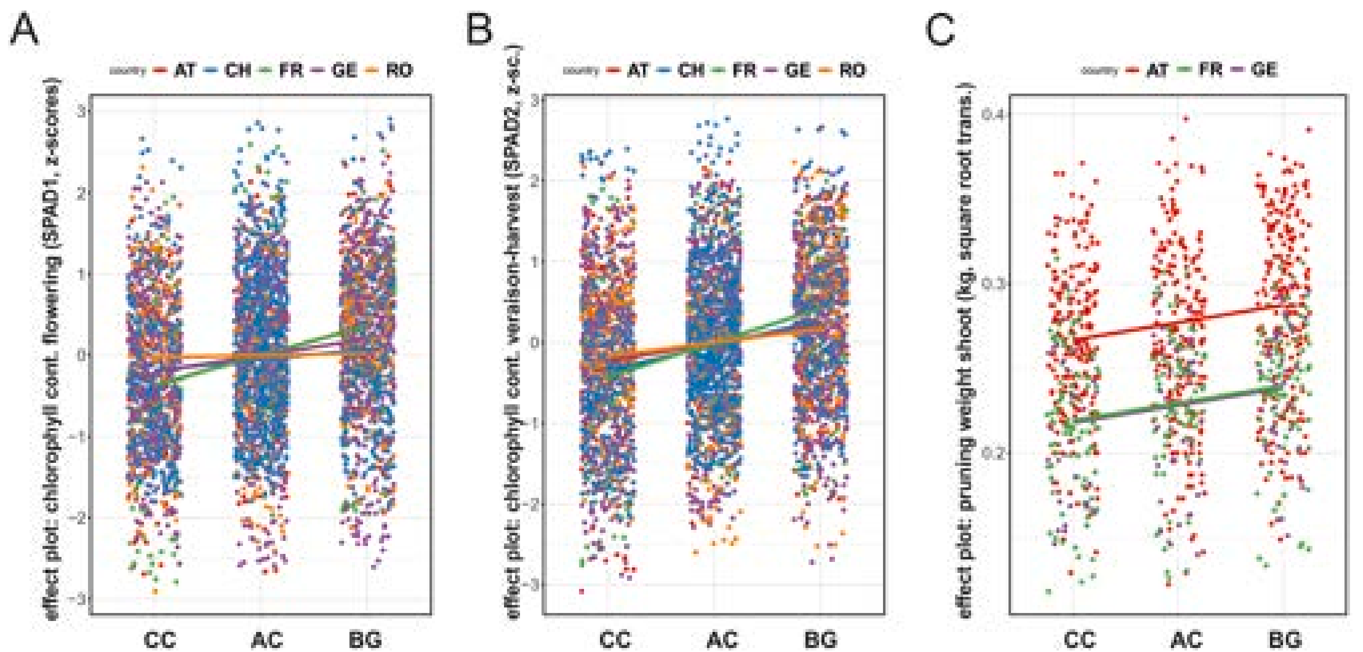

Fig. 3. Effect plots of a general linear mixed model including treatment as numerical value for plot disturbance (CC, complete vegetation cover; AC, alternating vegetation cover; BG, bare ground by tillage or herbicide application) and country (AT, Austria; CH, Switzerland, FR, France; GE, Germany; RO, Romania) as fixed factors and the random factor (1|vineyard). A) Results for the non-destructive measurement at flowering of the leaf chlorophyll content (SPAD/CCI values) standardized within each country. B) Results for the non-destructive measurement at veraison-harvest of the leaf chlorophyll content (SPAD/CCI values) standardized within each country. C) Results for the shoot pruning weight as square root transformed values of the weight per shoot within each country. LMM results shown as trend lined for the interaction between treatment and country.

treatment green manure (AC), a trend not observed in other countries (mean AC =3 4.9 ± 0.5, mean BG = 36.6 ± 0.4, $p = 0.001$). Values obtained later in the season (veraison-harvest) were similar to the obtained results in spring (Fig. 3 A, B). The chlorophyll content in complete vegetation cover (CC) was lower compared to bare ground (BG) in France (mean CC = 33.9 ± 0.5, mean BG = 39.4 ± 0.4, $p < 0.001$), Germany (mean CC = 38.1 ± 0.2, mean BG = 40.2 ± 0.2, $p < 0.001$), Austria (mean CC = 40.1 ± 0.5, mean BG = 42.2 ± 0.4, $p < 0.001$), Romania (mean CC = 40.7 ± 0.3, mean BG = 42.1 ± 0.4, $p < 0.001$) and Switzerland, although not significant in the later (mean CC = 22.4 ± 0.5, mean BG = 26.8 ± 0.5, $p = 0.1681$). Additionally, the leaf chlorophyll content with spatial or temporal alternating vegetation cover (AC) in France (mean AC = 38.5 ± 0.4, $p < 0.001$) and Germany (mean AC = 39.8 ± 0.2, $p < 0.001$) was also higher compared to the permanent vegetation cover (CC).

The pruning weight (as weight per shoot), determined in 2016 in Austria, France and Germany, turned out to be strongly affected by the applied inter-row management (Table 2; F (2, 957.43) = 28.4919, $p < 0.001$). Pruning weight was about 0.02 kg higher in the bare ground (BG) treatment ($p < 0.001$) as compared to complete vegetation coverage (CC) (Table S5). The trend is similar in all countries (Fig. 3 C) and within country pairwise comparisons confirmed that pruning weights obtained in treatments with bare ground (BG) were significantly higher than other treatments (Austria: mean CC = 0.074 ± 0.002, mean BG = 0.086 ± 0.002, $p < 0.001$; France: mean CC = 0.049 ± 0.002, mean BG = 0.060 ± 0.002, $p < 0.001$; Germany: mean CC = 0.050 ± 0.004, mean BG = 0.058 ± 0.003, $p < 0.001$).

3.3. Grape quality parameters show a mixed response to inter-row management

In order to select factors and variables influencing our grape quality results, general linear mixed models with the factors country and treatment and a selection of soil variables, pre-selected by correlation analyses (Table S6), were performed. A comparison of different models confirmed, that calculations with soil variables included in the equation, did not substantially improve model ranking (Table S3). Therefore, best ranked models including the factors country and treatment were further analyzed (Table 2, Table S5). Among the four measured grape quality parameters (total soluble solids, total titratable acidity, yeast assimilable nitrogen, 100-berry weight), the yeast assimilable nitrogen (YAN) was strongest influenced by the applied inter-row vegetation management treatments (F (2, 75.0) = 13.674, $p < 0.001$; Table 2). The grape must YAN was higher by 24 mg L^{-1} in bare ground plots (BG) compared to permanent vegetation cover (CC) (Table S5). The effect plot (Fig. 4 D) and pairwise comparisons of treatments within each country confirmed the strong effect in all countries (Austria: mean CC = 108.8 ± 15.1, mean BG = 133.5 ± 10.8, $p < 0.001$; France: mean CC = 57.5 ± 8.1, mean BG = 91.7 ± 12.4, $p < 0.001$; Germany: mean CC =134 ± 19.2, mean BG = 179.6 ± 19.1, $p < 0.001$; Romania: mean CC = 89.6 ± 21.9, mean BG = 100.7 ± 22.0, $p < 0.001$; Switzerland: mean CC = 213.2 ± 19.0, mean BG = 257.5 ± 12.9, $p < 0.001$). In absolute values, the highest YAN values were obtained in Switzerland followed by Germany and Austria and were lowest in France and Romania (Fig. 4 D). The grape parameters total soluble solids, titratable acidity and 100-berry weight were not strongly affected by the inter-row vegetation management treatments as shown in Fig. 4 A-C, but there was a non-significant trend of lower titratable acidity and 100-berry weight in complete vegetation cover (CC) as compared to both other inter-row management treatments (Table S5). Soil potassium content did enhance the overall model performance of TA with factors treatment and country but a direct comparison of both models (with and without soil potassium content) determined no difference.

Inter-row ground cover treatments did not affect the measured grape quality parameters with the exception of yeast assimilable nitrogen (Fig. 4, Table 2, Table S5). To identify further influencing factors on yeast assimilable nitrogen, we performed a correlation analysis with selected soil variables (SOM, soil N content) and vine vigor parameters (chlorophyll content, pruning weight, berry weight) within each country (Table 3). Yeast assimilable nitrogen in berries showed a positive

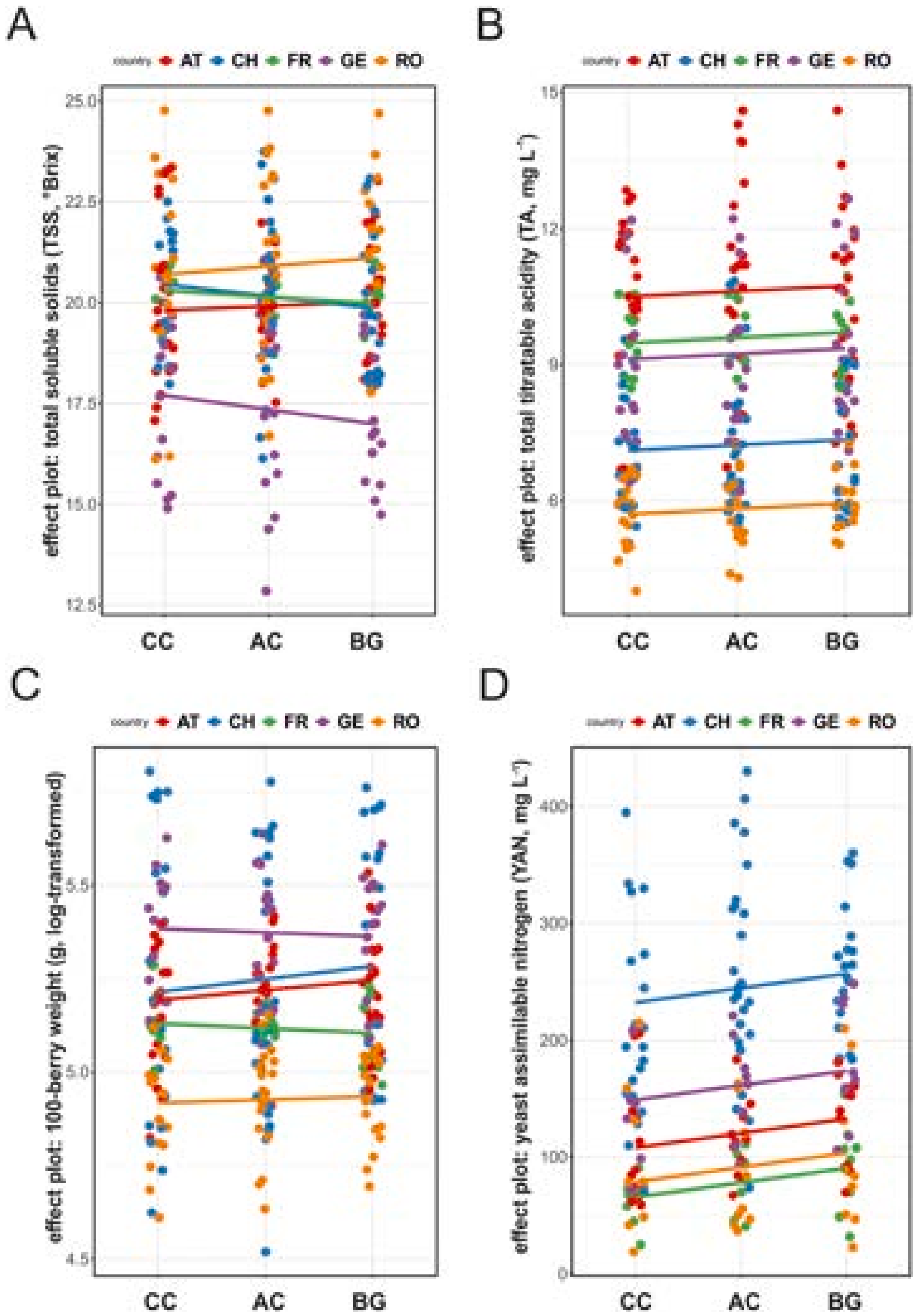

Fig. 4. Effect plots of a general linear mixed model including treatment as numerical value for plot disturbance with factor levels 1 (CC, complete vegetation cover), 2 (AC, alternating vegetation cover), 3 (BG, bare ground by tillage or herbicide application)) and country (AT, Austria; CH, Switzerland, FR, France; GE, Germany; RO, Romania) as fixed factors and the random factor (1|vineyard/year). A) Results obtained for total soluble solids (TSS, °Brix) within each country (filled circles) and the obtained effects trend line for treatments in each country. B) Results obtained for total titratable acidity (TA, mg L^{-1}) within each country (filled circles) and the obtained effects trend line for treatments in each country. C) Results obtained for 100-berry weight (g) within each country (filled circles) and the obtained effects trend line for treatments in each country. D) Results obtained for yeast assimilable nitrogen (YAN, mg L^{-1}) within each country (filled circles) and the obtained effects trend line for treatments in each country.

correlation with chlorophyll content, but not with soil nitrogen content. In general, the vine vigor related parameters, chlorophyll content, shoot pruning weight and yeast assimilable nitrogen were positively correlated. The total soil nitrogen content had the strongest effect on berry weight, while no relation or even a negative correlation in Germany was found with yeast assimilable nitrogen in grape juice.

4. Discussion

In our study we analyzed the effects of standard inter-row vegetation management strategies on vine vigor and grape quality parameters in five European temperate viticulture regions with the aim to determine generalized grapevine responses to different inter-row management independent from pedo-climatic conditions and grape varieties.

Across all countries we found a consistent influence of the applied inter-row vegetation management strategies on vine vigor and nutrition. Leaf chlorophyll content, shoot pruning weight and yeast assimilable nitrogen in grape must were highly correlated and substantially higher in bare ground inter-rows (BG) as compared to other treatments, across a wide variety of grape cultivars and pedo-climatic conditions. Soil nitrogen content is often assumed as the main driver of such vigor promotion, as the positive impact of plant-available nitrogen on grapevine biomass production is well documented (Gatti et al., 2018). However, this did not seem to be the case in our study, as the total soil nitrogen content was either not or sometimes even negatively correlated with the yeast assimilable nitrogen in grape must, the pruning weight or the leaf chlorophyll content. Nitrate and ammonium represent a small fraction of the total soil nitrogen content and levels vary significantly depending

Table 3
Correlation analyses of vigor (leaf chlorophyll content at flowering (SPAD1), leaf chlorophyll content at veraison-harvest (SPAD2), shoot pruning weight (PW)) and berry quality parameters (berry weight (BW), yeast assimilable nitrogen (YAN)) with soil variables (soil organic matter content (SOM), soil total nitrogen content (N) and percentage sand in soil texture (sand)) as well as with each other. Results represent Spearman Rho correlation coefficients and asterisks indicate significant relationships ("*"$\alpha = 0.05$; "**"$\alpha = 0.01$) for countries Austria (AT), France (FR), Germany (GE), Romania (RO) and Switzerland (CH). Not available data: n.d.

Country		BW	SOM	N	Sand	PW	SPAD1	SPAD2
AT	**SPAD1**		-0.164	**-0.317** *	-0.044	-0.050	1	**0.530** * *
FR	**SPAD1**		0.373	0.276	**-0.408** *	**0.776** * *	1	**0.910** * *
GE	**SPAD1**		0.033	0.055	0.299	**0.694** * *	1	**0.714** * *
RO	**SPAD1**		-0.107	0.056	0.381	n.d.	1	**0.534** *
CH	**SPAD1**		-0.35	0.041	-0.177	n.d.	1	**0.740** * *
AT	**SPAD2**		**0.482** * *	0.141	**-0.443** * *	0.201	**0.530** * *	1
FR	**SPAD2**		0.212	0.178	-0.262	**0.703** * *	**0.910** * *	1
GE	**SPAD2**		0.152	0.004	0.293	**0.861** * *	**0.714** * *	1
RO	**SPAD2**		0.217	0.230	**0.393** *	n.d.	**0.534** *	1
CH	**SPAD2**		-0.046	0.063	-0.137	n.d.	**0.740** * *	1
AT	**PW**		0.138	0.047	-0.193	1	-0.050	0.201
FR	**PW**		0.334	0.149	**-0.432** *	1	**0.776** * *	**0.703** * *
GE	**PW**		0.235	-0.254	**0.445** *	1	**0.694** * *	**0.861** * *
RO	**PW**		n.d.	n.d.	n.d.	1	n.d.	n.d.
CH	**PW**		n.d.	n.d.	n.d.	1	n.d.	n.d.
AT	**BW**	1	**-0.250** *	**0.246** *	**0.499** * *	**-0.608** * *	**0.501** * *	0.249
FR	**BW**	1	0.218	-0.061	**-0.487** *	0.381	-0.009	-0.090
GE	**BW**	1	0.170	**0.511** * *	-0.247	-0.301	-0.279	-0.304
RO	**BW**	1	**0.357** *	**0.376** *	-0.140	n.d.	0.004	0.132
CH	**BW**	1	0.031	-0.104	0.143	n.d.	**-0.565** * *	**-0.542** * *
AT	**YAN**	0.158	**0.387** *	-0.086	-0.164	n.d.	n.d.	n.d.
FR	**YAN**	-0.249	0.327	0.203	-0.217	**0.605** * *	**0.887** * *	**0.928** * *
GE	**YAN**	0.074	**-0.724** * *	**-0.583** * *	**0.423** *	n.d.	n.d.	n.d.
RO	**YAN**	**0.444** *	0.133	-0.069	0.023	n.d.	n.d.	n.d.
CH	**YAN**	**-0.510** * *	0.145	0.238	-0.206	n.d.	**0.511** * *	**0.661** * *

on the rates of nitrogen mineralization, plant nitrogen uptake and soil nitrogen losses (Verdenal et al., 2021). In our study, it seems that the total soil nitrogen content did not necessarily reflect the dynamics of the plant-available mineral nitrogen fraction or other nitrogen sources. A fast degradation of plant debris and a degradation of the soil organic matter after soil tillage may also be an influencing factor. Degradation of SOM is often associated with soil tillage thereby leading to a loss in aggregate stability and the capacity of water storage (Salome et al., 2016; Garcia-Diaz et al., 2017; Garcia et al., 2019). It has recently been shown in studies in southern Spain and Italy, that a spontaneous vegetation can positively influence the macroaggregate stability and the organic carbon content in soils (Guzman et al., 2019; Novara et al., 2020). These aspects, enhanced SOM degradation through tillage and promotion of carbon sequestration through vegetation cover, may both be applicable for our results, as we observed consistently lower soil organic matter content in bare ground inter-rows as compared to inter-rows with vegetation cover. SOM contributes to the soil water holding capacities, although plant available water is predominantly determined by soil texture classes (Lazcano et al., 2020). Nevertheless, it has been shown that mowed cover crops increased the water infiltration by 45% as compared to tillage and provide with increased SOM levels higher storage capacities (Ruiz-Colmenero et al., 2013). The observed higher levels of SOM in vegetation cover inter-rows as compared to bare ground in our study, did not translate into higher shoot pruning weights or leaf chlorophyll contents in treatment comparisons, which could be due to the short period of assessment.

Plant-based analyses, especially the non-destructive measurements with hand-held chlorophyll meters or hyperspectral reflectance instruments, provide flexible and high-throughput options to measure the leaf chlorophyll content, and thereby indirectly the leaf nitrogen content throughout the season (Vrignon-Brenas et al., 2019; Verdenal et al., 2021). In our study, the nitrogen dynamics in the soil influenced by the applied inter-row vegetation management strategies was best reflected by leaf chlorophyll content measurements. This is in accordance with higher yeast assimilable nitrogen in grape juice and enhanced shoot pruning weights in treatments where the vegetation has been disturbed by tillage or herbicide application. The response of vine growth to different inter-row vegetation management strategies is well documented (Monteiro and Lopes, 2007; Guerra and Steenwerth, 2012; Giese et al., 2014; Steenwerth et al., 2016; Sulas et al., 2017; Coniberti et al., 2018a). A study in Mediterranean climate analyzed the effects of bare ground by tillage and different cover crop compositions (natural vegetation, grass mixture, legume rich seed mixture) in the inter-rows on grape yield and quality in a three-year experiment (Muscas et al., 2017). The shoot pruning weights were lower in all treatments with cover crops compared to the bare ground inter-rows, while the leaf chlorophyll contents were reduced by a mainly grass based cover crop composition (Muscas et al., 2017). These results support our observations on shoot pruning weight and leaf chlorophyll content with consistently higher values determined in bare ground treatments as compared with complete vegetation cover. Although our results were obtained in temperate climates, the similarities to the results obtained in a Mediterranean country may be the first consequences of climate change. Interestingly, a legume-based cover crop vegetation seems to counteract the negative effects of competition from cover crops for vine available soil nutrients. Recently, a subset of our data from Switzerland was analyzed with structural equation modelling and showed that N-fixing plants did enhance yeast assimilable nitrogen in grapes, while the total richness of spontaneous plant vegetation as cover crops did not have detectable effects (Steiner et al., 2021). Additionally, the study determined a grapevine cultivar-specific response, with Chasselas grapes being affected by the competition with cover crops, while this effect was counteracted by an increasing number of legumes in the inter-row vegetation in vineyards with Pinot noir (Steiner et al., 2021). Effects of species composition on vine growth and yeast assimilable nitrogen in grapes has also been observed in other studies. Legume-based cover crop mixtures did enhance leaf nitrogen content and YAN in grape berries (Messiga et al., 2015; Perez-Alvarez et al., 2015), while grass-based cover crop vegetation did decrease YAN in grape berries in studies performed in Northern California, France and Spain (Ripoche et al., 2010; Giese et al., 2014; Perez-Alvarez et al., 2015). A study aiming to quantify the nitrogen fluxes in a Mediterranean vineyard determined a nitrogen fixing capability of burr medic (*Medicago polymorpha*) of 125 kg ha^{-1} year^{-1}, a potential which could only be traced in vines of about 10% (Sulas et al., 2017). The difference in vine nitrogen content was specifically shown in comparison with a grass cover crop treatment with lower N contents, while similar values were obtained with soil tillage (Sulas et al., 2017). In our study, a conclusion on the effects of legumes in the complete vegetation cover treatments is difficult, as different cover crop mixtures were not established in the same vineyard. Between country comparisons of the percentage of legumes in complete vegetation cover, does not explain the obtained results for soil nitrogen or yeast assimilable nitrogen in different countries. Therefore, fixed nitrogen by legumes could have contributed to vine nutrition, but we cannot entangle and specify this effect from other factors as nitrogen pools in the soil are very dynamic and rely on rapid mineralization, nitrification and immobilization (Lazcano et al., 2020).

Soil microorganisms and plants compete for newly mineralized available nitrogen and healthy soils supply nitrogen to plants during their main uptake periods, while access soil nitrogen is retained at periods of low plant demands by cycling it through the soil food web (Lazcano et al., 2020). This concept is supported by the effects of cover crops on soil microbial diversity and activity (Burns et al., 2015; Garcia et al., 2018; Abad et al., 2021a). As part of the PromESSinG project (www.promessing.eu) microbial community composition was mainly explained by the vineyard location and soil covariates, while the effects of the inter-row vegetation management were rather small (Steiner et al., 2022, submitted). In contrast, the microbial respiration was consistently increased in inter-rows with vegetation cover across all countries underlining the positive effect on microbial activity (Steiner et al., 2022, submitted).

Our results of other grape must quality parameters showed no consistent impacts of inter-row management on total soluble solids, total titratable acidity or berry weight. Local trends were observed as e.g. in France and Germany with lower total soluble solids in bare ground inter-rows as compared to complete vegetation cover. The low consistent impact of inter-row management on these grape quality parameters goes along with a recent review stating that in the majority of the analyzed studies the consequences of cover crops on total soluble solids, titratable acidity and grape must pH were negligible (Abad et al., 2021b). Pedo-climatic conditions are strong drivers of grape quality also defined as "terroir" of a wine (Poni et al., 2018). We considered pedo-climatic conditions by accounting for the different countries in the analysis. The country effect was highly significant for all determined grape must quality parameters, while adding soil covariates did not substantially enhance the model performances, with the possible exception of total titratable acidity (TA). One of the first studies systematically approaching the terroir concept confirmed that grape quality is stronger influenced by weather and season effects than by soil type or grapevine cultivar (van Leeuwen et al., 2004). Recent studies confirmed these early results and specify the main factors as weather, soil temperature, water supply and nutrients availability (Delpuech and Metay, 2018; van Leeuwen et al., 2018; Garcia et al., 2020; Lazcano et al., 2020; Martinez et al., 2021). It is well known, that the vine water status has a major impact on vine growth, fruit composition and vine quality (van Leeuwen et al., 2018) and that the water and nutrient availability is influenced by soil properties (Garcia et al., 2020). Our study did not directly address this interaction between climate, soil, water balance and nutrient uptake and their interplay effect on vine and grape parameters. But we could consistently determine the influence of the inter-row vegetation management on some of these parameters as e.g. the higher values in leaf chlorophyll content, shoot pruning weight and yeast assimilable nitrogen in grapes in bare ground plots as compared to a permanent vegetation cover in inter-rows. This conserved pattern of response was obtained beyond different pedo-climatic conditions and grape varieties in temperate study regions. Nevertheless, the current knowledge on cover crop effects on vine and grapes in non-irrigated vineyards needs to be differentiated between results obtained in humid to temperate climates and semi-arid to arid climates, e.g. Mediterranean countries. In temperate and humid climates planting cover crops in inter-rows could be a strategy to reduce the vegetative growth of vines, to drain wet soils and to optimize grape yield and biochemical aroma compounds (Gaudin et al., 2014; Messiga et al., 2016; Chou and Vanden Heuvel, 2019). In general, an enhanced vine vigor could result in more dense canopies, higher nitrogen levels in grapes and more compact grape cluster (Thomidis et al., 2016). As a consequence, these vines could be more susceptible to pathogens as e.g. downy and powdery mildew (de Oliveira et al., 2021) or pests as e.g. mealybugs (Muscas et al., 2017) which was shown after tillage was applied as inter-row management also in Mediterranean regions (Valdes-Gomez et al., 2011; Muscas et al., 2017; de Oliveira et al., 2021). On the other hand, cover crops had a positive effect on grape cluster health by reducing gray mold incidence *(Botrytis cinerea*) in humid climates (Valdes-Gomeza et al., 2008; Coniberti et al., 2018b). In contrast to humid climates, a growth reduction of vines, usually determined as shoot pruning weight, is detrimental to sustain grape yields in semi-arid and arid climates. Previous studies performed in the Mediterranean region confirmed highly impacted vegetative growth of vines and reduced grape yield due to water shortage (Ruiz-Colmenero et al., 2011; Gaudin et al., 2014; Garcia et al., 2020). Recently it was reported, that especially in shallow soils, grapevine yield was decreasing with an increase in vegetation cover in vineyards in three years in France, but the study did also show that an adapted cover crop management is possible under Mediterranean climate (Delpuech and Metay, 2018). Similarly, relative to soil tillage, legume cover crop mixtures reduced the cluster weight, whereas grass cover crop mixtures reduced both, the number of clusters as well as the cluster weight under semi-arid conditions (Muscas et al., 2017). The same study also determined must qualities with increased contents of sugar, anthocyanins and polyphenols by grass mixtures and reduced anthocyanins and total polyphenols by legume cover crops. Mowing of cover crops could be one option to counteract the competing effect on vine growth and grape quality, as has been shown by a study conducted in Italy (Centinari et al., 2013). Nevertheless, temporary cover crops could enhance biodiversity in vineyards and ensure the prevention of soil loss due to erosion in case of heavy rain events also in semi-arid and arid climates (Celette et al., 2008; Martinez et al., 2021) and cover crops are the pillars of soil conservation strategies in vineyards, improving soil aggregate stability by increasing the soil organic matter content (Garcia et al., 2019; Guzman et al., 2019).

In conclusion, our study shows that bare ground by soil tillage or herbicide application can have agronomic advantages by reducing the competing effect of vegetation cover in inter-rows on the availability of water and nutrients for growing vines. Across different pedo-climatic conditions, countries and grape varieties, we demonstrated that the establishment of an inter-row vegetation negatively affected vine vigor and grape quality parameters important for vinification (YAN). Thus, cover crops can only be recommended under conditions where such losses are outweighed by other gains, e.g. in biodiversity or subsidies. In parallel, the growth of plants in inter-rows enhanced the soil organic matter content, a parameter providing important soil functions and classified as ecosystem service. Therefore, ecosystem services and disservices were observed from the same management treatments simultaneously, which underlines the need to understand the functional relationships among them. These unique results could be implemented into adaptive vineyard management strategies to combat climate change or to enhance biodiversity and sustain ecosystem functions in vineyards. To this effect, we hope that this work will trigger in-depth, on-site studies to further quantify the effects of vegetation growth in inter-rows on vine growth and grape quality.

Funding

Results presented here are part of the PromESSinG project, funded by the 2013–2014 BiodivER-sA/FACCE JPI joint call for research proposals (assessed 17th June 2014). With the national funders, Ilona Leyer and Annette Reineke received funding from the Bundesministerium für

Bildung und Forschung (BMBF, Germany, https://www.bmbf.de, grant number 01LC1405A); Brice Giffard and Pauline Tolle received funding from Agence Nationale de la Recherche (ANR, France, https://anr.fr/, ANR-14-EBID-0004); Cristina Preda and Danyar Memedemin received funding from the Romanian National Authority for Scientific Research and Innovation (ANCS, Romania, http://www.ancs.ro/en, CCCDI–UE-FISCDI, Romania, project number PN3-P3–61 contract 21/2015, within PNCDI III); Astrid Forneck received funding from the Austrian Science Fund (FWF, Austria, https://www.fwf.ac.at/de/, project number I 2053-B25); and Sven Bacher received funding from the Swiss National Science Foundation (SNSF, Switzerland, https://www.snf.ch/de, project number 40FA40_158390).

CRediT authorship contribution statement

Astrid Forneck, Ilona Leyer, Annette Reineke, Sven Bacher, Cristina Preda and Michaela Griesser conceived and designed the study, coordinated the sampling strategies and decided on analyses conducted; Michaela Griesser, Magdalena Steiner, Martin Pingel, Brice Giffard, Deniz Uzman, Pauline Tolle, Daniyar Memedemin and Cristina Preda conducted measurements and evaluation in the experimental vineyards and performed laboratory analyses; Michaela Griesser with inputs from Sven Bacher performed data analyses, interpretation of results and drafted the manuscript; all authors revised, read and approved the final manuscript.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Astrid Forneck reports financial support was provided by Austrian Science Fund.

Acknowledgments

We wish to thank the Department of Soil Science and Plant Nutrition of Geisenheim University for conducting soil analyses. Our special thanks go to all wineries and farmers helping us to establish the different soil management treatments in their vineyards, supporting the project with their enthusiasm and interest and fruitful discussions. Additionally, we would like to thank all students helping in performing the analyses and acquiring data in the frame of their Bachelor or Master Thesis.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2022.108073.

References

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

Abad, J., de Mendoza, I.H., Marin, D., Orcaray, L., Santesteban, L.G., 2021b. Cover crops in viticulture. A systematic review (2): Implications on vineyard agronomic performance. Oeno One 55, 1–27. https://doi.org/10.20870/oeno-one.2021.55.2.4481.

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 067. https://doi.org/10.18637/jss.v067.i01.

Ben-Shachar, M., Lüdecke, D., Makowski, D., 2020. effectsize: estimation of effect size indices and standardized parameters. J. Open Source Softw. 5 (56), 2815. https://doi.org/10.21105/joss.02815.

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

Blanco-Canqui, H., Wortmann, C.S., 2020. Does occasional tillage undo the ecosystem services gained with no-till? A review. Soil . Res 198. https://doi.org/10.1016/j.still.2019.104534.

Bruggisser, O.T., Schmidt-Entling, M.H., Bacher, S., 2010. Effects of vineyard management on biodiversity at three trophic levels. Biol. Conserv. 143, 1521–1528. https://doi.org/10.1016/j.biocon.2010.03.034.

Burns, K.N., Bokulich, N.A., Cantu, D., Greenhut, R.F., Kluepfel, D.A., O'Geen, A.T., Strauss, S.L., Steenwerth, K.L., 2016. Vineyard soil bacterial diversity and composition revealed by 16S rRNA genes: Differentiation by vineyard management. Soil Biol. Biochem. 103, 337–348. https://doi.org/10.1016/j.soilbio.2016.09.007.

Burns, K.N., Kluepfel, D.A., Strauss, S.L., Bokulich, N.A., Cantu, D., Steenwerth, K.L., 2015. Vineyard soil bacterial diversity and composition revealed by 16S rRNA genes: Differentiation by geographic features. Soil Biol. Biochem 91, 232–247. https://doi.org/10.1016/j.soilbio.2015.09.002.

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

Centinari, M., Filippetti, I., Bauerle, T., Allegro, G., Valentini, G., Poni, S., 2013. Cover crop water use in relation to vineyard floor management practices. Am. J. Enol. Viticult. 64, 522–526. https://doi.org/10.5344/ajev.2013.13025.

Chou, M.Y., Vanden Heuvel, J., Bell, T.H., Panke-Buisse, K., Kao-Kniffin, J., 2018. Vineyard under-vine floor management alters soil microbial composition, while the fruit microbiome shows no corresponding shifts. Sci. Rep. -Uk 8. https://doi.org/10.1038/s41598-018-29346-1.

Chou, M.Y., Vanden Heuvel, J.E., 2019. Annual under-vine cover crops mitigate vine vigor in a mature and Vigorous Cabernet franc Vineyard. Am. J. Enol. Viticult. 70, 98–108. https://doi.org/10.5344/ajev.2018.18037.

Coniberti, A., Ferrari, V., Disegna, E., Dellacassa, E., Lakso, A.N., 2018a. Under-trellis cover crop and deficit irrigation to regulate water availability and enhance Tannat wine sensory attributes in a humid climate. Sci. Hort. 235, 244–252. https://doi.org/10.1016/j.scienta.2018.03.018.

Coniberti, A., Ferrari, V., Disegna, E., Petillo, M.G., Lakso, A.N., 2018b. Complete vineyard floor cover crop to reduce grapevine susceptibility to bunch rot. Eur. J. Agron. 99, 167–176. https://doi.org/10.1016/j.eja.2018.07.006.

Coniberti, A., Ferrari, V., Disegna, E., Petillo, M.G., Lakso, A.N., 2018c. Under-trellis cover crop and planting density to achieve vine balance in a humid climate. Sci. Hort. 227, 65–74. https://doi.org/10.1016/j.scienta.2017.09.012.

de Oliveira, A.F., Serra, S., Ligios, V., Satta, D., Nieddu, G., 2021. Assessing the Effects of Vineyard Soil Management on Downy and Powdery Mildew Development. Horti 7. https://doi.org/10.3390/horticulturae7080209.

Delpuech, X., Metay, A., 2018. Adapting cover crop soil coverage to soil depth to limit competition for water in a Mediterranean vineyard. Eur. J. Agron. 97, 60–69. https://doi.org/10.1016/j.eja.2018.04.013.

Donnini, S., Tessarin, P., Ribera-Fonseca, A., Di Foggia, M., Parpinello, G.P., Rombola, A. D., 2016. Glyphosate impacts on polyphenolic composition in grapevine (Vitis vinifera L.) berries and wine. Food Chem. 213, 26–30. https://doi.org/10.1016/j.foodchem.2016.06.040.

Fernandez-Mena, H., Frey, H., Celette, F., Garcia, L., Barkaoui, K., Hossard, L., Naulleau, A., Metral, R., Gary, C., Metay, A., 2021. Spatial and temporal diversity of service plant management strategies across vineyards in the south of France. Analysis through the Coverage Index. Eur. J. Agron. 123. https://doi.org/10.1016/j.eja.2020.126191.

Fox, J., Weisberg, S., 2019. An R Companion to Applied Regression, 3rd edition.,. Sage, Thousand Oaks CA. ⟨https://socialsciences.mcmaster.ca/jfox/Books/Companion/index.html⟩.

Garcia-Diaz, A., Bienes, R., Sastre, B., Novara, A., Gristina, L., Cerda, A., 2017. Nitrogen losses in vineyards under different types of soil groundcover. A field runoff simulator approach in central Spain. Agr. Ecosyst. Environ. 236, 256–267. https://doi.org/10.1016/j.agee.2016.12.013.

Garcia, L., Celette, F., Gary, C., Ripoche, A., Valdes-Gomez, H., Metay, A., 2018. Management of service crops for the provision of ecosystem services in vineyards: A review. Agr. Ecosyst. Environ. 251, 158–170. https://doi.org/10.1016/j.agee.2017.09.030.

Garcia, L., Damour, G., Gary, C., Follain, S., Le Bissonnais, Y., Metay, A., 2019. Trait-based approach for agroecology: contribution of service crop root traits to explain soil aggregate stability in vineyards. Plant Soil 435, 1–14 https://link.springer.com/article/10.1007/s11104-018-3874-4.

Garcia, L., Metay, A., Kazakou, E., Storkey, J., Gary, C., Damour, G., 2020. Optimizing the choice of service crops in vineyards to achieve both runoff mitigation and water provisioning for grapevine: a trait-based approach. Plant Soil 452, 87–104 https://link.springer.com/article/10.1007/s11104-020-04543-y.

Gatti, M., Squeri, C., Garavani, A., Vercesi, A., Dosso, P., Diti, I., Poni, S., 2018. Effects of Variable Rate Nitrogen Application on cv. Barbera Performance: Vegetative Growth and Leaf Nutritional Status. Am. J. Enol. Viticult. 69, 196–209. https://doi.org/10.5344/ajev.2018.17084.

Gaudin, R., Celette, F., Gary, C., 2010. Contribution of runoff to incomplete off season soil water refilling in a Mediterranean vineyard. Agr. Water Manag. 97, 1534–1540. https://doi.org/10.1016/j.agwat.2010.05.007.

Gaudin, R., Kansou, K., Payan, J.C., Pellegrino, A., Gary, C., 2014. A Water Stress Index Based on Water Balance Modelling for Discrimination of Grapevine Quality and Yield. J. Int. Sci. Vigne Vin. 48, 1–9. https://doi.org/10.20870/oeno-one.2014.48.1.1655.

Geldenhuys, M., Gaigher, R., Pryke, J.S., Samways, M.J., 2021. Diverse herbaceous cover crops promote vineyard arthropod diversity across different management regimes. Agr. Ecosyst. Environ. 307. https://doi.org/10.1016/j.agee.2020.107222.

Giese, G., Velasco-Cruz, C., Roberts, L., Heitman, J., Wolf, T.K., 2014. Complete vineyard floor cover crops favorably limit grapevine vegetative growth. Sci. Horti. 170, 256–266. https://doi.org/10.1016/j.scienta.2014.03.011.

Guerra, B., Steenwerth, K., 2012. Influence of Floor Management Technique on Grapevine Growth, Disease Pressure, and Juice and Wine Composition: A Review. Am. J. Enol. Viticult. 63, 149–164. https://doi.org/10.5344/ajev.2011.10001.

Guzman, G., Cabezas, J.M., Sanchez-Cuesta, R., Lora, A., Bauer, T., Strauss, P., Winter, S., Zaller, J.G., Gomez, J.A., 2019. A field evaluation of the impact of temporary cover crops on soil properties and vegetation communities in southern Spain vineyards. Agr. Ecosyst. Environ. 272, 135–145. https://doi.org/10.1016/j.agee.2018.11.010.

Hall, R.M., Penke, N., Kriechbaum, M., Kratschmer, S., Jung, V., Chollet, S., Guernion, M., Nicolai, A., Burel, F., Fertil, A., Lora, A., Sanchez-Cuesta, R., Guzman, G., Gomez, J., Popescu, D., Hoble, A., Bunea, C.I., Zaller, J.G., Winter, S., 2020. Vegetation management intensity and landscape diversity alter plant species richness, functional traits and community composition across European vineyards. Agr. Syst. 177. https://doi.org/10.1016/j.agsy.2019.102706.

Hammer, Ø., Harper, D.A.T., Ryan, P.D., 2001. PAST: Paleontological statistics software package for education and data analysis. Palaeontol. Electron. 4 (1), 9. ⟨http://palaeo-electronica.org/2001_1/past/issue1_01.htm⟩.

Hartig, F., 2021, DHARMa: Residual Diagnostics for Hierarchical (Multi-Level / Mixed) Regression Models. R package version 0.4.3. ⟨https://CRAN.R-project.org/package=DHARMa⟩.

Lazcano, C., Decock, C., Wilson, S.G., 2020. Defining and managing for healthy vineyard soils, intersections with the concept of terroir. Front. Env. Sci. 8. https://doi.org/10.3389/fenvs.2020.00068.

Lenth, R.V., 2021. emmeans: Estimated Marginal Means, aka Least-Squares Means. R. Package Version 1. 6. 3. ⟨https://CRAN.R-project.org/package=emmeans⟩.

Lüdecke, D., Ben-Shachar, M., Patil, I., Waggoner, P., Makowski, D., 2021. performance: An R Package for Assessment, Comparison and Testing of Statistical Models. J. Open Source Softw. 6 (60), 3139. https://doi.org/10.21105/joss.03139.

Lüdecke, D., 2021. sjPlot: data visualization for statistics in social science. R. Package Version 2. 8. 10. ⟨https://CRAN.R-project.org/package=sjPlot⟩.

Martinez, F.S., Baez, C.G.G., Monreal, F.J.C., Peregrina, F., 2021. Long-range correlations of soil water content time series under tillage and different cover crops in a semi-arid vineyard. Eur. J. Soil Sci. 72, 623–634. https://doi.org/10.1111/ejss.13036.

Messiga, A.J., Gallant, K.S., Sharifi, M., Hammermeister, A., Fuller, K., Tango, M., Fillmore, S., 2016. Grape Yield and Quality Response to Cover Crops and Amendments in a Vineyard in Nova Scotia, Canada. Am. J. Enol. Viticult. 67, 77–85. https://doi.org/10.5344/ajev.2015.15013.

Messiga, A.J., Sharifi, M., Hammermeister, A., Gallant, K., Fuller, K., Tango, M., 2015. Soil quality response to cover crops and amendments in a vineyard in Nova Scotia, Canada. Sci. Horti 188, 6–14. https://doi.org/10.1016/j.scienta.2015.02.041.

Monteiro, A., Lopes, C.M., 2007. Influence of cover crop on water use and performance of vineyard in Mediterranean Portugal. Agr. Ecosyst. Environ. 121, 336–342. https://doi.org/10.1016/j.agee.2006.11.016.

Muscas, E., Cocco, A., Mercenaro, L., Cabras, M., Lentini, A., Porqueddu, C., Nieddu, G., 2017. Effects of vineyard floor cover crops on grapevine vigor, yield, and fruit quality, and the development of the vine mealybug under a Mediterranean climate. Agr. Ecosyst. Environ. 237, 203–212. https://doi.org/10.1016/j.agee.2016.12.035.

Novara, A., Catania, V., Tolone, M., Gristina, L., Laudicina, V.A., Quatrini, P., 2020. Cover crop impact on soil organic carbon, nitrogen dynamics and microbial diversity in a Mediterranean Semiarid Vineyard. Sustain. -Basel 12. https://doi.org/10.3390/su12083256.

Novara, A., Cerda, A., Barone, E., Gristina, L., 2021. Cover crop management and water conservation in vineyard and olive orchards. Soil . Res 208. https://doi.org/10.1016/j.still.2020.104896.

OIV, 2020. OIV Statistical report on world vitiviniculture. Int. Organ. Vine Wine Intergov. Organ. 2020.

Paiola, A., Assandri, G., Brambilla, M., Zottini, M., Pedrini, P., Nascimbene, J., 2020. Exploring the potential of vineyards for biodiversity conservation and delivery of biodiversity-mediated ecosystem services: A global-scale systematic review. Sci. Total Environ. 706. https://doi.org/10.1016/j.scitotenv.2019.135839.

Perez-Alvarez, E.P., Garcia-Escudero, E., Peregrina, F., 2015. Soil Nutrient Availability under Cover Crops: Effects on Vines, Must, and Wine in a Tempranillo Vineyard. Am. J. Enol. Viticult. 66, 311–320. https://doi.org/10.5344/ajev.2015.14092.

Poni, S., Gatti, M., Palliotti, A., Dai, Z.W., Duchene, E., Truong, T.T., Ferrara, G., Matarrese, A.M.S., Gallotta, A., Bellincontro, A., Mencarelli, F., Tombesi, S., 2018. Grapevine quality: A multiple choice issue. Sci. Horti. 234, 445–462. https://doi.org/10.1016/j.scienta.2017.12.035.

Pou, A., Gulias, J., Moreno, M., Tomas, M., Medrano, H., Cifre, J., 2011. Cover Cropping in Vitis vinifera L. Cv. Manto Negro Vineyards under Mediterranean Conditions: Effects on Plant Vigour, Yield and Grape Quality. J. Int. Sci. Vigne Vin. 45, 223–234. https://doi.org/10.20870/oeno-one.2011.45.4.1501.

Pustejovsky, J., 2021, clubSandwich: Cluster-Robust (Sandwich) Variance Estimators with Small-Sample Corrections. R package version 0.5.3. ⟨https://CRAN.R-project.org/package=clubSandwich⟩.

R Core Team, 2020. R: A language and environment for statistical computing. R. Found. Stat. Comput., Vienna, Austria (URL). ⟨https://www.R-project.org/⟩.

Ripoche, A., Celette, F., Cinna, J.P., Gary, C., 2010. Design of intercrop management plans to fulfil production and environmental objectives in vineyards. Eur. J. Agron. 32, 30–39. https://doi.org/10.1016/j.eja.2009.05.005.

Romero, I., Garcia-Escudero, E., Martin, I., 2013. Leaf Blade versus Petiole Analysis for Nutritional Diagnosis of Vitis vinifera L. cv. Tempranillo. Am. J. Enol. Viticult 64, 50–64. https://doi.org/10.5424/sjar/2014121-4308.

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

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

Saenz-Romo, M.G., Veas-Bernal, A., Martinez-Garcia, H., Campos-Herrera, R., Ibanez-Pascual, S., Martinez-Villar, E., Perez-Moreno, I., Marco-Mancebon, V.S., 2019. Ground cover management in a Mediterranean vineyard: Impact on insect abundance and diversity. Agr. Ecosyst. Environ. 283. https://doi.org/10.1016/j.agee.2019.106571.

Schaller, K., 2000. Praktikum zur Bodenkunde und Pflanzenernährung. 8. Ed. Geisenheim: Ges. zur Förderung der Forschungsanst. Geisenh. (Geisenh. Ber., 2).

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

Steenwerth, K., Belina, K.M., 2008. Cover crops and cultivation: Impacts on soil N dynamics and microbiological function in a Mediterranean vineyard agroecosystem. Appl. Soil Ecol. 40, 370–380. https://doi.org/10.1016/j.apsoil.2008.06.004.

Steenwerth, K.L., Calderon-Orellana, A., Hanifin, R.C., Storm, C., McElrone, A.J., 2016. Effects of various vineyard floor management techniques on weed community shifts and grapevine water relations. Am. J. Enol. Viticult. 67, 153–162. https://doi.org/10.5344/ajev.2015.15050.

Steiner, M., Grace, J.B., Bacher, S., 2021. Biodiversity effects on grape quality depend on variety and management intensity. J. Appl. Ecol. 58, 1442–1454. https://doi.org/10.1111/1365-2664.13899.

Steiner, M., Pingel, M., Falquet, L., Giffard, B., Griesser, M., Leyer, I., Preda, C., Uzman, D., Bacher, S., Reineke, A., 2022, Local conditions matter: Minimal and unpredictable effects of soil disturbance on microbial communities and functions in European vineyards. Submitted.

Sulas, L., Mercenaro, L., Campesi, G., Nieddu, G., 2017. Different cover crops affect nitrogen fluxes in Mediterranean Vineyard. Agron. J. 109, 2579–2585. https://doi.org/10.2134/agronj2017.05.0283.

Thomidis, T., Zioziou, E., Koundouras, S., Karagiannidis, C., Navrozidis, I., Nikolaou, N., 2016. Effects of nitrogen and irrigation on the quality of grapes and the susceptibility to Botrytis bunch rot. Sci. Horti 212, 60–68. https://doi.org/10.1016/j.scienta.2016.09.036.

Valdes-Gomez, H., Gary, C., Cartolaro, P., Lolas-Caneo, M., Calonnec, A., 2011. Powdery mildew development is positively influenced by grapevine vegetative growth induced by different soil management strategies. Crop Prot. 30, 1168–1177. https://doi.org/10.1016/j.cropro.2011.05.014.

Valdes-Gomeza, H., Fermaud, M., Roudet, J., Calonnec, A., Gary, C., 2008. Grey mould incidence is reduced on grapevines with lower vegetative and reproductive growth. Crop Prot. 27, 1174–1186. https://doi.org/10.1016/j.cropro.2008.02.003.

van Leeuwen, C., Friant, P., Chone, X., Tregoat, O., Koundouras, S., Dubourdieu, D., 2004. Influence of climate, soil, and cultivar on terroir. Am. J. Enol. Viticult. 55, 207–217.

van Leeuwen, C., Roby, J.P., de Resseguier, L., 2018. Soil-related terroir factors: a review. Oeno One 52, 173–188. https://doi.org/10.20870/oeno-one.2018.52.2.2208.

Verdenal, T., Dienes-Nagy, Á., Spangenberg, J.E., Zufferey, V., Spring, J.-L., Viret, O., Marin-Carbonne, J., van Leeuwen, C., 2021. Understanding and managing nitrogen nutrition in grapevine: a review. Oeno One 55, 1–43. https://doi.org/10.20870/oeno-one.2021.55.1.3866.

Vrignon-Brenas, S., Metay, A., Leporatti, R., Gharibi, S., Fraga, A., Dauzat, M., Rolland, G., Pellegrino, A., 2019. Gradual responses of grapevine yield components and carbon status to nitrogen supply. Oeno One 53, 289–306. https://doi.org/10.20870/oeno-one.2019.53.2.2431.

Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag, New York. ISBN 978-3-319-24277-4. ⟨https://ggplot2.tidyverse.org⟩.

Winkler, K.J., Viers, J.H., Nicholas, K.A., 2017. Assessing Ecosystem Services and Multifunctionality for Vineyard Systems. Front. Env. Sci. -Switz. 5 https://doi.org/10.3389/fenvs.2017.00015.

Zaller, J.G., Cantelmo, C., Dos Santos, G., Muther, S., Gruber, E., Pallua, P., Mandl, K., Friedrich, B., Hofstetter, I., Schmuckenschlager, B., Faber, F., 2018. Herbicides in vineyards reduce grapevine root mycorrhization and alter soil microorganisms and the nutrient composition in grapevine roots, leaves, xylem sap and grape juice. Environ. Sci. Pollut. R. 25, 23215–23226 https://dx.doi.org/10.1007%2Fs11356-018-2422-3.

Zanettin, G., Bullo, A., Pozzebon, A., Burgio, G., Duso, C., 2021. Influence of Vineyard inter-row groundcover vegetation management on arthropod assemblages in the Vineyards of North-Eastern Italy. Insects 12 (4), 349. https://doi.org/10.3390/insects12040349.