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On-farm evaluation of service crops termination strategies to reduce water competition with grapevine

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ABSTRACT

Viticulture currently faces major challenges, as it is among the land uses most prone to erosion and most reliant on pesticide applications. One of the answers to these challenges is to establish service crops, which are non-commercial crops grown to provide ecosystem services. However, service crops are also prone to competing with grapevines for water and nitrogen and need to be managed to balance ecosystem services. In the present study, we conducted a three-year on-farm experiment between 2022 and 2024 on 7 commercial organic farms in the French departments of Hérault, Aude, and Pyrénées-Orientales. During three years, we evaluated different service crop termination strategies for service crop mixtures, combining two service crop termination periods (around budburst and one month after budburst) and two termination methods (mower + superficial tillage, roller-crimper), compared with a tilled control treatment. We monitored the service crop biomass, the surface temperature and water potential of the soil in the inter-row, and a variety of indicators on the grapevine (yield components, pruning weight, apex growth indicator, $\delta^{13}C$, yeast assimilable nitrogen (YAN), sugar and pH in musts). The results showed that the early termination using tillage (E-T) caused no vine water stress or production loss compared to other termination strategies. In contrast, late terminations and roller-crimping led to yield reductions, fewer bunches, lower berry weight, and reduced vigour. Overall, our findings demonstrate that, in a Mediterranean context, service crop termination by tillage at grapevine budburst limits vine water stress and preserves vine yield and vigour, and is therefore a preferable strategy in the case of a dry year.

KEYWORDS: *Vitis vinifera*, cover crops, cover crop management, sustainable viticulture, water stress, on-farm experiment

INTRODUCTION

Viticulture currently faces major challenges, being among the land uses most prone to erosion (Rodrigo-Comino, 2018) and one of the most reliant on pesticide applications (Chayre *et al*., 2024; Leal & Gramaje, 2024; Pertot *et al*., 2017). The practice of maintaining bare soils, along with frequent tractor use, results in soil compaction, the reduction of water infiltration, and leads to runoff and erosion. These phenomena are responsible for significant soil loss, but also at a broader scale for landslides, floods, and water pollution through the leaching of nutrients and pesticides (Rodrigo-Comino, 2018). Mediterranean vineyards are particularly affected because of a climate characterised by severe summer droughts combined with brief and intense rainfall events (Gaume *et al*., 2016), all the more so in a context of climate change, with shifts in the frequency and intensity of extreme precipitation events and intensified drought conditions (Dinis *et al*., 2022). Moreover, the decline in soil organic matter (Visconti *et al*., 2024) limits the formation of aggregates and increases soil erodibility (Le Bissonnais & Arrouays, 1997). There is an urgent need to improve the resilience of winegrowing systems by reducing pesticide use (Fouillet *et al*., 2022) and addressing the degradation of vineyard soils and water contamination associated with intensive management practices (Winter *et al*., 2018).

One of the answers to these challenges is to establish service crops, which are non-commercial crops grown to provide ecosystem services (Garcia *et al*., 2018; Lamichhane & Alletto, 2022). Indeed, service crops in viticulture improve aggregate stability, reduce soil erosion, and improve water infiltration (Garcia *et al*., 2018; Giffard *et al*., 2022). They also increase belowground and aboveground biodiversity, including natural enemies for vineyard pests that can help reduce the use of pesticides. In addition, service crops have a positive effect on increasing Soil Organic Carbon (SOC), which means they sequester carbon in the soil and help mitigate CO_2 emissions in the atmosphere (Abad *et al*., 2021a).

However, service crops are also prone to compete with grapevines for water and nitrogen (N) (Celette & Gary, 2013). Water stress induces vine stomatal closure, which reduces photosynthesis and grapevine growth (De Souza *et al*., 2005; Pellegrino *et al*., 2005). Water stress is intensified by the mismatch between the water demands of service crops, which start absorbing water before budburst, and those of grapevines, whose primary water requirements occur after budburst. Although the vine can concentrate its root system more in depth below the row instead of in the inter-row in the presence of a service crop in the inter-row, this is not likely to totally compensate for transpiration by the service crop (Celette *et al*., 2008). While in wet climates, the competition between service crops and vines can reduce excessive vigour and yield and improve wine quality, it is not the case in Mediterranean vineyards where water availability is a major limiting factor (Novara *et al*., 2021). Regarding soil N, legume service crops usually increase soil N content by fixing N^2 from the atmosphere (Ovalle *et al*., 2010; Ovalle *et al*., 2007), but grass service crops may compete for N with the grapevine (Celette *et al*., 2009). In the case of low soil moisture, service crops can also result in a decrease in N due to reduced N mineralisation (Celette & Gary, 2013). Moreover, an increase in soil N content in the presence of a legume service crop does not always result in an increase in Yeast Assimilable Nitrogen (YAN) (Abad *et al*., 2021a; Abad *et al*., 2021b). Finally, the risk of competition for water and N between grapevine and service crops is an obstacle to the adoption of service crops by winegrowers (Fernández-Mena *et al*., 2021; Sharifi & Zolfaghari, 2025), and may explain the relatively low proportion of vineyard associated with service crops in Languedoc (43 %) compared with the rest of France (64 %) (Agreste, 2025).

Service crop management strategies allow for achieving a balance between ecosystem services and disservices (Garcia *et al*., 2018; Griesser *et al*., 2022; Liebhard *et al*., 2024; Winter *et al*., 2018). In particular, it has been demonstrated that the choice of service crop species influences their impact on soil structure and the extent to which service crops compete with the vine for water (Capri *et al*., 2023; Novara *et al*., 2021; Garcia *et al*., 2020) and N (Curtright *et al*., 2025; Fernandez Pulido *et al*., 2025). A survey conducted in 2016 among 334 winegrowers in the Languedoc-Roussillon region of France highlighted the considerable spatial and temporal diversity in service crop management strategies employed by farmers (Fernández-Mena *et al*., 2021). Despite this diversity, most studies evaluating the ecosystem services provided by service crops in viticulture or their impacts on vineyards in dry climates do not reflect this complexity. Instead, they typically adopt a binary perspective, contrasting soil tillage practices with permanent cover using either sown or natural vegetation (Gaudin *et al*., 2010; Lopes, 2016; Pou *et al*., 2011; Ramírez-Pérez *et al*., 2024). The effect of a third treatment involving partial spatial or temporal disturbance in the inter-row was assessed by Griesser *et al*. (2022) in temperate wine-growing regions. Similarly, the importance of service crop termination methods has been demonstrated in other crops, such as vegetable production (Eivazi *et al*., 2024) and irrigated corn (Alonso-Ayuso *et al*., 2020). All the same, Delpuech and Metay (2018) demonstrated a decrease in grapevine yield with the percentage of soil covered by a service crop and recommended partial service crops for Mediterranean vineyards. Recently, new service crop termination methods have also been studied, such as interrow rolling and sub-row mulching compared with green manuring and alternate tilled-grassed interrow in Northern Italy (Cunial *et al*., 2025; Pelusi *et al*., 2025). However, there is still a lack of knowledge on how the diversity of service crop management strategies affects both vineyards and ecosystem services in the Mediterranean context.

Garcia *et al*. (2024) studied the combined effects of service crop termination tool (mower, mower + superficial tillage, roller-crimper) and period (early termination *vs* budburst termination) with a three-year experiment. They observed that the termination through superficial tillage was more effective

at killing service crops and thus at reducing competition for water and N with the grapevine compared to other methods. If the budburst termination period combined with no-till termination methods showed higher soil microbial biomass, the termination period was not shown to influence soil water stock and grapevine water status. However, the termination at budburst analysed in this study is not very late, and one wonders about the impact of termination at grapevine flowering when there is no study on the subject.

In the present study, we conducted a three-year on-farm experiment between 2022 and 2024 on 7 commercial farms in the French departments of Hérault, Aude, and Pyrénées-Orientales. During three years, we evaluated different service crop termination strategies for service crop mixtures, combining two service crop termination periods (around budburst and one month after budburst) and two termination methods (mower + superficial tillage, roller-crimper), compared with a tilled control treatment. We monitored the service crop biomass, the surface temperature and water potential of the soil in the inter-row, and a variety of indicators on the grapevine (yield components, pruning weight, apex growth indicator, $\delta^{13}C$, yeast assimilable nitrogen (YAN), sugar and pH in musts).

The following question was investigated: Which operational service crop management strategy can be adapted to limit disservices in a Mediterranean context? We hypothesised that i) terminating the service crop at grapevine budburst and with a superficial tillage suppresses competition for water and N, thus promoting grapevine yield and vigour, and that ii) roller-crimper termination has a greater soil surface temperature buffering effect than superficial tillage termination, due to the plant residues left on the soil surface, but increases competition with the grapevine for water and N.

MATERIALS AND METHODS

1. Site description and experimental design

The experiment took place over three years in 2022, 2023, and 2024 on seven fields from a network of organic wine farms in the departments of Hérault, Aude, and Pyrénées-Orientales (Occitanie region of France, Figure 1A). Monthly rainfall and mean monthly temperature data for the seven fields and over the three years of the experiment are presented in Figure 2. It should be noted that the years of the experiment, in particular 2022–2023 and 2023–2024, were dry years compared with the rainfall usually observed in the region. Indeed, mean annual rainfall over the experimental period was below the 30-year regional average in all three seasons, with deficits of 47 mm (2021–2022), 227 mm (2022–2023), and 195 mm (2023–2024). All fields were planted with a Syrah cultivar except fields 34.2 (Carignan cultivar) and 66.3 (Grenache cultivar), and had different topographical contexts, soil types, and management practices (Tables 1 and 2).

Each field was divided into 5 groups of 2 to 3 inter-rows (Figure 1B) to which 5 different treatments were applied. The treatments consisted of a control maintained with bare soil with tillage, and 4 sown treatments differing in the method and period of service crop termination: early tillage (*i.e.*, around budburst, E-T) or late tillage (*i.e.*, around 1 month after budburst, L-T), early roller (E-R) or late roller (L-R) (Figure 1B). In the E-T and B-T treatments, tillage was preceded by mowing to improve termination efficiency and prevent crop residues from being carried out of the inter-row. Each treatment had 4 to 6 plots of 5 vines each. The dates of sowing, early and late termination, and the species sown for each year and each field are listed in Tables S1 and S2.

The service crops sown were generally composed of a mixture of legumes (Fabaceae), grasses (Poaceae), and crucifers (Brassicaceae). The precise composition of the mixture varied from field to field and from year to year depending on farmers' choice (Table S1). The seeds came from a local cooperative producing population varieties (SCIC Graines équitables).

2. Data gaps, missing data and experimental errors

In the framework of this participatory research conducted with winegrowers, some data gaps were inevitable due to the diversity of farm contexts and the autonomy of participants in managing their fields (Roques *et al*., 2022). In particular, precise information on the exact composition of the sown service crop mixtures and on the specific dates of sowing and termination was sometimes unavailable. Additional missing data may also occur when farmers do not inform the research team before destroying the service crop or pruning the vines. These variations and occasional data gaps reflect the flexibility inherent to on-farm experiments, where farmers adapt practices to local conditions, seasonal constraints, and their own decision-making, thereby enriching the study with real-world relevance despite incomplete records. All missing data are indicated in Tables S3 and S4.

Regarding the treatments, in a few cases, when the biomass of the service crops was not sufficient to be effectively destroyed by the roller, the service crops were mown instead of being rolled (Table S3).

3. Measured variables

3.1. Service crop biomass

The fresh biomass of the service crops was measured before each termination period. Three 1 m^2 quadrats were randomly taken from the modalities sharing the same termination period, and the species were sorted to record their fresh biomass (Table S5). The dry biomass was then calculated from the fresh biomass using the MERCI method (Constantin *et al*., 2024). This method enables the estimation of the dry biomass and nutrient content of many service crop species through a large database, by indicating their sowing and biomass sampling dates.

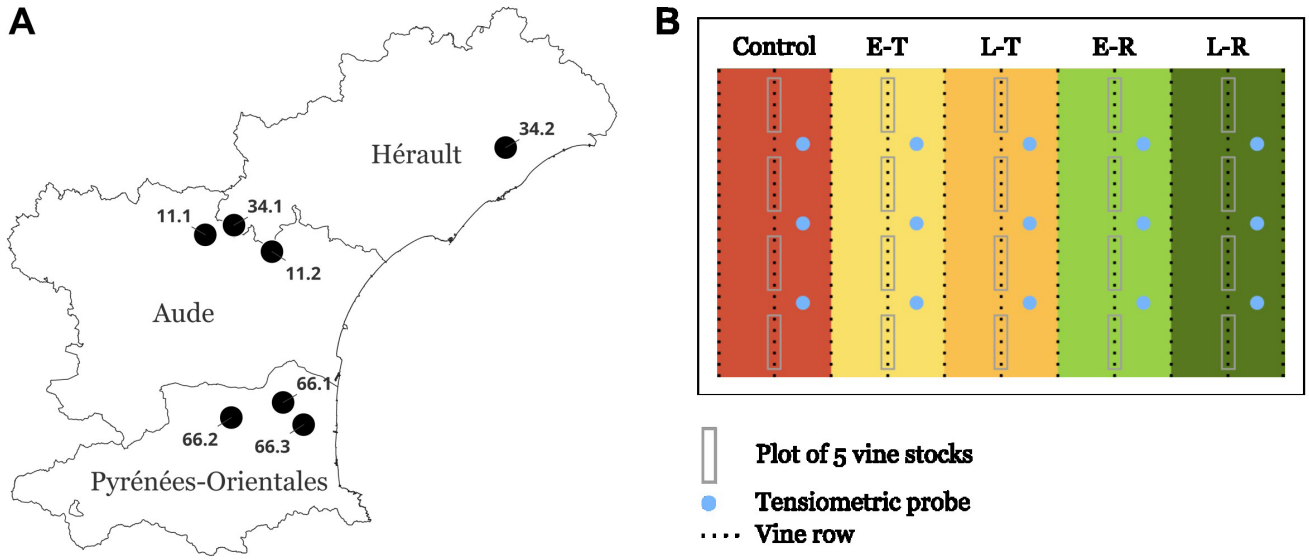


FIGURE 1. A: location of the commercial farms. The dots correspond to the locations of the fields. The lines correspond to the administrative boundaries of the departments of Hérault, Aude, and Pyrénées-Orientales. B: experimental design for each field. E: early termination; L: late termination; T: tillage; R: roller.

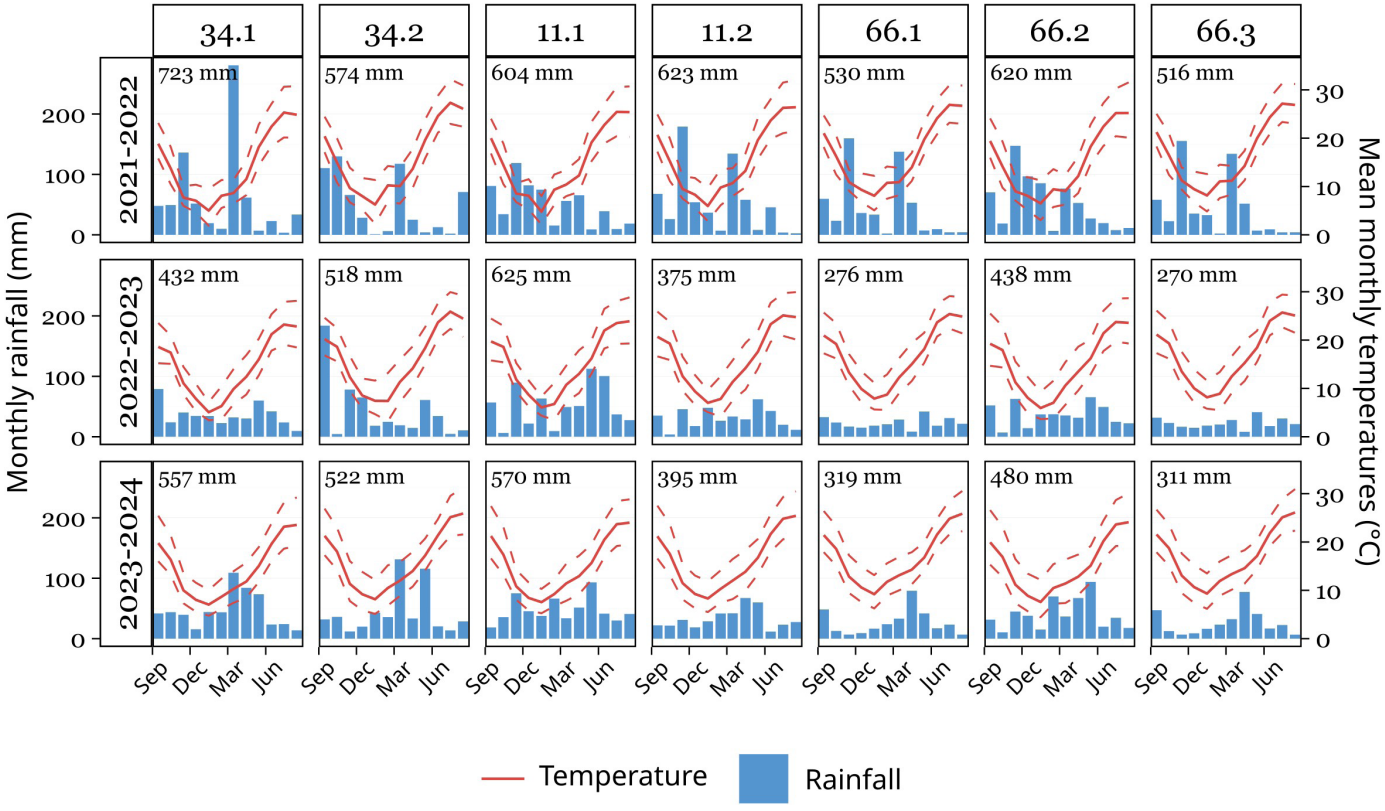


FIGURE 2. Umbrothermal diagram for 2021–2022, 2022–2023, and 2023–2024 for the 7 fields monitored during the experiment. In blue, monthly cumulative rainfall. In red, the mean monthly temperature (solid line) and the mean monthly lower and upper temperatures (dotted lines). For each year and each field, the cumulative annual rainfall from September to August is shown. For comparison, mean rainfall calculated over the last 30 years for each field: 34.1: 794 mm, 34.2: 647 mm, 11.1: 672 mm, 11.2: 610 mm, 66.1: 575 mm, 66.2: 661 mm, 66.3: 562 mm. Data source: Météo-France via the SICLIMA platform (Maury *et al.*, 2024).

Some service crops were destroyed before biomass measurements could be done. At the time of early termination, plots assigned to the late termination treatment had not yet been destroyed and therefore continued to accumulate biomass. Consequently, their standing biomass at late termination was necessarily at least equal to – and likely greater than – the biomass recorded just before early termination, consistent with the well-established relationship between growing duration and service crop biomass production (Pessotto *et al*., 2025). For site-years where only pre-early-termination biomass data were available, this value was therefore used as a conservative lower-bound estimate of biomass at late termination. Furthermore, biomass values were not included as explanatory variables in the statistical models used to assess vine performance. The field was treated as a random effect, which accounts for the agronomic variability across the trial network – including differences in service crop development levels – without requiring each site-year to provide a complete set of biomass measurements.

3.2. Soil water potential

To measure soil water potential (0 to 199 kPa), three tensiometric probes (Watermark) per treatment were installed at a depth of 45 cm, in the middle of the inter-row in each treatment (Figure 1B). Measurements were taken once a week over the three seasons of the experiment, from around September to August for the fields in the Pyrénées Orientales and from around March to August for the fields in the Aude and Hérault.

3.3. Soil surface temperature

The soil surface temperature was measured using a probe thermometer at 5 cm depth, with 3 replicates next to each tensiometer probe, for a total of 9 replicates per treatment. The measurements were carried out once a week from April to August, in the morning, at the same time as the tensiometer probe measurements.

TABLE 1. Characteristics of the fields monitored during the experiment.

Field	Topographical context	Soil	Grape cultivar	Rootstock	Density
66.1	Plain	Fine chalky silt	Syrah	110 Richter	4,000 vines ha^{-1}
11.1	Plateau	Clay-silt	Syrah	140 Ruggeri	4,500 vines ha^{-1}
11.2	Plain (canal side)	Clay-limestone, 40 % stones	Syrah	Fercal	5,000 vines ha^{-1}
34.1	Scrubland	Clay-silt	Syrah	101-14 Mgt	5,000 vines ha^{-1}
66.2	Hillsides	Sandy-limestone schist	Syrah	110 Richter	4,444 vines ha^{-1}
34.2	Plain	Alluvial deposits, clayey-silt-limestone, low stone content.	Carignan	110 Richter	4,000 vines ha^{-1}
66.3	Plain	Quaternary limestone alluvium	Grenache	110 Richter	4,000 vines ha^{-1}

TABLE 2. General management practices of the fields monitored during the experiment.

Field	Training system	Irrigation	Fertilisation
66.1	Cordon spur pruning	No irrigation	Chicken manure pellets (5-5-5), 500 kg ha^{-1}
11.1	Cordon spur pruning	No irrigation	Humiflor® Germi'One®, 1 t ha^{-1}
11.2	Guyot Poussard	100 mm per season from May to August (20 mm every 15 days)	Organic fertiliser (9-4-0), 600 kg ha^{-1} + green waste in winter, 20 t ha^{-1}
34.1	Cordon spur pruning	No irrigation	No fertilisation
66.2	Cordon spur pruning	No irrigation	20 t ha^{-1} of green waste compost every 3 years (application at the beginning of the trial only)
34.2	Goblet pruning	No irrigation	Organic fertiliser (5-3-2), 500 kg ha^{-1}
66.3	Cordon spur pruning	156 mm per season from May to August (12 mm every 7 days)	Chicken manure pellets (5-5-5), 500 kg ha^{-1}

3.4. Apex growth index

The apex growth index was calculated using the ApeX-Vigne method and a smartphone application (Pichon *et al*., 2021). This method classifies shoot growth into three categories: full growth (FG), slow growth (MG), and stopped growth (SG). Scoring was carried out on 50 shoot tips per treatment in the experimental plots by observing between 10 and 15 randomly selected shoots per plot. The percentages of each category were used to calculate the index of growing apex (iG-Apex) according to the following formula:

$$iGApex = P_{FG} \times 1 + P_{MG} \times 0.5 + P_{SG} \times 0 \quad \text{(Equation 1)}$$

where P_{FG} represents the proportion of full-growing shoot tips, P_{MG} the proportion of slow-growing shoot tips, and P_{SG} the proportion of dead shoot tips. Measurements were recorded every two weeks, from the end of vine flowering to the beginning of veraison, on vines that had not been pruned or topped.

3.5. Vine yield and berry quality

Different components of vine yield were measured each year. The number of bunches per vine was counted after vine flowering, on each plant in the 4 plots of each treatment (20 replicates per treatment). This measurement was only carried out in 2023 and 2024, as the number of bunches in that year was determined by the water and N stress around flowering in the previous year (Guilpart *et al*., 2014). At harvest, the total harvest from each plot of 5 vines was weighed (4 replicates per treatment), and the berry weight was measured on one sample of 200 berries taken from each treatment. The 200 berries were then sent to a laboratory to analyse the pH, yeast assimilable nitrogen (YAN), sugar concentration and $\delta^{13}C$ of the musts. The $\delta^{13}C$ is an indicator of grapevine water status (Gaudillère *et al*., 2002).

3.6. Pruning weight

The total pruning weight of each plot was weighed when the vines were pruned as decided by the winegrowers (4 replicates per treatment). For the field 34.2 in 2024, the vines had already been pruned at the time of the measurements, and the pruned shoots were left on the ground near the plots. Under these conditions, it was not possible to ensure that all shoots originating from the targeted plot were collected. Consequently, the protocol was adapted, and pruning weight was estimated by collecting 20 vine shoots randomly selected in the immediate vicinity of each plot. To ensure consistency across fields, pruning weight data were subsequently analysed as relative differences compared with the control treatment for all fields.

4. Climatic variables

The Climatic Water Balance (CWB) was calculated over different periods of the vine cycle, with CWB = P – ETP, where P: precipitation and ETP: potential evapotranspiration. The climatic data came from Météo-France and were downloaded via the SICLIMA platform developed by AgroClim-INRAE (Maury *et al*., 2024). Different periods of the vine cycle were considered: the CWB from mid-May to mid-June of year n–1, the critical period for determining the number of bunches in year n being around flowering in year n–1 (Guilpart *et al*., 2014), the CWB from July to August of year n, the period between fruit set and veraison, which has a major influence on berry size and nutrient uptake (Ojeda & Saurin, 2014), and finally the CWB from April to August, *i.e.*, during the vine vegetative growth period.

5. Statistical analyses

5.1. Calculations on variables

For yield, number of bunches, 200-berry weight, and must quality variables, differences from the control treatment (ΔY) were calculated. That is, for each field and year, the mean value of the control ($\overline{Y}$) was subtracted from all observed values.

$$\Delta Y = Y - \overline{Y}_{control} \quad \text{(Equation 2)}$$

For the pruning weight, relative differences compared with the control ($\Delta Y/\overline{Y}_{control}$) were calculated to include data from field 34.2 in 2024:

$$\Delta Y/\overline{Y}_{control} = \frac{Y - \overline{Y}_{control}}{\overline{Y}_{control}} \quad \text{(Equation 3)}$$

5.2. Data analysis strategy

Linear mixed models were used to explain the variables yield, number of bunches per vine, pruning wood mass, berry weight, yeast assimilable nitrogen, sugar, and pH. For each of these variables, the Treatment, Year and CWB(s) (calculated from mid-May to mid-June of year n–1 for the number of bunches and yield, from July to August of year n for berries weight, must quality variables and yield, and from April to August of year n for pruning wood mass), as well as the interaction between Year and Treatment, were tested as explanatory variables. For the must quality variables (YAN, sugar, and pH), berry weight was also added as an explanatory variable. The assumptions of the linear model were systematically verified. For all the models, the factor Field was considered as a random effect by adding a random intercept. Random slopes linked to the field and associated with climatic variables and the berry weight variable were also tested for inclusion. The random effects, then the fixed effects, were selected using a top-down approach, starting with the complete model and then progressively eliminating certain variables on the basis of likelihood ratio tests. The assumptions of normality and heteroscedasticity were systematically verified on the residuals.

Hierarchical generalised additive models (HGAM) were used to explain the soil water potential, soil surface temperature, and iG-Apex data, which are temporal data, represented by curves. HGAMs can be used to model complex non-linear functions between covariates, with the form of the function varying according to levels of

qualitative variables (Pedersen *et al*., 2019). The formula for the model used for the three temporal variables analysed was as indicated in Equation 1.

$$Y_{ijkl}(t) = s(t) + s_{1i}(t) + s_{2j}(t) + s_{3k}(t) + \epsilon_{ijkl}(t)$$

(Equation 4)

Y is the variable to be explained, i the index for treatment, j for the year, k for the field, and l for the replicate. t denotes the time of observation. Hence, $Y_{ijkl}(t)$ is the measure of Y for the i^{th} treatment, during the j^{th} year, in the k^{th} field, for the l^{th} replicate, and at time t. s(t) represents a temporal curve representing the overall, global non-linear effect of time (*i.e*., days of the experiment) over the season, $s1_i(t)$ represents the time effect specific to the modality of treatment, $s2_j(t)$ represents the time effect specific to the year, $s3_k(t)$ the time effect specific to the field, and the $\epsilon_{ijkl}(t)$ are i.i.d. $N(0,\sigma^2)$ random variables. Diagnostics were used to check the obtained models. First, convergence of the fitting algorithm was checked. Then, residual plots were used to verify normality and homoscedasticity of the residuals. The number of basis functions used for smooth terms was also studied and compared to the effective degrees of freedom, to ensure that they are not too small, in which case the terms could fail to capture the relationships in the data. Plots to compare fitted values and responses were also plotted to visualise the adequacy of models to the data.

All analyses were carried out using R version 4.4.0. The package nlme (Pinheiro *et al*., 1999) was used for the linear mixed models. For the HGAM models, the analyses were carried out with the mgcv package (Pedersen *et al*., 2019; Wood, 2000).

RESULTS

1. Service crops biomass

The biomass of the service crops for the different fields and years of the experiment varied between around 0.5 t ha^{-1} and 7.5 t ha^{-1} (Figure 3). In general, biomass differences between late and early termination were low, except for field 66.2 in 2022, where the biomass increased by a factor of ~1.5 between the two periods, and field 11.2 in 2023, where the biomass doubled between the two periods (Figure 3).

2. Grapevine growth and yield

2.1. Yield components

All fields and years combined, the number of bunches per vine varied from 0 to 52 bunches, with an average of 16.08. Only the factor "Treatment" significantly explained the number of bunches (Table 3). Treatments E-R and L-R showed significantly lower numbers of bunches of –1.46 and –1.78 bunches per vine, respectively, compared with the control treatment (Figure 4A, Table 3). There was no significant difference in the number of bunches between E-T, L-T, and the control treatment.

The berry weight ranged from 83.3 to 560 g, with an average of 317.1 g. The factors retained after model selection were Treatment and Year, but not their interaction (Table 3), meaning that the Treatment effect was the same each year. Berry weight was significantly lower at 24.84 g in 2023 compared to 2022. In 2024, however, the berry weight was not significantly different from 2022. Treatments L-T, E-R, and L-R showed significant differences of –21.06, –45.47, and –30.27 g, respectively, compared with the control treatment, whereas no significant difference was observed between the E-T and the control treatment (Table 3, Figure 4B).

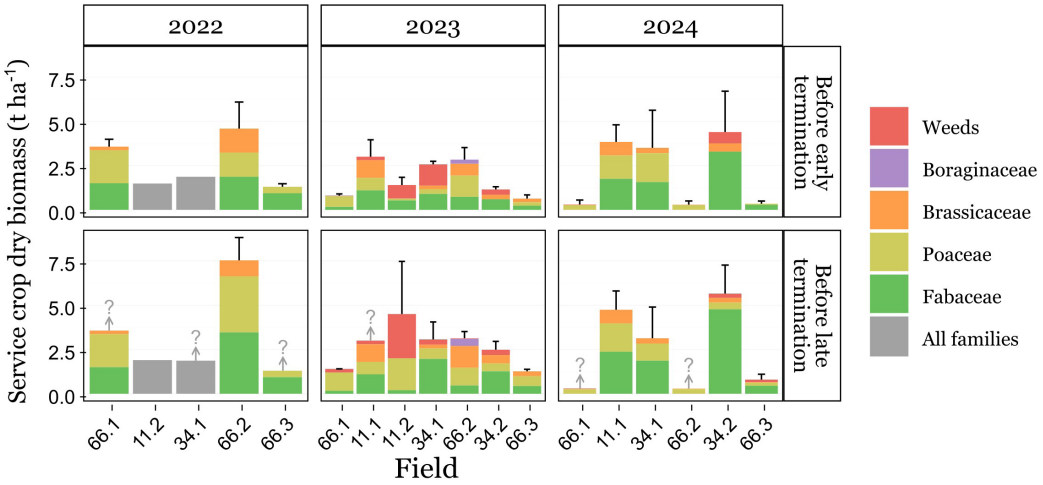


FIGURE 3. Dry biomass of the service crop before early termination and before late termination for the three years and for each of the fields monitored during the experiment. For fields 11.2 and 34.1 in 2022, the data represent the average dry biomass value for all families combined, due to missing data (Table S5). For some missing data, we assumed that the biomass before late termination was at least equal to the biomass measured before early termination, represented by grey question marks on the graph. Error bars represent standard deviations around the mean total biomass per field.

TABLE 3. Results of the linear mixed models explaining berry weight, number of bunches, yield, pruning weight, YAN, pH, sugar and $\delta^{13}C$ in musts. The table gives mean differences between the different levels of the factors and the control, associated standard errors, and a *p*-value for the comparison between the levels and the control (intercept). For berry weight and pruning weight, the intercept corresponds to the control treatment in 2022. The letters in the Group column correspond to the result of a post-hoc multiple comparison test; uppercase letters indicate significant differences among years, whereas lowercase letters indicate significant differences among treatments. Two levels sharing the same letter do not differ significantly at a first-order risk of $\alpha = 0.05$. E: early termination; L: late termination; T: tillage; R: roller. Part 1/2.

Term	Estimate	Standard error	*p*-value	Group*
Difference in berry weight relative to control (g)				
(Intercept)	15.89	8.74	0.07279	
2023	–24.84	10.23	0.01739	A
2024	–3.04	10.50	0.77326	B
E-T	–5.18	9.51	0.58720	cd
L-T	–21.05	9.51	0.02965	bc
E-R	–45.47	9.51	<0.001	a
L-R	–30.27	9.51	0.00206	ab
Difference in number of bunches relative to control				
(Intercept)	–0.11	0.81	0.89521	
E-T	0.76	0.59	0.19939	c
L-T	0.17	0.59	0.77248	c
E-R	–1.46	0.59	0.01353	ab
L-R	–1.78	0.59	0.00263	a
Difference in yield relative to control (kg)				
(Intercept)	–0.23	0.14	0.09245	
E-T	0.14	0.13	0.27835	c
L-T	–0.24	0.13	0.06681	ab
E-R	–0.35	0.13	0.00905	a
L-R	–0.35	0.13	0.00812	a
Difference in pruning weight relative to control (%)				
(Intercept)	–93.38	33.00	0.00534	
2023	9.38	8.63	0.27872	A
2024	22.49	10.94	0.04157	A
E-T	–3.00	5.19	0.56497	c
L-T	–20.49	5.19	<0.001	b
E-R	–34.48	5.06	<0.001	a
L-R	–40.11	5.06	<0.001	a
CWB April-August	–0.12	0.04	0.00513	
Difference in YAN relative to control (mg L^{-1})				
(Intercept)	–43.39	17.63	0.01588	
E-T	–27.43	9.39	0.00449	a
L-T	–42.22	9.43	<0.001	a
E-R	–38.41	9.59	<0.001	a
L-R	–41.68	9.48	<0.001	a
Weight 200 berries	0.15	0.04	<0.001	
Difference in pH relative to control				
(Intercept)	0.01	0.02	0.44954	
E-T	–0.05	0.02	0.00650	a
L-T	–0.05	0.02	0.00920	ab
E-R	–0.05	0.02	0.00926	ab
L-R	–0.07	0.02	<0.001	a

TABLE 3. Results of the linear mixed models explaining berry weight, number of bunches, yield, pruning weight, YAN, pH, sugar and $\delta^{13}C$ in musts. The table gives mean differences between the different levels of the factors and the control, associated standard errors, and a *p*-value for the comparison between the levels and the control (intercept). For berry weight and pruning weight, the intercept corresponds to the control treatment in 2022. The letters in the Group column correspond to the result of a post-hoc multiple comparison test; uppercase letters indicate significant differences among years, whereas lowercase letters indicate significant differences among treatments. Two levels sharing the same letter do not differ significantly at a first-order risk of $\alpha = 0.05$. E: early termination; L: late termination; T: tillage; R: roller. Part 2/2.

Term	Estimate	Standard error	*p*-value	Group*
Difference in sugar relative to control (g L^{-1})				
(Intercept)	0.80	2.19	0.71609	
E-T	1.52	2.36	0.52162	ab
L-T	6.10	2.36	0.01132	ab
E-R	7.28	2.36	0.00271	b
L-R	5.97	2.36	0.01313	ab
Difference in $\delta^{13}C$ relative to control				
(Intercept)	–0.18	0.25	0.4677	
2023	–0.23	0.17	0.1875	A
2024	0.47	0.21	0.0246	B

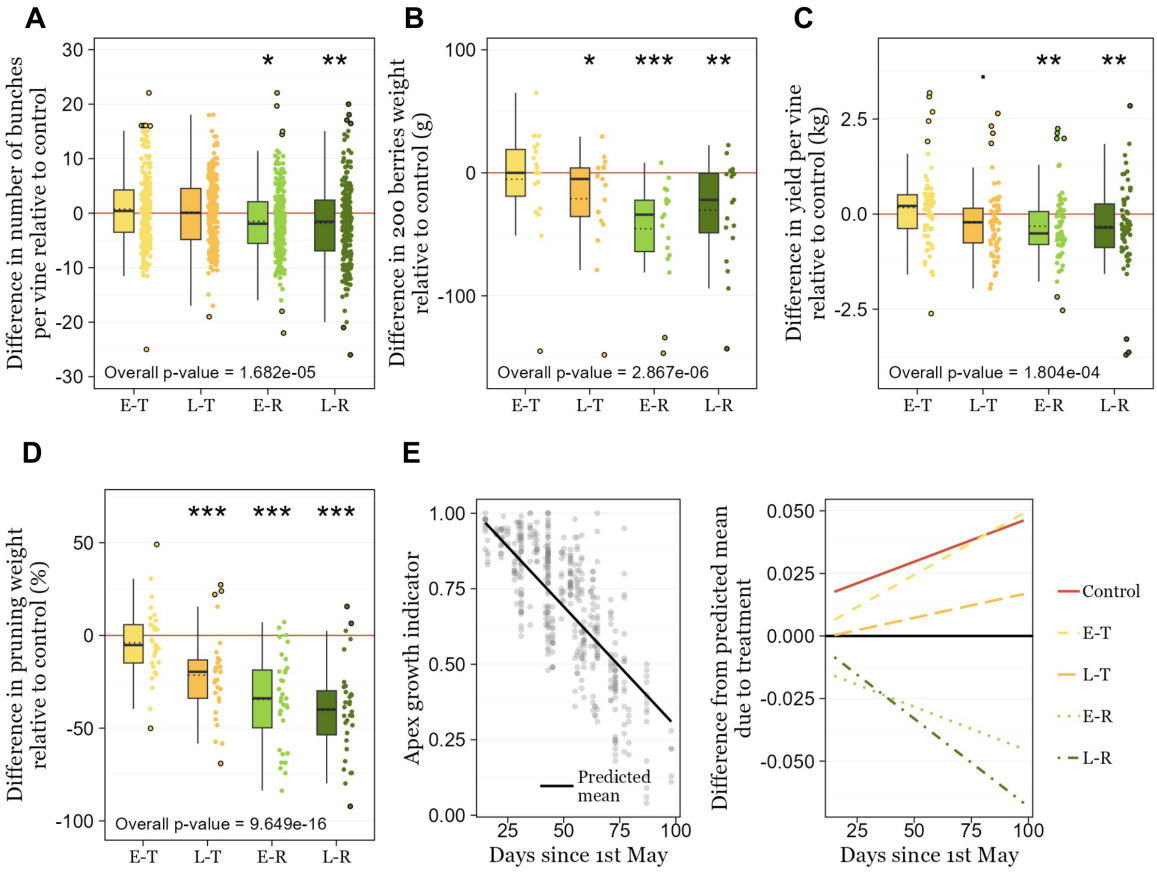


FIGURE 4. Effect of termination date and method on the number of bunches (A), berry weight (B), yield (C), pruning weight (D), and apex growth indicator (E). E: early termination; L: late termination; T: tillage; R: roller. (A, B, C, D) For the number of bunches and yield, only the Treatment factor was retained after model selection. For berry weight and pruning weight, only the factors Treatment and Year were retained after model selection. The stars indicate the significant differences resulting from tests comparing each of the termination methods with the control (*** : *p*-value ≤ 0.001; ** : *p*-value ≤ 0.01; * : *p*-value ≤ 0.05; . : *p*-value ≤ 0.1; : *p*-value > 0.1). The points surrounded in black correspond to the outliers calculated using the Tukey criterion. (E) Global function s(t) and treatment-specific deviations $s_{1i}(t)$ for the HGAM model on the apex growth indicator. The actual data for all years, treatments and fields combined are represented by the grey dots.

All fields and years combined, the average yield was 2.309 kg vine^{-1}, with a minimum of 0.095 kg vine^{-1} and a maximum of 8.054 kg vine^{-1}. Only the factor Treatment significantly explained the difference in yield relative to the control (Table 3). Treatments E-R and L-R showed significantly lower yields of 0.35 kg vine^{-1} compared with the control (Figure 4C, Table 3). There was no significant difference in yield between treatments E-T, L-T, and the control, but we observed a yield difference of 0.24 kg vine^{-1} between L-T and the control.

To sum up, roller terminations (E-R and L-R) significantly impacted grapevine yield and number of bunches, contrary to tillage termination strategies (E-T and L-T). The late tillage termination (L-T) and the roller termination strategies (E-R and L-R) had lower berry weight compared to the control. Finally, the early tillage termination (E-T) did not affect any of the yield components.

2.2. Pruning weight

Over the experiment, the pruning weight per vine varied from 0.014 to 0.937 kg vine^{-1}, with an average of 0.378 kg vine^{-1}. The factors Treatment, Year, and $CWB_{[April\text{-}August]}$ were retained after model selection but not the interaction Treatment:Year. Pruning weight in 2024 was significantly higher by 22.49 % compared to 2022, whereas 2023 did not differ significantly from 2022 (Table 3). Treatments L-T, E-R and L-R had significantly lower pruning weights than the control by –20.49 %, –34.48 % and –40.11 %, respectively (Table 3, Figure 4D). On the other hand, the pruning weight of the E-T treatment was not significantly different from the control (Figure 4D).

2.3. Apex growth index

For the apex growth index (iG-Apex), the results of the hierarchical generalised additive model (HGAM) showed a global curve decreasing from approximately 1 to 0.3 from May 1st to the beginning of August, meaning that iG-Apex decreased overall during the season (Figure 4E). The factors Treatment, Year, and Field significantly influenced the variation of iG-Apex over time (Table 4). Analysis of the model-predicted data showed that the E-T treatment exhibited a similar apex growth dynamic to the control, with a slower growth termination rate than the other treatments (*i.e.*, a less negative slope due to a positive deviation from the overall mean slope across treatments). The L-T treatment also displayed a positive deviation from the mean slope, although to a lesser extent, indicating a somewhat faster growth termination (Figure 4E). In contrast, both roller treatments showed negative deviations from the overall mean slope, reflecting an earlier and faster termination of shoot growth compared with the other treatments.

TABLE 4. Results of the HGAM models for the variable Apex growth index. The column "edf" gives the effective degrees of freedom for each term: this value represents the complexity of the smooth. An edf of 1 is equivalent to a straight line. An edf of 2 is equivalent to a quadratic curve, and so on, with higher edfs describing more wiggly curves. The *p*-value columns show the results of significance tests for each smooth term: a significant smooth term is one for which one cannot draw a horizontal line through 0 within the 95 % confidence interval. $s(t)$ represents a temporal curve representing the overall, global non-linear effect of time (*i.e.*, days of the experiment) over the season; $s_{1_i}(t)$ represents the time effect specific to the modality of treatment; $s_{2_j}(t)$ represents the time effect specific to the year; $s_{3k}(t)$ represents the time effect specific to the field.

Term	edf	*p*-value
Apex growth indicator		
$s(t)$	1.00	<0.001
$s_{1i}(t)$	6.68	<0.001
$s_{2j}(t)$	12.42	<0.001
$s_{3k}(t)$	31.01	<0.001
Soil water potential		
$s(t)$	2.84	0.31
$s_{1i}(t)$	14.79	<0.001
$s_{2j}(t)$	23.09	<0.001
$s_{3k}(t)$	36.28	<0.001
Soil surface temperature		
$s(t)$	1.01	<0.001
$s_{1i}(t)$	3.66	<0.001
$s_{2j}(t)$	24.16	<0.001
$s_{3k}(t)$	28.20	<0.001

3. Must quality: Yeast Assimilable Nitrogen (YAN), sugar, and pH

For YAN, the fixed effects retained after model selection were the factors Treatment and Berries weight. For pH and sugar, only the factor Treatment was retained after model selection (Table 3).

Across all fields and years, YAN varied from 33 to 427 mg L^{-1} with an average of 183.1 mg L^{-1}, pH varied from 3.21 to 4.48 with an average of 3.61, and sugar from 185 to 264 g L^{-1} with an average of 233 g L^{-1}. All treatments showed a significantly lower YAN concentration compared with the control treatment, respectively by –27.43, –42.22, –38.41, and –41.68 mg L^{-1} for treatments E-T, L-T, E-R, and L-R, respectively, although the differences between treatments E-T, L-T, E-R, and L-R were not significant (Figure 5A, Table 3). The sugar content in the musts also varied according to treatment. Treatments L-T, E-R, and L-R had a significantly higher sugar concentration of 6.10, 7.28, and 5.97 g L^{-1} compared with the control treatment,

while the sugar concentration of treatment E-T was not significantly different from the control (Table 3, Figure 5C). Finally, all treatments had a significantly lower pH compared with the control treatment: –0.05 units for treatments E-T, L-T, and E-R and –0.07 units for treatment L-R (Table 3). The presence of service crops, regardless of the termination method used, therefore had the effect of lowering the pH of the musts (Figure 5B). With regard to the $\delta^{13}C$ of the musts, only the factor Year was retained after selection of the model, meaning that Treatment did not significantly affect the $\delta^{13}C$ (Table 3).

4. Soil variables: water potential and temperature at ground surface

Regarding the soil surface temperature, the results of the HGAM model showed an average curve increasing from approximately 20 °C to 32 °C from April 1st to the end of August. The factors Treatment, Year, and Field significantly affected the variation in soil surface temperature over time (Table 5). Analysis of the model's predicted data showed that treatments L-T, E-R, and L-R had lower soil surface temperatures from 1.5 °C at the beginning of April and 1.05 °C at the end of August compared with the control (Figures 6A and 6B). To a lesser extent, E-T had a soil surface temperature 0.5 °C lower than the control throughout the season.

Regarding the soil water potential, the results of the hierarchical generalised additive model (HGAM) showed a global curve rising from around 50 to 160 kPa from March 1st to the end of August, indicating that the soil dried out during this period (Figure 6C). The factors Treatment, Year, and Field significantly influenced the variation in soil water potential over time (Table 5). Analysis of the data predicted by the model (Figures 6C and 6D) showed that from the beginning of April, the control and E-T treatments had a soil water potential around 20 to 50 kPa lower than the L-T, E-R, and L-R treatments, indicating higher soil water content in the control and E-T treatments. In contrast, in the fields 66.1, 66.2, and 66.3, where water potential was monitored during the autumn–winter period (September to December), the E-R and L-R treatments exhibited soil water potential approximately 50 kPa lower than those of the control, E-T, and L-T treatments. In other words, during winter, soils were drier under the control, E-T, and L-T treatments than under the E-R and L-R treatments (Figure S1).

TABLE 5. Results of the HGAM models for the variables Soil water potential and Surface Temperature. The column "edf" gives the effective degrees of freedom for each term: this value represents the complexity of the smooth. An edf of 1 is equivalent to a straight line. An edf of 2 is equivalent to a quadratic curve, and so on, with higher edfs describing more wiggly curves. The *p*-value columns show the results of significance tests for each smooth term: a significant smooth term is one for which one cannot draw a horizontal line through 0 within the 95 % confidence interval. $s(t)$ represents a temporal curve representing the overall, global non-linear effect of time (*i.e.*, days of the experiment) over the season, $s_{1i}(t)$ represents the time effect specific to the modality of treatment, $s_{2j}(t)$ represents the time effect specific to the year, $s_{3k}(t)$ represents the time effect specific to the field.

Term	edf	*p*-value
Soil water potential		
$s(t)$	2.84	0.31
$s_{1i}(t)$	14.79	<0.001
$s_{2j}(t)$	23.09	<0.001
$s_{3k}(t)$	36.28	<0.001
Soil surface temperature		
$s(t)$	1.01	<0.001
$s_{1i}(t)$	3.66	<0.001
$s_{2j}(t)$	24.16	<0.001
$s_{3k}(t)$	28.20	<0.001

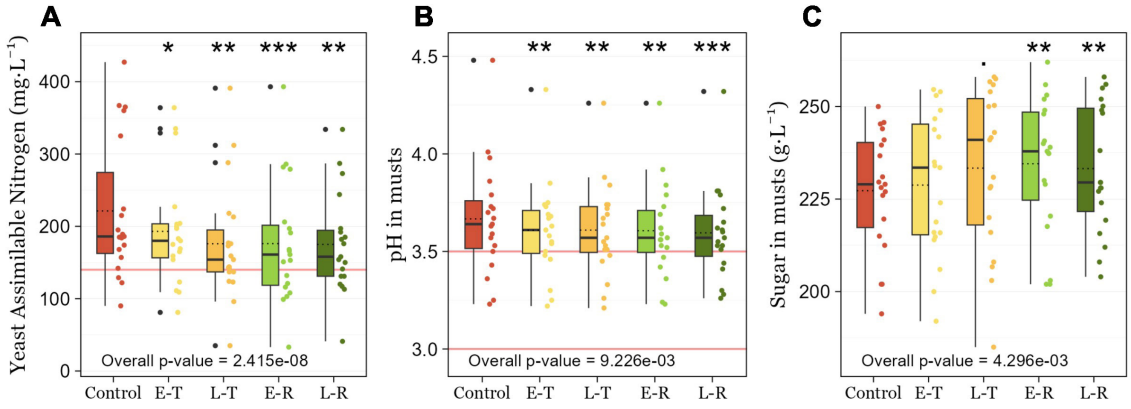


FIGURE 5. Effect of termination date and method on A: the Yeast Assimilable Nitrogen (YAN), B: pH, and C: sugar in musts. E: early termination; L: late termination; T: tillage; R: roller. For YAN, the factors Treatment and Berries weight (co-variable) were retained after model selection. For pH and sugar, only the factor Treatment was retained after model selection. The points surrounded in black correspond to the outliers calculated using the Tukey criterion. The stars indicate the significant differences resulting from tests comparing each of the termination methods with the control (*** : *p*-value ≤ 0.001 ; ** : *p*-value ≤ 0.01 ; * : *p*-value ≤ 0.05 ; . : *p*-value ≤ 0.1 ; : *p*-value > 0.1).

DISCUSSION

1. Effect of service crop termination date and method on vine and soil

1.1. Implications of service crop termination strategies for soil water and vine water stress, vigour, and yield components

We observed that the E-T treatment did not affect yield components or vine vigour compared with the control treatment (Figure 4). In contrast, the L-T treatment reduced berry weight and pruning weight, whereas the E-R and L-R treatments reduced berry weight, number of bunches, yield, and pruning weight (Figure 4). These responses observed for the L-T, E-R, and L-R treatments are consistent with previous studies indicating that service crops, particularly under Mediterranean conditions, often reduce vine vigour and yield (Abad *et al.*, 2021b). Consistent with recent literature, vines whose service crops were terminated by tillage exhibited greater vigour and higher yields than those where termination was achieved using a roller-crimper (Garcia *et al.*, 2024; Pelusi *et al.*, 2025). The effectiveness of roller crimping has been shown to strongly depend on both service crop composition and termination timing, with later termination – typically at the flowering stage of herbaceous species – being more effective (Alonso-Ayuso *et al.*, 2020; Cabrera-Pérez *et al.*, 2024; Hefner *et al.*, 2020). In this context, the composition of the service crop mixtures was not specifically adapted to roller termination (Table S1), and the biomass production was sometimes too low to allow an effective termination by roller (Alonso-Ayuso *et al.*, 2020; Garcia *et al.*, 2024; Kornecki & Kichler, 2022). Moreover, roller-termination at grapevine budburst is likely too early to ensure complete growth arrest and effectively limit transpiration and N uptake in the service crop. Conversely, late termination may increase risks under Mediterranean conditions, particularly due to enhanced competition for water and N (Celette & Gary, 2013).

Beyond roller efficiency, the considerable variability in service crop mixture composition across fields and years may also have influenced nitrogen dynamics and, more broadly, the magnitude of treatment effects. Mixtures with a high proportion of legumes tend to accumulate more nitrogen in their biomass and release it more rapidly after termination due to their lower C:N ratio, potentially increasing the risk of vine nitrogen uptake and vigour stimulation compared to grass-dominated mixtures (Ovalle *et al.*, 2010; Redin *et al.*, 2014; Tribouillois *et al.*, 2016 ; Tribouillois *et al.*, 2015; White *et al.*, 2017). Conversely, grass-dominated mixtures produce recalcitrant residues that immobilise soil nitrogen

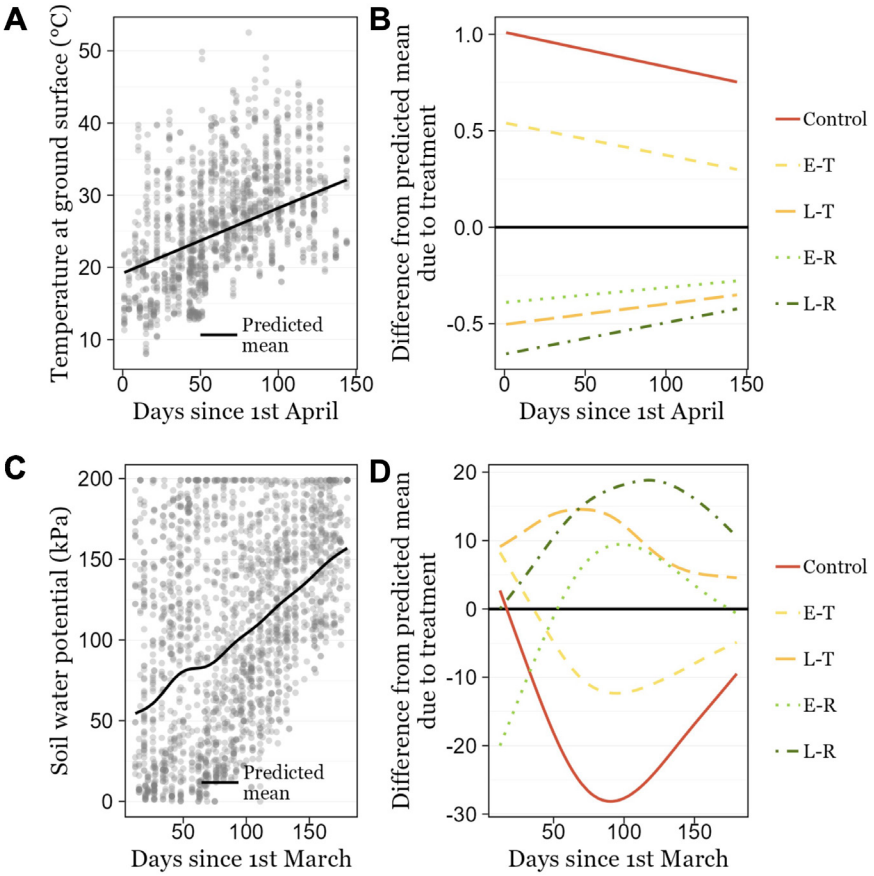


FIGURE 6. Effect of termination date and method on the Temperature at the ground surface (A, B) and on the soil water potential (C, D). The black line and curve on the left panels (A, C) correspond to the global function s(t) and the coloured lines and curves in the right panels (B, D) correspond to treatment-specific deviations $s_{1i}(t)$ from the HGAM models. The data for all years, treatments, and fields combined are represented by the grey dots. E: early termination; L: late termination; T: tillage; R: roller.

over a longer period. These contrasting dynamics mean that the consequences of termination timing – and particularly of late termination – on vine nutrition and water status may have differed among fields depending on mixture composition (Garcia *et al*., 2026). However, the factor Field was treated as a random effect in our statistical models, which partly accounts for between-site variability in mixture composition and its agronomic consequences. The consistency of treatment effects across this diversity of situations nonetheless suggests that termination date and method showed a dominant influence on the observed results, regardless of specific mixture composition.

The contrasting soil water potential and apex growth dynamics among treatments provide mechanistic support for these observations. In the soil water potential range observed in this study (50–160 kPa), soil water potential cannot be used as a direct proxy for vine water status, as predawn leaf water potential does not necessarily equilibrate with soil water potential in this range due to nighttime transpiration (Groenveld *et al*., 2023). Nevertheless, the contrasting drying dynamics observed between treatments, with differences of approximately 50 kPa around grapevine flowering, a phenologically sensitive stage, suggest a higher risk of water stress for E-R, L-R, and L-T treatments, a pattern that is consistent with the significant treatment effects observed on yield components. Treatments E-R, L-R, and L-T led to drier soil conditions during the grapevine growing season compared with the E-T and control treatments, whereas soils under the E-R and L-R treatments were wetter during the winter period than those under the other treatments (Figures 6C and 6D, Figure S1). This pattern likely reflects differences in residue management following service crop termination. In the E-R and L-R treatments, plant residues were rolled and left on the soil surface, which may have enhanced water infiltration during winter (Alonso-Ayuso *et al*., 2020; Coppens *et al*., 2006; Gaudin *et al*., 2010; Kornecki *et al*., 2013). However, increased transpiration of the service crops during spring subsequently led to greater soil drying (Celette & Gary, 2013).

In the L-T treatment, late termination likely promoted soil drying in early spring due to continued evapotranspiration, while winter water infiltration was not enhanced because residues were incorporated into the soil rather than left on the surface (Prosdocimi *et al*., 2016). Conversely, the E-T and control treatments may have limited spring transpiration, thereby reducing soil drying during the growing season (McMillen, 2013; Zribi *et al*., 2015), although they were less favourable to water infiltration during winter. As a result, vines under the L-T, E-R, and L-R treatments experienced higher water stress during the growing season, as reflected by lower apex growth index values – an indicator of vine water stress (Pichon *et al*., 2021). Increased water stress during key phenological stages therefore provides a plausible mechanistic explanation for the observed reductions in vine vigour and yield components under L-T, E-R, and L-R treatments (Figure 4, Table 3).

However, in contrast to Garcia *et al*. (2024), who reported no effect of termination timing on vine yield and vigour, our results show that early tillage termination resulted in higher vigour and berry weight than late tillage termination (Figures 4B and 4D). This discrepancy is likely explained by differences in the termination dates considered: February compared with termination at budburst in Garcia *et al*. (2024), and termination at budburst compared to one month after budburst in the present study. Delayed termination increases the risk of competition for water and N and may affect the mineralisation dynamics of organic N from service crops (Alonso-Ayuso *et al*., 2017), which likely contributed to the lower vigour and berry weight observed under late termination treatments.

Overall, our findings demonstrate that, in a Mediterranean context, service crop termination by tillage at grapevine budburst limits vine water stress and preserves vine yield and vigour. Although the three study years were characterised by below-average rainfall, limiting our ability to generalise to wetter conditions, our results specifically document service crop performance under dry conditions, which are becoming increasingly frequent in Mediterranean wine regions due to climate change (Dinis *et al*., 2022; van Leeuwen *et al*., 2019). Early tillage termination therefore appears as a preferable strategy for dry years, which are projected to become the norm rather than the exception in these regions. However, the use of a roller-crimper may have other benefits that were not studied in this experiment, such as the improvement of soil microbial biomass (Centurión *et al*., 2022; Garcia *et al*., 2024), and deserves investigation under a broader range of climatic conditions.

1.2. Implications of service crop termination strategies for must composition

All of the treatments had a lower Yeast Assimilable Nitrogen (YAN) concentration in the musts than the control (Figure 5A), probably due to N competition between the service crops and the vines (Celette *et al*., 2009; Celette & Gary, 2013). In light of the study of Garcia *et al*. (2024), we might have expected that the tillage termination would have a higher concentration of YAN in the musts than the roller-crimper termination, due to the mineralisation of the organic matter encouraged by the tillage (Coppens *et al*., 2006). In addition, given that all the service crops had a certain percentage of N-fixing legumes, we could have expected a neutral or even positive effect of the service crops on YAN compared with the tilled control (Abad *et al*., 2021b; Bloszies *et al*., 2022; White *et al*., 2017). However, the particularly intense drought during the three years of the experiment (Figure 3) has reduced the proportion of legumes in the mix compared to what was sown. It may also have reduced the mineralisation of the soil, leading to a low N content in the soil and a poor transfer of this N to the vines (Mabrouk, 2012; Sulas *et al*., 2017). In addition, pre-emptive competition may have occurred in the service-cropped treatments, decreasing N availability for the grapevine (Alonso-Ayuso *et al*., 2014; Alonso-Ayuso *et al*., 2020; Thorup-Kristensen *et al*., 2003).

However, the impact of reduced YAN associated with service crop treatments must be assessed considering the production objectives of the winegrower. Indeed, although a YAN concentration of 140 mg L^{-1} is commonly used as a technical threshold below which the risk of N deficiency during fermentation may increase (Bely *et al*., 1990; Walker *et al*., 2022), the occurrence of sluggish or stuck fermentations depends less on a fixed YAN value than on yeast strain, fermentation conditions, and the targeted wine style (Bell & Henschke, 2005; Bisson, 1999). Consequently, this threshold should be regarded as an indicative reference rather than a strict limit. Finally, corrective options are available during grapevine growth or fermentation to avoid YAN deficiency (Hilbert *et al*., 2003), and the use of service crop mixtures richer in legumes may also help limit N competition between service crops and vines (Celette *et al*., 2009; Garcia *et al*., 2024).

We observed that all treatments resulted in a decrease in must pH (Figure 5B). This effect may be related to changes in the relative proportions of organic acids in the must associated with the presence of a service crop (Mattii *et al*., 2005). Across all fields, years, and treatments, must pH values ranged from 3.210 to 4.480, with 73 % of observations exceeding 3.5, a level associated with an increased risk of bacterial contamination (Payan *et al*., 2023). In this context, the pH reduction induced by service crops could be considered favourable for alcoholic fermentation. However, this effect should be interpreted with caution, as the observed pH decrease was relatively small (0.05–0.07 units), and reductions in must pH associated with service crops have rarely been reported in the literature (Abad *et al*., 2021b).

Finally, the E-T treatment exhibited must sugar concentrations comparable to those of the control treatment. In contrast, the L-T, E-R, and L-R treatments showed sugar concentrations approximately 6–7 g L^{-1} higher than the control. These differences may reflect several non-exclusive mechanisms: a more advanced ripening stage at harvest, a concentration effect associated with the lower berry weight observed in these treatments, or a crop load effect linked to their reduced yield. Disentangling these contributions would require further investigation. In the context of global warming, which is associated with excessive increases in grape sugar concentration and wine alcohol content in southern France and Mediterranean regions (Dinis *et al*., 2022; van Leeuwen *et al*., 2019), our results suggest that the use of service crops terminated by tillage at budburst is unlikely to increase wine alcohol levels further.

The lack of effect observed for $\delta^{13}C$ can be explained by the fact that $\delta^{13}C$ only accounts for the water stress experienced from the grape ripening period onwards (Gaudillère *et al*., 2002), whereas according to the soil water potential data, the differences in soil water potential between the treatments were greater at the start of the vine's reproductive cycle and more attenuated at veraison (Figure 6D).

1.3. Implications of service crop termination strategies for temperature at the soil surface

Regarding soil surface temperature, treatments L-T, E-R, and L-R exhibited an average temperature reduction of 1.0 to 1.5 °C compared with the control during the grapevine vegetative growth period, whereas the reduction observed under the E-T treatment was more limited, at approximately 0.5 °C (Figure 6B). These results are consistent with previous studies reporting that plant cover exerts a buffering effect on soil temperature, leading to lower temperatures during daytime and warm periods, and higher temperatures during nighttime and cooler periods (Blanco-Canqui & Ruis, 2020).

The greater temperature reduction observed for the E-R and L-R treatments can likely be attributed to the larger amount of biomass left on the soil surface following late termination and/or rolling, which increases soil shading and reduces heat transfer. According to Onwuka (2018), optimal temperature ranges for soil microorganisms and macro-organisms are approximately 10–35.6 °C and around 24 °C, respectively. During the experiment, soil surface temperatures exceeded 35.6 °C for 3.7 % of measurements under the control treatment, compared with 3.1 % for E-T and only 1.7 % for the L-T, E-R, and L-R treatments (Figure 6B). This suggests that service crop treatments, particularly those leaving surface residues, reduced the frequency of potentially detrimental high-temperature conditions for soil biological activity.

High soil surface temperatures may also indirectly affect grapevine roots: although the relationship between root zone temperature and vine physiology remains poorly documented in the literature, available evidence suggests that temperatures above 30 °C at root level can impair vine growth and yield (Su *et al*., 2024). However, as this was demonstrated under controlled conditions using potted vines, the link between soil surface temperature, and root zone temperature under field conditions warrants caution. Assuming that the relative differences in temperature measured at the soil surface are also reflected at depth, the temperature reductions observed under the L-T, E-R, and L-R treatments could, therefore, contribute to mitigating heat-related constraints on vine performance. However, in the present study, this potential benefit appears minor compared with the stronger negative effects associated with increased water competition and the resulting reductions in vine yield and vigour observed under these same treatments.

2. Challenges of on-farm experimentation and data quality

The scientific community has shown increasing interest in on-farm experimentation, which is widely regarded as a key lever for the agroecological transition and a response to the growing demand for decentralised, inclusive, and context-specific research (Lacoste *et al*., 2022). By adopting a farmer-centred perspective, on-farm experiments are seen as effective tools for producing actionable knowledge and fostering innovations that are better aligned with farmers' needs, constraints, and objectives (Toffolini & Jeuffroy, 2022). However, compared with controlled experimental trials,

on-farm experimentation entails specific challenges and a higher risk of failure, including partial withdrawal of farmers, deviations from experimental protocols, and missing or incomplete datasets, particularly for yield-related variables (Roques *et al*., 2022).

In the present study, such challenges were encountered to a limited extent. A small number of protocol deviations occurred, and a few farmers – whose data are not presented here – discontinued their participation during the course of the project. In addition, some data gaps were inevitable due to the diversity of farm contexts and the autonomy of winegrowers in managing their fields, a common feature of participatory research (Roques *et al*., 2022). In particular, precise information on the exact composition of sown service crop mixtures and on the specific dates of sowing and termination was occasionally unavailable. Additional missing data also occurred when farmers did not inform the research team in advance of service crop termination or vine pruning. Consequently, the year effect observed for pruning weight (Table 3) should, however, be interpreted with caution. Pruning weight data were available for only one field in 2022, compared to three in 2023 and five in 2024, so the apparent difference between years may partly reflect differences in field composition across years rather than a true temporal effect. Furthermore, in a few cases where service crop biomass was insufficient to allow effective termination by roller-crimping, mowing was performed instead (Table S3).

Despite these limitations, protocol deviations were minor and are unlikely to compromise the robustness of the conclusions. In cases where roller-crimping could not be performed due to insufficient service crop biomass and was replaced by mowing, we argue that results remain valid: both techniques leave the service crop residues on the soil surface without incorporating them, and previous work has shown that mowed and rolled service crops exhibit similar performance because neither method achieves effective plant destruction – unlike tillage, which does (Garcia *et al*., 2024). For the site-year where late termination was carried out by soil tillage rather than roller-crimping due to the farmer's concern about excessive competition, this deviation would be expected to reduce the contrast between treatments, thereby working against detecting a significant treatment effect. The fact that significant effects are nonetheless observed across the full dataset suggests that the treatment effects are sufficiently strong to be detected despite this local protocol deviation. Similarly, missing data for some estates in some years reduce statistical power but do not introduce bias: the detection of significant effects under reduced statistical power implies that the underlying agronomic signal is robust. Finally, the alternative pruning wood measurement protocol applied to one estate in the final year was addressed by expressing data as relative deviations from the control treatment, which preserves the comparability of this site-year within the dataset while making absolute values uninterpretable – a trade-off we consider acceptable given the overall sample size.

CONCLUSION

This on-farm experiment conducted in Mediterranean vineyards demonstrates that the date and method of service crop termination strongly condition their agronomic outcomes, particularly through their effects on soil water dynamics and vine water stress. However, given the variability in soil types, grapevine management, and climatic conditions across the different fields, and the participatory nature of the experiment, these results should be interpreted as context-dependent: the relative performance of termination strategies may vary with local agronomic conditions, and early tillage termination may not be equally preferable in wetter climates or on soils with higher water-holding capacity. Among the tested strategies, termination by tillage at grapevine budburst emerged as the most balanced option, as it preserved vine vigour and yield at levels comparable to the tilled control, while avoiding the increased water stress observed under late-termination or roller-crimping treatments. In contrast, late termination and roller-crimping, despite improving winter water infiltration and reducing soil surface temperature, induced higher soil drying during the growing season, greater vine water stress, and subsequent reductions in yield components. Service crops also modified must composition, notably by reducing yeast assimilable N and slightly decreasing pH, effects that should be interpreted in light of winegrowers' production objectives and the availability of adaptive management options during vine growth and vinification. Importantly, early tillage termination did not increase must sugar concentration, suggesting that this strategy is unlikely to exacerbate rising alcohol levels under climate change. Finally, despite the inherent challenges of participatory on-farm experimentation – including protocol deviations and occasional data gaps – the trust-based relationships established between researchers, facilitators, and winegrowers, together with the co-construction of experimental objectives and protocols, contributed to the overall quality of the dataset and to the relevance of the knowledge produced. For most participating winegrowers, who were already using service crops prior to the experiment, this approach provided an opportunity to refine their management strategies through collective discussion and iterative learning. This study thus highlights the value of actively involving farmers in knowledge production and confirms the relevance of on-farm experimentation as a cornerstone of the agroecological transition of viticulture under increasing climatic constraints.

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REFERENCES

Abad, J., Hermoso de Mendoza, I., Marín, 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., Hermoso de Mendoza, I., Marín, 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

Agreste, P. (2025). GRAPH'AGRI 2025 : Agriculture – Forêt – Pêche – Alimentation – Industries agroalimentaires – Environnement – Territoire. Ministère de l'Agriculture, de l'Agro-alimentaire et de la Souveraineté alimentaire, Secrétariat général, Service de la statistique et de la prospective, Paris.

Alonso-Ayuso, M., Gabriel, J.L., Hontoria, C., Ibáñez, M.Á., Quemada, M. (2020). The cover crop termination choice to designing sustainable cropping systems. Eur. J. Agron. 114, 126000. https://doi.org/10.1016/j.eja.2020.126000

Alonso-Ayuso, M., Gabriel, J.L., Quemada, M. (2014). The Kill Date as a Management Tool for Cover Cropping Success. PLoS ONE 9, e109587. https://doi.org/10.1371/journal.pone.0109587

Alonso-Ayuso, M., Quemada, M., Vanclooster, M., Ruiz-Ramos, M., Rodriguez, A., Gabriel, J.L. (2017). Assessing cover crop management under actual and climate change conditions. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2017.10.095

Bell, S.-J., Henschke, P.A. (2005). Implications of nitrogen nutrition for grapes, fermentation and wine. Aust. J. Grape Wine Res. 11, 242–295. https://doi.org/10.1111/j.1755-0238.2005.tb00028.x

Bely, M., Sablayrolles, J.-M., Barre, P. (1990). Automatic detection of assimilable nitrogen deficiencies during alcoholic fermentation in oenological conditions. J. Ferment. Bioeng. 70, 246–252. https://doi.org/10.1016/0922-338X(90)90057-4

Bisson, L.F. (1999). Stuck and Sluggish Fermentations. Am. J. Enol. Vitic. 50, 107–119. https://doi.org/10.5344/ajev.1999.50.1.107

Blanco-Canqui, H., Ruis, S.J. (2020). Cover crop impacts on soil physical properties: A review. Soil Sci. Soc. Am. J. 84, 1527–1576. https://doi.org/https://doi.org/10.1002/saj2.20129

Bloszies, S.A., Reberg-Horton, S.C., Heitman, J.L., Woodley, A.L., Grossman, J.M., Hu, S. (2022). Legume cover crop type and termination method effects on labile soil carbon and nitrogen and aggregation. Agron. J. 114, 1817–1832. https://doi.org/https://doi.org/10.1002/agj2.21022

Cabrera-Pérez, C., Royo-Esnal, A., Català, B., Baraibar, B., Recasens, J. (2024). Cover crops terminated with roller-crimper to manage *Cynodon dactylon* and other weeds in vineyards. Pest Manag. Sci. 80, 2162–2169. https://doi.org/10.1002/ps.7953

Capri, C., Gatti, M., Fiorini, A., Ardenti, F., Tabaglio, V., Poni, S. (2023). A comparative study of fifteen cover crop species for orchard soil management: water uptake, root density traits and soil aggregate stability. Sci. Rep. 13, 721. https://doi.org/10.1038/s41598-023-27915-7

Celette, F., Findeling, A., Gary, C. (2009). Competition for nitrogen in an unfertilized intercropping system: The case of an association of grapevine and grass cover in a Mediterranean climate. Eur. J. Agron. 30, 41–51. https://doi.org/10.1016/j.eja.2008.07.003

Celette, F., Gary, C. (2013). Dynamics of water and nitrogen stress along the grapevine cycle as affected by cover cropping. Eur. J. Agron. 45, 142–152. https://doi.org/10.1016/j.eja.2012.10.001

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

Centurión, N., Ulcuango, K., Navas, M., Mariscal-Sancho, I., Ibáñez, M.A., Moliner, A., Hontoria, C. (2022). Soil Microbial Response to Cover Crop Termination Methods under Two Water Levels. Agronomy 12, 3002. https://doi.org/10.3390/agronomy12123002

Chayre, A., Gibert, C., Mezilet, Y., Pointereau, P. (2024). Carte Adonis présentant par commune l'usage des pesticides au travers de l'indice de fréquence de traitement (IFT).

Constantin, J., Minette, S., Vericel, G., Jordan-Meille, L., Justes, E. (2024). MERCI: a simple method and decision-support tool to estimate availability of nitrogen from a wide range of cover crops to the next cash crop. Plant Soil 494, 333–351. https://doi.org/10.1007/s11104-023-06283-1

Coppens, F., Garnier, P., De Gryze, S., Merckx, R., Recous, S. (2006). Soil moisture, carbon and nitrogen dynamics following incorporation and surface application of labelled crop residues in soil columns. Eur. J. Soil Sci. 57, 894–905. https://doi.org/10.1111/j.1365-2389.2006.00783.x

Cunial, L., Diti, I., Bonini, P., Patelli, R., Gatti, M., Cola, G., Bordoni, M., Nguyen, T.N.A., Meisina, C., Confalonieri, R., Paleari, L., Poni, S. (2025). Novel termination techniques of winter cover crops in the vineyard: Effects on physiology and performance of Pinot Noir and Malvasia di Candia aromatica grapevines. Eur. J. Agron. 164, 127514. https://doi.org/10.1016/j.eja.2025.127514

Curtright, A.J., Zapata-Rojas, D., Horwath, W.R., Zhu-Barker, X. (2025). Quantifying nitrogen provisioning and release from cover crops in walnut orchards. Agric. Ecosyst. Environ. 383, 109529. https://doi.org/10.1016/j.agee.2025.109529

De Souza, C.R., Maroco, J.P., Dos Santos, T.P., Rodrigues, M.L., Lopes, C., Pereira, J.S., Chaves, M.M. (2005). Control of stomatal aperture and carbon uptake by deficit irrigation in two grapevine cultivars. Agric. Ecosyst. Environ. 106, 261–274. https://doi.org/10.1016/j.agee.2004.10.014

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

Dinis, L.-T., Bernardo, S., Yang, C., Fraga, H., Malheiro, A.C., Moutinho-Pereira, J., Santos, J.A. (2022). Mediterranean viticulture in the context of climate change. Ciênc. E Téc. Vitivinícola 37, 139–158. https://doi.org/10.1051/ctv/ctv20223702139

Eivazi, F., Pinero, J., Dolan-Timpe, M., Doggett, W. (2024). Comparison of cover crop termination methods for small-scale organic vegetable production: effect on soil fertility and health. J. Plant Nutr. 47, 1378–1389. https://doi.org/10.1080/01904167.2024.2308196

Fernandez Pulido, C.R., Rasmussen, J., Eriksen, J., Abalos, D. (2025). Cover crops for nitrogen loss reductions: functional groups, species identity and traits. Plant Soil 507, 127–140. https://doi.org/10.1007/s11104-023-05895-x

Fernández-Mena, H., Frey, H., Celette, F., Garcia, L., Barkaoui, K., Hossard, L., Naulleau, A., Métral, 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, 126191. https://doi.org/10.1016/j.eja.2020.126191

Fouillet, E., Delière, L., Chartier, N., Munier-Jolain, N., Cortel, S., Rapidel, B., Merot, A. (2022). Reducing pesticide use in vineyards. Evidence from the analysis of the French DEPHY network. Eur. J. Agron. 136, 126503. https://doi.org/10.1016/j.eja.2022.126503

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

Garcia, L., Krafft, G., Enard, C., Bouisson, Y., Metay, A. (2024). Adapting service crop termination strategy in viticulture to increase soil ecosystem functions and limit competition with grapevine. Eur. J. Agron. 156, 127161. https://doi.org/10.1016/j.eja.2024.127161

Garcia, L., Metay, A., Damour, G. (2026). Assessing the multifunctionality of service crops in mediterranean vineyards using a functional trait approach. PLOS One 21, e0343005. https://doi.org/10.1371/journal.pone.0343005

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://doi.org/10.1007/s11104-020-04543-y

Gaudillère, J., van Leeuwen, C., Ollat, N. (2002). Carbon isotope composition of sugars in grapevine, an integrated indicator of vineyard water status. J. Exp. Bot. 53, 757–763. https://doi.org/10.1093/jexbot/53.369.757

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

Gaume, E., Borga, M., Llassat, M.C., Maouche, S., Lang, M., Diakakis, M. (2016). Mediterranean extreme floods and flash floods, in: The Mediterranean Region under Climate Change. A Scientific Update, Coll. Synthèses. IRD Editions, pp. 133–144. https://doi.org/10.4000/books.irdeditions.23181

Giffard, B., Winter, S., Guidoni, S., Nicolai, A., Castaldini, M., Cluzeau, D., Coll, P., Cortet, J., Le Cadre, E., d'Errico, G., Forneck, A., Gagnarli, E., Griesser, M., Guernion, M., Lagomarsino, A., Landi, S., Bissonnais, Y.L., Mania, E., Mocali, S., Preda, C., Priori, S., Reineke, A., Rusch, A., Schroers, H.-J., Simoni, S., Steiner, M., Temneanu, E., Bacher, S., Costantini, E.A.C., Zaller, J., Leyer, I. (2022). Vineyard Management and Its Impacts on Soil Biodiversity, Functions, and Ecosystem Services. Front. Ecol. Evol. 10, 850272. https://doi.org/10.3389/fevo.2022.850272

Griesser, M., Steiner, M., Pingel, M., Uzman, D., Preda, C., Giffard, B., Tolle, P., Memedemin, D., Forneck, A., Reineke, A., Leyer, I., Bacher, S. (2022). General trends of different inter-row vegetation management affecting vine vigor and grape quality across European vineyards. Agric. Ecosyst. Environ. 338, 108073. https://doi.org/10.1016/j.agee.2022.108073

Groenveld, T., Obiero, C., Yu, Y., Flury, M., Keller, M. (2023). Predawn leaf water potential of grapevines is not necessarily a good proxy for soil moisture. BMC Plant Biol. 23, 369. https://doi.org/10.1186/s12870-023-04378-6

Guilpart, N., Metay, A., Gary, C. (2014). Grapevine bud fertility and number of berries per bunch are determined by water and nitrogen stress around flowering in the previous year. Eur. J. Agron. 54, 9–20. https://doi.org/10.1016/j.eja.2013.11.002

Hefner, M., Gebremikael, M.T., Canali, S., Sans Serra, F.X., Petersen, K.K., Sorensen, J.N., De Neve, S., Labouriau, R., Kristensen, H.L. (2020). Cover crop composition mediates the constraints and benefits of roller-crimping and incorporation in organic white cabbage production. Agric. Ecosyst. Environ. 296, 106908. https://doi.org/10.1016/j.agee.2020.106908

Hilbert, G., Soyer, J.P., Molot, C., Giraudon, J., Milin, S., Gaudillere, J.P. (2003). Effects of nitrogen supply on must quality and anthocyanin accumulation in berries of cv. Merlot. Vitis 42, 69–76.

Kornecki, T.S., Arriaga, F.J., Price, A.J., Balkcom, K.S. (2013). Effects of Recurrent Rolling/Crimping Operations on Cover Crop Termination, Soil Moisture, and Soil Strength for Conservation Organic Systems. Appl. Eng. Agric. 841–850. https://doi.org/10.13031/aea.29.10186

Kornecki, T.S., Kichler, C.M. (2022). Effectiveness of Cover Crop Termination Methods on No-Till Cantaloupe. Agriculture 12, 66. https://doi.org/10.3390/agriculture12010066

Lacoste, M., Cook, S., McNee, M., Gale, D., Ingram, J., Bellon-Maurel, V., MacMillan, T., Sylvester-Bradley, R., Kindred, D., Bramley, R., Tremblay, N., Longchamps, L., Thompson, L., Ruiz, J., García, F.O., Maxwell, B., Griffin, T., Oberthür, T., Huyghe, C., Zhang, W., McNamara, J., Hall, A. (2022). On-Farm Experimentation to transform global agriculture. Nat. Food 3, 11–18. https://doi.org/10.1038/s43016-021-00424-4

Lamichhane, J.R., Alletto, L. (2022). Ecosystem services of cover crops: a research roadmap. Trends Plant Sci., Special issue: Climate change and sustainability II 27, 758–768. https://doi.org/10.1016/j.tplants.2022.03.014

Le Bissonnais, Y., Arrouays, D. (1997). Aggregate stability and assessment of soil crustability and erodibility: II. Application to humic loamy soils with various organic carbon contents. Eur. J. Soil Sci. 48, 39–48. https://doi.org/10.1111/j.1365-2389.1997.tb00183.x

Leal, C., Gramaje, D. (2024). Chapter Five - Management strategies for reducing pesticide use against diseases caused by fungi and oomycetes in grapevine, in: Martins-Lopes, P. (Ed.), Grapevine: From Origin to the Vineyard, Advances in Botanical Research. Academic Press, pp. 197–253. https://doi.org/https://doi.org/10.1016/bs.abr.2024.04.002

Liebhard, G., Guzmán, G., Gómez, J.A., Winter, S., Zaller, J.G., Bauer, T., Nicolai, A., Cluzeau, D., Popescu, D., Bunea, C.-I., Strauss, P. (2024). Vineyard cover crop management strategies and their effect on soil properties across Europe. Eur. J. Soil Sci. 75, e13573. https://doi.org/10.1111/ejss.13573

Lopes, C.M. (2016). over crops competition for water in vineyards : case studies in mediterranean terroirs, in: 11th International Terroir Congress 2016. Presented at the 11th International Terroir Congress 2016, Linfield College, Mcminnville, Oregon.

Mabrouk, Y. (2012). Enhancing the biological nitrogen fixation of leguminous crops grown under stressed environments. Afr. J. Biotechnol. https://doi.org/10.5897/AJB10.2170

Mattii, G.B., Storchi, P., Ferrini, F. (2005). Effects of soil management on physiological, vegetative and reproductive characteristics of Sangiovese grapevine. Adv. Hortic. Sci. 19, 198–205.

Maury, O., Garcia de Cortazar Atauri, I., Bertuzzi, P., Persyn, B., Lagier, M. (2024). SICLIMA : Système d'information de données climatiques maillées. https://doi.org/10.15454/HIPDPZ

McMillen, M. (2013). The Effect of Mulch Type and Thickness on the Soil Surface Evaporation Rate 14.

Novara, A., Cerda, A., Barone, E., Gristina, L. (2021). Cover crop management and water conservation in vineyard and olive orchards. Soil Tillage Res. 208, 104896. https://doi.org/10.1016/j.still.2020.104896

Ojeda, H., Saurin, N. (2014). L'irrigation de précision de la vigne : méthodes, outils et stratégies pour maximiser la qualité et les rendements de la vendange en économisant de l'eau. Innov. Agron. 38, 97–108. https://doi.org/10.17180/n4p2-pr93

Onwuka, B. (2018). Effects of Soil Temperature on Some Soil Properties and Plant Growth. Adv. Plants Agric. Res. 8. https://doi.org/10.15406/apar.2018.08.00288

Ovalle, C., del Pozo, A., Lavín, A., Hirzel, J. (2007). Cover crops in vineyards: performance of annual forage legume mixtures and effects on soil fertility. Agric. Téc. 67, 384–392. https://doi.org/10.4067/S0365-28072007000400006

Ovalle, C., del Pozo, A., Peoples, M.B., Lavín, A. (2010). Estimating the contribution of nitrogen from legume cover crops to the nitrogen nutrition of grapevines using a 15N dilution technique. Plant Soil 334, 247–259. https://doi.org/10.1007/s11104-010-0379-1

Payan, C., Gancel, A.-L., Jourdes, M., Christmann, M., Teissedre, P.-L. (2023). Wine acidification methods: a review. OENO One 57, 113–126. https://doi.org/10.20870/oeno-one.2023.57.3.7476

Pedersen, E.J., Miller, D.L., Simpson, G.L., Ross, N. (2019). Hierarchical generalized additive models in ecology: an introduction with mgcv. PeerJ 7, e6876. https://doi.org/10.7717/peerj.6876

Pellegrino, A., Lebon, E., Simonneau, T., Wery, J. (2005). Towards a simple indicator of water stress in grapevine (*Vitis vinifera* L.) based on the differential sensitivities. Aust. J. Grape Wine Res. 11, 306–315. https://doi.org/10.1111/j.1755-0238.2005.tb00030.x

Pelusi, F., Gatti, M., Cunial, L., Zozzo, F.D., Santelli, S., Poni, S. (2025). Effects of Winter Cover Crop Mixture and Termination on the Performance and Physiology of cv. Barbera (*Vitis vinifera* L.) Grapevines. Aust. J. Grape Wine Res. 2025, 4271832. https://doi.org/10.1155/ajgw/4271832

Pertot, I., Caffi, T., Rossi, V., Mugnai, L., Hoffmann, C., Grando, M.S., Gary, C., Lafond, D., Duso, C., Thiery, D., Mazzoni, V., Anfora, G. (2017). A critical review of plant protection tools for reducing pesticide use on grapevine and new perspectives for the implementation of IPM in viticulture. Crop Prot. 97, 70–84. https://doi.org/10.1016/j.cropro.2016.11.025

Pessotto, M.V., Roberts, T.L., Dos Santos, C., Hoegenauer, K.A., Bertucci, M., Ross, W.J., Savin, M. (2025). Use of growing degree days to model the dynamics of aboveground biomass and nitrogen accumulation of winter cover crops. Agrosystems Geosci. Environ. 8, e70249. https://doi.org/10.1002/agg2.70249

Pichon, L., Brunel, G., Payan, J.C., Taylor, J., Bellon-Maurel, V., Tisseyre, B. (2021). ApeX-Vigne: experiences in monitoring vine water status from within-field to regional scales using crowdsourcing data from a free mobile phone application. Precis. Agric. 22, 608–626. https://doi.org/10.1007/s11119-021-09797-9

Pinheiro, J., Bates, D., R Core Team. (1999). nlme: Linear and Nonlinear Mixed Effects Models. https://doi.org/10.32614/CRAN.package.nlme

Pou, A., Gulías, J., Moreno, M., Tomàs, 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. OENO One 45, 223–234. https://doi.org/10.20870/oeno-one.2011.45.4.1501

Prosdocimi, M., Tarolli, P., Cerdà, A. (2016). Mulching practices for reducing soil water erosion: A review. Earth-Sci. Rev. 161, 191–203. https://doi.org/10.1016/j.earscirev.2016.08.006

Ramírez-Pérez, P., López-Granados, F., León-Gutiérrez, J.M., Mesas-Carrascosa, F.J., Pérez-Porras, F., Torres-Sánchez, J. (2024). Influence of soil management on vegetative growth, yield, and wine quality parameters in an organic "Pedro Ximénez" vineyard: field and UAV data. Agron. Sustain. Dev. 44, 10. https://doi.org/10.1007/s13593-024-00946-8

Redin, M., Recous, S., Aita, C., Dietrich, G., Skolaude, A.C., Ludke, W.H., Schmatz, R., Giacomini, S.J. (2014). How the chemical composition and heterogeneity of crop residue mixtures decomposing at the soil surface affects C and N mineralization. Soil Biol. Biochem. 78, 65–75. https://doi.org/10.1016/j.soilbio.2014.07.014

Rodrigo-Comino, J. (2018). Five decades of soil erosion research in "terroir". The State-of-the-Art. Earth-Sci. Rev. 179, 436–447. https://doi.org/10.1016/j.earscirev.2018.02.014

Roques, S.E., Kindred, D.R., Berry, P., Helliwell, J. (2022). Successful approaches for on-farm experimentation. Field Crops Res. 287, 108651. https://doi.org/10.1016/j.fcr.2022.108651

Sharifi, M., Zolfaghari, Z. (2025). Companion Crops as Catalysts for Sustainable Cover Cropping in Vineyards—A Critical Review and Research Agenda. Plants 14, 3056. https://doi.org/10.3390/plants14193056

Su, Y., Li, X., Cao, Z., Gao, Z., Du, Y. (2024). Effects of Long-Term High Temperatures in the Root Zone on the Physiological Characteristics of Grapevine Leaves and Roots: Implications for Viticulture Practices. Horticulturae 10, 245. https://doi.org/10.3390/horticulturae10030245

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

Thorup-Kristensen, K., Magid, J., Jensen, L.S. (2003). Catch crops and green manures as biological tools in nitrogen management in temperate zones. Adv. Agron. 79, 227–302. https://doi.org/10.1016/S0065-2113(02)79005-6

Toffolini, Q., Jeuffroy, M.-H. (2022). On-farm experimentation practices and associated farmer-researcher relationships: a systematic literature review. Agron. Sustain. Dev. 42, 114. https://doi.org/10.1007/s13593-022-00845-w

Tribouillois, H., Cohan, J.-P.P., Justes, E. (2016). Cover crop mixtures including legume produce ecosystem services of nitrate capture and green manuring: assessment combining experimentation and modelling. Plant Soil 401, 347–364. https://doi.org/10.1007/s11104-015-2734-8

Tribouillois, H., Fort, F., Cruz, P., Charles, R., Flores, O., Garnier, E., Justes, E. (2015). A Functional Characterisation of a Wide Range of Cover Crop Species: Growth and Nitrogen Acquisition Rates, Leaf Traits and Ecological Strategies. PLOS ONE 10, e0122156. https://doi.org/10.1371/journal.pone.0122156

van Leeuwen, Destrac-Irvine, Dubernet, Duchêne, Gowdy, Marguerit, Pieri, Parker, de Rességuier, Ollat. (2019). An Update on the Impact of Climate Change in Viticulture and Potential Adaptations. Agronomy 9, 514. https://doi.org/10.3390/agronomy9090514

Visconti, F., López, R., Olego, M.Á. (2024). The Health of Vineyard Soils: Towards a Sustainable Viticulture. Horticulturae 10, 154. https://doi.org/10.3390/horticulturae10020154

Walker, H.V., Jones, J.E., Swarts, N.D., Kerslake, F. (2022). Manipulating Nitrogen and Water Resources for Improved Cool Climate Vine to Wine Quality. Am. J. Enol. Vitic. 73, 11–25. https://doi.org/10.5344/ajev.2021.21004

White, C.M., DuPont, S.T., Hautau, M., Hartman, D., Finney, D.M., Bradley, B., LaChance, J.C., Kaye, J.P. (2017). Managing the trade off between nitrogen supply and retention with cover crop mixtures. Agric. Ecosyst. Environ. 237, 121–133. https://doi.org/10.1016/j.agee.2016.12.016

Winter, S., Bauer, T., Strauss, P., Kratschmer, S., Paredes, D., Popescu, D., Landa, B., Guzmán, G., Gómez, J.A., Guernion, M., Zaller, J.G., Batáry, P. (2018). Effects of vegetation management intensity on biodiversity and ecosystem services in vineyards: A meta-analysis. J. Appl. Ecol. 55, 2484–2495. https://doi.org/10.1111/1365-2664.13124

Wood, S. (2000). mgcv: Mixed GAM Computation Vehicle with Automatic Smoothness Estimation. https://doi.org/10.32614/CRAN.package.mgcv

Zribi, W., Aragüés, R., Medina, E., Faci, J.M. (2015). Efficiency of inorganic and organic mulching materials for soil evaporation control. Soil Tillage Res. 148, 40–45. https://doi.org/10.1016/j.still.2014.12.003