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The Impact of the Age of Vines on Soil Hydraulic Conductivity in Vineyards in Eastern Spain

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Abstract: Soil infiltration processes manage runoff generation, which in turn affects soil erosion. There is limited information on infiltration rates. In this study, the impact of vine age on soil bulk density (BD) and hydraulic conductivity (K_s) was assessed on a loam soil tilled by chisel plough. Soil sampling was conducted in the inter row area of six vineyards, which differed by the age from planting: 0 (Age 0; just planted), 1, 3, 6, 13, and 25 years (Age 1, Age 3, Age 6, Age 13, and Age 25, respectively). The One Ponding Depth (OPD) approach was applied to ring infiltration data to estimate soil K_s with an α^* parameter equal to 0.012 mm^{-1}. Soil bulk density for Age 0 was about 1.5 times greater than for Age 25, i.e., the long-term managed vineyards. Saturated hydraulic conductivity at Age 0 was 86% less than at Age 25. The planting works were considered a major factor for soil compaction and the reduction of hydraulic conductivity. Compared to the long-term managed vineyards, soil compaction was a very short-term effect given that BD was restored in one year due to ploughing. Reestablishment of K_s to the long-term value required more time.

Keywords: vineyards; infiltration rate; age of planting; saturated hydraulic conductivity

1. Introduction

Extensive research has been carried out on vineyard soils, not only due to their effect on wine quality and quantity [1,2], but also because soils in vineyards affect the environmental health, as they can be a source of pollutants [3,4], pesticides [5], sediments [5], and overland flow [6]. Also, soil management in vineyard land use is relevant for the effect that it can have on soil properties [7,8]. The recently planted vineyards require more farming operations than the older ones. These practices, which are necessary for plant growth (e.g., application of pesticides, nutrients, installation of espalier), involve the continued use of heavy machinery and, consequently, cause changes in soil physical properties. Intensive agricultural activities determine soil structure degradation, compaction, and the formation of surface crusts that in turn reduce water infiltration. If soil infiltration capacity is less than rainfall intensity, the potential risks of runoff and soil erosion are increased. The water stored in the soil, as well sediments, nutrients, and pollutants, export out of the vineyards are also affected by infiltration.

Despite being a key to understanding the hydrological cycle, there is very limited information about the infiltration rates in vineyards. The research developed by Wainwright [9], Leonard, and Andrieux [10], and Van Dijck and Van Asch [11], are some of the most relevant studies, which have demonstrated that the infiltration process is highly variable and difficult to predict. However, nowadays, several new findings demonstrate that there are many shortcomings regarding specific information. The research of Biddoccu et al. [12], Rodrigo-Comino et al. [13], and Alagna et al. [14] showed the renewed interest in understanding the infiltration process in vineyards, as (i) during the vintage and tillage, infiltration decreases due to the compaction by trampling effect and tractor passes; (ii) after abandonment, hydrological soil properties are less variable and easy to be predicted; and (iii) there are several differences in infiltration patterns among slope positions.

Among the key parameters that indicate soil health [15], the saturated hydraulic conductivity (K_s) is easy to measure and particularly important, because it controls several soil hydrological processes such as infiltration. Furthermore, K_s is used as runoff-model inputs to assess soil losses.

In vineyards soil redistribution by both tillage [16] and water erosion [17] contributes to high short-term [13,18] and long-term soil erosion rates [6,19,20]. However, there are few studies on seasonal and temporal changes in soil erosion and runoff generation. Recently, Rodrigo-Comino et al. [21,22] and Cerdà et al. [23] found that high erosion rates in vineyards are mainly observed during the planting period. Thus, sustainable management requires attention to erosion control some time after planting. However, the factors that determine the higher runoff and soil erosion rates during vineyard establishment were not enough investigated in prior studies.

This research focused on temporal variability of soil compaction and infiltration rates in a loam soil planted with vines of different ages. Soil cores sampling and ring infiltrometer experiments were conducted in vineyards planted 0, 1, 3, 6, 13, and 25 years prior to the survey with the aim of detecting the temporal changes in bulk density and saturated hydraulic conductivity, but also to shed light on the impact of vines planting work on soil infiltration and erosion processes.

2. Materials and Methods

2.1. Study Area

Field experiments were conducted in the Terres dels Alforins vine production area (4000 ha) in province of Valencia (Spain), a representative zone of the Mediterranean vineyards. The vineyards (40 ha) between the Pago Casa Gran and Celler del Roure farms (Figure 1) were selected that are located within the Canyoles river watershed. They were chosen because they were ploughed by the same tractor and chisel plough for 25 years at the time of vineyards planting. The selected vineyards, with a Monastrell grape variety, are from 0 to 25-year old with a plantation framework of 3.0 × 1.4 m. The measurements were conducted in the south-facing slope of the Les Alcusses valley which has a slope of 5%, where the presence of colluvium from soils formed on limestone parent material is common. The soils are basic (pH = 8) and are classified as Typic Xerothent [24], with an average depth of 60 cm. The observed soil profiles were relatively homogeneous due to the tillage practices and same soil managements. The mean annual rainfall is 350 mm year^{-1}, with maximum peak intensities (higher than 200 mm day^{-1}) occurring in the autumn season. The mean annual temperature is 13.8 °C.

2.2. Soil Sampling

The six experimental sites were characterized by different ages of vines. Age 0 is the recently planted vineyard, and Age 1, Age 3, Age 6, Age 13, and Age 25 are vines planted 1, 3, 6, 13, and 25 years prior to field investigation. Age 25 was selected, as it corresponds to the average replanting interval in this region. For each experimental site, an area of approximately 100 m^2 was chosen. Fifteen soil samples were collected randomly from the top 5 cm of the soil with a 100 cm^3 steel cylinder to determine gravimetric soil water content (SWC), organic matter (OM), and bulk density (BD). Samples were weighted immediately following collection, then oven dried at 105 °C for 24 h and re-weighted at room temperature. Organic matter was measured by the dichromate method [25], and grain size distribution was measured by the pipette method [26]. Tillage is common to all the experimental sites and has been the historic management method for centuries. All samples were collected in the inter row ploughed area. Four different tractor passes are usually conducted each year to till and aerate the soil. At all sampling sites, the wheel tracks were avoided during sampling. Furthermore, the last tillage had been done more than one month before the field experiments and no rainfall occurred in this time spell. Herbicides are not applied in the study area.

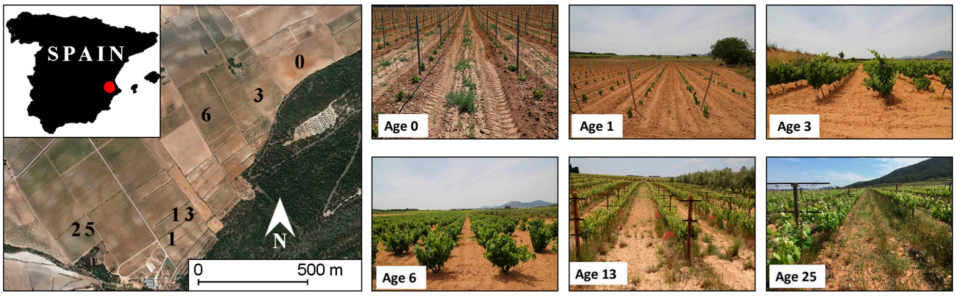

Figure 1. Areal view of the studied areas with investigated vineyard sites.

2.3. *Infiltration Measurements*

At each selected site, 15 single ring infiltrometer measurements [27,28] were carried out at randomly chosen points within a 100 m^2 area. Field tests were conducted in summer 2014 during the typical Mediterranean drought period to limit variability in initial soil water content (SWC). A 100 mm inner-diameter steel ring was inserted vertically to a depth of about 0.01 m into the soil surface to avoid lateral loss of the ponded water. The ring was filled with fresh water and, at prescribed time intervals, the water level was measured using a ruler; then the ring was filled again. Flow rates were calculated from water level measurements at successive time steps, and steady-states were attained within 60 min for all experiments. A total of ninety experimental cumulative infiltration curves were then deduced (15 for each site (Figure 2)). The One Ponding Depth (OPD) calculation approach [28] was applied to compute field-saturated soil hydraulic conductivity, K_s (mm h^{-1}), for each infiltration run. The OPD approach makes use of the steady-state infiltration flux, Q_s (mm^3 h^{-1}), which is estimated from the cumulative infiltration vs. time plot. It also requires an estimate of the α^* (mm^{-1}) parameter, equal to the ratio between K_s and the field-saturated soil matric flux potential. In this investigation, an α^* value of 0.012 mm^{-1} was used, as it is the recommended value for the loam soil [29]. The equilibration time, t_s (min), i.e., the duration of the transient phase of the infiltration process, was estimated according to the criterion proposed by Bagarello et al. [30] for analyzing cumulative infiltration data.

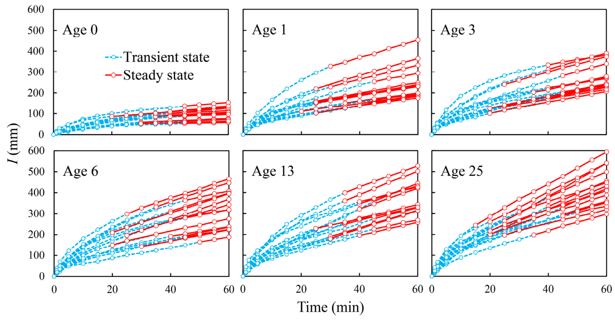

Figure 2. Cumulative infiltration, *I* (mm), vs. time (min) at the six investigated sites. Blue lines and red lines show, respectively, the transient and the steady-state conditions of infiltration process.

2.4. Statistical Analisis

The hypothesis of normal distribution of both the untransformed and the log-transformed K_s data was tested by the Kolmogorov–Smirnov test at $p = 0.05$ significance level [31]. The other parameters were assumed normally distributed, and thus, no transformation was performed on these data before statistical analysis. The probability level, $p = 0.05$, was used for all statistical comparisons. One-way analysis of variance (ANOVA) was performed with raw and transformed data. If the ANOVA showed significant differences between the means, we used multiple comparisons to detect differences between pairs by applying the Tukey's honestly significant difference test. Multiple comparisons analyses allowed us to group together mean values that were not statistical different. In addition, Pearson's correlation coefficient was performed between BD and K_s. All statistical analyses were carried out using the Minitab© computer program (Minitab Inc., State College, PA, USA).

3. Results

3.1. Soil Properties

Table 1 summarizes soil physical and chemical properties of the six study sites. Organic matter content ranged from 1.2% to 1.4% and did not differ between the ninety sampling points even if relatively higher CV values were observed for Age 0 and Age 25 (respectively, 20.2% and 24.1%). The average gravimetric SWC prior to the infiltration experiments ranged from 0.051 to 0.056 g g^{-1}, and the statistical comparisons did not show significant differences among the six sites. Grain size distribution was similar among ages. According to the USDA standards, the three fractions, i.e., clay (0–2 μm), silt (2–50 μm), and sand (50–2000 μm), were, on average, 17.9%, 38.8%, and 43.3%, and the soil of the studied area was classified as loam [24]. It was concluded that the soil properties at the six selected sites can be considered homogeneous despite the different age from vine planting.

Table 1. Mean values of initial soil water content (g g^{-1}), organic matter (%), clay, silt, and sand content (%) (USDA classification system). Sample size is $N = 15$ for each site. Coefficient of variation (%) is in brackets.

Variable	Age (Year)					
	0	**1**	**3**	**6**	**13**	**25**
Initial SWC	0.053 (14.9) a	0.056 (12.3) a	0.052 (15.5) a	0.055 (13.0) a	0.051 (8.8) a	0.053 (11.4) a
Organic matter	1.4 (20.2) a	1.2 (11.5) a	1.4 (16.7) a	1.3 (17.3) a	1.3 (19.0) a	1.3 (24.1) a
Clay	20.1 (17.3)	14.8 (28.3)	14.9 (26.8)	18.3 (28.2)	20.5 (18.8)	18.9 (18.1)
Silt	37.1 (9.7)	41.3 (5.9)	40.3 (8.0)	38.9 (8.1)	36.5 (10.3)	38.6 (7.4)
Sand	42.8 (6.5)	43.9 (5.8)	44.9 (6.7)	42.7 (7.9)	43.0 (6.5)	42.5 (6.6)

Note: For a given variable, mean values followed by the same lower case letter were not significantly different according to the Tukey Honestly Significant Difference test ($p = 0.05$).

3.2. Effect of Age on Soil Bulk Density, BD

The soil bulk density ranged from 1.03 to 1.53 g cm^{-3} (Figure 3). Within each site, the variability of BD was low (CV < 4%), confirming that this soil property generally exhibits low spatial variability [32]. The box plot comparison shows a pronounced decline of soil bulk density from Age 0 to Age 25.

Figure 4 summarizes the multiple comparison results between data pairs by using the Tukey's honestly significant difference test. Multiple comparisons resulted in four groups (horizontal bars), whose members are not significantly different from one another. The soil bulk density is significantly higher in the Age 0 (1.53 g cm^{-3}). In the second group (Age 1, Age 3, and Age 6), bulk density ranges from 1.07 to 1.10 g cm^{-3}. The third group (ages from three to 12 years) shows BD = 1.05–1.08 g cm^{-3}. The last group includes vines older than 6 years (BD = 1.03–1.07 g cm^{-3}). From Age 0 to Age 1, BD decreases by a factor of 1.5; afterwards, it decreases more slightly, reaching the lowest value for Age 25.

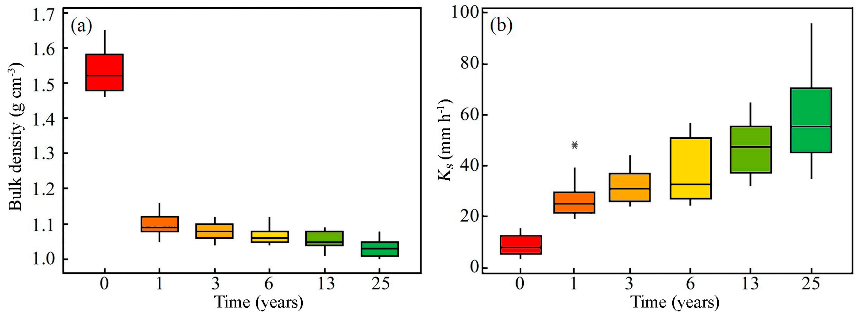

Figure 3. Box plots of (**a**) the soil bulk density (g cm^{-3}) and (**b**) the field saturated soil hydraulic conductivity (K_s, mm h^{-1}) values. Boundaries indicate median, 25th, and 75th quartiles; the top and bottom whiskers indicate the minimum and maximum values. Values beyond the whiskers are outliers. Outliers are defined as data points more than 1.5 times the interquartile range away from the upper or lower quartile.

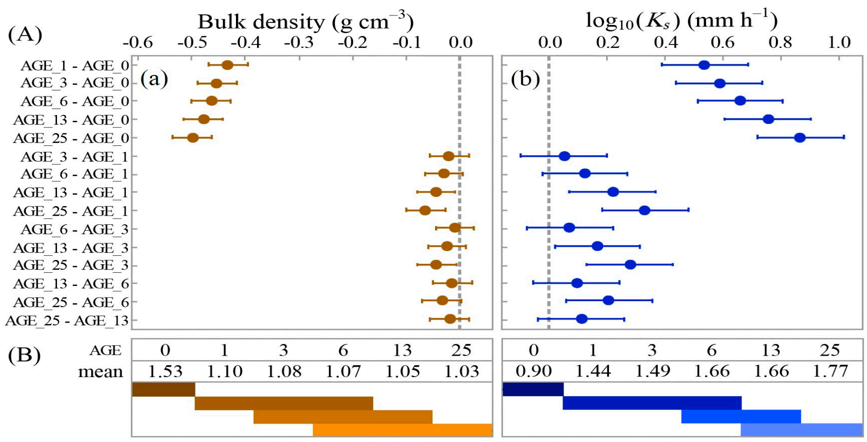

Figure 4. Results of the Tukey Honestly Significant Difference test for (**a**) the soil bulk density and (**b**) the log-transformed field saturated hydraulic conductivity (K_s) values. (**A**) Multiple comparisons at 95% simultaneous confidence intervals of all pairs of groups. The circles represent difference between means; the confidence intervals represent the likely ranges for all the mean differences. If an interval does not contain zero, the corresponding means are significantly different. (**B**) The grouping information table highlights the significant and not significant comparisons. Each horizontal bar groups together members that are not statistically different.

3.3. Effect of Age on Infiltration and Saturated Hydraulic Conductivity, K_s

Figure 2 depicts cumulative infiltration curves from the 90 tests. All the curves exhibited a common shape, with a concave part corresponding to the transient stage of infiltration (blue lines) and a linear part detecting that the steady-state conditions (red lines) were achieved [33]. It should be noted that the total infiltrated depth, I_{end} (mm), increased progressively with age (Table 2). The mean I_{end} values ranged from 103 to 426 mm. Water flow reached, on average, steady-state rate after 31–38 min, depending on the site. The infiltrated depth at the equilibration time, $I(t_s)$ (mm), also increased progressively with age.

The Kolgomorov-Smirnov test indicated that the K_s results were conformed to a log-normal distribution [32]. Therefore, statistical analyses were performed on log-transformed values. Geometric means of K_s and associated CVs corresponding to the different ages from vine planting are reported in Table 3. Similar to BD, K_s increased with time from planting by a factor of 3.4 from Age 0 to Age 1; thereafter, the differences decreased (Figure 3).

Table 2. Minimum, Min, maximum, Max, mean, and coefficient of variation, CV (%), of the total infiltrated depth, I_{end} (mm), infiltrated depth at the equilibration time, $I(t_s)$ (mm), and equilibration time, t_s (min) (N = 15 for each site).

Variable	I_{end}				$I(t_s)$				t_s			
Statistic	**Min**	**Max**	**Mean**	**CV**	**Min**	**Max**	**Mean**	**CV**	**Min**	**Max**	**Mean**	**CV**
Age (Year)												
0	58	154	103 a	26.5	52	137	85 a	25.9	10	50	35 a	32
1	175	453	250 b	31.6	102	328	176 b	33.3	20	45	31 a	27.3
3	207	390	275 b	23.2	101	334	207 bc	32.6	20	45	36 a	27.5
6	189	465	323 bc	27.5	143	364	239 bcd	29.7	20	50	37 a	27.6
13	258	528	371 cd	22.1	180	399	280 d	25.7	25	45	38 a	16.5
25	298	594	426 d	20.7	197	377	271 cd	20.6	15	50	32 a	35.8

Note: For a given variable, mean values followed by the same lower case letter were not significantly different according to the Tukey Honestly Significant Difference test (p = 0.05).

Table 3. Geometric mean, GM, and coefficient of variation, CV (%), of the saturated soil hydraulic conductivity, K_s (mm h^{-1}), and results of the Kolmogorov-Smirnov test. Sample size, N = 15 for each site.

Age	Statistic		Distribution	
(Year)	**GM**	**CV**	**Normal**	**Log-Normal**
0	8.0	51.8	not rejected	not rejected
1	27.4	29.9	rejected	not rejected
3	30.9	21.4	rejected	not rejected
6	36.4	32.9	not rejected	not rejected
13	45.4	24.3	not rejected	not rejected
25	58.7	31.3	not rejected	not rejected

Multiple comparisons resulted in four groups (Figure 4B). At Age 0, mean K_s value (8.0 mm h^{-1}) was significantly lower than at the other ages. There were also significant differences among the second group (Age 1, Age 3, and Age 6) with mean K_s ranging from 27.4 to 36.4 mm h^{-1}, the third group (Age 6 and Age 13) with K_s = 36.4–45.4 mm h^{-1}, and the last group (Age 13 and Age 25) that showed the highest K_s values (45.4–58.7 mm h^{-1}). It is well known from previous studies that K_s is highly variable compared to other soil physical properties [32,34]. However, a relatively high variability was observed in this study only at Age 0.

A significant negative correlation was found between mean BD and K_s values ($r = -0.677$, $p < 0.001$) (Figure 5), highlighting that reduction in soil bulk density as a consequence of age clearly influenced the field saturated soil hydraulic conductivity.

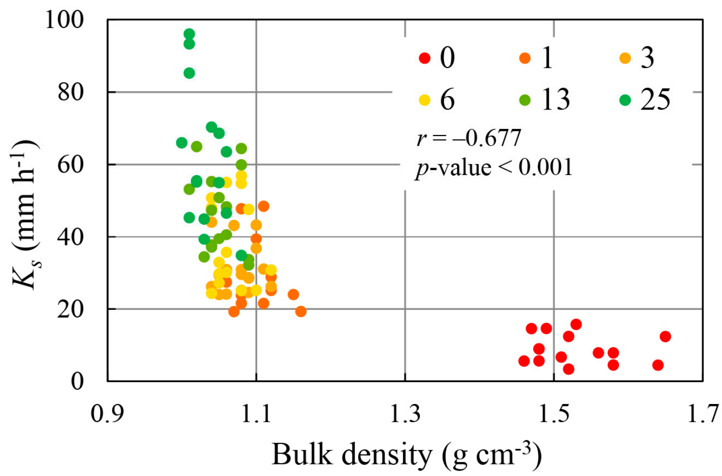

Figure 5. Correlation between the soil bulk density (g cm^{-3}) and field saturated soil hydraulic conductivity, K_s (mm h^{-1}). Pearson's correlation coefficients (*r*) and probability of error (*p*) are reported.

4. Discussion

As is known, soil management modifies soil bulk density, pore structure and connectivity, hydraulic conductivity, and air permeability (e.g., [35,36]). Machine traffic often causes soil compaction and, consequently, a reduction of soil physical quality (e.g., [11,15,37,38]). The average initial soil bulk density (Age 0) was 1.53 g cm^{-3} for the experimental site, far greater than the optimal bulk density range (0.9–1.2 g cm^{-3}) suggested for a large range of agricultural soils [39,40]. Associated bulk density values up to 1.51 g cm^{-3} were observed for a loamy soil under vineyard and orchard land uses subjected to vehicle traffic [11]. In a loam soil of the Swiss Plateau, tilled with a direct drilling, Gut et al. [41] found an average BD value of 1.47 g cm^{-3} at depth 0.1–0.16 m. In an investigation conducted by Boydell and Boydell [42] in Vertisols used for grain cropping, machinery traffic determined bulk densities in the range 1.25–1.45 g cm^{-3} at depth of 0.05–0.5 m. In a sandy loam soil, machinery traffic applied when the soil was dry (mean soil moisture 0.066 g g^{-1}) resulted in an average BD = 1.59 g cm^{-3} at 0.15 to 0.30 depth [43]. Although care was put to avoid the wheel tracks during sampling, these results also indicate that Les Alcusses soil was throughout compacted by machinery operations due to the pass of lorries, vans, tractors, and men at the time of vineyard establishment.

During the first year from planting, the decreased BD rate was 0.43 g cm^{-3} $year^{-1}$, and in the time spell between Age 1 and Age 25 it was 0.003 g cm^{-3} $year^{-1}$. Assuming the value of BD at Age 25 as long-term condition for the loam soil under study, these results indicated that soil resilience determined an immediate response that allowed it to recover 86% of the final value during the first year and only 14% in the following 24 years. However, low differences between two successive ages were significant. Therefore, the routinely adopted vineyard management did not prevent recovery of the long-term bulk density conditions for this soil.

The average K_s value of 8 mm h^{-1} at Age 0 (Table 3) was approximately similar to that expected for a loam soil (10.4 mm h^{-1}, [44]), but it was 3.4–7.3 times lower than that measured at the successive ages. Excluding this site, the average K_s values varied within a relatively narrow range (27.4 to 58.7 mm h^{-1}, i.e., by a factor of 2.1), and spatial variability was very similar for the five selected sites. According to Elrick and Reynolds [29], difference in K_s by a factor of two or three can be considered negligible for practical purposes. The rate of K_s increase during the first year (Age 0 to Age 1) was equal to 19.4 mm h^{-1} $year^{-1}$, whereas in the following period K_s increased at a rate of 1.30 mm h^{-1} $year^{-1}$. Compared to BD, the short-term reestablishment rate of K_s is less effective given that only 38% of the final value was recovered within one year. Therefore, the saturated soil hydraulic conductivity required more time to restore its long-term condition. The significant differences in K_s highlighted by multiple comparisons among second group (Age 1, Age 3, and Age 6), third group (Age 6 and

Age 13) and fourth group (Age 13 and Age 25) can be probably explained by the fact that as vines grow, fewer and fewer farming operations are required that result in reduced soil compaction by machinery traffic. Moreover, soil tillages, performed in subsequent years in order to control weeds, destroyed the surface crust, homogenized soil properties, and led to increased K_s values.

Negative correlation between soil hydraulic conductivity and bulk density is well documented in literature (e.g., [45]). For instance, Meek et al. [46] found hydraulic conductivity of a sandy loam soil decreased by 58% when BD increased from 1.6 to 1.8 g cm^{-3}.

In the studied area, the vines are replaced on average every 25 years; thus, attention should be paid during vineyard planting to avoid soil compaction that may have negative consequence on the hydrological processes. In this case, high intensity rainfalls, frequently occurring in Mediterranean climate, can trigger rill formation and high erosion rates [23]. Rehabilitation strategies aiming at increasing water infiltration and reducing surface runoff and soil erosion include use of cover crops [47,48], intercropping [49], and use of mulching or straw [50,51].

5. Conclusions

The vineyard's age affected infiltration and some soil physical properties but did not influence soil organic matter. After planting, bulk density was 1.5 times greater than the long-term bulk density corresponding to Age 25. Accordingly, field saturated soil hydraulic conductivity was 86% less than the long-term value. Planting operations caused soil compaction, which reduced hydraulic conductivity. Such modifications were reversible over 24 years following planting, notwithstanding normal machinery traffic, due to ordinary management that attended to reducing surface soil compaction and restoring the aeration of surface layer. The rate of soil recovery was greatest following disturbance and declined thereafter, demonstrating the resilience of the considered soil to the stress induced by planting works. The results of this investigation suggest that strategies to reduce soil compaction during vineyard establishment will be valuable to maintaining the soil infiltration capacity and reducing the erosion potential.

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