horticulturae

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Falanghina Grapevine (*Vitis vinifera* L.) Yield and Berry Quality under Different Pedoclimatic Conditions in Southern Italy

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Abstract: Climate is a determinant driver for grapevine geographical distribution, influencing yield and berry quality. The current environmental changes are intensifying the need to improve the knowledge of the soil–plant–atmosphere system in the vineyard, to properly manage cultivation factors and to increase berry yield and quality. Since most of the berry growth and ripening phases occur during the driest period in the Mediterranean area, increasing environmental constraints are expected to impose more and more limitations on grapevine productivity and finally on wine quality. The aim of this study was to evaluate whether different pedoclimatic conditions in four proximally located vineyards of the Campania Region in Southern Italy determine differences in crop yield and must quality of *Vitis vinifera* L. subsp. *vinifera* "Falanghina". This study was conducted over three growing seasons, by monitoring vine growth and characterizing yield and must quality. The overall results showed differences in yield and berry quality characteristics for the four vineyards, with the field CA (Calvese) and GR (Grottole) showing pedoclimatic conditions limiting growth and yield compared to SL (Santa Lucia) and AC (Acquefredde).

Keywords: must quality; climate changes; grapevine drought stress

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Citation: Damiano, N.; Cirillo, C.; Petracca, F.; Caputo, R.; Erbaggio, A.; Giulioli, M.; De Micco, V. Falanghina Grapevine (*Vitis vinifera* L.) Yield and Berry Quality under Different Pedoclimatic Conditions in Southern Italy. *Horticulturae* **2022**, *8*, 829. https://doi.org/10.3390/horticulturae8090829

Academic Editor: Yan Xu

Received: 27 July 2022
Accepted: 7 September 2022
Published: 8 September 2022

1. Introduction

Climate is a determinant driver for grapevine geographical distribution, berry characteristics, and must and wine quality around the world [1]. The Mediterranean region is threatened by climate change, where climate models consistently project significant increase in temperature and high irregularities in precipitation patterns [2]. Since a dramatic change in the landscape has been forecasted with geographical shifting of the grapevine production regions, climate change is one of the major challenges for future viticulture, especially in arid and semi-arid regions of Europe [3]. Often, the combination of heat and severe water-deficit stress may compromise photosynthesis, causing a source–sink imbalance and incomplete berry maturation, with the consequence of obtaining reduced yield and low quality grapes and musts for vinification. Increases in the frequency, duration, and severity of drought events, as well as a shift in time of their occurrence, will likely induce plastic adaptive responses in plants, with a negative impact on plant growth, as is the case of grapevine, which is one of the most widespread crops worldwide, with about 38% of vineyards areas located in Europe [4,5]. Mild water stress can positively impact berry composition, flavors, and color, while high drought stress negatively affects grapevine production, acting on vine vigor, yield, and berry quality [6]. Water-deficit stress can also lead to a reduction in yield through metabolic pathways modifications, shifting the relative abundance of transcripts and metabolites involved in phenylpropanoid, isoprenoid, carotenoid, amino acid, and fatty acid metabolism [7–9]. Temperature variability strongly influences the developmental cycle of plants, affecting both carbon assimilation in source organs, as well as the activity of carbon sinks. The optimum temperature for photosynthesis is between 25 and 35 °C, while below 10 °C and above 40 °C physiological processes decline [10]. Therefore, changes in temperature can promote or inhibit the development and growth rate of flowers, fruits, and shoots, according to vine sensitivity, risking impairing the balance between vegetative growth, reproductive activity, and then grapevine quality and wine production [10,11]. The first effect of climate changes is an alteration of the normal course of the phenological phases (e.g., flowering, fruit set, veraison, ripening), which are reached earlier [12–14]. As consequence of increasing temperature, grape ripening occurs earlier in the season and in warmer conditions than in the past. Concerning grape quality, a common problem in Mediterranean vineyards is related to the influence of high temperature on the dynamics of soluble solids accumulation in the berries during ripening, with subsequent changes in berry chemical composition, resulting in higher sugar content, lower organic acid concentration, and higher pH [15,16]. High temperature is also known to decrease the accumulation of anthocyanins in berry skins, with effects on color and aromas [14,17–19]. Moreover, the high temperatures in summer, combined with drought stress, create optimal conditions for sunburn damages in sun-exposed grapes, inducing an imbalance between light energy absorption and usage, which compromises the electron transport activity. As a consequence, fruit respiratory mechanisms are altered and the higher level of anaerobic respiration caused by raising temperatures induces the accumulation of reactive oxygen species [20]. The temperature level that berries reach during the day is a function of radiative heat transfer and air temperature [21]. In particular, a direct exposure to the sun increases fruit surface temperature by 12–15 °C above air temperature on the berry's sun-exposed side [17].

As in any agricultural crop, an increased water deficit is likely to impact the yield and economic sustainability of wine producing estates. In the last 15 years, a decrease in yield has been recorded in most winegrowing regions in France [14]. For this reason, in semi-arid areas, irrigation management is becoming a compelling solution to better control grape ripening, mitigating the negative effects of climatic changes. In order to adapt the viticulture to this changing situation, there is increasing interest in designing proper management techniques, suitable either to improve the way the vines use water or to introduce irrigation techniques, such as deficit irrigation (DI) at different percentages of the estimated crop evapotranspiration (ETc). However, there are still difficulties in precisely establishing the irrigation strategies (e.g., volumes, timing, etc.), in order to stabilize seasonal yield and improve must and wine quality. Indeed, there is still a lack of systematic knowledge about *if*, *how*, and *to what extent* the same cultivar in different pedoclimatic contexts can develop different morpho-physiological traits, affecting the quantity and quality of berries and related musts [22].

Within this general framework, the aim of this work was to analyze the variability in terms of growth, yield, and berry/must quality, as well as their relations, in four vineyards of Falanghina grapevine growing in Southern Italy under four pedoclimatic conditions, two more mesic the others more xeric, over three years. The Falanghina grapevine is a cultivar cultivated for the production of white wines, autochthonous of the Campania region in southern Italy [23]. It is characterized by a middle trunk conical bunch, medium sized grapes with waxy peel, and crispy pulp [24,25]. The pulp has a slightly floral flavor and musts generally have high acidity [25]. In this cultivar, climate changes are expected to influence the quality of musts more than yield, therefore knowing the relations between vegetative growth and berry quality can furnish valuable information for vineyard management targeted to specific oenological objectives.

2. Materials and Methods

2.1. Study Site

The selected study area was located at Guardia Sanframondi (Benevento), in a hilly environment in the Campania region (southern Italy), characterized by a Mediterranean climate (cold wet winters and hot dry summers). The four selected vineyards are owned by members of La Guardiense consortium and they are named referring to their geographical district: (1) SL-Santa Lucia, on flat ground; (2) CA-Calvese, with a slope of 10% facing the west side; (3) GR-Grottole, on flat ground; (4) AC-Acquafredde, with a slope of 15% facing the west side (Figure 1). The vine cultivar studied was *Vitis vinifera* L. subsp. vinifera "Falanghina" (Controlled origin designation—DOC/AOC), and the vineyards were selected with the idea of identifying four sites similar for their plant material and cultivation management, but different in water availability and plant water usage [26]. For the three years of study, in each vineyard were closed 20 vines, 8–13 years old, grafted onto 157-11 Couderc rootstock, spaced 1–1.25 m on the row and with 2.1–2.2 m between the rows, and trained at double Guyot. The SL, GR, and CA vineyards are cultivated with a rain-fed regime, while at AC supplemental irrigation is applied [27]. Air temperature during the phenological phase of veraison (Guardia Sanframondi meteorological station—www.agricoltura.regione.campania.it/meteo/agrometeo.htm, accessed on 20 December 2021) was similar in 2019, 2020, and 2021. In July, the average temperature was 26.9 °C, 26.0 °C, and 26.2 °C, maximum temperature was 34.0 °C, 34.3 °C, and 34.0 °C, minimum temperature was 20.4 °C, 19.1 °C, and 19.2 °C, respectively, in 2019, 2020, and 2021. The cumulative rainfall and ET0 in July were 29 mm and 176 mm in the year 2019, 14 mm and 120 mm in 2020, and 43 mm and 167 mm in 2021. A different distribution of the soil water content (SWC) among the four vineyards at three different soil depth levels (15 cm, 30 cm, and 75 cm) was observed [27].

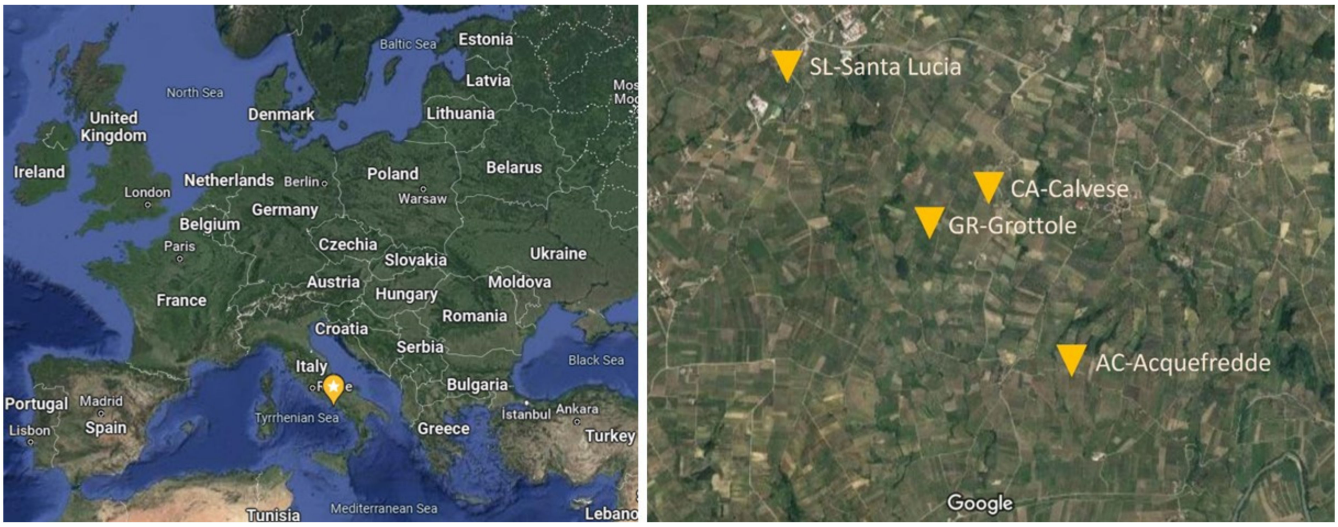

Figure 1. Location of the four selected vineyards: SL-Santa Lucia (41°14′45″ N, 14°34′16″ E, 194 m above sea level—a.s.l.), CA-Calvese (41°14′19″ N, 14°35′11″ E, 163 m a.s.l.), GR-Grottole (41°14′21″ N, 14°34′56″ E, 158 m a.s.l.), AC-Acquefredde (41°13′44″ N, 14°35′33″ E, 84 m a.s.l.). Source: Google Earth Pro.

The soils in the experimental sites are the Mollisols type, classified as Typic Calciustolls and assigned to two principal soil series of the Valle Telesina soil map 1:50.000, [28], which are Consociazione dei suoli Pennine (SL, CA and GR sites) and Consociazione dei suoli Taverna Starze (CA site). The differences between the four sites are principally due to the variability of the percentage of stones along the soil profile [27] and due to the modification in thickness and depth of the soil horizons in the sites, induced by vineyard planting. Moreover, previous studies demonstrated that the four vineyards can be grouped into two groups, with SL and CA characterized by higher water availability compared to CA end GR [26]. Growth and development analyses and analytical determinations on berries and musts were performed in the three growing seasons 2019, 2020, and 2021.

2.2. Vegetative Growth and Yield Components, at Harvest

The biometrical parameters total leaf area, bunch weight per vine (yield), and number of bunches per vine (n° bunches) were recorded on 20 vines per vineyard. On the same vines, the actual fertility was calculated as the ratio between the number of fertile shoots and the total number of shoots per vine. The total shoot leaf area was estimated during the maximum vegetative vigor, corresponding to the veraison phenological phase 81 BBCH (Biologische Bundesantalt, Bundessortenamt, and Chemische Industrie). Estimation of leaf area was performed by applying an allometric estimation model measuring the leaf lamina width in the field and applying equations calculated based on the measurement of width and area of 20 leaves per site, by means of an electronic leaf area meter (LI-3100 model, LI-COR Inc., Lincoln, NE, USA) [29,30]. The yield and n° bunches were quantified at ripening stage (89 BBCH), by weighing and counting the entire grape production for each of the 20 selected vines in the four studied vineyards. The yield/total leaf area ratio (Y/LA) was also calculated for each vineyard.

2.3. Berry and Must Quality Traits

At harvest, for each vineyard, analytical determinations of standard chemical parameters were performed. For each vineyard, pH and titratable acidity (TA) were analyzed on 6 must samples (i.e., fresh juice without any fermentation). Samples were obtained by squeezing 60 berries from 6 vines (selected among the 20 vines), and the soluble solids content (SSC) was analyzed on 10 berries for each of the 20 selected vines. Berries were sampled by picking from the internal to the external part and from the top to the bottom of the harvested bunches, to ensure a representative sample. The SSC expressed in °Brix, was determined using a digital refractometer (HI96801, HANNA Instruments Italia Srl, Padua) by individually squeezing the 10 berries [31]. For pH and TA, 6 must samples per vineyard were filtered, 20 mL of must was kept and diluted 1:1 in distilled water. Afterwards, pH values were measured using a digital pH-meter (CLB22, Crison Instruments, Alella, Barcelona, Spain); whereas for TA determination, samples were titrated with a solution of NaOH 0.1 N to the endpoint of pH 8.2, and TA was expressed as g/L of tartaric acid equivalents [31].

Then, for each vineyard, a WineScan™ analysis with Foss Integrator software v. 2.0.4 (FOSS Italia s.r.l., Padova, Italy) and Dyonisos 150 (SinaTech s.r.l., Grottazzolina, Fermo, Italy) was performed on the 3 must samples obtained by squeezing 60 berries from 3 vines to quantify the following parameters: reducing sugars (RSU), pH, yeast assimilable nitrogen (YAN), calcium (Ca), catechins (CAT), total polyphenols (TPO), titratable acidity (TA), volatile acidity (VOL), malic acid (MAL), gluconic acid (GLU), citric acid (CIT), and tartaric acid (TAR).

2.4. Berry Mineral Composition

The analyses of must mineral composition were performed on 3 must samples obtained by squeezing 60 berries of 3 vines for each vineyard. For the evaluation of must mineral composition in terms of cations (Na^+, K^+, Mg^{2+}, and Ca^{2+}), anions ($SO_4{}^{2-}$, $PO_4{}^{3-}$), and organic acids (malate, tartrate, citrate, and isocitrate), 1 g of must was suspended in 20 mL of ultrapure water (Milli-Q, Merk Millipore, Darmstadt, Germany), frozen and subjected to 10 min shaking in a water bath (ShakeTemp SW22, Julabo, Seelbach, Germany) at 80 °C. Subsequently, the extracts were centrifuged, and the supernatant was collected and stored in vials. Anions and cations were separated and quantified by ion chromatography, equipped with conductivity detection (ICP 3000 Dionex, Thermo fisher Scientific Inc., Waltham, MA, USA), according to Zhifeng and Chengguang [32].

2.5. Data Elaboration

All experimental data were analyzed with the SPSS 13 statistical software (SPSS Inc., Chicago, IL, USA). A two-way ANOVA was performed considering the main effects of field (F) and year (Y) on data collected for growth parameters, yield, must quality, and mineral composition. Whenever the interactions were significant, a one-way ANOVA was performed. To separate means for each measured parameter, Duncan's multiple range test was performed. Verification of normality was performed using the Shapiro–Wilk test; the percentage data were pre-subjected to arcsine transformation. Pearson correlation was performed among biometrical parameters, yield, and must quality traits. Asterisks indicate the significance of the Pearson correlation coefficient (*, **, ***, **** correspond to $p < 0.1$, 0.05, 0.02, and 0.01, respectively).

3. Results

3.1. Growth and Berry Quality Traits

Growth parameters (total leaf area, yield (bunch weight), bunch number, actual fertility, and Y/LA) and berry quality traits (SSC, pH, and TA) of the four vineyards, measured during the three growing seasons (2019–2020–2021) are reported in Table 1. The main effect of field (F) was significant for all analyzed parameters, except for pH and TA; the year (Y) as main factor showed significant effects on all parameters (Table 1). In particular, the total shoot leaf area was significantly different among the vineyards, with SL showing the highest value, followed by GR, CA, and AC.

Table 1. Effects of field (F), year (Y), and their interaction (F × Y) on total total leaf area, yield, bunch number, actual fertility, Y/LA, SSC, pH, TA, of *V. vinifera* subsp. *vinifera* "Falanghina" vines at the four study sites: SL-Santa Lucia, CA-Calvese, GR-Grottole, and AC-Acquafredde. Mean values and standard errors are shown. Different letters within each column indicate significant differences according to Duncan's multiple-range test ($p \leq 0.05$).

	Total Leaf Area	**Yield**	**Bunch Number**	**Actual Fertility**	**Y/LA**	**SSC**	**pH**	**TA**
	m^{2} vine^{-1}	kg vine^{-1}	n° vine^{-1}		Kg m^{-2}	°Brix		g l^{-1} tartaric acid equivalent
Field (F)								
SL	7.87 ± 0.60 a	6.92 ± 0.28 a	23.2 ± 1.20 a	1.06 ± 0.030 b	1.12 ± 0.12 b	16.3 ± 0.32 c	3.16 ± 0.076 a	6.26 ± 0.615 a
CA	5.04 ± 0.30 c	2.25 ± 0.15 d	13.8 ± 0.65 d	0.92 ± 0.037 c	0.53 ± 0.03 c	19.3 ± 0.45 a	3.30 ± 0.082 a	5.47 ± 0.600 a
GR	6.30 ± 0.46 b	3.65 ± 0.23 c	20.4 ± 0.99 b	1.06 ± 0.034 b	0.67 ± 0.09 c	17.8 ± 0.47 b	3.39 ± 0.079 a	5.61 ± 0.572 a
AC	3.79 ± 0.22 d	4.37 ± 0.20 b	17.1 ± 0.81 c	1.23 ± 0.053 a	1.40 ± 0.10 a	18.4 ± 0.57 ab	3.22 ± 0.042 a	5.76 ± 0.443 a
Year (Y)								
2019	7.14 ± 0.48 a	4.85 ± 0.27 a	17.7 ± 0.60 b	1.22 ± 0.034 a	0.89 ± 0.07 b	20.0 ± 0.40 a	3.26 ± 0.070 ab	7.62 ± 0.603 a
2020	5.49 ± 0.22 b	3.56 ± 0.23 b	14.2 ± 0.59 c	0.80 ± 0.031 b	0.66 ± 0.03 b	17.8 ± 0.44 b	3.16 ± 0.033 b	5.63 ± 0.195 b
2021	3.50 ± 0.24 c	4.48 ± 0.29 a	23.9 ± 1.04 a	1.18 ± 0.029 a	1.56 ± 0.16 a	16.0 ± 0.32 c	3.38 ± 0.073 a	4.07 ± 0.186 c
Significance [1]								
F	**	***	***	***	***	***	NS	NS
Y	***	***	***	***	***	***	*	*
F × Y	NS	***	***	***	***	***	NS	NS

[1] NS, *, **, and ***, not significant or significant at $p \leq 0.05$, 0.01, and 0.001, respectively.

Yield was significantly different among vineyards, with the highest value in SL followed by AC, GR, and CA. Bunch number showed the highest value in SL, followed by GR, AC, and CA. Actual fertility in AC reached a significant higher value than both SL and GR, which in turn were higher than CA. The rate of Y/LA in AC showed a significantly higher value than SL, which in turn was significantly higher than both CA and GR. For SSC, CA grapes showed a higher value than GR, while AC grapes showed intermediate values; SL grapes showed the lowest value. Concerning the main factor Y, its effect was significant for all analyzed parameters: for total shoot leaf area, SSC, and TA, the values in 2019 were significantly higher than 2020, which in turn were significantly higher than 2021. For yield and actual fertility, in 2019 and 2021 the values were similar and were higher than 2020. Bunch number showed the highest value in year 2021, followed by 2019 and 2020. The rate of Y/LA showed significant higher values for the year 2021 than both 2019 and 2020. The pH in 2021 was higher than in 2020, while 2019 showed intermediate values. The interaction F × Y was significant for bunch weight, bunch number, actual fertility, Y/LA, and SSC (Table S1). For bunch weight, the highest values were found in SL among the three years, and for SSC, the highest values were found in the years 2019 and 2020 for all the fields (Table S1).

3.2. Must Mineral and Organic Acids Composition

Must mineral and organic acids composition of the four vineyards in the three years (2019–2020–2021) are reported in Tables 2 and 3. The main effect of field (F) was significant for all analyzed parameters, except Na^+. Considering the main factor F, the values for $SO_4{}^{2-}$ and Isocitrate concentrations were significantly higher for must in CA and GR than the SL and AC must. For the $PO_4{}^{3-}$ in the must of CA, the value was higher than SL, with the musts of AC and GR having intermediate values (Table 2). For malate, SL and AC must showed higher values than the CA and GR must. For tartrate and Ca^{2+}, CA grapes showed values significantly higher than GR, which in turn showed significantly higher values than SL and AC (Tables 2 and 3). For citrate, GR must showed significantly higher values than all the other fields. For Mg^{2+}, CA must showed significantly higher values than all the other fields. For $K^{+\prime}$, CA grapes had a higher value than GR and AC, which in turn showed higher values than SL. The main factor year (Y) was significant for all parameters apart from Na^+ and K^+. For $SO_4{}^{2-}$ and Ca^{2+}, the values in 2019 were significantly lower than 2020 and 2021. For $PO_4{}^{3-}$ and Mg^{2+}, in the must of 2020 there was a significant higher value than 2019 and 2021 (Table 2). For malate in the must of 2019, there was a value significantly higher than 2020 and 2021. For tartrate in must of 2021, there was a significantly higher value in 2021 than the previous years. For citrate in the must of 2019 and 2020, there were values significantly lower than 2021. For isocitrate in the must of 2020, the value was higher than 2019, which in turn was higher than in 2021 (Table 3). The interaction F × Y was significant for tartrate, citrate, isocitrate, K^+, Mg^{2+}, and Ca^{2+}, with the differences shown in the table of the Supplementary Materials. For K^+, the highest values were found in CA must and the lowest in SL must. Mg^{2+} was significantly higher in the must of 2020 than the other two years for all the fields. Ca^{2+} showed the highest values in the must of CA 2021, CA 2020, and GR 2020. Tartrate showed highest values for the must CA 2021, CA 2019, and GR 2021. Citrate showed highest values in the must of GR 2019, GR 2020, and CA 2019. Isocitrate showed the highest values for the musts of GR 2020 and AC 2020 (Table S2).

Table 2. Effects of field (F), year (Y), and their interaction (F × Y) on must minerals (Na^+, K^+, Mg^{2+}, Ca^{2+}, $SO_4{}^{2-}$, $PO_4{}^{3-}$) content in *V. vinifera* subsp. *vinifera* "Falanghina" vines at the four study sites: SL-Santa Lucia, CA-Calvese, GR-Grottole, and AC-Acquafredde. Mean values and standard errors are shown. Different letters within each column indicate significant differences according to Duncan's multiple-range test ($p \leq 0.05$).

	Na^+	**K^+**	**Mg^{2+}**	**Ca^{2+}**	**$SO_4{}^{2-}$**	**$PO_4{}^{3-}$**
	(g kg^{-1} DW)	(g kg^{-1} DW)	(g kg^{-1} DW)	(g kg^{-1} DW)	(g kg^{-1} DW)	(g kg^{-1} DW)
Field (F)						
SL	0.150 ± 0.024 a	0.97 ± 0.04 c	0.066 ± 0.004 b	0.081 ± 0.003 bc	0.034 ± 0.002 b	0.101 ± 0.007 c
CA	0.091 ± 0.030 a	1.60 ± 0.10 a	0.089 ± 0.005 a	0.128 ± 0.016 a	0.045 ± 0.004 a	0.174 ± 0.012 a
GR	0.106 ± 0.021 a	1.34 ± 0.07 b	0.065 ± 0.006 b	0.086 ± 0.007 b	0.045 ± 0.003 a	0.128 ± 0.009 bc
AC	0.097 ± 0.016 a	1.38 ± 0.04 b	0.068 ± 0.008 b	0.068 ± 0.006 c	0.035 ± 0.003 b	0.156 ± 0.014 ab
Year (Y)						
2019	0.091 ± 0.023 a	1.31 ± 0.09 a	0.064 ± 0.002 b	0.069 ± 0.004 b	0.033 ± 0.002 b	0.140 ± 0.012 ab
2020	0.129 ± 0.019 a	1.31 ± 0.08 a	0.093 ± 0.003 a	0.101 ± 0.005 a	0.042 ± 0.002 a	0.155 ± 0.012 a
2021	0.113 ± 0.020 a	1.35 ± 0.09 a	0.059 ± 0.006 b	0.103 ± 0.015 a	0.044 ± 0.004 a	0.123 ± 0.011 b
Significance [1]						
F	NS	***	***	***	**	***
Y	NS	NS	***	***	**	*
F × Y	NS	**	**	***	NS	NS

[1] NS, *, **, and ***, not significant or significant at $p \leq 0.05$, 0.01, and 0.001, respectively.

Table 3. Effects of field (F), year (Y), and their interaction (F × Y) on must organic acids content in *V. vinifera* subsp. *vinifera* "Falanghina" vines at the four study sites: SL-Santa Lucia, CA-Calvese, GR-Grottole, AC-Acquafredde. Mean values and standard errors are shown. Different letters within each column indicate significant differences according to Duncan's multiple-range test ($p \leq 0.05$).

	Malate	Tartrate	Citrate	Isocitrate
	(g kg^{-1} DW)	(g kg^{-1} DW)	(g kg^{-1} DW)	(g kg^{-1} DW)
Field (F)				
SL	2.46 ± 0.37 a	6.64 ± 0.27 c	0.358 ± 0.011 b	0.079 ± 0.011 b
CA	1.59 ± 0.33 b	10.0 ± 1.18 a	0.371 ± 0.028 b	0.098 ± 0.011 a
GR	1.86 ± 0.25 b	7.63 ± 0.43 b	0.458 ± 0.028 a	0.100 ± 0.013 a
AC	2.76 ± 0.22 a	6.48 ± 0.26 c	0.373 ± 0.018 b	0.083 ± 0.012 b
Year (Y)				
2019	3.04 ± 0.24 a	7.18 ± 0.42 b	0.430 ± 0.024 a	0.101 ± 0.007 b
2020	1.83 ± 0.12 b	6.60 ± 0.25 b	0.403 ± 0.022 a	0.119 ± 0.006 a
2021	1.63 ± 0.28 b	9.29 ± 0.94 a	0.338 ± 0.009 b	0.051 ± 0.003 c
Significance [1]				
F	**	***	***	*
Y	***	***	***	***
F × Y	NS	***	**	*

[1] NS, *, **, and ***, not significant or significant at $p \leq 0.05$, 0.01, and 0.001, respectively.

3.3. Must Chemical Analysis

Must chemical analysis of the four vineyards in the three years (2019-2020-2021) is reported in Table 4. The main effect of field (F) was significant for all parameters analyzed, with the exception of catechins. For reducing sugars, SL and AC showed significantly lower values than CA, with GR showing an intermediate value. For pH, the AC must showed a higher value than GR, which in turn had a higher value than SL, with CA showing an intermediate value. For YAN, the musts of SL, CA, and AC showed a significant lower values than GR. Calcium content was significantly higher in the must of CA than GR musts, which in turn showed significantly higher values than AC; SL showed intermediate values. Total polyphenols content was significantly lower in the must of SL and GR compared to CA, with AC must showing intermediate values. The main factor of year (Y) was significant for all the studied parameters, apart from Catechins. The reducing sugars showed a higher value in 2020 compared to 2019 and 2021. For pH, in 2021 there was a higher value than in 2019, which in turn showed a higher value than 2020. For YAN, in 2021 there was a significant lower value than 2019 and 2020. For calcium, in 2020 there was a significant lower value than 2019 and 2021. For total polyphenols, the year 2019 showed a significant higher value than the subsequent years. The interaction F × Y was significant for YAN, calcium, and total polyphenols, with significant differences shown in the table of Supplementary Materials. Reducing sugars showed the highest values for CA 2020, AC 2020, and AC 2021, and the lowest for SL in the three years. The highest values of YAN were found in GR 2019 and GR 2020. Calcium showed the highest value in CA 2019. Total polyphenols were significantly higher in 2019 than 2020 and 2021 for all the fields (Table S3).

3.4. Must Organic Acids

The analysis of must organic acids analysis of the four vineyards in the three years (2019–2020–2021) is reported in Table 5. The main effect of field (F) was significant for all the parameters, with the exception of gluconic acid. Titratable acidity was significantly higher in the must of SL, CA, and GR than in AC. Volatile acidity in the must of CA showed a higher value than both GR and SL, with must of AC showing an intermediate values. Malic acid in must of SL showed a significantly higher value than AC, with the must of GR showing an intermediate value; CA must showed the lowest value. For citric acid, the must in CA showed a higher value than SL, GR, and AC. For tartaric acid, the must CA showed a higher value than SL and GR, which in turn showed a higher value than must of

AC. The effect of the main factor year (Y) was significant for all parameters, except gluconic acid. Titratable acidity in the must of 2020 showed a significantly lower value than 2019 and 2021. The volatile acidity in the must of 2020 showed a significantly higher value than 2019, which in turn was higher than the must of 2021. Malic acid was significantly higher in the must of 2019 than in 2020 and 2021. Citric acid showed a significant lower value in must of 2021 compared to 2019 and 2020. Tartaric acid showed a significant lower value in the must of 2020 compared to the other two years. The interaction F × Y was significant for all analyzed parameters, except Gluconic acid. The interaction effects are shown in the table of Supplementary Materials. Titratable acidity showed the highest values for SL 2019, CA 2019, and GR 2019. Volatile acidity showed values highest in CA 2020 and AC 2020. Malic acid content was highest in SL 2019, GR 2019, and AC 2021, whereas citric acid was highest only in CA for all the three years of study. Tartaric acid showed highest values for CA 2019, CA 2021, and GR 2019 (Table S4).

Table 4. Effects of field (F), year (Y) and their interaction (F × Y) on reducing sugars, pH, YAN, calcium, catechins, total polyphenols of *V. vinifera* subsp. vinifera "Falanghina" vines at the four study sites: SL-Santa Lucia, CA-Calvese, GR-Grottole, and AC-Acquafredde. Mean values and standard errors are shown. Different letters within each column indicate significant differences according to Duncan's multiple comparison tests ($p \leq 0.05$).

	Reducing Sugars	pH	YAN	Calcium	Catechins	Total Polyphenols
	g/L		mg/L	mg/L	mg/L	ppm
Field (F)						
SL	201 ± 4.90 b	3.11 ± 0.01 c	88.4 ± 15.7 b	58.8 ± 7.49 bc	5.49 ± 1.24 a	628.5 ± 254.2 b
CA	230 ± 12.07 a	3.14 ± 0.05 bc	81.0 ± 10.2 b	103 ± 16.4 a	8.78 ± 1.61 a	1011 ± 233.5 a
GR	213 ± 6.88 ab	3.21 ± 0.04 b	144 ± 22.8 a	66.0 ± 7.02 b	6.98 ± 1.35 a	708.2 ± 218.8 b
AC	208 ± 25.47 b	3.32 ± 0.05 a	82.0 ± 13.0 b	46.6 ± 9.01 c	7.47 ± 1.48 a	854.4 ± 120.4 ab
Year (Y)						
2019	196 ± 16.08 b	3.14 ± 0.03 b	117 ± 17.5 a	81.5 ± 15.4 a	7.40 ± 1.23 a	1467 ± 123.6 a
2020	236 ± 8.60 a	3.32 ± 0.04 c	125 ± 11.3 a	42.4 ± 6.13 b	6.49 ± 1.19 a	543.4 ± 130.0 b
2021	207 ± 9.72 b	3.13 ± 0.03 a	53.7 ± 6.39 b	82.3 ± 2.01 a	7.65 ± 1.35 a	391.3 ± 105.1 b
Significance [1]						
F	*	***	***	***	NS	*
Y	***	***	***	***	NS	***
F × Y	***	NS	*	***	NS	***

[1] NS, * and ***, not significant or significant at $p \leq 0.05$, and 0.001, respectively.

A correlation analysis was carried out to highlight the possible relationships among biometrical, berry yield, and must quality traits for each season of the trial (Table 6). Concerning the data collected in the season 2019, a significant negative correlation was observed between bunch weight and SSC and pH, whereas a significant positive correlation was found between SSC and pH. The pH and TA (as well as the content of organic acids) were positively correlated with total polyphenols.

In 2020, bunch weight was significantly positively correlated with total SLA. SSC was positively correlated with pH, citric acid, and total polyphenols, and negatively correlated with TA, malic acid, and tartaric acid. The parameter pH was significantly correlated with total polyphenols. In 2021, bunch weight was negatively correlated with SSC and Citric Acid. SSC was positively correlated with total polyphenols and organic acids, with the exclusion of tartaric acid.

Table 5. Effects of field (F), year (Y), and their interaction (F × Y) on titratable acidity, volatile acidity, malic acid, gluconic acid, citric acid, tartaric acid of V. vinifera subsp. vinifera "Falanghina" vines at the four study sites: SL-Santa Lucia, CA-Calvese, GR-Grottole, and AC-Acquafredde. Mean values and standard errors are shown. Different letters within each column indicate significant differences according to Duncan's multiple comparison tests ($p \leq 0.05$).

	Titratable Acidity	**Volatile Acidity**	**Malic Acid**	**Gluconic Acid**	**Citric Acid**	**Tartaric Acid**
	g/L	g/L	g/L	g/L	g/L	g/L
Field (F)						
SL	6.80 ± 0.44 a	0.067 ± 0.012 b	2.81 ± 0.36 a	0.350 ± 0.033 a	0.290 ± 0.023 b	5.09 ± 0.24 b
CA	6.56 ± 0.49 a	0.091 ± 0.018 a	1.93 ± 0.13 c	0.462 ± 0.088 a	0.396 ± 0.017 a	6.06 ± 0.56 a
GR	6.34 ± 0.37 a	0.064 ± 0.111 b	2.53 ± 0.29 ab	0.281 ± 0.058 a	0.285 ± 0.042 b	5.38 ± 0.26 b
AC	4.64 ± 0.44 b	0.082 ± 0.022 ab	2.33 ± 0.23 b	0.408 ± 0.111 a	0.161 ± 0.054 b	3.22 ± 0.17 c
Year (Y)						
2019	6.88 ± 0.58 a	0.233 ± 0.004 b	2.98 ± 0.30 a	0.436 ± 0.079 a	0.340 ± 0.037 a	5.47 ± 0.52 a
2020	5.12 ± 0.27 b	0.127 ± 0.009 a	1.97 ± 0.11 b	0.348 ± 0.067 a	0.360 ± 0.026 a	4.07 ± 0.20 b
2021	6.26 ± 0.24 a	0.078 ± 0.007 c	2.23 ± 0.18 b	0.343 ± 0.059 a	0.276 ± 0.036 b	5.28 ± 0.38 a
Significance [1]						
F	***	*	***	NS	***	***
Y	***	***	***	NS	**	***
F × Y	***	*	***	NS	***	**

[1] NS, *, **, and ***, not significant or significant at $p \leq 0.05$, 0.01, and 0.001, respectively.

Table 6. Correlations among the main analyzed parameters during the three-year study.

	Year 2019				**Year 2020**				**Year 2021**		
		r	**s** [1]			**r**	**s** [1]			**r**	**s** [1]
BW	TLA	−0.111	NS	BW	TLA	0.585	****	BW	TLA	0.054	NS
BW	SSC	−0.749	****	BW	SSC	−0.198	NS	BW	SSC	−0.615	****
BW	pH	−0.551	****	BW	pH	−0.475	**	BW	pH	0.226	NS
BW	GLU	−0.421	NS	BW	GLU	−0.112	NS	BW	GLU	−0.051	NS
BW	CIT	−0.359	NS	BW	CIT	0.001	NS	BW	CIT	−0.650	***
BW	ANT	−0.555	**	BW	ANT	−0.427	NS	BW	ANT	−0.216	NS
SSC	pH	0.546	****	SSC	pH	0.620	****	SSC	pH	−0.252	NS
SSC	TA	0.180	NS	SSC	TA	−0.368	*	SSC	TA	0.327	NS
SSC	MAL	−0.386	NS	SSC	MAL	−0.497	*	SSC	MAL	0.642	***
SSC	GLU	0.390	NS	SSC	GLU	0.206	NS	SSC	GLU	0.688	****
SSC	CIT	0.373	NS	SSC	CIT	0.718	****	SSC	CIT	0.860	****
SSC	TAR	0.394	NS	SSC	TAR	−0.683	****	SSC	TAR	−0.374	NS
SSC	TPO	0.320	NS	SSC	TPO	0.864	****	SSC	TPO	0.791	****
pH	MAL	−0.017	NS	pH	MAL	0.197	**	pH	MAL	−0.064	NS
pH	GLU	−0.010	NS	pH	GLU	−0.188	**	pH	GLU	−0.209	NS
pH	CIT	0.464	*	pH	CIT	0.600	**	pH	CIT	0.090	NS
pH	TAR	0.607	**	pH	TAR	−0.644	***	pH	TAR	−0.239	NS
pH	TPO	0.450	*	pH	TPO	0.628	***	pH	TPO	0.024	NS
TA	CIT	0.672	****	TA	CIT	−0.102	NS	TA	CIT	0.150	NS
TA	TAR	0.686	****	TA	TAR	0.255	NS	TA	TAR	0.718	****
TA	TPO	0.760	****	TA	TPO	−0.329	NS	TA	TPO	−0.253	NS
MAL	GLU	−0.021	NS	MAL	GLU	−0.267	NS	MAL	GLU	0.888	****
MAL	CIT	0.551	**	MAL	CIT	−0.001	NS	MAL	CIT	0.494	*
MAL	TAR	0.386	NS	MAL	TAR	−0.030	NS	MAL	TAR	−0.718	****
MAL	TPO	0.429	NS	MAL	TPO	−0.301	NS	MAL	TPO	0.572	**
GLU	CIT	0.257	NS	GLU	CIT	0.432	NS	GLU	CIT	0.596	**
GLU	TAR	0.374	NS	GLU	TAR	0.028	NS	GLU	TAR	−0.579	**
GLU	TPO	0.561	**	GLU	TPO	0.391	NS	GLU	TPO	0.534	**
CIT	TAR	0.943	****	CIT	TAR	−0.658	***	CIT	TAR	−0.118	NS
CIT	TPO	0.946	****	CIT	TPO	0.851	****	CIT	TPO	0.741	****
TAR	TPO	0.942	****	TAR	TPO	−0.582	**	TAR	TPO	−0.338	NS

[1] NS,*, **, ***, ****: non-significant or significant at $p \leq 0.1$, 0.05, 0.02, 0.01, respectively.

4. Discussion

Falanghina grapevine is one of the most economically important and cultivated varieties of the Campania region [23]. Since climate changes are expected to affect vine growth and the quality of the production, the variability of growth and must quality traits were investigated in vineyards characterized by different microclimatic and pedological characteristics. Vine growth, yield, and grape quality in the four analyzed experimental vineyards were characterized by significant differences, suggesting a different regulation of the source-sink balance according to the different microclimatic and pedological conditions, which can differentially influence the water availability for the vines [26]. In general, during the three years, the SL vineyard proved to be the best performing in terms of vegetative growth compared to the other four vineyards, in agreement with the morphophysiological and carbon isotopic analyses performed in the 2019–2020 season for the same vineyards [26,27]. Indeed, in a previous study, Damiano et al. [26] found that SL and AC showed lower values of $\delta^{13}C$ in must, indicating that the two vineyards experienced reduced stress compared to the other two vineyards CA and GR. Plants grown under water-limited conditions are known to experience a strong stomatal regulation, which leads to partial or total stomatal closure, determining a decrease in $^{13}CO_2$ discrimination and an increase of $\delta^{13}C$ values [33]. In CA, the lowest yield was not only due to the morpho-physiological traits [26,27], but also to the actual fertility that resulted as the lowest among the four vineyards, partly accounting for the low number of bunches at harvest.

Moreover, the grapes of vineyard CA showed significantly higher values of SSC, suggesting that the more limiting drought condition experienced by the vines at this site may have significantly accelerated the ripening dynamics in the bunches developed by the vines. Probably, as reported in [34], the period after veraison is the period for which the thermal conditions have a more significant effect on the technical ripening process. Usually in drought conditions there is a common reaction of the plants, which consists in the closure of leaf stomata in order to avoid an excess of water loss and the increase of soluble solids concentration in the berries, but when the drought is strong this mechanism it is probably not sufficient to avoid a concentration effect of soluble solids. Grape berry water loss in the ripening stage, known as berry dehydration, is an irreversible regression process in berry fresh weight, accelerated by hot and dry growing conditions, which occurs as a consequence of berry water depletion through xylem back-flow and transpiration that exceeds the import of water and solutes into the berry [35,36]. Another indicator of the advanced metabolic process in the ripening stage of the CA vineyard was the level of malic acid in grapes, which was significantly lower than in grapes of the other three vineyards. Malic acid breakdown is not an intrinsic part of the veraison program because external parameters such as temperature and internals such as carbon balance may be determinants of malate breakdown. Normally, malic acid is the main organic acid that is actively metabolized throughout the ripening of grapes, and the degradation of grape berry malate occurs after an earlier period of accumulation [16] compared to tartaric acid, which is less dependent on increasing temperature [37]. Under high-temperature regimes, malate content decreases as soon as sugar accumulates in the berry. On the contrary, in cool conditions, the malic acid decrease is only evident when sugar content has reached 500 mM [38]. Observing the interaction among the analyzed parameters, a negative correlation for Bunch Weight-Brix° was observed over the three years, confirming the dilution effect of the grape chemical compounds with the increase in bunch weight. Concerning the yield of grape production when observing the bunch weight, in CA there was a lower significant value, in accordance with the significant lower values Y/LA ratio. The leaf area is crucial for carbohydrates allocation in the reproductive organs of grapevine, for reaching and maintaining a high productivity in terms of fruit yield [39,40]. For this reason, CA may have had a reduced yield compared to the other three vineyards, while in SL vineyards, the high shoot leaf area may have been able to hold a higher yield.

Regarding the mineral nutrition, vines need an adequate supply of macro- and micronutrients in order to achieve their normal physiological and biochemical function. Basic mineral nutrients are considered to be essential for plant metabolic processes, seeing that they are cofactors and/or activators of many metabolic enzymes [41]. These nutrients are required for vine life cycle from budburst to leaf senescence, and generally they limit grape production [42]. Excessive nutrient supply and deficiencies can both lead to physiological disorders. Deficiencies occur when plants do not have sufficient availability of nutrients for their basic metabolism in the surrounding environment, while an abundance of minerals, in particular trace metals (e.g., zinc, copper, manganese) can sometimes induce toxicity phenomena [43]. In the case of CA, a significantly higher level of the cations K^+, Mg^{2+}, and Ca^{2+} and anions ${SO_4}^{2-}$ and ${PO_4}^{3-}$ was found compared to the other three vineyards. A high level of salt in soils generates both ionic and osmotic disruptions in plant function [44,45]. The osmotic effect, with similar symptoms to water deficit [45], characterized by low water potential in the soils due to the increased salt concentration, could have been responsible for the low vigor of the vines in these vineyards. This reduction of soil water potential restrains water uptake into the plant, consequently decreasing growth and nutrient uptake [46]. Another indicator of the drought stress conditions in the vineyard CA was the high content of total polyphenols in the berries (Table 4). Usually, water stress causes relevant losses of berry weight, also affecting the concentration of several polyphenols [47]. Due to the drought stress, in CA the plant may have reacted with the polyphenol accumulation, being part of the chemical resources mediating the adaptive response to abiotic stress, by acting against oxidative damages through the scavenging of reactive oxygen species produced during drought stress [48]. The YAN was significantly higher in GR compared to the other three vineyards, indicating a high presence of nitrogen in the must of this vineyard.

Observing Table 6 with the correlations among biometrical, berry yield, and must quality traits for each season, with bunch weight tending to increase, there is a decrease of SSC and pH, showing a negative correlation between the parameters, due to both a well-known crop load effect and a dilution effect. This negative correlation is significant for the years 2019 and 2021, which are also the years with a significantly high bunch weight compared to the year 2020.

The optimal grape maturity is cultivar specific and defined by a specific combination of three main factors: (i) technological maturity (i.e., sugar, acids or their ratio); (ii) phenolic maturity (i.e., quantity and quality of all tannins and pigments); (iii) aromatic ripeness (i.e., typical olfactory features reached without appearance of untypical aging or excessive veggie-green aromas). The decoupling between the above three factors is strongly aggravated under a global warming scenario [49]. Higher temperatures increase the speed of sugar accumulation, hasten acid degradation, alter flavor compounds [7,50,51], and affect the synthesis/degradation of certain compounds as polyphenols [17,52–54].

In this scenario, there is an increasing interest in avoiding alterations of ripening and controlling berry quality in the white berry grapevine, in order to preserve the features of the wines. Besides the regulation of source-sink relationships through correct summer pruning, recently the application of anti-transpirant treatments at veraison has been evaluated to reduce berry sugar content, ultimately aiming at the production of medium alcohol wines [24].

Concerning the water management and irrigation in the vineyard, due to the wide cultivation under quality label regulations, no results are available for southern Italy local cultivars. This indicates a future need to better investigate pedoclimatic impact on vine water use, yield, and quality, to design optimal irrigation strategies to counteract the drought season and avoid unbalances in the grape ripening process.

5. Conclusions

The overall results showed differences in growth, yield, and must quality characteristics for the four vineyards, with the field CA and GR showing pedoclimatic conditions constraining vegetative growth and berry production compared to SL and AC. These findings are in line with data from previous studies, in which a different leaf anatomical development was evidenced in the four vineyards, being the reason for the different eco-physiological behaviors. Therefore, it is clear that microclimatic and spatial variability in soil water availability can induce a different vine development and eco-physiological behavior, which is reflected in yield and berry quality and must be taken into account when designing strategies for Falanghina cultivation management in the pursuit of precision viticulture in a climate change scenario.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/horticulturae8090829/s1, Table S1, Data of interaction analysis F × Y for bunch weight and SSC; Table S2, Data of interaction analysis F × Y for Reducing sugar, YAN, Calcium, Total polyphenols; Table S3, Data of interaction analysis F × Y for K^+, Mg^{2+}, Ca^{2+}, Tartrate, Citrate, Isocitrate; Table S4, Data of interaction analysis F × Y for Titratable acidity, Volatile acidity, Malic acid, Gluconic acid, Citric acid, Tartaric acid.

Author Contributions: Conceptualization, N.D., V.D.M. and C.C.; methodology, C.C., M.G. and V.D.M.; formal analysis, N.D., F.P., R.C. and A.E.; investigation, N.D., C.C. and V.D.M.; resources, C.C., M.G. and V.D.M.; data curation, N.D., F.P., R.C., A.E., C.C. and V.D.M.; writing—original draft preparation, N.D., C.C. and V.D.M.; writing—review and editing, N.D., C.C., F.P., R.C., A.E., M.G. and V.D.M.; supervision, C.C., M.G. and V.D.M.; project administration, V.D.M.; funding acquisition, V.D.M. All authors have read and agreed to the published version of the manuscript.

Funding: The work of Nicola Damiano was funded within the PhD Programme "Dottorati di Ricerca con Caratterizzazione Industriale", P.O.R. CAMPANIA FSE 2014/2020. ASSE III—OBIETTIVO SPECIFICO 14 Azione 10.4.5.

Data Availability Statement: The data supporting the findings of this study are available from the corresponding authors (V.D.M. and C.C.) upon reasonable request.

Acknowledgments: The authors wish to thank La Guardiense Farm (Guardia Sanframondi—BN) for logistic support and especially Concetta Pigna for support during the different phases of the project. The authors also wish to thank Antonello Bonfante for scientific consulting, Chiara Amitrano and Sara De Francesco for technical support in field and laboratory activities.

Conflicts of Interest: The authors declare no conflict of interest.

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