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FINAL REPORT 2020

Winetech Number : P04000082

1. PROGRAMME & PROJECT LEADER INFORMATION

	Research Organisation leader	Project leader
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2. PROJECT INFORMATION

Project title	Effect of in-row vine spacing under high soil potential conditions on grapevine performance
Short title	Effect of vine spacing

Fruit kind(s)	Wine grapes		
Start date (mm/yyyy)	2008-04	**End date** (mm/yyyy)	2020-08

Key words	Vine spacing, soil potential, growth, yield, grape, wine, quality

	CFPA	DFTS	HORTGRO	SATI	WINETECH	ARC	OTHER
TOTALS All years	R 0	R 0	R 0	R 0	R 3294371	R 3428120	R 0

Total cost of entire project	R 6722491

3. EXECUTIVE SUMMARY

Objectives and Rationale

Knowledge of vine reaction to plant spacing under high potential soil conditions is restricted. This project was done to determine effects of vine spacing (with fixed row spacing) of Shiraz/101-14 Mgt on a high potential soil on establishment cost and labour, vine physiological behaviour, growth, yield, and grape and wine quality.

Methods

The project was carried out in Robertson, SA. Shiraz/101-14 Mgt vines were planted during 2008 to a VSP trellis with fixed row spacing of 2.2 m. In-row vine spacing varied from 0.3 – 4.5 m with increments of 30 cm (from 15151 – 1010 vines/ha; 0.66 – 9.9 m^2/vine). Two bud spurs were equally spaced. Grapes were harvested at two ripeness levels.

Key Results

Total costs, labour and yields showed clear trends, peaking around 1.8 m vine spacing.
Root density in fine, extension and permanent categories increased and roots penetrated deeper with narrower spacing.
Leaf size increased and trunk circumference, and shoot and cane mass mostly decreased with narrower spacing.
Yield:cane mass ratios increased towards wider vine spacing.
Fertility and bunch mass increased from narrow to wide spacing.
Bunches of narrow spacing treatments were more compact.
Sugar levels (°B) and pH decreased and titratable acidity (TA) increased from narrow to wide spacing.
With a few exceptions, all sensory descriptors showed decreasing trends from narrow to wide vine spacing in wines from both grape ripeness levels.

Key Conclusion of Discussion

Results indicate a gradual transition from a higher vigour (higher canopy and root density) to a lower vigour (lower canopy and root density) condition, from narrow to wide vine spacing. This led to wider spaced vines having lower leaf:fruit ratios that caused disharmony between increasing spacing and yielding return as well as delayed grape sugar accumulation, ultimately also reflected in the wine composition and sensory profiles. Physiological parameters revealed a complex interplay between vine structure expansion, microclimate, water relations, photosynthetic output, and carbon distribution, most likely comprising unequal development of aboveground and belowground growth; translocation distances; crop load; as well as water and nutrient demands. Balanced development remains essential to minimise erratic grapevine behaviour, beyond normal biotic and abiotic complexities in the field.

Take Home message for Industry

Considering graft material, labour for planting, training and annual management, as well as yields and grape and wine quality, a vine spacing of 1.8 m (approx. 4 m^2 surface area/vine) appeared to be optimum under the conditions of this experiment. Although narrower and wider spacing may be plausible under specific circumstances (depending on soil, rootstock, water, fertilization and ambient temperature), vine spacing of less than 1.2m (approx. 2.5 m^2/vine) and more than 2.4 m (approx. 5.5 m^2/vine) may not be sustainable.

4. PROBLEM IDENTIFICATION AND MOTIVATION

Problem Identification

To satisfy requirements regarding land/terroir utilisation and sustainability at farm level (especially yield, wine quality and production costs), the distance between grapevine rows is normally restricted to the minimum. However, inter- and intra-row spacing of vines should still conform to current scientific-technological (practical) criteria regarding viticultural and physiological requirements to obtain best performance in terms of size and efficiency of the canopy, root system, and grapes. Considerable research has already been done on growth accommodation and related implications. Over the years, canopy management experiments demonstrated that vine vigour should be managed judiciously and proper canopy size and composition (referring to physical dimensions and leaf age) and canopy porosity/microclimate are essential for sustainable, product-focused grape and wine production (Smart *et al*., 1990; Poni *et al*., 1994; Hunter *et al*., 2004, and references therein; Hunter *et al*., 2016). Despite the fact that the spacing of rows and vines is an integral, major impacting factor in the quest for optimal grapevine functioning, balance and sustainability, it has received little focused attention in research efforts. The most comprehensive studies on this aspect were done in South Africa and these contributed to the establishment of a commonly used principle by which vines are spaced wider with higher soil potential (Archer & Strauss, 1985, 1989, 1990; Hunter, 1998a, 1998b). These studies were done on a medium potential, depth-restricted soil under dryland and low intensity (supplementary) irrigation and both row and vine spacings were changed in the different treatments (comprising a range of 1 000 – 20 000 vines/ha). However, these studies did not answer the repetitive global question as to what extent vine performance and related parameters are affected or would change by vine spacing in terroirs with deep, high potential soil conditions (with minimum limitations to root penetration and intensive irrigation). Under such conditions, growth balances may change when roots utilise the deeper soil layers whilst penetrating more vertically and/or more horizontally (with closer/wider spacing) (Archer & Strauss, 1985; Hunter, 1998b). Water relations, photosynthetic activity, shoot growth (and thus microclimate), yield, and the final grape and wine quality/style are expected to be affected under any of these circumstances. The purpose of this project was to obtain the sole effect of vine spacing on establishment costs, labour costs, physiological processes, shoot growth, microclimate, yield, and grape and wine quality/style under high potential soil conditions with minimum limitations to root penetration.

Motivation

Previous studies on the spacing of grapevines comprised both row and vine spacing and were done under dryland and low intensity (supplementary) irrigation on a medium potential soil in the Stellenbosch region. These studies, together with research on canopy management, led to a principle that is now commonly considered during establishment, namely “the higher the soil potential, the wider the vine spacing”. However, a global, recurring question is to what extent vine performance may be affected by vine spacing under deep, high potential soil conditions and intensive irrigation, especially when in-row vine spacing is restricted. In this project, the physiological and viticultural reaction and oenological outcomes of the grapevine to varying vine spacing, but fixed row spacing, were determined to:

Make recommendations on the relationship between (in-row) vine spacing, yield levels, viticultural and physiological aspects, grape and wine quality/styles, and product objectives.

Obtain information regarding the most practical and economic vine spacing for wine grapes

under high potential soil conditions.
Contribute to the optimal utilisation of terroir potential.

5. ACCUMULATED PROGRESS TABLE

Objectives	Milestones (Significant event or stage in a project)	Date Achieved
M1. Establishment M2. Pruning & cordon development M3. Canopy management M4. Physiological measurements M5. Canopy development & yield parameters M6. Grape quality M7. Wine making M8. Wine quality M9. Root development M10. Economic analysis	M1. Complete establishment [fixed row spacing of 2.2 m and 15 vine spacing treatments (0.3, 0.6, 0.9, 1.2, 1.5, 1.8, 2.1, 2.4, 2.7, 3.0, 3.3, 3.6, 3.9, 4.2, 4.5 m)] - spring 2008 M2. Complete cordon development critical for comparison - summer 2011/2012 M3. Continuous uniform management essential (suckering, shoot positioning, topping) - seasonal M4. Physiological performance critical during growth season, particularly during ripening - annually during post-véraison stage - later inclusion of pre-véraison stage M5. Essential to study performance as affected by treatment - annually at harvest – harvest dates to include different ripeness levels from 2014/15 harvest M6. Essential to determine different price points - annually at harvest and after harvest M7. Essential to match grape quality - annually after harvest M8. Evaluation to determine different wine styles and price points if possible - annually during winter/spring M9. Essential to determine growth balances - end of project M10. To obtain relation between economic viability, yield, and grape and wine quality/style - continuously	2020-08-07

6. WORKPLAN (MATERIALS AND METHODS)

M1 - M2: Completed in the beginning.
W1 - M3 - M4: Physiological parameters (photosynthesis, stem water potential, microclimate) during the grape ripening period. Completed.
W2 - M2, M5: Canopy development (cane mass during pruning, leaf areas and primary and secondary shoot growth at harvest). Completed.
W3 - M5: Yield parameters (bunch mass/volume, rachis mass/volume, berry mass/volume, yield/vine & yield/ha) at harvest. Completed.
W4 - M6: Grape quality (°B, pH, titratable acid) at harvest (to be followed if possible at different harvest times). Completed.
W5 - M7: Winemaking (wines will be made in the cellar at ARC Infruitec-Nietvoorbij on small scale – 20L quantities). Completed.
W6 - M8: Wine quality (organoleptic evaluation, anthocyanins, phenolics) after bottling. Completed.
W7 - M9: Root development (a root study will be done at the end of the study period in order to quantify the effect of vine spacing on root distribution - 2019). Completed.
W8 - M10: Economic analysis (establishment costs, production costs, expected price realisation

of grapes and wine). All relevant costs completed.

To obtain the sole effect of vine spacing on physiological processes, shoot growth, microclimate, yield, and grape and wine quality/style under high potential soil conditions with minimum limitations to root penetration, an experiment was established under fairly homogeneous soil conditions at the Robertson experiment farm of ARC Infruitec-Nietvoorbij (GPS coordinates 33°49'29.87"S; 19°52'50.67"E). The vineyard row spacing was fixed at 2.2 m and conforms to current vine cultivation principles, meaning that the available space and development and accommodation of canopies (on a VSP trellis) should be such that overshadowing of adjacent/opposite canopy surfaces is largely prevented and that practices, with consideration of mechanization, are not damaging growth, are not hampered, and can still be efficiently and easily applied. A VSP cordon system was used, as it is considered a physiologically sound (when managed correctly) and most practical and familiar system locally and globally.

Experiment layout and Measurements

Shiraz (clone SH 9C)/101-14 Mgt was planted during spring of 2008 with an approximate NNE-SSW (30°) row orientation at the Robertson experiment farm of ARC Infruitec-Nietvoorbij, located in the Breede River Valley, South Africa (GPS coordinates 33°49'29.87"S; 19°52'50.67"E). Vines were spaced from 0.3 m to 4.5 m with incremental increases of 30 cm from narrowest to widest, representing 15 treatments. Row spacing was fixed at 2.2 m. Vines were double cordon-trained on a VSP trellis with four sets of movable foliage wires. Each treatment was replicated four times on a total surface of about 2 ha. Irrigation was applied according to crop factors (0.3 – 0.6, corresponding to average daily ET0 of 5 – 6.7 mm) and averaged 25 mm/week from approximately pea berry size growth stage. To enhance complete cordon development of all treatments, vines were pruned to one-bud spurs for two winters (2010 and 2011) after planting in spring of 2008, where after two-bud spurs were pruned since the winter of 2012. Spurs were spaced similarly, irrespective of treatment, and the number of spurs only restricted by the length of the cordons. To restrict other cultural practice influences, vines were irrigated and fertilised similarly, avoiding excessive deficit or deficiency. Typical experiment appearance is shown in Fig. 1.

Fig. 1. Canopy appearance affected by different plant spacing, ARC Experiment Farm, Robertson.

Root studies were done by using the well-known root profile method of Böhm (1979), whereby a trench of 1.8 m deep was dug parallel to the vine row and 300 mm from the vine trunk. After careful exposure of roots, a grid system was set up against the profile wall. Roots were plotted in five root diameter classes, i.e. < 0.5 mm; 0.5 to 2 mm; 2 to 5 mm; 5 to 10 mm, and > 10 mm.

To simplify the data, classes were combined and reduced to three categories, namely < 0.5 – 2 mm; 2 – 5 mm; and > 5 mm. Pictures of the root study are shown in Fig. 2.

Fig. 2. Root studies done in the plant spacing project, ARC Experiment Farm, Robertson.

The ambient and inter-canopy photosynthetic active radiation (PAR) (400–700 nm, mol/m^2/s) (in the bunch zone and upper third of the canopy at 10:30, expressed as % of ambient) was captured by means of a LI-COR LI-191 Line Quantum sensor. Photosynthetic activity (mol/m^2/s) was measured during mid-morning (10:30) using an open system LI-COR LI-6400 portable photosynthesis meter, whereas stem water potential (–kPa) measurements were done during mid-day using two equally calibrated Scholander pressure chambers. Measurements were done during the pre- and post-véraison growth periods on basal primary shoot leaves in the bunch zone. Shoots (including bunches) were sampled at two grape ripeness level stages per treatment replicate and used for determination of vegetative and reproductive growth characteristics. Cane mass was measured in winter.

Soluble solid content [by refractometry, °Balling (°B)], titratable acidity (as tartaric acid equivalents by means of titration), and pH of the supernatant of settled, strained grape must of each treatment replicate were assessed immediately after crushing. Grapes from seven shoots per replicate, sampled at two harvest dates targeting 23 °B and 25 °B, respectively, were used for further measurements, such as mass and volume of the whole bunch, rachis and berries.

For winemaking and analyses, approximately 40 kg of grapes were harvested at each of the two ripeness levels mentioned above per replicate. Grapes were cooled overnight to the same temperature (20 °C) before processing. These batches of grapes were individually de-stemmed and crushed by means of a custom-made de-stemmer/crusher suitable for small batches. Wines were made according to a standard winemaking procedure prescribed by the Experimental Cellar. Juice volume was measured and 50 mg/L SO_2 added (determination of SO_2 based on Ripper method). After one hour of skin contact, the pomace was inoculated with 30 g/hL re-hydrated pure yeast (VIN 13). As a source of nutrients for yeasts, di-ammonium phosphate was added at 50 g/hL. Fermentation was conducted in 60 L food grade plastic containers with lids, in a temperature-controlled room at 24 °C. The pomace cap was punched down three times per day throughout the fermentation period. Fermentation on skins averaged four days, after which the pomace was pressed once with a custom-built balloon press at 2 bar. Pressed and free-run parts of wine were mixed into 20 L stainless steel canisters and allowed to further ferment at 25 °C until dry (less than 5 g/L residual sugar). Wines were cold-stabilised at 0 °C for approximately 21 days. Since no malolactic fermentation was performed, the SO_2 levels were adjusted to 85 mg/L of wine before bottling. Wines were stored in 750 mL bottles under screw cap. All bottled wines were analysed spectrophotometrically (UV/VIS Biochrom LKB Ultrospec II E, Cambridge, England) for total anthocyanin (A_{520}) and phenolic (A_{280}) contents after proper dilution.

For the wine sensory evaluation an expert tasting panel consisting of 12 trained and experienced persons was used. The panel comprised SA Wine Industry winemakers (50 %) and tasters from the ARC Infruitec-Nietvoorbij Institute. The tasters were trained as follows: to recognise the descriptors to be used during the tastings (by means of prepared mixtures of different aromas that are associated with fruity, spicy and jammy nuances) and understand their relation to the evaluation method; synchronised in the use of the evaluation method and intensity line-scale; and familiarised in the nuances generally associated with young experimental wines, on an ongoing basis during the weeks preceding the commencement of tasting of the wines of each season. In addition to this and together with an explanation of the project treatments and sub-treatments, the tasting methodology and descriptor terminology and recognition by the tasters were refreshed before each tasting, using unmarked wines from the wine batches to be tasted. Treatments and replicates were completely randomised within a ripeness level. Tasters were presented with numbered tasting sheets in a random order without any identification that can be traced to the wine origin/treatment.

Each tasting sheet consisted of a list of pre-selected sensory attributes/descriptors, each having a non-structured 0 - 100 mm line next to it. The non-structured 100 mm line-scale method was used to indicate the level of intensity of a specific sensory attribute (Jackson, 2002). The line next to the descriptor was marked by the taster according to the scale of its sensory perception of the descriptor. The same sensory descriptors were consistently repeated from season to season during the course of the experiment and comprised the following: colour intensity; fruity aroma intensity; spicy aroma intensity; pepper aroma intensity; jammy aroma intensity; overall aroma intensity; acidity intensity; tannin intensity; body mouthfeel; alcohol intensity; finish persistence; and overall quality. These sensory descriptors were scored separately per wine by each taster on the line scale provided. The scores of the experts were averaged per descriptor and per wine replicate and used as a quantitative measurement of sensory perception. In order to avoid sensory fatigue, tasting batches were limited to approximately 30 wines per tasting panel per day. The temperature-controlled tasting room comprised a set-up of separate cubicles, with each taster allocated an individual private cubicle. The tasting room interior, tasting set-up and procedure, wine tasting glasses and wine volumes were standardised from year to year. Wines were served individually and sequentially to the tasters through a frontal window as soon as the previous wine was tasted and the tasting sheet completed. Tasters were not given any time limits for tasting.

Statistical design and Methods

The experimental design is a randomised block design with 15 spacing treatments and four block replications. Most data was subjected to ANOVA using the General Linear Models Procedure (PROC GLM) of SAS software (Version 9.4; SAS Institute Inc, Cary, USA) to determine polynomial trends. The data was then either subjected to the regression procedure (PROC REG) to fit linear and quadratic regressions or to the non-linear regression procedure (PROC NLIN). PROC NLIN was performed to fit more than one line to the data to determine the "joint-point" (also called segmented or broken stick regression) of lines (Hudson, 1966). Outliers were determined using the Shapiro-Wilk test on standardized residuals from the model to verify normality (Shapiro & Wilk, 1965). Outliers were replaced by predicted values of the model.

7. RESULTS AND DISCUSSIONS

Costs and Labour input - during planting and training

Data on the vine purchasing costs and labour for planting, summer training, shoot (spur) selection (including further cordon extension on the cordon wire for cordons not fully developed and bunch removal to one bunch per shoot) and harvesting for the different treatments are shown in Table 1. Purchasing costs and planting time increased sharply with planting to less than 1.2 m vine spacing. Noticeably lower initial costs were realised when planting to wider than 3.6 m. Based on planting time, spacing treatments could be grouped as follows: 0.3 m (~300 day man hours/ha); 0.6 m (~140 day man hours/ha); 0.9 m (~100 day man hours/ha); 1.2 m (~80 day man hours/ha); 1.5 – 2.1 m (average ~70 day man hours/ha); 2.4 – 3.3 m (average ~50 day man hours/ha); and 3.6 – 4.5 m (average ~35 day man hours/ha) (@ 1 day = 8 hours). Trends for summer training actions showed a decrease in labour input with wider spacing. After shoot spacing and removal of grapes to one bunch per shoot, a more uniform labour input was required for harvesting. However, the very narrow spaced vines (0.3 – 0.6 m) still required higher inputs and spacing from 3.3 m and wider needed less.

Table 1. Vine purchasing costs, and labour for planting, summer training, shoot selection and harvesting of the Shiraz/101-14 Mgt vineyard, planted to different vine spacing.

Vine spacing (m)	Number of vines/ha	Vine purchasing (price/ha*) (2008)	Labour for planting (day man hrs/ha**)	Labour for training of young vines*** (day man hrs/ha)	Total labour required for planting & training (day man hrs/ha)	Vine shoot (spur) selection**** (day man hrs/ha)
0.3	15152	150459.4	303.0	119.8	422.8	8.84
0.6	7576	75229.7	136.4	50.3	186.7	8.77
0.9	5051	50156.4	101.0	65.7	166.7	6.77
1.2	3788	37614.8	83.3	40.8	124.1	8.11
1.5	3030	30087.9	68.2	45.2	113.4	4.63
1.8	2525	25073.3	70.7	24.3	95.0	5.04
2.1	2165	21498.5	63.2	24.9	88.1	3.32
2.4	1894	18807.4	50.5	26.3	76.8	3.07
2.7	1684	16722.1	48.0	21.3	69.3	3.51
3.0	1515	15044.0	42.9	20.3	63.2	3.42
3.3	1377	13673.6	50.5	20.3	70.8	2.95
3.6	1263	12541.6	35.4	14.6	50.0	2.85
3.9	1166	11578.4	37.9	12.1	50.0	3.64
4.2	1082	10744.3	32.8	21.9	54.7	2.07
4.5	1010	10029.3	35.4	20.0	55.4	1.40

*@R9.93/nursery vine (2008); **Calculated @1day = 8 hrs; ***Incl. topping, trunk suckering, selection and fixing of cordon arms; ****Includes shoot removal to select spur positions, cordon extension and bunch removal to 1 bunch/shoot.

Results on the bunch and shoot mass removed during shoot (spur) selection (suckering practice) and mass of bunches removed during bunch removal (to one bunch per shoot) from the young vines between berry set and pea size (mid-November 2010) are shown in Table 2. The bunch mass removed (along with the sucker shoots) increased from the narrowest spacing up to 1.2 m, kept stable between 1.2 m and 2.1 m, and then increased again to 2.4 m spacing, after which it remained more or less similar. The shoot mass (vegetative tissue) removed showed a similar initial increase up to 1.2 m spacing, where after it kept more or less stable. Bunch mass removed during bunch removal showed the same pattern than that observed when bunches were removed along with the shoots during suckering.

Table 2. Bunch and shoot mass removed during shoot (spur) selection (suckering) and mass of bunches removed during bunch removal during the season 2010/2011 on Shiraz/101-14 Mgt, planted to different vine spacing.

Vine spacing (m)	Number of vines/ha	Bunch mass removed during suckering			Shoot mass removed during suckering	Bunch mass removed during bunch removal		
		g/bunch	g/vine	g/m cordon	kg/vine	g/vine	g/m cordon	kg/ha
0.3	15152	5.03	10.41	34.70	0.12	2.36	7.87	35.76
0.6	7576	6.10	18.11	30.18	0.18	8.33	13.88	63.11
0.9	5051	4.86	26.68	29.64	0.16	12.11	13.46	61.17
1.2	3788	4.70	46.59	38.83	0.37	25.14	20.95	95.23
1.5	3030	5.31	46.80	31.20	0.31	30.05	16.69	92.42
1.8	2525	5.80	39.90	22.17	0.29	29.08	16.16	73.43
2.1	2165	5.65	46.28	22.04	0.39	29.41	14.00	63.67
2.4	1894	5.20	66.81	27.84	0.30	43.51	18.13	82.41
2.7	1684	5.31	64.87	24.03	0.40	41.29	15.29	69.53
3.0	1515	6.39	61.10	20.37	0.38	42.17	14.06	63.89
3.3	1377	4.86	43.87	13.29	0.31	34.25	10.38	47.16
3.6	1263	5.59	68.59	19.05	0.30	34.89	9.69	44.07
3.9	1166	5.35	79.54	20.39	0.54	47.06	12.07	54.87
4.2	1082	5.07	90.70	21.60	0.38	62.36	14.85	67.47
4.5	1010	5.10	59.45	13.21	0.29	41.70	9.27	42.12

The data on labour inputs for pruning and harvesting from 2011 onwards showed that, except for a trend towards lower values for wider spaced vines (especially for pruning/ha and grapes harvested/ton), the hours required were reasonably similar for all treatments but varied according to the season (Table 3). This indicates that spurs were largely distributed uniformly, irrespective of plant spacing. The pruning time for vines that were narrowly spaced, however, may have increased because of compensatory (lateral/secondary shoot) growth after topping of the primary shoots in summer; this might have affected the labour time for cleaning of canes from the trellis wires. The data on harvesting time per hectare showed slightly higher values with wider spacing, whereas the reverse seemed to occur for the labour hours required for harvesting a ton of grapes. For the former, this is different from that found during the previous years. The pruning and harvesting figures indicate general uniform development, implying that there would be no need for differential canopy-related management practices, such as shoot positioning, leaf removal, tipping/topping, spraying, etc.

Table 3. Labour for pruning (2011 – 2019) and harvesting (2011 – 2020) of Shiraz/101-14 Mgt, planted to different vine spacing.

Vine spacing (m)	*Pruning (day man hrs/ha)								
	2011	2012	2013	2014	2015	2016	2017	2018	2019
0.3	19.86	14.62	16.24	18.01	9.49	8.30	8,51	6,93	10,2
0.6	12.18	12.59	11.97	13.34	7.71	6.28	7,55	6,58	8,5
0.9	12.17	11.34	11.05	14.26	7.43	6.60	6,47	5,76	8,4
1.2	10.42	10.93	10.02	12.43	7.24	6.07	6,24	5,65	7,5
1.5	9.21	10.24	9.91	13.07	7.18	5.99	5,74	5,24	7,4
1.8	10.57	10.31	9.66	11.92	7.13	6.18	6,38	7,78	7,8
2.1	12.27	9.41	10.15	11.39	6.73	5.45	6,49	4,88	8,5
2.4	12.69	10.40	10.11	12.19	6.52	5.49	5,91	4,75	7,4
2.7	11.03	10.00	9.93	12.54	6.54	6.00	6,15	5,10	7,7
3.0	10.85	7.79	7.28	11.76	6.75	5.12	5,44	5,22	7,4
3.3	9.01	9.17	9.41	12.11	6.02	5.34	5,94	4,81	7,6
3.6	10.73	10.35	9.49	12.61	6.64	6.54	5,65	5,10	7,1
3.9	10.52	8.99	9.60	11.55	6.64	4.85	4,96	4,74	6,5
4.2	14.19	10.27	10.44	11.50	6.87	5.35	6,05	5,39	7,4
4.5	9.63	9.28	9.44	11.99	6.65	5.58	6,06	4,53	6,9

Vine spacing (m)	*Harvesting (day man hrs/ha)										Harvesting (man hrs/ton grapes)									
	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
0.3	3.26	11.95	17.32	18.77	12.58	12.91	13.04	10,12	10,99	12,45	7,45	12,42	8.31	11.20	9.06	9.05	9.29	7,05	15,53	13,49
0.6	3.49	13.44	17.86	17.57	11.74	15.00	11.75	8,87	9,41	12,80	6,16	9,11	7.33	8.45	8.42	8.32	7.55	5,28	11,93	11,65
0.9	2.54	13.23	16.46	17.92	11.71	13.48	11.95	12,93	9,19	14,14	5,26	9,12	6.42	7.55	8.39	6.97	7.07	6,33	10,92	11,88
1.2	2.40	13.25	20.66	17.63	13.49	14.43	13.22	13,38	8,74	15,95	5,07	8,03	6.35	6.38	8.13	7.29	6.93	6,41	9,42	9,92
1.5	2.20	12.17	16.47	17.96	12.40	12.38	12.51	14,17	9,30	15,94	5,00	8,05	5.90	6.55	8.73	6.25	6.46	6,05	8,10	8,79
1.8	2.25	13.58	14.62	15.99	13.18	15.46	11.17	12,66	9,53	15,01	5,44	7,76	4.26	5.34	8.66	7.11	6.54	5,85	11,70	9,20
2.1	2.29	13.36	19.33	17.35	10.72	12.86	13.61	11,63	8,98	14,20	5,71	6,94	5.62	6.17	8.18	6.01	7.30	5,68	11,09	8,85
2.4	1.80	12.53	16.27	13.25	12.37	12.81	12.42	12,45	9,32	15,59	5,27	6,77	4.66	4.92	8.18	5.85	6.45	5,86	10,00	7,90
2.7	2.17	13.06	17.99	12.65	13.32	14.36	12.00	15,33	11,00	13,99	5,58	5,94	5.80	4.81	8.54	6.36	6.38	6,13	9,57	7,69
3.0	2.15	11.10	15.19	16.32	13.31	13.66	10.77	11,43	8,06	15,00	5,71	6,99	5.94	5.88	8.51	6.21	5.42	5,01	8,28	8,41
3.3	1.30	12.82	17.38	15.33	10.75	12.93	10.49	13,45	8,82	14,79	5,59	5,96	5.16	5.02	7.41	5.49	5.39	5,35	10,12	7,41
3.6	1.51	11.45	14.39	14.05	12.46	12.48	11.39	14,79	7,37	14,09	6,43	6,89	5.10	5.50	8.45	5.93	5.73	6,22	9,78	8,93
3.9	1.47	12.84	15.00	16.68	11.33	13.16	10.33	15,65	9,63	16,92	4,80	5,58	5.34	5.74	8.21	5.71	5.47	5,95	8,88	7,36
4.2	1.42	13.60	16.21	17.70	11.12	13.32	11.33	15,39	10,41	19,01	4,96	5,76	4.73	5.03	8.71	5.65	5.05	5,70	9,73	7,44
4.5	1.18	13.50	14.26	15.36	11.18	11.91	10.05	15,09	8,87	16,12	4,89	6,55	5.15	5.35	8.73	5.37	5.14	5,13	8,23	7,16

*Calculated @1 day man hr = 8 hrs.

The collective vine purchasing cost, total labour required for planting and young vine training, cumulative pruning and harvesting time, and cumulative yield for different vine spacing treatments show very clear return trends with turning points around 1.5 - 1.8 m vine spacing (Fig. 3). Figures on cost, labour and yields give a rough estimate of what may be expected when a specific vine spacing is selected. This would change from farm to farm, depending on farm conditions and level of training of the labour force, etc. Furthermore, the gross difference would only be valid if all other costs are generalised and standardised; total cost of production needs to be considered, i.e. interest, tax, entrepreneurial remuneration, provision for renewal and cash expenditure. With reference to the latter, other cost components, such as direct costs (fertilisers; compost; pesticides; insecticides; herbicides; cover crop seed; repair and binding material), labour (canopy management; supervision; permanent, seasonal, and contract labour salaries, wages and provision), mechanisation (fuel; repair parts and maintenance; licenses and insurance; hired transport), fixed improvements (repair and maintenance; insurance) and general overhead expenditure (electricity tariffs; water tariffs; administration costs; petty items; land-, property- and municipal taxes) should also be taken into account. Vine spacing selection requires overall sustainability consideration that includes cost and market implications of the intended produce.

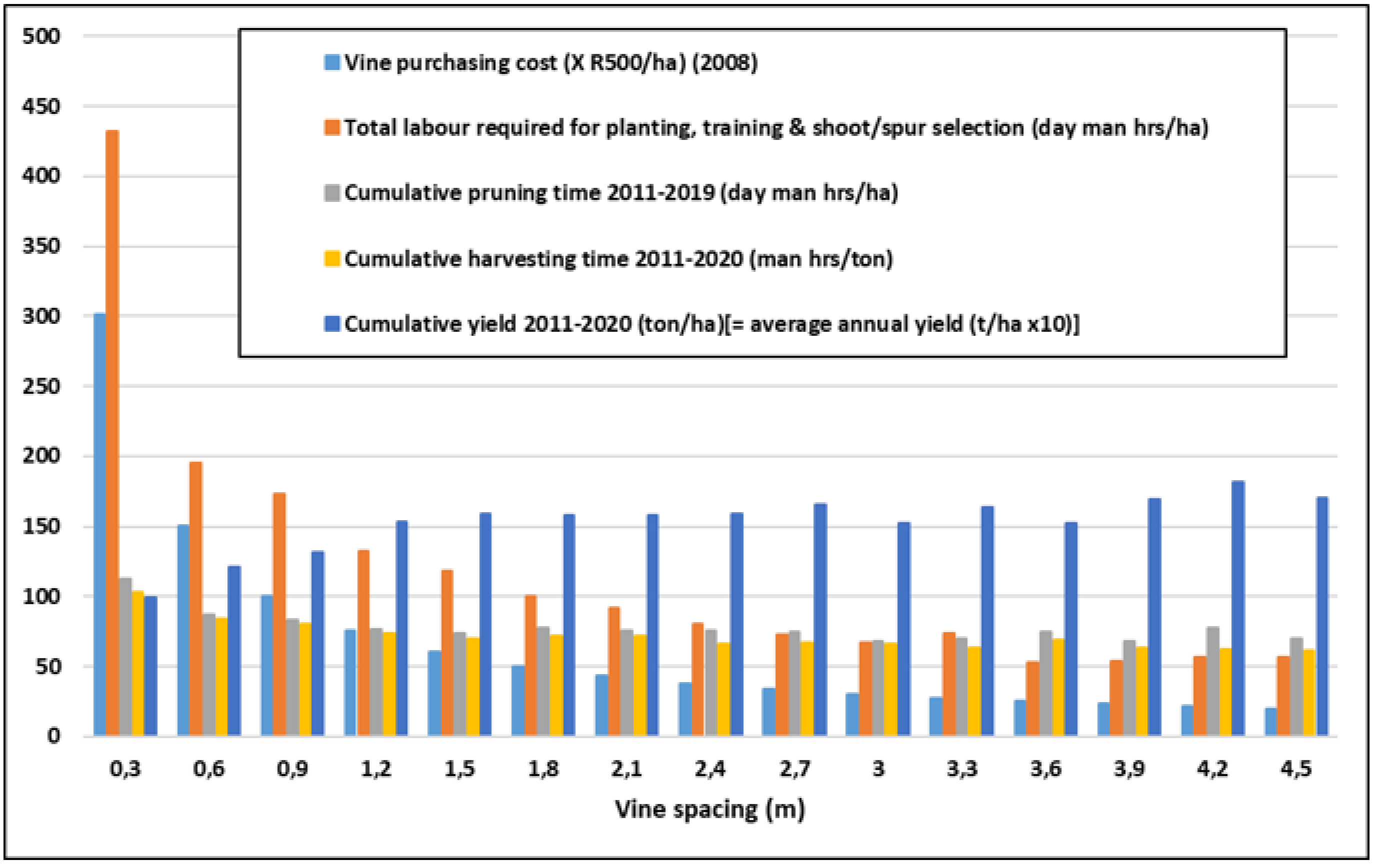


Fig. 3. Collective figure showing grafted vine purchasing cost, total labour required for planting and young vine training, cumulative pruning and harvesting time, and cumulative and annual yield (at ripeness level 1) for the different vine spacing treatments.

Root development

Previous vine spacing research done on Pinot noir/99 Richter (Archer & Strauss, 1985; Hunter, 1998a) showed that the limitation (because of the presence of the root system of adjacent vines) to closely spaced vines on soil volume availability steered the root system into a more vertical penetration angle, whereas wider spacing resulted in more horizontal development. Intra-row space had a higher restrictive bearing on root system distribution than inter-row space. The closer the vines were spaced the more the density of the root system and the ratio of fine:thick roots increased; this also led to a naturally higher water and nutrient absorption by the root system and a higher vine starch depletion or lower starch accumulation (Hunter, 1998a), the latter indicating preferential sucrose export instead of transitory starch formation, thereby actively supporting seasonal aboveground growth, grape development and fine root formation. A root system with a higher fine root component would also increase hormone production, such as cytokinins, thereby regulating shoot and fruit development (Richards, 1983), whereas the soil environment-induced stress enhancement would stimulate abscisic acid formation in the xylem sap (Hunter, 1998b), thereby regulating stomatal movement, transpiration, photosynthetic activity and water relations, amongst others. However, in the previous research both vine spacing and row spacing were changed. In this experiment on Shiraz/101-14 Mgt, vine spacing was the only variable. The other major difference between the previous and this research (except for variety and rootstock), is the difference in soil fertility and depth as well as irrigation volume, the former having been done on a medium potential, relatively shallow Glenrosa soil and vines either being grown under dryland conditions or only being supplementary irrigated at

pea size and at véraison.
Root development of the different vine spacing treatments over an 11-year period of the experiment is shown in Fig. 4. It clearly shows the increase in root density with closer spacing, particularly in the fine, extension and permanent categories, thereby increasing the total number of roots and confirming the trends found with previous research. Considering the number of roots per grape mass and per cane mass, the optimum appeared to be reached at approximately 1.8 m spacing, followed by a plateau, and further change with very wide spacing. The number of roots/kg grape mass varied from 600 – 100 (and 1600 – 1100/kg cane mass) from the narrowest to the widest spacing, with approximately 180 being the requirement for a wide range from 1.5 – 3.6 m vine spacing and that for 1.2 m spacing being just more than 200. Although these figures are not universally applicable (because of the likely effects of soil, climate, variety and rootstock on general growth and root system dynamics), they should be judged by producers as indicators of the importance of a proper root system to support grape development as well as the necessity of creating judicious aboveground:subterranean growth ratios/balances, along with crop load.

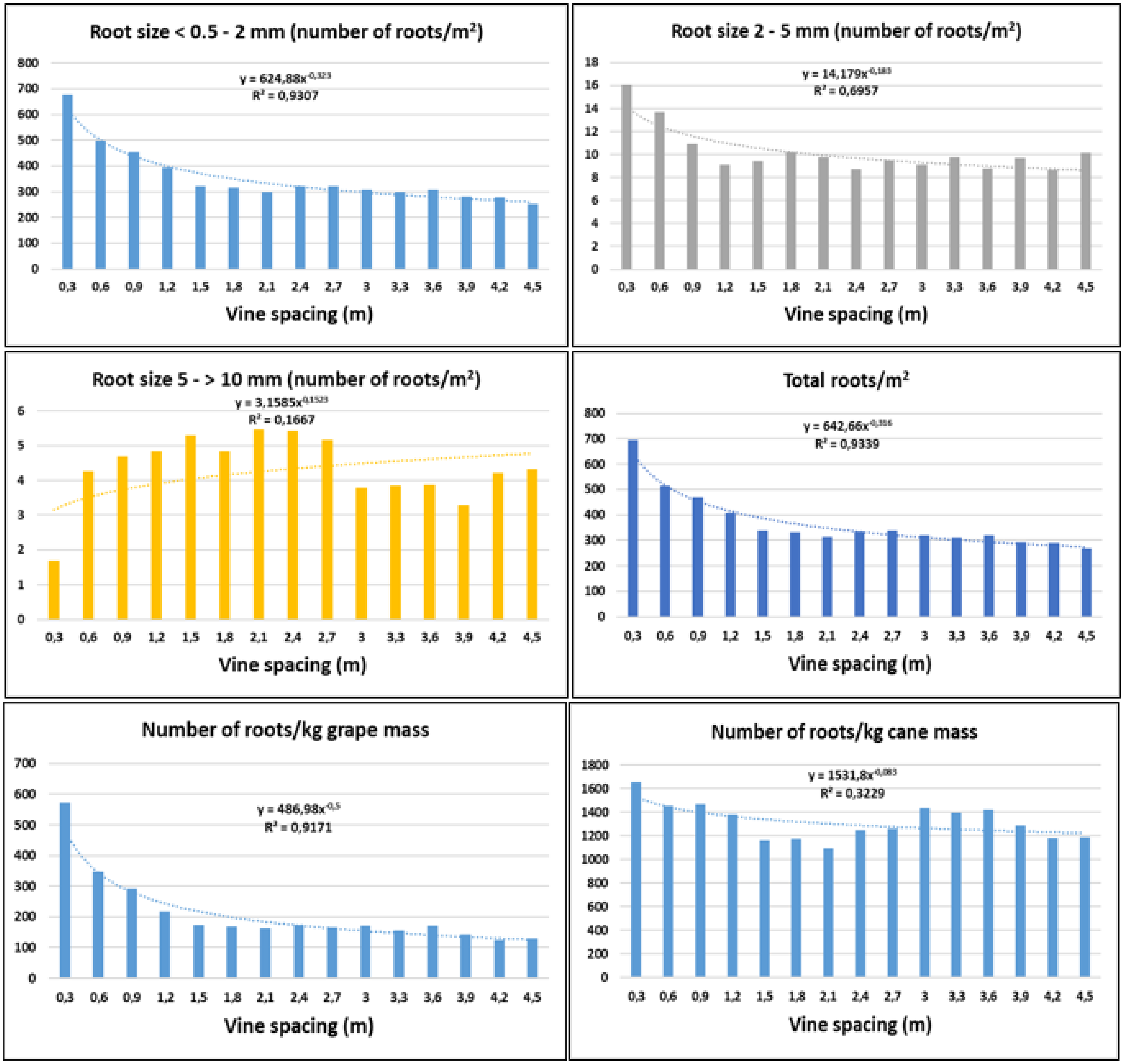


Fig. 4. Vine spacing effect on the development of different root sizes, total number of roots, and the ratios between roots and grape and cane mass of Shiraz/101-14 Mgt.

The most roots were found in the 0 – 120 cm deep soil layer, beyond which the number of roots decreased drastically (Fig. 5). The data shows higher root numbers of the narrower spaced vines (< 1.5 m) in the deeper soil layers, demonstrating that their roots penetrated at a steeper angle towards deeper soil layers. Interestingly, despite the root density differences amongst the different spacing treatments, the lateral development shows an almost uniform distribution for each spacing within their separate confined spaces. Root density and depth appeared to be most affected by spacing. The results confirm the steering effect of vine spacing on the development of the root system and validate the hypothesis that the deeper and more fertile, clay-loam soil conditions in this experiment allowed the roots to explore the deeper soil layers and to compensate for the lateral space restriction, induced by the root systems of the adjacent vines, especially in the case of the narrower spaced vines. The data is clear evidence of the dynamic responsive nature and regenerative ability of the root system. Higher root density may lead to higher localised water depletion per soil volume, which may be enhanced in environments where high ambient temperatures prevail. Although a lower leaf water potential would be expected under such conditions compared to wider spacing, vines may react by closing stomata to reduce water loss *via* transpiration under conditions of water deficit. However, under moderate water supply growth may be stimulated, which may lead to a more shaded canopy that in turn would have a further restrictive effect on leaf activity (Kriedemann, 1973; Düring, 1991; Hunter *et al*., 2014, 2020) when vines are very closely spaced under vigorous growth conditions. On the other hand, a more open canopy would naturally lead to higher leaf activity (Hunter & Visser, 1988), unless it is too open, leaf senescence and photo-inhibition occur, water stress prevail and stomatal movement is restricted (Hunter & Visser, 1989).

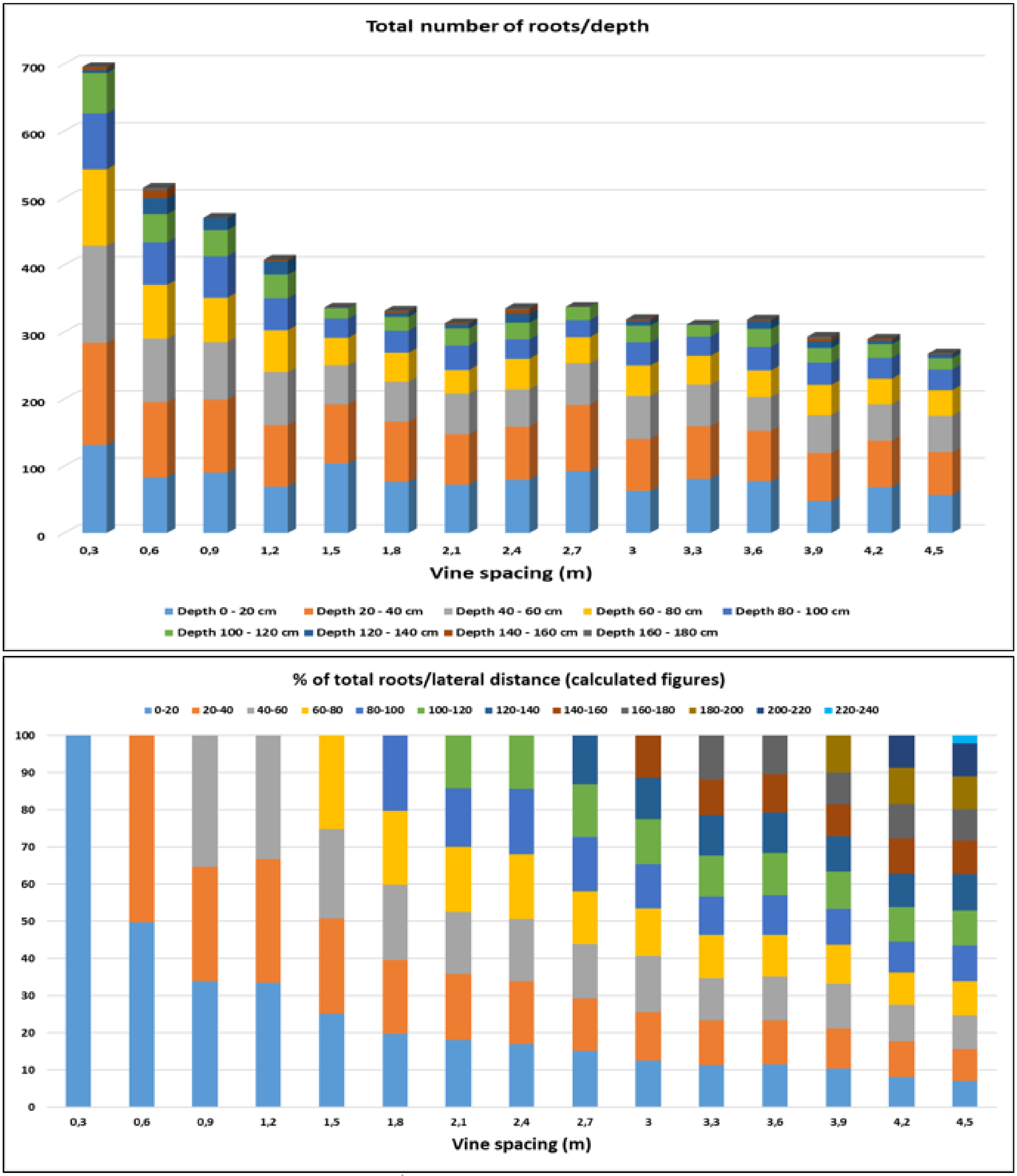


Fig. 5. Vine spacing effect on the development of roots in different soil layers (vertically and horizontally) for Shiraz/101-14 Mgt.

Microclimate and Physiological parameters

Light microclimate (photosynthetic active radiation – PAR) in the upper and lower zones of the canopy followed an increasing trend from narrow to wide spacing (Fig. 6), indicating a difference in canopy density between narrower and wider spaced vines, regardless of the uniform spur distribution across treatments. Mid-day stem water potential values (negative) at pre- and post-véraison stages followed an ostensible decreasing trend, i.e. increasing water stress, towards wider vine spacing (Fig. 7). At the same stages, photosynthetic activity showed very little movement with a change in spacing, despite an apparent increase in PAR with wider spacing (Fig. 8). Considering the PAR and stem water potential trends, photosynthetic activity of the leaves seemed to display the contrasting (and in this case counteracting) effects of PAR and water potential, the former generally having stimulating and the latter having reducing effects. Although an ageing canopy towards harvest time would have been a secondary contributing element to both effects, these two major, but generally opposite, impacting factors ostensibly had an almost equalizing consequence on the photosynthetic activity of the leaves.

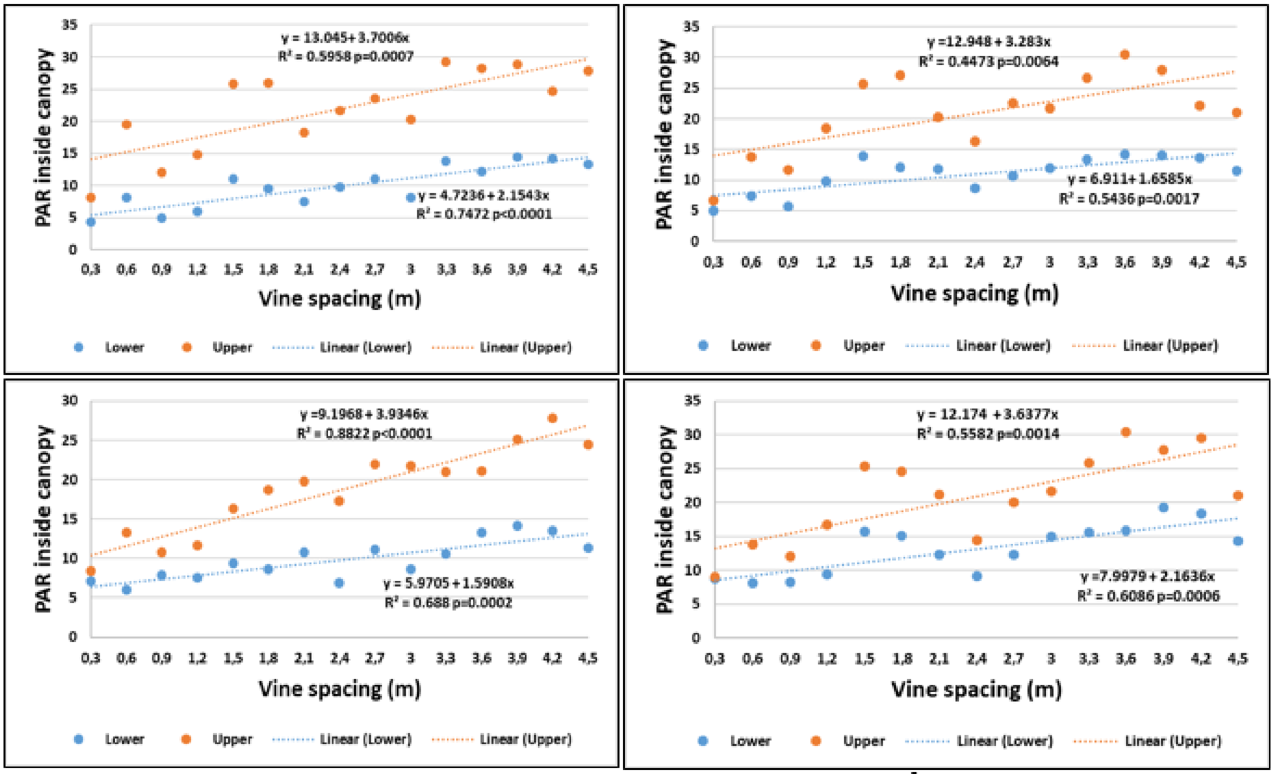


Fig. 6. Photosynthetic active radiation (PAR) (% of ambient – measured as μmol/m^2 /s) [pre-véraison (top) and post-véraison (bottom); morning (left) and afternoon (right)] in the bunch zone and upper zone of the canopy of Shiraz/101-14 Mgt (means of 2014 - 2020 seasons).

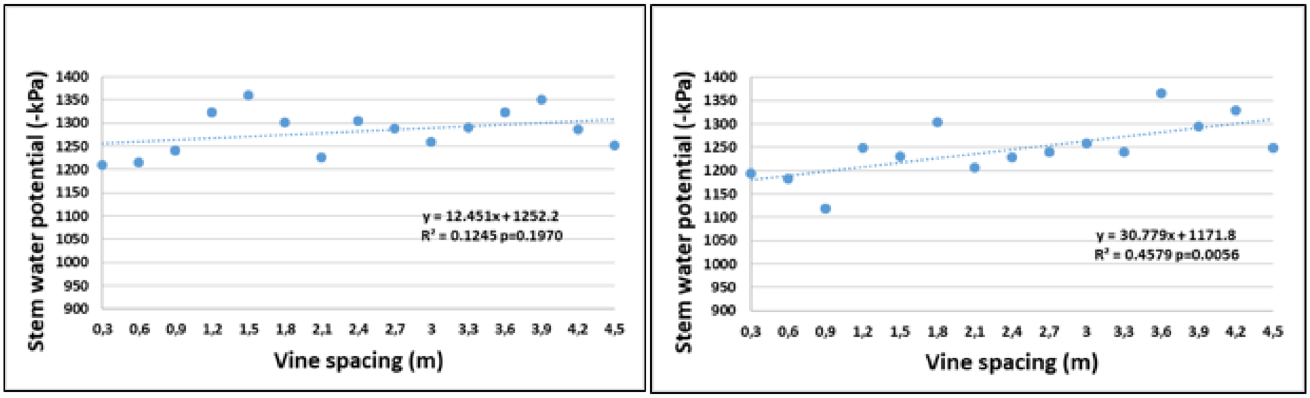


Fig. 7. Stem water potential [(pre-véraison (left) and post-véraison (right)] of Shiraz/101-14 Mgt (means of 2014 - 2020 seasons).

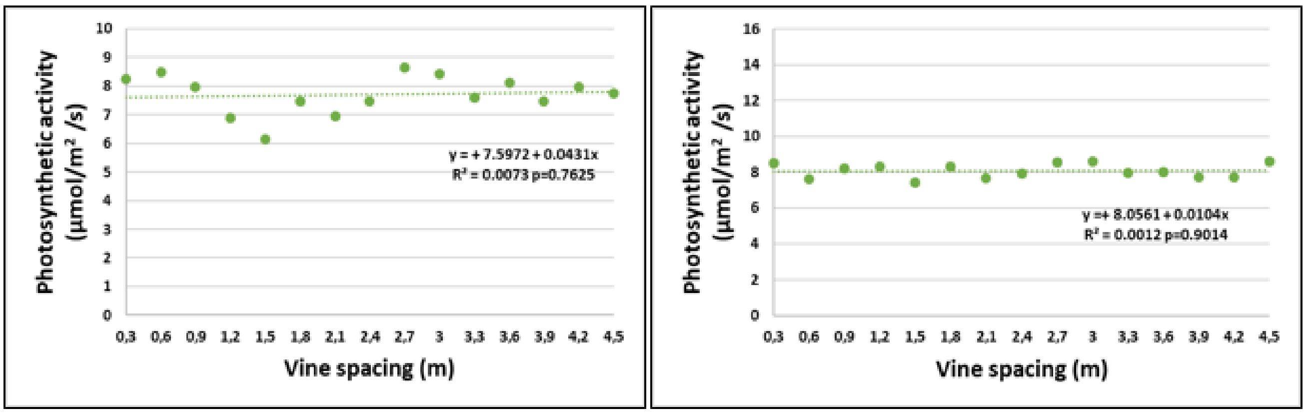


Fig. 8. Photosynthetic activity [(pre-véraison (left) and post-véraison (right)] of Shiraz/101-14 Mgt (means of 2014 - 2020 seasons).

The stomatal conductance, transpiration and vapour pressure deficit trends paralleled the findings on photosynthetic activity (data not shown). At the same time, the internal [CO_2] decreased with wider spacing, whereas the leaf temperature in the bunch zone increased with approximately 1.5 °C from narrow to wide treatments. The predicament of the vines surfaced from the amount of water transpired per photosynthetic output, showing a straight, horizontal line from narrow to wide spacing during both the active growth period and during the later stages of grape ripening when canopies were already senescing (data not shown), despite the better exposed canopies of wider spaced vines (Fig. 6). This indicates progressively higher water use and/or water loss per unit of photosynthesis with wider vine spacing or vines were metabolically inhibited to utilise available water for a similar photosynthetic output. The vines therefore did not show the expected response of higher water use efficiency during the active canopy period (more or less until véraison) that is normally driven by a better canopy microclimate. The abiotic environment (e.g. higher temperatures) and gradual ageing of the leaves with further grape ripening ostensibly reduced its water use efficiency, despite the positive radiation and the increasing sink demand for sucrose production (*via* photosynthesis) during this period, e.g. transport to and accumulation in the berries (Coombe, 1992; Hunter *et al*., 1994; Hunter *et al*., 2014; Carlomagno *et al*., 2018). Many factors that are important for optimal physiological performance, such as water status, light microclimate, ambient temperature, canopy activity, sugar distribution, sink demand, source supply, etc., may therefore have counterbalanced each other and affected the net physiological activity and supply to reproductive and reserve organs.

Vegetative and Reproductive parameters

Cane mass per vine and per surface area followed an increasing and decreasing trend, respectively, from narrowest to widest plant spacing (Fig. 9). The cane mass/vine trend corresponded to the decreasing cane mass per shoot length and linear increasing trunk circumference with wider spacing (Fig. 10), pointing to opposite responses of the seasonal and perennial growth structures of the vine. The former indicates weaker, and the latter stronger growth. A decrease in trunk diameter with higher density planting confirms the findings of Archer & Strauss (1991) on P. noir as well as those found for Citrus (Wheaton *et al*., 1995). Spacing the vines equally farther apart induced an initial almost linear seasonal vegetative reaction, but this response faded from approx. 2.1 m and no further movement occurred from 3.0 m and wider. The growth response and increase in spacing increment therefore became increasingly dissimilar. Vine carbon allocation seemed affected by distance between vines. The cane mass/ha is in line with the number of roots/ha.

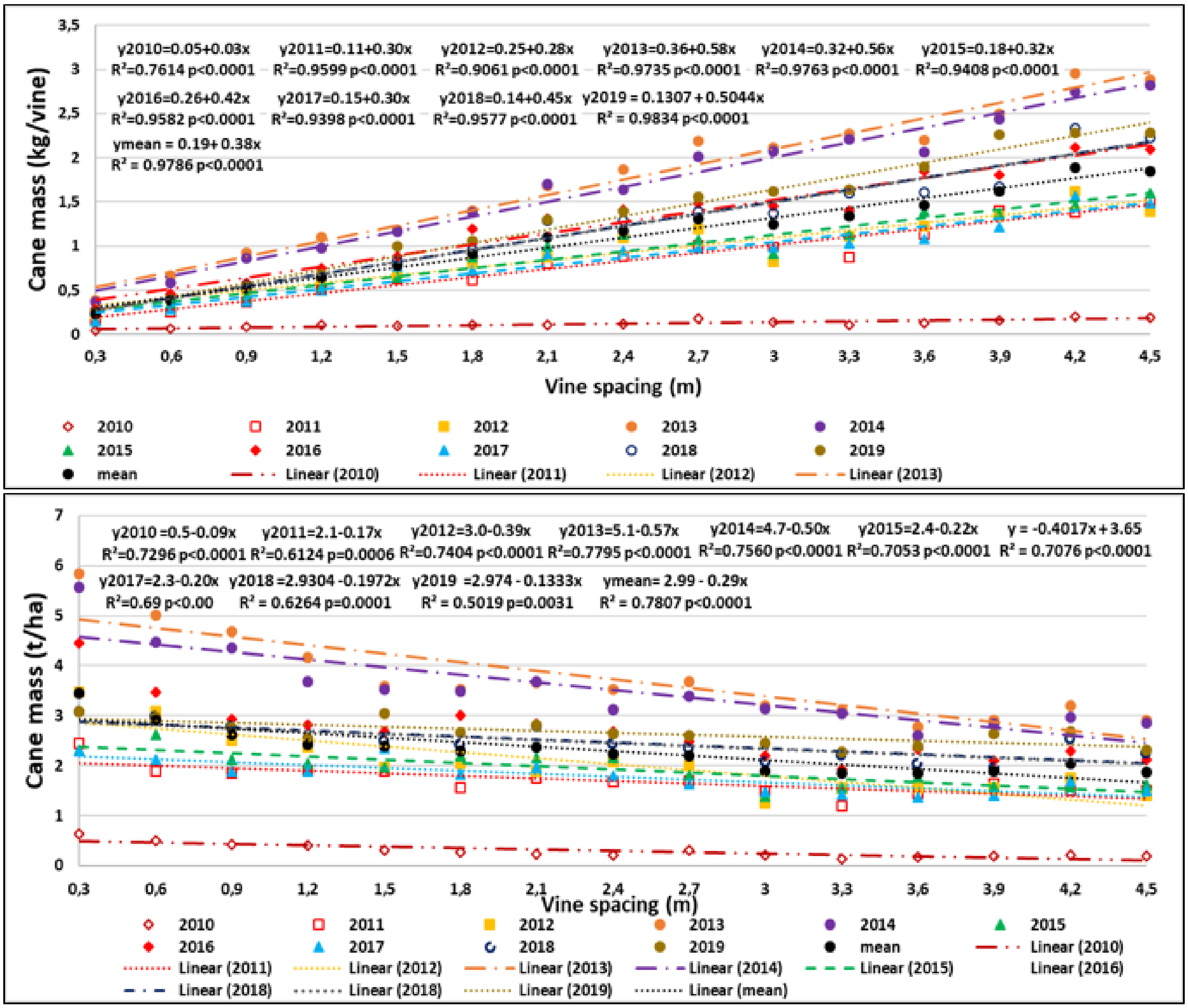


Fig. 9. Cane mass (per vine, top; per ha, bottom) of Shiraz/101-14 Mgt (2010 – 2019 seasons).

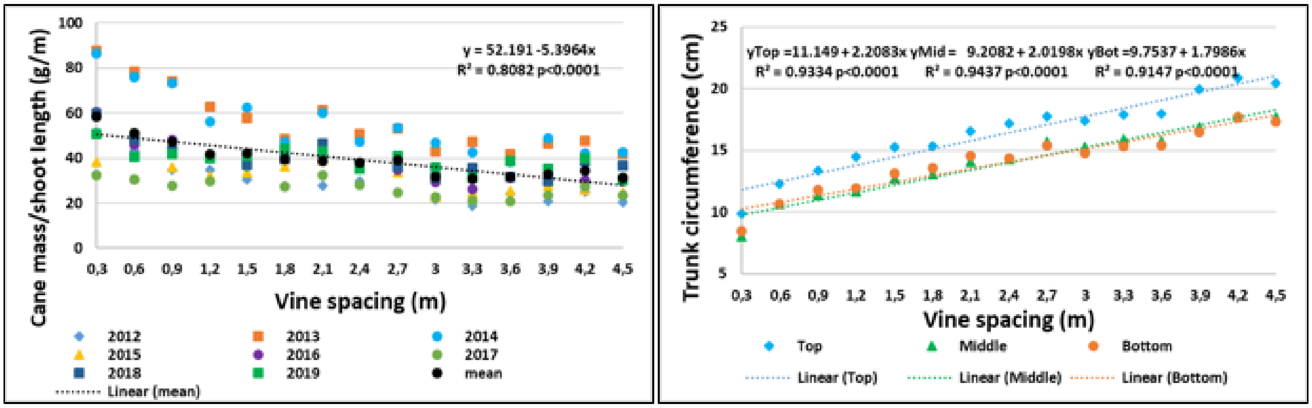


Fig. 10. Cane mass/shoot length (means 2012 – 2019 seasons) and trunk circumference (means of 2016 – 2019 seasons) of Shiraz/101-14 Mgt.

Although annual yields increased linearly from narrow to wide spacing, cumulative yields of the last five years harvested at the first ripeness level exhibited highest yield gain up to approximately 1.5/1.8 m spacing on a surface basis, after which no further gain was observed (except for the three widest spacing treatments) (Fig. 11). The turning point was apparently reached earlier at the first than at the second ripeness level. At the latter ripeness level, a flatter, linear increasing curve occurred that seemed to stabilise at 2.7 m spacing, beyond which available space for vine development seemed in discordance with yield obtained per surface area. The yield/ha followed an opposite trend to that of the cane mass/ha and the number of roots/ha. Thus, although the vegetative growth (canopy and roots) responded seemingly sufficiently to the narrower spacing, yields did not react in the same way, most likely because of physically insufficient space for bearing bunches and allocation of buds on the cordon. Yield responses occurred in spite of fertility and bunch mass showing increasing trends from narrow to wide spacing treatments and bunches of narrow spaced vines showing more compactness (data shown in Tables 6 & 7). This has significant implications from a material cost/establishment point of view.

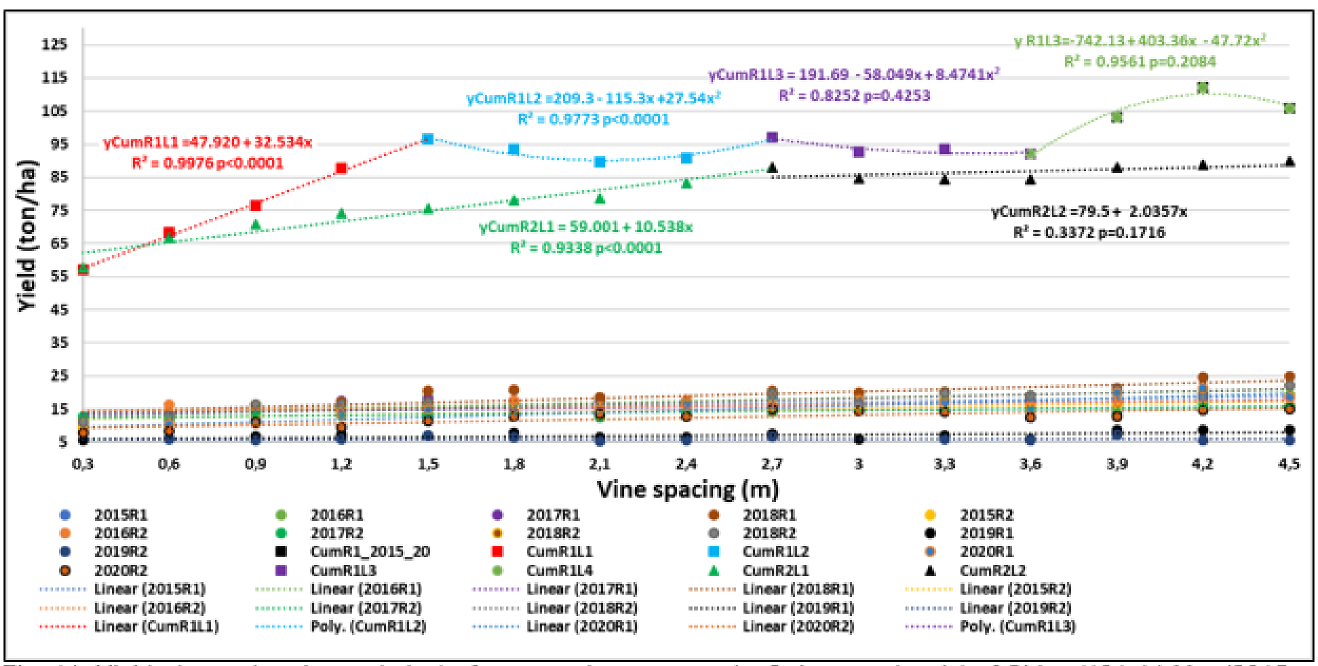


Fig. 11. Yields (annual and cumulative) of consecutive seasons (at 2 ripeness levels) of Shiraz/101-14 Mgt (2015 – 2020 seasons).

Substantial yield losses occurred with hang time (from first to second harvest). This is an aspect that should be considered when grape prices between growers and buyers are negotiated and when wine price points are fixed. The phenomenon is commonly found for Shiraz and most likely occurred as a result of continued berry transpiration, sluggish refill or even termination of water supply to the berry, and the resultant berry shrivel (Hunter *et al*., 2014, 2018; Carlomagno *et al*., 2018). Berries are more sensitive towards vine water relations during pre-véraison than during post-véraison, but berry transpiration has a significant role to play during both periods, especially late ripening. At véraison, congruent with an apparent xylem disruption, phloem sap becomes the source of water and solutes for the berry until maximum berry mass is attained. The phloem pathway thus becomes dominant compared to the xylem pathway. The continuation of berry transpiration and progressive isolation of the berry from vascular support, then lead to shrinking of the berry and/or solute concentration, depending on the vine physiological activity, physical dimensions of the canopy and environmental conditions, with the latter being a very important factor. In general, excessive shrivelling of the berry is not considered favourable for quality grapes and wine. Together with the unavoidable loss in grape mass with hang time, the development of a shrivelled grape condition should be evaded by both growers and winemakers to prevent a detrimental effect on grape and wine quality. The difference in yield trends between ripeness levels indicate that treatments with more open canopies/less growth per shoot (wider spaced vines) seemed more prone to yield loss with progressive ripening. Yields per cordon space/length (expressed on a per hectare basis) showed an initial fast decline from very narrow to approx. 2.4 m spacing, where after a slight further decrease occurred with wider spacing - this trend is reversed when yields per cordon space are expressed on a per vine basis (data not shown).

Vegetative growth parameters showed that individual primary and secondary leaves were larger with narrower vine spacing and that leaf size decreased from narrow to wide spacing, with a turning point at around 3.0 m, where after a slight upward curve was observed (Fig. 12). The primary:secondary leaf area ratio increased with wider spacing, as secondary leaf area/primary shoot showed a decreasing trend from narrow to wide spacing, thereby demonstrating a compensating response to more vigorous growth and most likely the physically restricted available growth volume with narrow spacing (Tables 4 & 5). This is in line with the lower light microclimate found for closer spaced vines (Fig. 6). As spur spacing was kept constant, this morphological response may be an explanation for differences in canopy density/appearance and light microclimate as shown/discussed earlier.

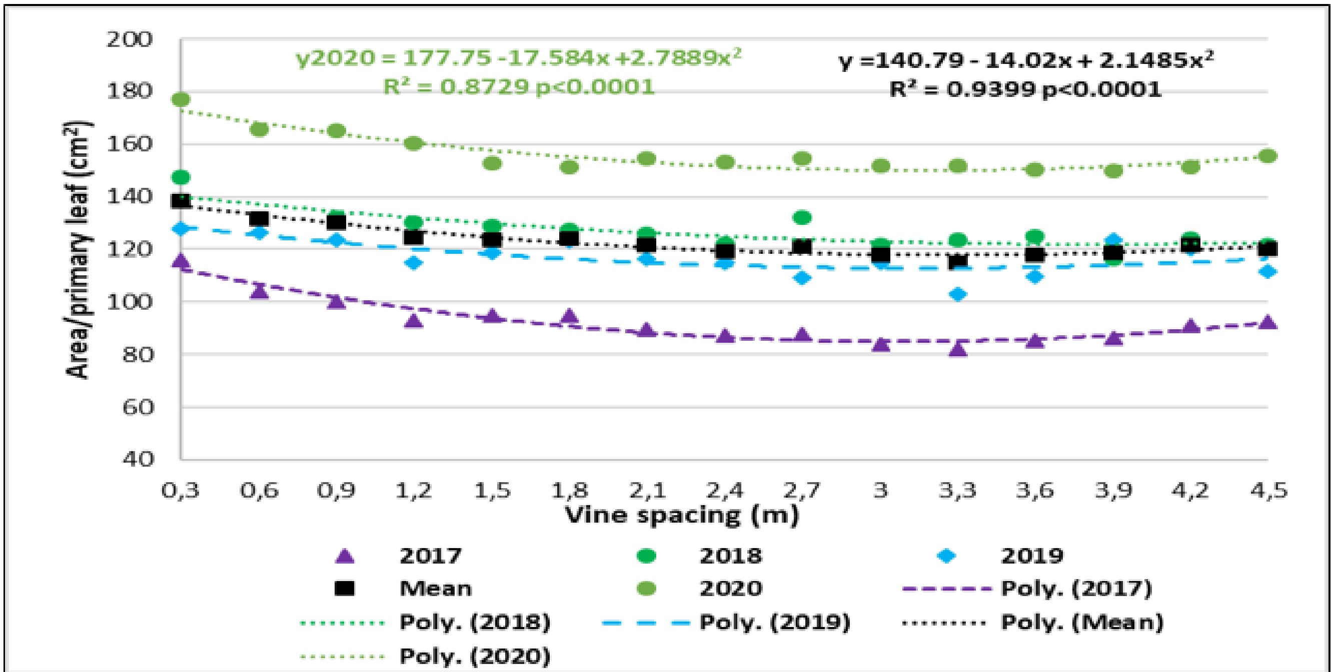


Fig. 12. Area/primary leaf of Shiraz/101-14 Mgt (2017 – 2020 seasons).

The total leaf area/vine showed a general stepwise increase from narrowest to widest spacing (data not shown), but total leaf area/grape mass showed a general decreasing trend from narrow to wide spacing with an apparent turning point around 2.1 m (Fig. 13). The increase in total leaf area/grape mass at the second *versus* the first ripeness level did not prevent the loss in yield (most likely as a result of berry shrivel) with hang time, providing evidence of the limited transport to the grapes at this stage. Yield/cane mass (Fig. 14) followed an increasing trend from narrow to wide spacing, similar to cane mass/vine (Fig. 9) and trunk circumference (Fig. 10); a stepwise increasing pattern and a plateau for the widest spacing treatments are recognisable, whereas definite joint points appeared at 1.8/2.1 m and at 3.3 m spacing.

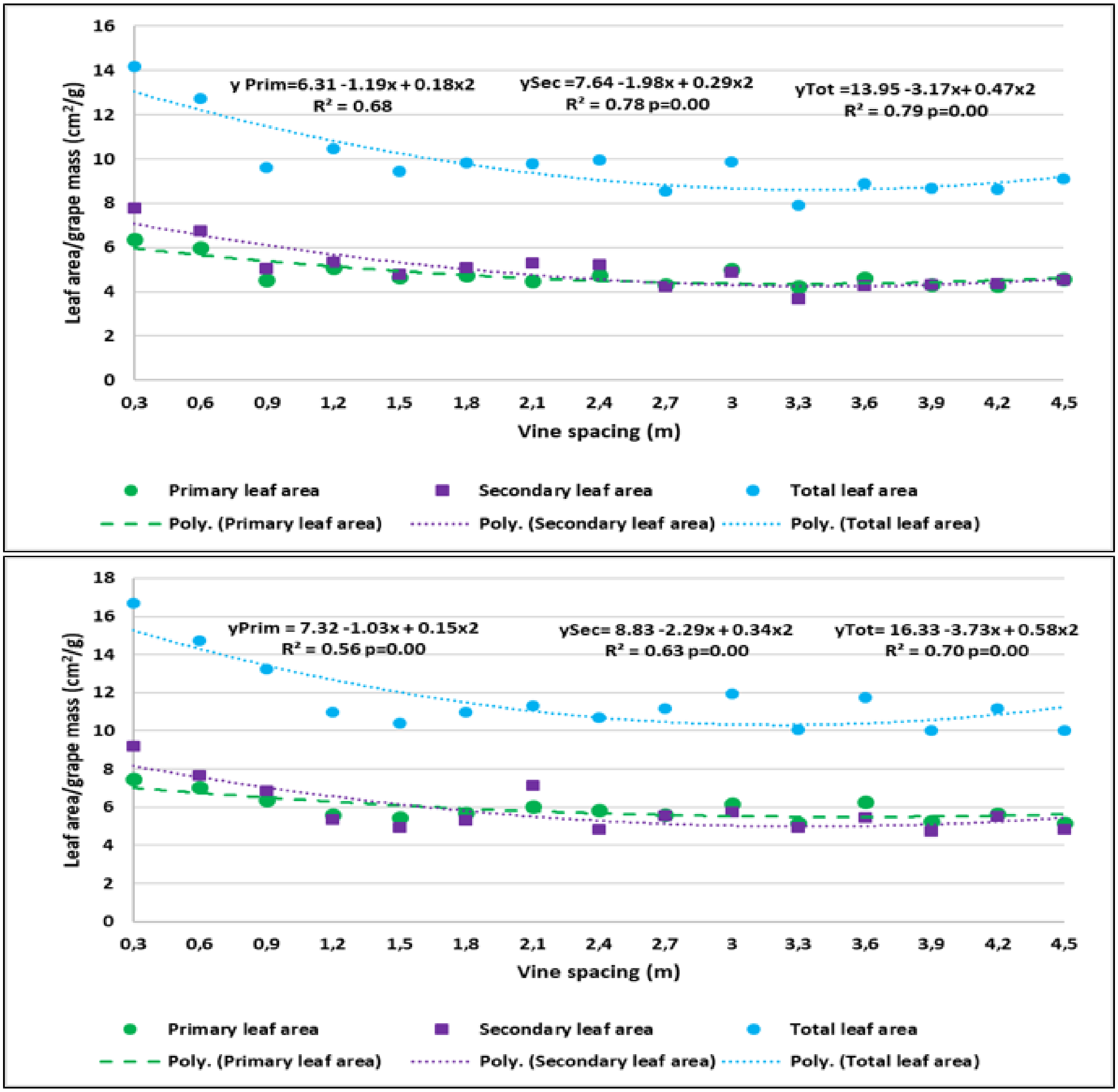


Fig. 13. Leaf area/grape mass (Ripeness level 1, top; Ripeness level 2, bottom) of Shiraz/101-14 Mgt (means of 2012(R1)/2015(R2) – 2019 seasons).

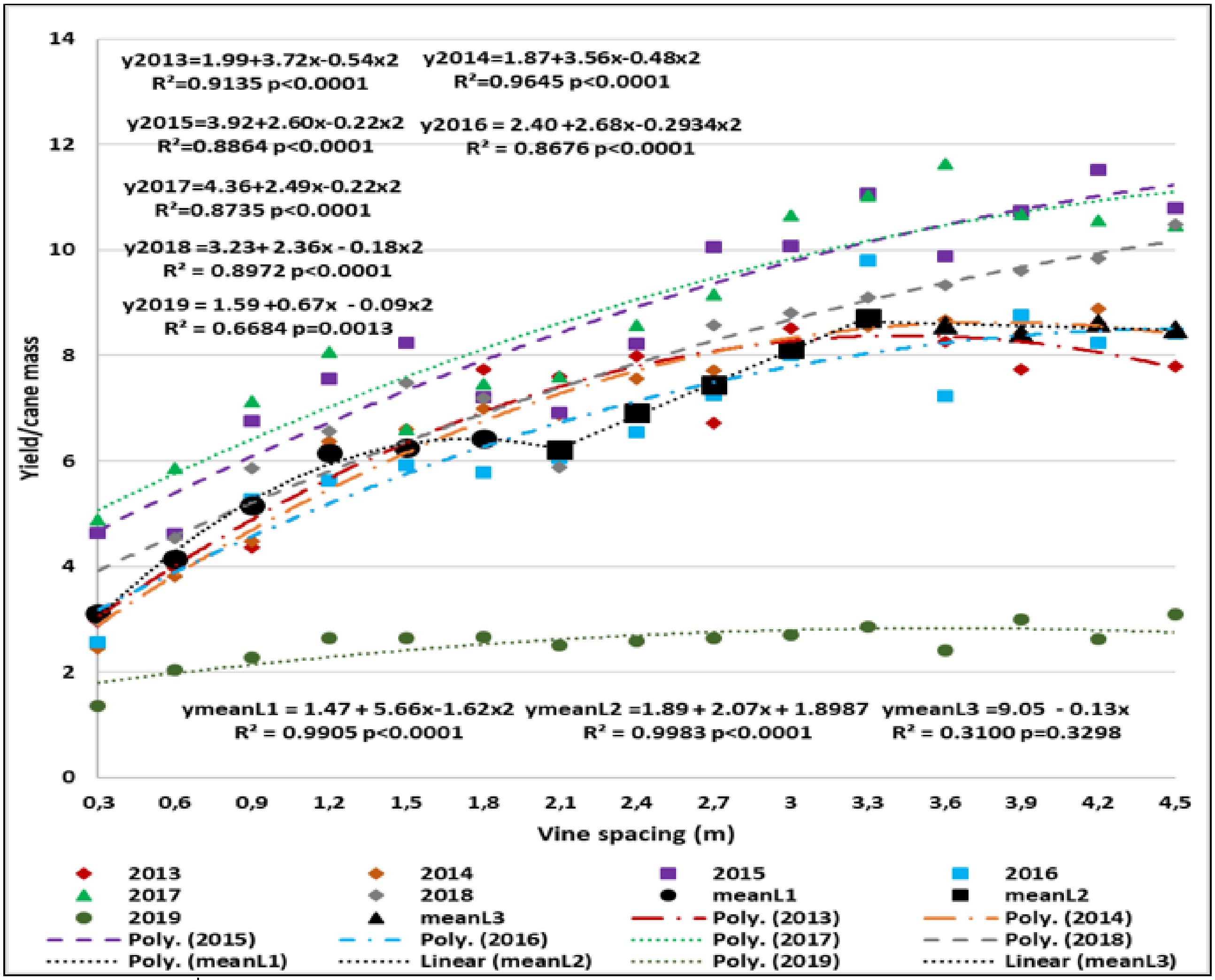


Fig. 14. Yield/cane mass (calculated from ton/ha - Ravaz) (either from single harvests or an average of two harvests, where applicable) of Shiraz/101-14 Mgt (2013 – 2018 seasons).

Further details of the vegetative and reproductive growth of the 2012 - 2019 seasons (Ripeness level 1) and the 2015 - 2019 seasons (Ripeness level 2) are presented in Tables 4 – 7.

Table 4. Vegetative growth parameters (primary & secondary shoots) at grape ripeness level 1 of Shiraz/101-14 Mgt. planted to different vine spacing (means of 2012-2019).

Vine spacing (m)	Number prim. leaves/ shoot	Prim. leaf mass (g)	Prim. leaf area/ shoot (cm²)	Prim. shoot length (cm)	Prim. leaf area/ vine (cm²)	Number sec. shoots/ prim. shoot	Number sec. leaves/ prim. shoot	Sec. leaf area/ prim. shoot (cm²)	Sec. leaf area/ vine (cm²)	Total leaf area/ shoot (cm²)	Total leaf area/ vine (cm²)	Leaf area Prim.: Sec. ratio	Total leaf area: yield ratio
0.3	9,57	3,43	1528	115,6	462	8,28	32,23	1862	7448	3390	13561	0,98	20162
0.6	11,15	3,14	1560	115,4	923	9,21	33,96	1781	14251	3342	26734	1,06	17061
0.9	10,94	2,90	1450	109,1	1310	8,27	29,36	1588	19054	3038	36451	1,02	14528
1.2	11,54	2,96	1560	115,0	1839	8,95	29,75	1563	25005	3123	49972	1,13	12440
1.5	11,99	2,97	1549	112,3	2246	8,99	31,11	1630	32601	3179	63577	1,17	11932
1.8	12,04	2,77	1523	114,9	2759	8,65	29,94	1650	39596	3173	76147	1,04	12293
2.1	11,00	2,95	1462	109,8	3074	8,95	32,21	1747	48909	3208	89836	0,95	13692
2.4	11,45	2,95	1563	114,4	3659	9,64	31,53	1750	56013	3296	105462	1,02	12785
2.7	12,66	2,76	1569	110,7	3985	8,72	29,14	1539	55417	3108	111886	1,20	10814
3.0	13,66	2,60	1621	116,5	4659	9,18	30,81	1510	60420	3131	125256	1,38	12036
3.3	13,74	2,56	1562	120,9	5321	8,70	29,08	1395	61370	2957	130087	1,26	11821
3.6	12,22	2,74	1497	114,6	5499	8,54	26,30	1384	66428	2881	138268	1,27	12278
3.9	13,37	2,66	1584	112,7	5859	8,57	30,59	1426	74173	3001	156027	1,30	11458
4.2	12,52	2,90	1610	115,0	6438	8,63	30,63	1679	94039	3289	184204	1,26	10492
4.5	13,00	2,85	1645	118,3	7098	9,43	31,15	1607	96408	3251	195087	1,21	11934
LSD (p=0.05)	**1,72**	**0,39**	**156**	**9,7**	**360**	**1,18**	**5,67**	**374**	**13824**	**425**	**17938**	**0,24**	**2676**
Ave	12,06	2,88	1552	114,3	3675	8,85	30,52	1607	50076	3158	100170	1,15	13048

Table 5. Vegetative growth parameters (primary & secondary shoots) at grape ripeness level 2 of Shiraz/101-14 Mgt. planted to different vine spacing (means of 2015-2019).

Vine spacing (m)	Number prim. leaves/ shoot	Prim. leaf mass (g)	Prim. leaf area/ shoot (cm²)	Prim. shoot length (cm)	Prim. leaf area/ vine (cm²)	Number sec. shoots/ prim. shoot	Number sec. leaves/ prim. shoot	Sec.leaf area/ prim. shoot (cm²)	Sec.leaf area/ vine (cm²)	Total leaf area/ shoot (cm²)	Total leaf area/ vine (cm²)	Leaf area Prim.: Sec. ratio	Total leaf area: yield ratio
0.3	10,68	2,96	1402	107,2	429	8,19	29,90	1576	6304	2978	11913	0,99	21754
0.6	11,13	2,82	1430	104,7	838	8,49	26,79	1385	11079	2815	22518	1,14	17300
0.9	11,92	2,81	1476	101,3	1215	8,29	30,12	1513	18151	2988	35858	1,09	15201
1.2	13,07	2,64	1468	98,2	1571	8,31	27,27	1335	21359	2803	44847	1,20	14831
1.5	13,38	2,67	1592	105,0	2100	8,83	29,71	1511	30225	3103	62067	1,17	16477
1.8	11,43	2,75	1398	98,4	2361	8,36	26,14	1268	30439	2666	63984	1,44	14233
2.1	12,02	2,79	1454	94,0	2632	7,86	28,64	1397	39114	2884	80739	1,32	15095
2.4	13,87	2,56	1583	108,2	3461	8,28	28,08	1294	41411	2877	92067	1,37	14824
2.7	14,68	2,64	1682	102,6	3692	9,86	31,20	1616	58168	3298	118736	1,23	16228
3.0	13,04	2,61	1514	104,4	4177	9,36	26,60	1246	49834	2760	110388	1,35	16400
3.3	14,77	2,56	1666	103,5	4555	8,99	30,77	1353	59534	3029	133285	1,34	13167
3.6	13,62	2,62	1594	105,1	5044	9,16	28,84	1310	62875	2904	139369	1,35	15095
3.9	13,60	2,64	1527	101,7	5290	8,78	30,97	1352	70318	2880	149743	1,32	13130
4.2	13,56	2,73	1660	102,6	5747	9,19	28,85	1498	83898	3158	176858	1,24	17090
4.5	13,49	2,65	1570	100,8	6046	8,44	27,32	1325	79484	2894	173658	1,36	14920
LSD (p=0.05)	**2,42**	**0,31**	**219**	**10,7**	**427**	**1,27**	**6,24**	**306**	**11114**	**406**	**16778**	**0,33**	**3300**
Ave	12,95	2,70	1534	102,5	3277	8,69	28,75	1399	44146	2936	94402	1,26	15716

Table 6. Reproductive growth parameters at grape ripeness level 1 of Shiraz/101-14 Mgt. planted to different vine spacing (means of 2012-2019).

Vine spacing (m)	Bunches/ shoot	Berries/ bunch	Bunch mass (g)	Bunch length (cm)	Bunch width (cm)	Bunch vol. (cm^3)	Rachis mass (g)	Rachis vol. (cm^3)	Berry vol. (cm^3)	Berry mass (g)	Number Berries/ Rachis vol.	Bunch vol.: Rachis vol. ratio
0.3	1,86	106,1	131,5	16,21	6,74	114,3	7,49	6,70	1,36	1,26	16,95	17,88
0.6	1,90	124,3	150,6	15,85	6,86	131,8	8,29	7,42	1,30	1,24	17,49	17,97
0.9	1,95	136,5	169,9	16,70	7,20	150,0	9,63	8,81	1,34	1,24	16,06	17,39
1.2	1,90	135,5	166,0	15,58	6,88	139,1	9,53	8,69	1,30	1,25	15,88	16,45
1.5	2,05	143,0	176,0	15,42	7,06	152,0	9,85	8,75	1,34	1,25	17,42	18,21
1.8	2,01	137,6	170,4	15,62	7,25	146,9	9,44	8,21	1,41	1,31	17,62	18,59
2.1	1,91	146,6	181,2	16,31	7,00	165,3	10,59	9,81	1,32	1,25	16,37	18,09
2.4	2,02	163,8	197,6	16,44	7,34	174,6	11,03	9,90	1,31	1,27	17,53	18,56
2.7	2,08	147,0	184,4	15,81	7,09	157,7	10,15	9,14	1,33	1,27	16,61	17,77
3.0	1,99	147,3	172,3	15,90	7,20	152,8	9,59	8,78	1,28	1,24	16,99	17,59
3.3	2,19	149,1	180,3	15,63	7,07	158,2	10,33	9,41	1,32	1,24	16,51	17,48
3.6	2,00	146,3	179,4	16,11	7,40	155,6	10,78	9,42	1,26	1,19	16,41	16,96
3.9	2,15	154,1	191,8	15,86	7,03	169,7	10,32	9,24	1,38	1,32	17,56	18,91
4.2	2,04	161,0	207,7	16,35	7,45	185,0	11,56	10,31	1,41	1,37	16,87	18,93
4.5	2,09	152,6	187,4	15,59	7,31	166,4	10,82	9,65	1,35	1,29	16,44	17,99
LSD (p=0.05)	**0,16**	**15,2**	**23,9**	**1,00**	**0,40**	**23,5**	**1,31**	**1,27**	**0,10**	**0,10**	**1,57**	**1,68**
Ave	2,01	143,4	176,4	15,96	7,12	154,6	9,96	8,95	1,33	1,26	16,85	17,92

Table 7. Reproductive growth parameters at grape ripeness level 2 of Shiraz/101-14 Mgt. planted to different vine spacing (means of 2015-2019).

Vine spacing (m)	Bunches/ shoot	Berries/ bunch	Bunch mass (g)	Bunch length (cm)	Bunch width (cm)	Bunch vol. (cm^3)	Rachis mass (g)	Rachis vol. (cm^3)	Berry vol. (cm^3)	Berry mass (g)	Number Berries/ Rachis vol.	Bunch vol.: Rachis vol. ratio
0.3	1,62	111,1	124,1	14,55	5,11	102,3	8,42	7,05	1,14	1,09	17,12	15,74
0.6	1,78	114,6	130,0	14,11	5,39	107,4	7,77	6,64	1,18	1,12	19,01	17,37
0.9	1,85	123,0	137,4	15,50	5,82	113,2	9,27	8,16	1,12	1,05	16,43	14,85
1.2	1,94	127,4	143,3	14,84	5,65	118,6	8,61	7,46	1,15	1,11	18,50	17,16
1.5	2,11	131,6	148,9	14,81	5,83	119,4	9,71	8,57	1,23	1,15	16,52	15,37
1.8	1,88	125,4	144,8	14,56	5,54	119,1	8,74	7,72	1,16	1,10	17,86	16,80
2.1	1,70	136,1	154,9	14,86	5,84	128,1	9,48	8,39	1,19	1,11	17,19	15,90
2.4	1,76	141,7	166,0	15,63	6,07	142,0	9,89	8,42	1,14	1,11	18,52	18,03
2.7	1,92	147,4	173,7	15,06	5,60	148,1	10,95	9,38	1,16	1,10	17,21	16,85
3.0	1,91	132,3	149,8	14,42	5,48	124,9	9,04	8,05	1,13	1,04	19,90	18,28
3.3	2,06	142,4	170,9	14,64	6,15	148,5	10,84	9,55	1,19	1,14	16,38	16,88
3.6	1,82	138,0	155,5	13,98	5,51	133,1	9,83	8,46	1,13	1,07	18,34	17,08
3.9	1,89	141,5	166,1	15,17	6,09	139,1	10,32	9,08	1,20	1,12	17,47	16,93
4.2	1,90	147,9	179,3	15,08	6,08	153,1	11,03	9,67	1,20	1,12	16,96	17,09
4.5	1,99	146,1	168,1	15,35	5,99	141,4	10,74	9,25	1,15	1,07	16,85	16,13
LSD (p=0.05)	**0,21**	**19,2**	**23,8**	**1,38**	**0,82**	**20,0**	**1,62**	**1,47**	**0,13**	**0,11**	**2,47**	**2,22**
Ave	1,88	133,8	154,2	14,84	5,74	129,2	9,64	8,39	1,16	1,10	17,62	16,70

Grape composition

The average grape composition at the two harvest dates over the last five years followed trends of decreasing sugar levels (°B) and pH, and slightly increasing titratable acidity (TA), resulting in °B:TA also decreasing, from narrow to wide spacing (Fig. 15). Similar results were found by Archer & Strauss (1991), Hunter (1998) and Murisier & Zufferey (2006). The soluble solid concentration followed a linear decrease from narrow to wide spacing. Although differences were small, the trends of titratable acidity and pH differed in slope. Delayed/inhibited sugar accumulation with wide vine spacing is in line with trends found for the physiological parameters water potential (Fig. 7), photosynthesis (Fig. 8) and water use efficiency (data not shown) that indicate that wider spaced vines experienced more stress, most likely caused by under-supply of water, photo-inhibition, excessive crop load and insufficient leaf area, all leading to sub-optimal photosynthetic output. This is clear from the available leaf area/fresh grape mass that decreased from generally acceptable values of approx. 13 - 15 cm^2/g for narrow spaced vines to less than two thirds of that for wider spaced vines (> 2.7 m), the latter bordering on over-cropping (Fig. 12). Although a poorer canopy light microclimate may normally also have a reducing effect on berry sugar accumulation, this was probably counteracted by the better leaf area/grape mass as well as the denser root system of the narrow spaced vines. This indicates differential irrigation/fertilisation needs per spacing group.

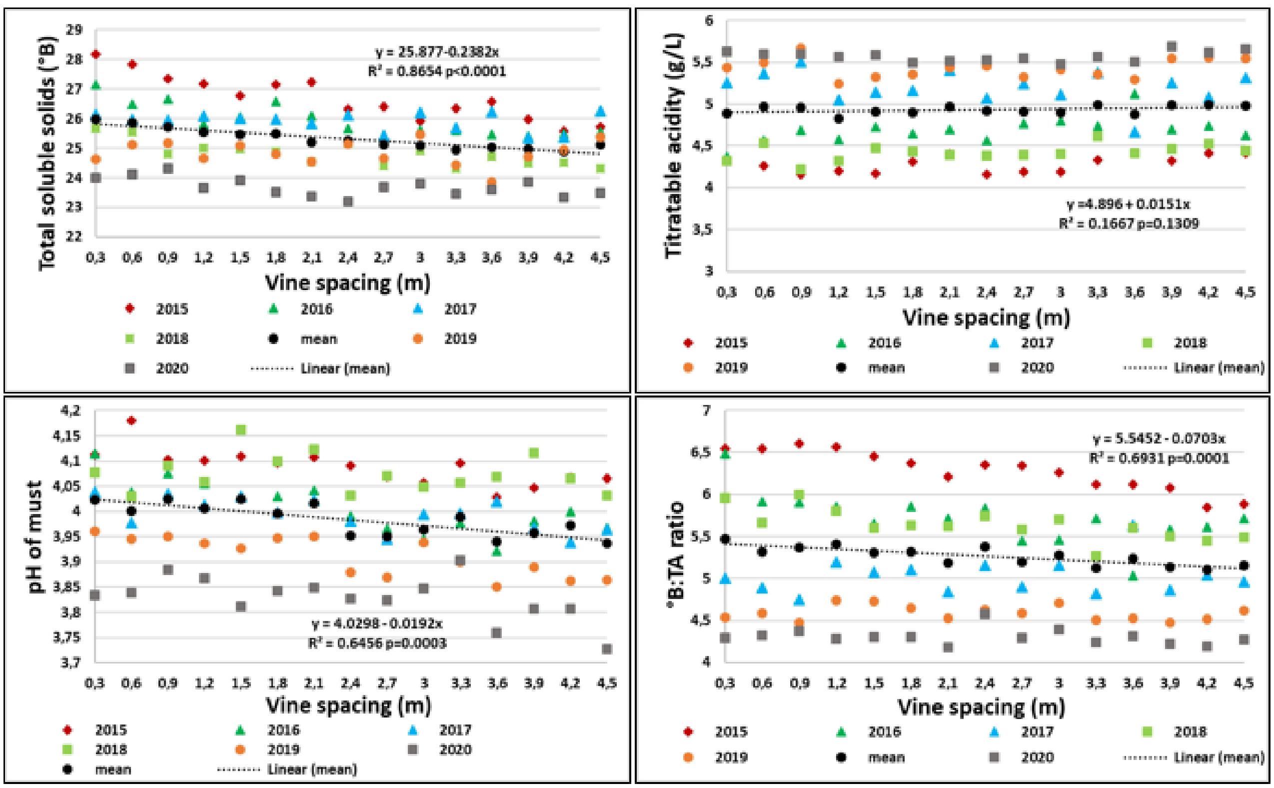


Fig. 15. Grape composition (means of two ripeness levels) (Soluble solids: Top left; Titratable acidity: Top right; pH: Bottom left; °B:TA ratio: Bottom right) of Shiraz/101-14 Mgt (2015 – 2020 seasons).

Organic acids are synthesised mainly during the pre-véraison period (Saito & Kasai, 1968; Ruffner, 1982a; Hunter & Ruffner, 2001). In practice, and especially under warm climatic conditions favouring malate respiration, it would therefore be of the utmost importance to create conditions in the grapevine canopy during the pre-véraison period that would favour photosynthetic activity/high sugar production and sucrose translocation to the berries to guarantee high organic acid, particularly tartaric acid, formation. This would allow the grapes to enter the ripening period at high acid levels, providing a buffer for adverse conditions during this period and favouring a lower berry pH at ripeness. Malic acid normally decreases, whereas tartaric acid is more or less stable from berry softening onwards (Ruffner, 1982a, 1982b;

Coombe, 1992; Hunter & Ruffner, 2001). A reduction in tartaric acid is mainly ascribed to dilution (Ruffner *et al*., 1983), while some of the free acid is converted to salt forms, mainly due to the influx of potassium during the ripening phase (Iland, 1987a, 1987b; Gutiérrez-Granda & Morrison, 1992; Hunter & Ruffner, 2001; Hunter *et al*., 2014b). In the case of malic acid, suggested additional reducing mechanisms include a decrease in malate formation by inhibition of glycolytic carbon flow (which would result in an accumulation of imported sugar); the latter seemed not to be the case for the wider spacing treatments. Rather, re-metabolisation of stored malic acid seemed a more plausible mechanism to satisfy a continuing demand for respiratory substrates under the conditions of the wider spaced vines with more open canopies and higher radiation (Steffan & Rapp, 1979, Possner & Kliewer, 1985, Gutiérrez-Granda & Morrison, 1992) or by increasing catabolic enzyme activity (Possner *et al*., 1983, Ruffner *et al*., 1983). However, in spite of the likely increased photosynthetic activity that essentially might have occurred and accompanied export of photo-assimilates because of an increase in sink:source relationship per shoot (Koblet, 1975, Hofäcker, 1978, Johnson *et al*., 1982, Hunter & Visser, 1988, Candolfi Vasconcelos & Koblet, 1990, Hunter *et al*., 1995, Koblet *et al*., 1996), the very low leaf area/grape mass was insufficient for persistent sucrose flow to the berries in order to prevent a decrease in soluble solid accumulation with wider spacing of the vines. It is likely that the respective bunches on the shoots of these vines were the preferred allocations for photo-assimilates, but further contribution to the build-up of soluble solids by the importing of sucrose from the rest of the vine structure (spurs, cordon, trunk, roots) cannot be excluded. This was previously found to occur in experiments involving leaf darkening and excessive defoliation (Quinlan and Weaver 1970; Hunter & Visser, 1988; Candolfi Vasconcelos & Koblet, 1990).

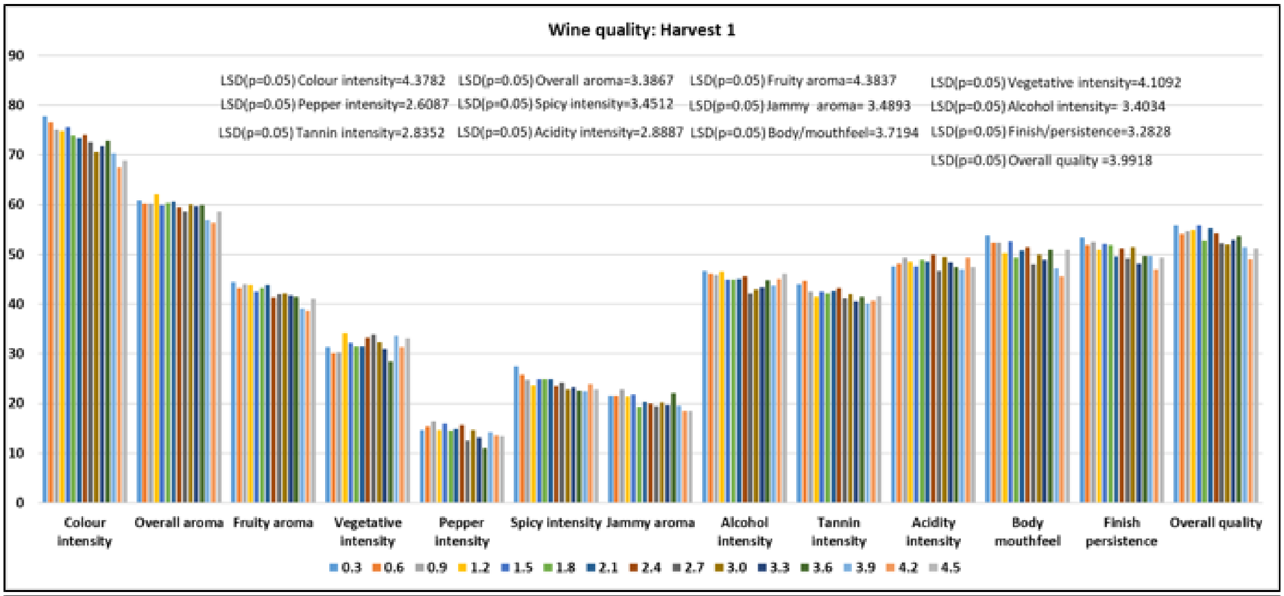
Colour intensity and density as well as total phenolics of the wine showed a decreasing trend with wider plant spacing (Table 8). This is in line with the basic grape composition results (e.g. soluble solids, pH, titratable acidity). Although an increase in grape colour and phenolics may have been expected under the better canopy microclimate conditions of the wider spaced vines, this is further evidence of the grapes being deleteriously affected by the stressful conditions experienced by these vines. Values noticeably increased from the first to the second harvest, congruent with a decrease in berry volume (Tables 6 & 7) that would have increased the skin:pulp ratio and extractability (Nadal & Hunter, 2007; Melo *et al*., 2015).

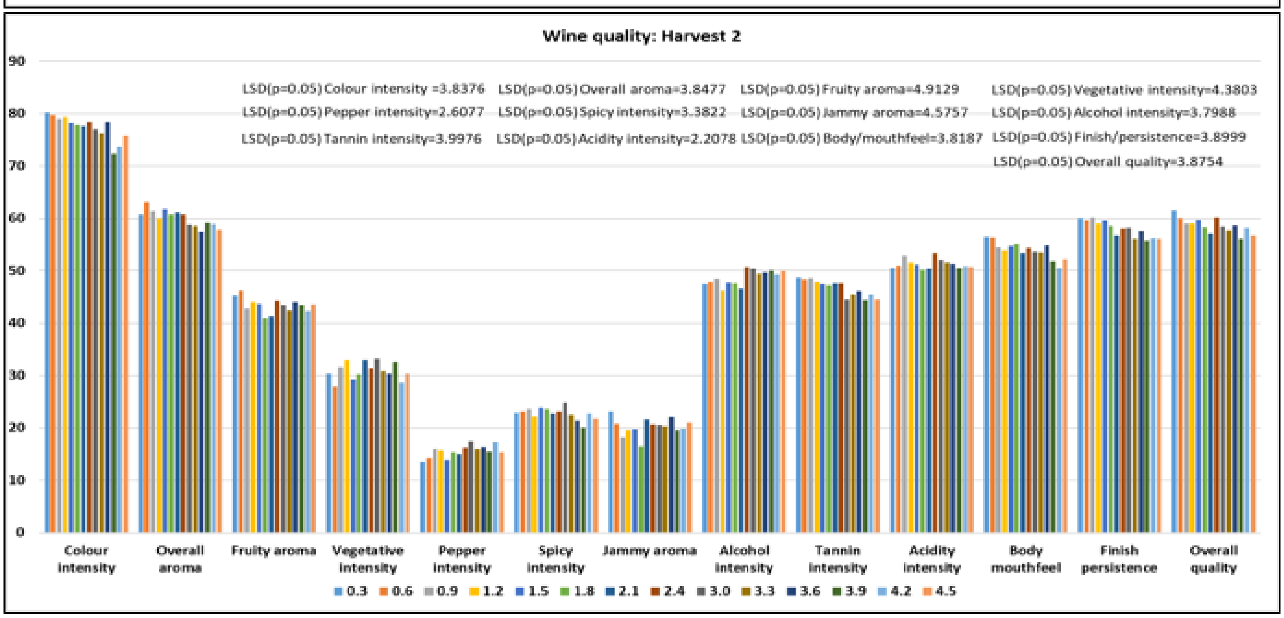
Table 8. Wine composition at two ripeness levels of Shiraz/101-14 Mgt, planted to different vine spacings (2015 – 2019 seasons).

Vine Spacing (m)	Wine colour & phenolics																	
	Colour (A_{520})						Colour (A_{420})						Phenolics (A_{280})					
	2015 Ripe 1 2015 Ripe 2	2016 Ripe 1 2016 Ripe 2	2017 Ripe 1 2017 Ripe 2	2018 Ripe 1 2018 Ripe 2	2019 Ripe 1 2019 Ripe 2	Ave Ripe 1 Ave Ripe 2	2015 Ripe 1 2015 Ripe 2	2016 Ripe 1 2016 Ripe 2	2017 Ripe 1 2017 Ripe 2	2018 Ripe 1 2018 Ripe 2	2019 Ripe 1 2019 Ripe 2	Ave Ripe 1 Ave Ripe 2	2015 Ripe 1 2015 Ripe 2	2016 Ripe 1 2016 Ripe 2	2017 Ripe 1 2017 Ripe 2	2018 Ripe 1 2018 Ripe 2	2019 Ripe 1 2019 Ripe 2	Ave Ripe 1 Ave Ripe 2
0,3	0,72 0,92	0,56 0,70	0,66 0,74	0,38 0,48	0,62 0,57	0,59 0,68	0,60 0,78	0,43 0,55	0,54 0,63	0,34 0,42	0,54 0,51	0,46 0,53	10,99 12,84	10,16 10,66	7,99 10,89	8,60 8,76	10,53 13,38	9,65 11,30
0,6	0,71 0,72	0,48 0,50	0,48 0,70	0,36 0,46	0,59 0,58	0,52 0,59	0,58 0,62	0,35 0,40	0,44 0,61	0,32 0,39	0,53 0,52	0,41 0,48	10,40 12,16	9,06 9,52	7,66 10,74	7,78 8,66	10,60 13,48	9,10 10,91
0,9	0,58 0,80	0,40 0,50	0,49 0,66	0,32 0,37	0,61 0,54	0,48 0,57	0,48 0,68	0,30 0,40	0,45 0,59	0,28 0,33	0,56 0,50	0,40 0,45	10,34 12,10	8,57 10,40	7,56 10,79	7,69 8,56	10,62 14,12	8,96 11,19
1,2	0,63 0,69	0,38 0,45	0,48 0,71	0,34 0,43	0,56 0,59	0,48 0,57	0,52 0,60	0,29 0,37	0,44 0,62	0,31 0,38	0,50 0,51	0,38 0,47	9,67 11,08	8,71 9,07	7,53 11,17	7,56 8,62	9,98 13,78	8,69 10,74
1,5	0,58 0,63	0,38 0,49	0,51 0,66	0,33 0,40	0,59 0,53	0,48 0,54	0,49 0,55	0,29 0,37	0,45 0,58	0,30 0,34	0,51 0,47	0,39 0,44	9,31 10,58	8,68 9,27	7,59 11,35	7,95 8,27	10,44 13,26	8,79 10,54
1,8	0,58 0,75	0,46 0,54	0,60 0,65	0,24 0,48	0,65 0,58	0,51 0,60	0,49 0,65	0,34 0,43	0,51 0,57	0,23 0,42	0,56 0,53	0,41 0,48	9,33 11,69	9,16 9,69	8,29 10,75	6,93 9,30	10,94 13,52	8,93 10,99
2,1	0,64 0,66	0,37 0,50	0,53 0,69	0,27 0,32	0,59 0,62	0,48 0,56	0,54 0,58	0,29 0,41	0,47 0,61	0,26 0,40	0,53 0,55	0,38 0,49	9,52 10,91	8,60 10,21	7,66 11,68	7,29 9,15	10,62 13,32	8,74 11,05
2,4	0,56 0,63	0,38 0,46	0,51 0,67	0,32 0,40	0,55 0,62	0,47 0,56	0,46 0,52	0,29 0,37	0,45 0,58	0,28 0,34	0,47 0,55	0,38 0,46	9,12 10,12	8,82 9,29	7,68 10,92	7,26 7,96	9,58 12,40	8,49 10,14
2,7	0,52 0,73	0,36 0,43	0,49 0,59	0,26 0,32	0,56 0,59	0,44 0,53	0,43 0,61	0,26 0,34	0,43 0,54	0,23 0,28	0,49 0,51	0,35 0,42	8,42 10,41	7,72 8,77	6,98 10,45	6,77 8,28	10,50 13,12	8,08 10,21
3	0,52 0,65	0,37 0,48	0,64 0,70	0,27 0,39	0,62 0,66	0,48 0,58	0,42 0,54	0,27 0,36	0,53 0,60	0,24 0,33	0,55 0,59	0,40 0,47	7,99 10,42	8,56 9,05	8,21 11,01	7,31 7,85	10,64 12,91	8,54 10,25
3,3	0,54 0,63	0,34 0,44	0,36 0,60	0,30 0,25	0,56 0,60	0,42 0,51	0,44 0,54	0,26 0,36	0,34 0,54	0,26 0,32	0,49 0,53	0,34 0,44	8,47 9,64	7,78 9,13	6,71 10,35	7,00 8,04	11,23 12,76	8,24 9,98
3,6	0,58 0,66	0,42 0,52	0,52 0,75	0,29 0,44	0,62 0,60	0,49 0,59	0,47 0,56	0,31 0,41	0,46 0,65	0,25 0,37	0,53 0,52	0,39 0,49	8,57 10,72	8,30 9,77	7,77 11,32	6,57 8,32	10,38 13,51	8,32 10,73
3,9	0,52 0,59	0,31 0,37	0,40 0,65	0,24 0,32	0,57 0,56	0,41 0,50	0,44 0,51	0,25 0,30	0,36 0,56	0,22 0,29	0,49 0,51	0,33 0,41	8,99 9,67	7,79 8,09	6,80 10,11	6,91 7,80	9,90 13,99	8,08 9,93
4,2	0,45 0,64	0,35 0,39	0,52 0,55	0,21 0,32	0,50 0,69	0,41 0,52	0,38 0,54	0,25 0,31	0,46 0,49	0,19 0,30	0,44 0,60	0,34 0,43	8,33 10,32	7,93 9,10	7,74 9,52	6,24 8,31	9,49 14,03	7,95 10,26
4,5	0,5 0,64	0,34 0,47	0,55 0,69	0,20 0,29	0,70 0,69	0,46 0,56	0,42 0,54	0,24 0,36	0,47 0,60	0,19 0,27	0,54 0,59	0,36 0,45	8,52 10,22	7,36 8,49	7,52 10,83	6,38 8,19	10,25 14,31	8,01 10,41
Ripe1 LSD(p=0.05)	0,086	0,095	0,173	0,096	0,166	0,078	0,066	0,070	0,124	0,070	0,120	0,06	1,287	1,281	1,216	0,814	1,920	0,732
Ripe2 LSD(p=0.05)	0,141	0,096	0,151	0,135	0,110	0,068	0,114	0,074	0,121	0,105	0,089	0,05	1,255	1,047	1,156	1,146	1,698	0,697

Sensory analyses of the wines showed clear trends (Fig. 15). Most sensory descriptors of the wines demonstrated decreasing trends from narrow to wide vine spacing at both grape ripeness levels. At the first harvest date, it is likely that wines may become less intense in colour, overall aroma, fruitiness, pepper aroma, spiciness, jammy aroma, alcohol, tannin, body, finish persistence and overall quality with wider spacing, whereas vegetative and acidity perception may increase. At the second harvest date, a similar profile seems evident, although pepper and alcohol intensity may increase with wider spacing and acidity intensity seems unaffected by spacing distance. Although a jammy aroma was prominent at the first harvest date for the narrower spacing treatments, this trend seemed reversed at the second harvest date. In general, wines made from grapes at the second harvest date showed higher colour intensity and overall aroma with slightly more fruitiness than wines made from grapes at the first harvest date; vegetative intensity perception appeared slightly lower in wines from riper grapes, whereas the pepper intensity, spiciness and jammy aroma had similar averages. Alcohol, tannin, acidity, body, finish persistence as well as overall quality showed overall higher profiles in wines made from grapes at the second harvest date. The results are in agreement with the findings from previous research showing an increase in grape skin colour and soluble solids as well as wine quality with denser planting/higher population per surface area (Archer & Strauss, 1991; Hunter, 1998b). The stress hormone abscisic acid showed a positive relationship with these two grape parameters and increased in the xylem sap with high density planting (Hunter, 1998b). Recent transcriptomic studies on the effects of vine root restriction showed phenolics, stilbenes, flavonols, anthocyanins and proanthocyanidins being induced to accumulate, implicating the role of functional genes in this response and stimulations involving environmental stress factors, such as water deficit, temperature, phytohormones and sunlight exposure (Leng *et al*., 2020).

This confirms the significant impact of terroir conditions and cultivation practices that alter the canopy and root system, on grape composition and wine quality. Vine spacing induces a natural competition between root systems and the resulting soil environment enhanced the occurrence of plant stress. The controlling effect of the root system on the physiological processes of the whole vine and the resultant plant interactions with the environment, is thus manifested and measurable at growth, production as well as wine quality levels.





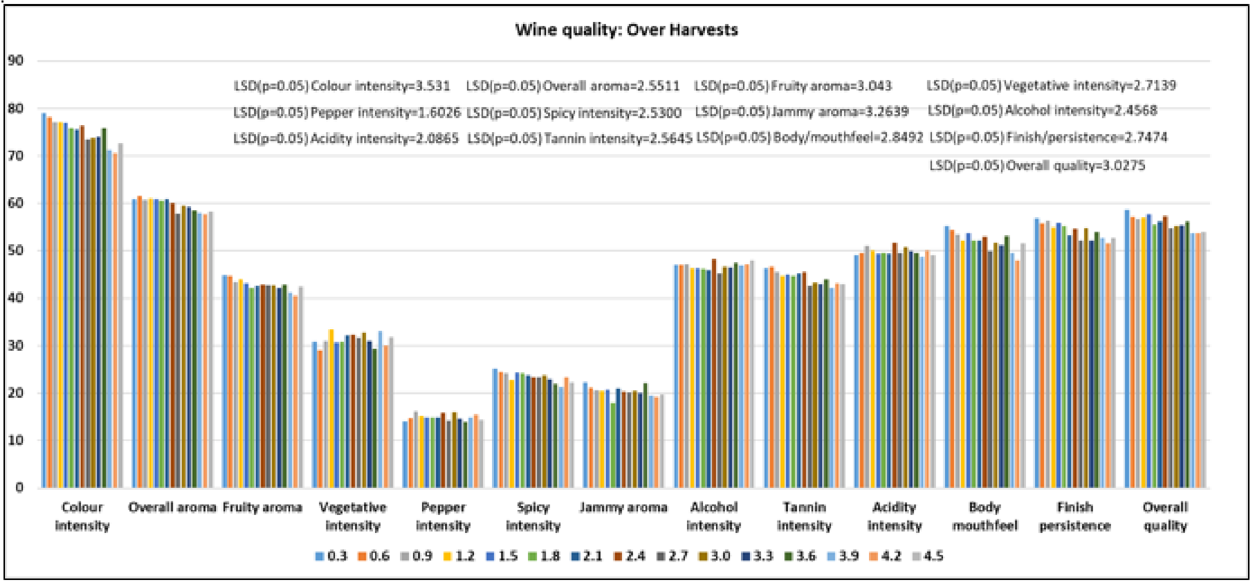


Fig. 15. Sensory quality (descriptor response and profile) of wines made from grapes harvested at two ripeness levels from Shiraz/101-14 Mgt. planted to different vine spacing (2015 – 2019 seasons).

General

Seasonal differences that occur in field experiments and in commercial vineyards are expected and commonly occur because of changes in the growth environments as well as perennial vine physiological adaptations. For example, sub-optimal growth balances and unfavourable weather conditions during the previous season (and even before that) as well as prevailing weather conditions during the seasonal formation of inflorescence primordia and differentiation of male and female flowers as well as during flowering/berry set stages greatly impact on reproductive growth. The physiological impact is related to multiple factors, including seasonal changes in the weather and irrigation, nutrition and canopy management practices. It reflects overall effects on general growth, reserve accumulation and root growth, the latter affecting hormone balances during spring and initial growth, thereby affecting both vegetative and reproductive development. Exposure of grapevines to prolonged adverse conditions (such as drought conditions, high temperatures, injudicious irrigation and fertilization programs, general poor seasonal management/neglect) may lead to a gradual depletion of reserves in perennial tissues such as the roots, trunk and cordons, affecting stability and longevity of the vine. Inadequate replenishment and a disturbance in growth balances that do not support the annual growth and yield demands may eventually lead to insufficient resilience of the vine during transient environmental extremes, thus challenging short- and long term sustainability objectives.

Many physiological responses to physical structure development with closer or wider spacing might have played a role in the behaviour of the vines in this experiment. These may have resulted, among others, from unequal development of aboveground and subterranean growth and thus disturbance in capacity of supply and demand bodies, resulting in disproportionate distribution; distance of translocation with wide spacing that may have deleteriously affected flow and volume of nutrient rich sap *via* xylem and phloem support channels; crop load may have imbalanced source:sink relationships per vine; and water (irrigation) and nutrition (fertilisation) may not have met the demands of all treatments. The latter may point to differential requirements of the different spacing treatments. Balanced development is essential to minimise erratic grapevine behaviour, beyond the normal field complexities that grapevines experience from year to year.

Following the data over a 10-year period, yields as well as grape and wine quality appeared to reach an optimum around 1.8 m vine spacing under the conditions of this experiment. Despite the expectations to the contrary, the vegetative (including the root system) and reproductive departments of the vines did not respond in a linear fashion to the increase in space when the double cordons were extended to cover the allocated lateral space. However, imbalances were observed towards both narrowly and widely spaced vines, the former responding vegetatively (shoot and root growth) very well but were slightly restricted in utilizing the growth for reproductive yield, whereas the latter were restricted in vegetative growth, but utilized the growth most effectively for reproductive yield. Thus, closely spaced vines ended up being slightly under-cropped and widely spaced vines over-cropped, the latter further confirmed by the lower berry sugar accumulation, despite the concentrating effect of a more open canopy.

Although it seems possible to increase growth and yield when vines are spaced wider than the apparent optimum as mentioned, this may require higher fertilisation and water supply, which in turn would increase production cost. A much lower establishment cost with wider spacing would have favoured such an approach, but this may be nullified by the progressively longer time that is required for full cordon development, especially for the wider spacings (plus 1-2 winters). Such a scenario does not seem plausible and sustainable in the current producer circumstances that are characterised by very difficult operational conditions, including a decreasing availability of water for agricultural use, increasing direct farming costs and labour, declining net income, and competitive markets. However, these vines still carried higher yields than the narrower spaced vines on a per vine and surface basis. If the irrigation and fertilization are adjusted and shoot growth of these vines is improved (with sufficient support wiring for both cordon weight and seasonal growth), higher yields in a better quality category than in this experiment may be obtained. This aspect may therefore justify a re-visit in future because of the very low graft material purchasing cost and low labour inputs for planting. In contrast, the very high graft material purchasing and establishment costs, including labour, required by spacing vines closer than 1.2 m under the conditions of this experiment do not seem viable, despite the positive effects observed for grape composition and wine quality performance.

This Shiraz/101-14 Mgt experiment with different in-row vine spacing was executed in a terroir characterised by a moderately fertile soil and a relatively hot summer climate with low winter rainfall. A vineyard row spacing of 2.2 m and a VSP trellis were used. The rootstock was of moderate vigour, vines were not overly irrigated and fertilized, and canopies were well accommodated. Under these conditions and according to all data at hand:

- Purchasing costs and planting time increased sharply with planting to less than 1.2 m vine spacing (approx. 2.5 m^2/vine; 3788 vines/ha).

- Vine spacing has a steering effect on the development of the root system.

- Root density in the fine, extension and permanent categories in particular, increased with narrower spacing, leading to a higher total number of roots, while utilizing deeper soil layers; lateral distribution appeared uniform over the allocated distance.

- Results validated the hypothesis that deeper and more fertile, clay-loam soil conditions would stimulate roots to explore deeper soil layers in order to compensate for lateral space restriction; this would be well aided by pre-establishment deep soil preparation.

- Cumulative pruning, harvesting and yield reached turning points around 1.8 m vine spacing, i.e. approx. 4 m^2 surface area/vine or 2525 vines/ha.

- Optimum vine spacing appeared to be 1.8 m, whereas closer spacing led to an increase in canopy density and wider spacing resulted in more open canopies, both scenarios inducing stressful conditions.

- Widest spaced vines in particular showed signs of over-cropping and stress, not satisfying the requirements for canopy condition, physiological performance, production and quality.

- Longevity of the widely spaced vines might have been affected in the long run; a progressive starch deprivation in the permanent vine structure would most likely occur.

- Harmony between the available space for vine development and the yield obtained per surface area, grape composition and sensory quality of the wine appeared to fade with wider vine spacing, especially beyond 2.7 m (approx. 6 m^2/vine; 1684 vines/ha).

- A 2.1 m (approx. 4.5 m^2/vine; 2165 vines/ha) vine spacing seemed credible, yet maximum, to satisfy production and quality, allowing a 10 - 12 cm^2 leaf area/g grape mass, which is a well-tested canopy-grape criterion, the performance of which would still provide a buffer under adverse conditions.

- Natural leaf size responses were induced in the vines by changing the distance between vines, narrower spacing than the optimum of 1.8 m leading to larger leaves.

- A vine spacing of 1.5 (approx. 3.5 m^2/vine; 3030 vines/ha) – 1.2 m (approx. 2.5 m^2/vine; 3788 vines/ha) is advisable as a strategy that could induce a naturally slightly denser canopy that would provide better protection to the grapes under e.g. hot to very hot climatic conditions, and that may increase root density and water and nutrient absorption, without hampering photosynthetic output and grape and wine quality.

- A vine spacing of 2.1 m (approx. 4.5 m^2/vine; 2165 vines/ha) and even slightly wider (2.4 m) (approx. 5.5 m^2/vine; 1894 vines/ha) could be advisable for cool to cold conditions to allow proper canopy function and grape ripening conditions, but at the potential risk of a decreased root density. However, in such conditions soil moisture may be better maintained, thus decreasing the impact on root density.

- Recommendations would only be applicable if water for irrigation is available and with proper nutrition of the vines.

- More fertile soils and the use of vigorous rootstocks would push vine spacing wider, whereas less fertile, poorer soils and the use of more moderately vigorous rootstocks would push spacing narrower; the same principle can be followed with more or less water availability and more or less fertilization (although these factors should always be adjusted according to yields and visual vegetative growth). In all cases, optimum utilisation of the soil potential should be pursued, avoiding the risk of under- or over-exploitation.

- VSP training and trellising would always result in a restricted space if the traditional cordon or cane pruning methods are followed. Space for carrying the yield would therefore be restricted. Options to increase yields and balances (under sufficient water and fertilisation supply) would be to divide the cordon or canopy and/or adding spurs/canes. Various methods exist to accomplish that, but it should be executed with extreme care and accompanied by judicious management.

- The size of the vine within a specific space and within the population per surface area is dictated by its own genetic capacity (scion-rootstock combination), competing influence of adjacent vines within the population and environmental conditions (climate, soil). Further influences are those brought about by vineyard practices such as soil preparation, fertilisation, irrigation, and bud load. If the spacing is beyond the growth capacity of the graft combination (as aided by other viticulture practices), the available surface area will be under-utilised and maximum crop will not be attained. This will be reached with closer spacing, but only if the distance does not lead to shoot crowding.

- Where favourable growth conditions exist, close planting may result in a crowding and interlacing of the canes and dense, shaded foliage which interferes with fertility, setting, bunch growth, colouring, and ripening of the fruit. The control of diseases and insects may be difficult. Cultivation, pruning and harvesting would be unduly costly. On the other hand, poor growth conditions would lead to open canopies with high radiation in the center of the canopy and on leaves, most likely resulting in high water loss *via* evapotranspiration and affecting the photosynthetic activity of the leaves negatively. Although pruning and harvesting would be easier, yields would be lower and acidity, pH, colour and flavour of the grapes would be deleteriously affected, resulting in wine with poor quality. Disease control may be more effective, but frugivorous (birds) and herbivorous (antelopes) animals may damage the visible, hanging grapes before harvest. The correct spacing of vines is a natural way of optimising root colonisation, canopy microclimate, yield, and grape composition, while maintaining fertility and longevity of the vine. Extreme circumspection is of the utmost importance during vineyard establishment.

- Both aboveground and belowground spaces/departments need to be fully utilised for full valorisation of the area to be planted. For the grapevine, aboveground utilisation is determined by the size and efficiency of the canopy and belowground utilisation by the size and density of the root system. The quality of both canopy and root system is important. For the canopy, primary and secondary leaves, and for the root system at least primary, secondary and tertiary roots are required. The reserve storage and regenerative ability of both departments for the formation of new leaves and roots is a crucial aspect for survival and for yield and quality potential of the grapevine and is driven by the vigour potential that can be established. In addition to these aspects, a continuous, uniform, well-exposed canopy that allows high photosynthetic output and a root system that allows high absorption and the utilisation of deep soil layers in a soil with good physical and chemical characteristics and drainage, are important. Collectively, these aspects determine the physiological functioning of the grapevine, microclimate, fertility, and grape development and composition as an expression of the specific terroir.

8. CONCLUSIONS AND RECOMMENDATIONS

The aim of the project was to provide answers on the most practical and economic vine spacing under high potential soil conditions, with a focus on finding a balance between production returns per investment and wine quality. The reaction of the grapevine to the respective aboveground and belowground spaces was monitored.
Carbon allocation differences among vine spacing treatments were evident in leaf size, trunk circumference, shoot and cane mass, root system density and depth, yield, and grape composition. As spurs were allocated uniformly, canopy microclimate and visual canopy differences probably resulted from morphological size responses that generally decreased from narrow to wide plant spacing. The delay in sugar accumulation, along with trends found for water potential, photosynthesis, efficiency of water use, vegetative:reproductive growth

relationships and root density seem to indicate that the wider spaced vines experienced development-originating physiological restrictions and more stress. Results indicate a gradual transition from a higher vigour (perhaps root-physiology/environment induced) to a lower vigour (perhaps canopy-physiology/environment induced) condition, from narrow to wide vine spacing. This led to wider spaced vines having lower leaf:fruit ratios that not only caused disharmony between increasing spacing, growth, canopy microclimate and yield return, but also delayed grape ripening. This was also reflected in the wine composition and sensory profiles of the different spacing treatments.

Physiological parameters revealed a complex interplay between vine structure expansion, microclimate, water relations, photosynthetic output, and carbon distribution that was also reflected in grape composition and wine quality. Both root system and canopy are involved in water potential and photosynthetic activity and the complex interaction between these two plant departments may lead to a lack of (expected) differences. It is clear that vine spacing affects both aboveground and belowground departments of the vine and therefore induces an array of physiological trigger and homeostatic mechanisms. If these departments are not developing in a balanced way, the reaction of the grapevine to environmental and cultivation practices would be disturbed, often leading to erratic and unpredictable behaviour beyond the normal complexities that are experienced under field conditions. Such a condition would thus not be conducive to resistance of the grapevine to environmental challenges, such as those associated with a change in the climate. The results confirm the necessity of field studies and the collection of whole vine information before any recommendations can be made at producer level.

It is clear that if the principles of grapevine growing and indeed the criteria for efficient leaf and root function are neglected, a specific selected vine spacing will not be efficient in delivering the required results. The reality is that each terroir (soil and climate), along with plant material choices and viticulture practices, will dictate the plant spacing that has to be selected. Choices must be made with judicious circumspection and perspective, taking into account all criteria involved in grapevine growing and the wine industry in general. Once establishment is completed, it is imperative that manipulation criteria concerning canopy structure, water relations, and nutrition of the grapevine be constantly re-assessed and optimised to accommodate the environmental and physiological events taking place during the season, to fully utilize the specific terroir conditions. This project provides information to aid producers in making the correct vine spacing choices from a cost, management, production and quality perspective.

9. PLANNED OUTPUTS

a) TECHNOLOGY DEVELOPMENT, PRODUCTS AND PATENTS

The results have the potential to be included in an application regarding long term viticulture choices.

b) SUGGESTIONS FOR TECHNOLOGY TRANSFER

Scientific articles Popular articles Presentations Demonstrations Consultation

c) HUMAN RESOURCES DEVELOPMENT / TRAINING (STUDENTS)

Student Name and Surname	Student Nationality	Degree (eg Hons, MSc)	Level of studies in final year of project	Total Bursary Cost for Industry for entire project
Honours				
Masters				
PhD				
Postdocs				

d) LIKELY PUBLICATIONS (POPULAR, PRESS RELEASES, SCIENTIFIC)

Scientific: Vine physiological response to intra-row spacing: root system, canopy and yield.

Scientific: Intra-row vine spacing implications for grape composition and wine quality.

Popular: Vine spacing effects on root growth

Popular: Vine spacing effects on labour, canopy growth and yield

Popular: Vine spacing effects on grape composition and wine quality

e) PRESENTATIONS/PAPERS THAT COULD BE DELIVERED

Hunter, J.J., Booyse, M. & Volschenk, C.G., 2019. Response of Shiraz/101-14 Mgt to in-row vine spacing. 21st International Meeting of Viticulture GiESCO, Thessaloniki, Greece, 23 – 28 June 2019.

Hunter, J.J., 2020. In-row vine spacing implications. VinPro/Winetech Webinar, 19 May 2020.

10. PROJECT OUTCOME AND IMPACT

New Knowledge	Benefits Supply Chain	Direct Grower Application	Direct Packhouse/Winery/ Cellar Application	Other
X		X		

Other is:

The Value of the project to industry

This project provides information to growers and winemakers on the importance and implications of grapevine spacing. This information is required to make informed decisions during vineyard establishment.

The decision on the spacing of young vines is one of the most critical and is primarily based on soil type, water availability, and the growth potential of the chosen scion-rootstock combination. The aim is to establish a continuous canopy with good microclimate that would allow a consistent, sustainable yield of high quality per hectare, without any deleterious effect on longevity of the vines. The range of vine spacing distances that were included at fixed row spacing are wide and novel. Information regarding the optimal utilisation of a high potential soil in terms of costs, growth, yield, and grape and wine quality under conditions of intensive irrigation and high summer temperature was obtained. Clear guidelines regarding the outcomes that may be expected with different inter-vine spacing are provided to industry. Results are expected to significantly contribute to pre- and post-plant decision-making, sustainable grape growing and winemaking outcomes.

11. PERSONS PARTICIPATING IN THE PROJECT:

INITIALS AND SURNAME	HIGHEST QUALIFICATION	RACE (M,W)	GENDER (M,F)	INSTITUTE DEPARTM	POSITION	TOTAL COST TO PROJECT
RESEARCH PERSONNEL						R NaN
JJ Hunter	PhD	W	M	ARC	PL	R 0
CG Volschenk	MSc	W	M	ARC	Co	R 0
LF Adams	Grade 12	B	M	ARC	TA	R 0
A Marais	Grade 10	W	F	ARC	RA	R
SUPPORT PERSONNEL						R NaN
Farm personnel (10)	Grade 8 - 12	B	M, F	ARC	Farm worker	R

POSITION: Co = Co-worker (other researcher at your institution)
Coll = Collaborator (participating researcher that does not receive funding for this project from industry)
PF = Post-doctoral fellow
PL = Project leader
RA = Research assistant
TA = Technical assistant/ technician

12. TOTAL COST OF PROJECT

TOTAL ANNUAL COSTS (ALL YEARS)	CFPA	Raisin SA	HORTGRO	SATI	WINETECH	ARC	OTHER	TOTAL
2015	R 0	R 0	R 0	R 0	R 430129	R 446969	R 0	R 877098
2016	R 0	R 0	R 0	R 0	R 572112	R 595463	R 0	R 1167575
2017	R 0	R 0	R 0	R 0	R 686553	R 714576	R 0	R 1401129
2018	R 0	R 0	R 0	R 0	R 734611	R 764596	R 0	R 1499207
2019	R 0	R 0	R 0	R 0	R 785966	R 818047	R 0	R 1604013
2020	R 0	R 0	R 0	R 0	R 85000	R 88469	R 0	R 173469
TOTAL	R 0	R 0	R 0	R 0	R 3294371	R 3428120	R 0	R 6722491