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ORIGINAL RESEARCH ARTICLE

Vine spacing of *Vitis vinifera* cv. Shiraz/101-14 Mgt II. Establishment, and vegetative and reproductive growth

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ABSTRACT

Knowledge of vine growth reaction to plant spacing under relatively high potential soil conditions is limited. This study aimed to determine the effects of vine spacing (with fixed row spacing) of Shiraz (clone SH 9C)/101-14 Mgt on a relatively high potential soil in the Breede River Valley, Robertson, South Africa on establishment and training labour, aboveground growth, and yield. The vineyard was planted in 2008 to a Vertical Shoot Positioning trellis, a fixed row spacing of 2.2 m and row orientation of approximately NNE-SSW (30 °). The 15 in-row vine spacing treatments changed from 0.3 - 4.5 m with increments of 30 cm (from 15151 – 1010 vines/ha). Results were generated over six seasons after cordon development was completed. Grapes were harvested at two ripeness levels. Clear groupings were evident for establishment and further training management. Total costs showed trends with an optimal of around 1.8 m vine spacing, but were markedly higher for closer spacing. Canopies developed uniformly with cordon extension. General vegetative growth (over treatments) varied according to seasonal conditions. Individual leaf size was higher for more closely spaced vines. Total vegetative growth parameters mostly showed increasing and decreasing trends on a /vine and /ha basis, respectively, with an increase in spacing. Yields showed a general increase with wider spacing on a /vine and /ha basis. Yield:cane mass ratios displayed an increasing trend from narrow to wide vine spacing, as did fertility and bunch mass. The bunches from the narrowly spaced treatments seemed more compact. Growth and yield parameters showed very clear trends reaching an optimal at around 1.8 m vine spacing. The results of this study can be applied in vine spacing selection and sustainability strategies for different terroirs. Comprehensive guidelines for extrapolation to different growth conditions and terroirs are provided.

KEYWORDS: Vine spacing, Training, Costs, Growth, Canopy, Yield, Sustainability

INTRODUCTION

To fulfill farming land/terroir utilisation and sustainability (especially yield) needs the distance between vineyard rows is normally restricted to the minimum. However, the inter- and intra-row spacing of vines should conform to scientific-technological (practical) criteria regarding viticultural and physiological requirements to obtain best performance in terms of size, efficiency and uniformity of the canopy, root system and grapes.

Studies carried out over many years in different parts of the world have contributed to existing knowledge regarding the spacing of grapevines; in, for example, the USA (Bioletti and Winkler, 1934; Winkler, 1959; Winkler, 1969; Shaulis, 1980; Kliewer *et al*., 1996; Cawthon, 2002), Canada (Reynolds *et al*., 2004), France (Cazenave, 1889; Branas, 1949; Seguin, 1970; Champagnol, 1979; Casteran *et al*., 1980; Dumartin *et al*., 1982; Champagnol, 1982; Champagnol, 1984; Morlat *et al*., 1984), Italy (Liuni *et al*., 1985; Intrieri, 1987; Bandinelli *et al*., 1993; Valenti *et al*., 1996), Spain (Hidalgo and Candela, 1979; Munoz, 1982; Yuste *et al*., 2004), Switzerland (Neukomm, 1984; Murisier and Zufferey, 2006) and India (Brar and Bindra, 1986). In South Africa (Stellenbosch region), comprehensive experiments were done on young and older vines grown on a medium-potential, depth-restricted soil under dryland and low intensity (supplementary) irrigation conditions (Archer and Strauss, 1985; Archer and Strauss, 1989; Archer and Strauss, 1991; Hunter, 1998a; Hunter, 1998b). Both row and vine spacing were altered in the different treatments (comprising a range of 1000 – 20000 vines/ha). These studies included physiological measurements, microclimate, vegetative and reproductive growth, root growth and distribution, grape composition, wine quality and labour costs. The vines responded physiologically and morphologically to confinement/boundaries; responses included very clear aboveground:belowground balance shifts. In general, balances can shift under more, or less, invigorating conditions depending on soil potential, cultivar-rootstock combination, climatic conditions, and cultivation practices.

Plant reactions seem to be dictated by soil water content, the presence of layers that impede root penetration and genetic vine vigour potential, all of which steer the carbon distribution for canopy, root system and yield expansion (Hunter *et al*., 2016; Archer and Saayman, 2018). Combining plant spacing with different sizes of trellising systems, Van Zyl and Van Huyssteen (1980) and Archer *et al*. (1988) found that the preferential rooting zone vertically increased with a larger trellising system, whereas the ratio between different root diameter classes remained relatively constant. The augmentation of the root system was brought about mainly by changes in root density. The balance between aerial growth and root development was verified. In a study in France (Bordeaux and southern Côtes du Rhône regions) a meta-analysis of research data was used to calculate the significance of plant (row) spacing on vine drought resilience and profitability in the context of climate change (Van Leeuwen *et al*., 2019). The authors concluded that dryland grape growing might benefit from lower density plantings (wider rows) in warm, dry-climate terroirs where soils have reasonable water holding capacity. However, this seemed to be applicable to the production of grapes at a lower price point and would not lead to profitable production when targeting a premium category. Low plant density should also be avoided in areas where soil water holding capacity is very low and/or the soil water deficit is very high (low fraction of transpirable soil water). Yields per hectare decreased with lower vine density and higher water deficit (Van Leeuwen *et al*., 2019). The study implicated that soils with good water holding capacity (per implication a higher percentage clay/loam content) are more suitable for wider spaced plantings when targeting higher yields and higher quality grapes.

Notwithstanding all the previous research upon which the commonly used principle of spacing vines wider under higher soil potential and more favourable cultivation conditions was adopted, the general recurring question regarding the extent to which vine performance and related parameters are affected by vine spacing in terroirs comprising deep, unrestricted, and high potential soil conditions, has still not been fully addressed. Systematic experimentation is lacking. Growth balances may change and a natural increase in aboveground growth can be expected under conditions in which roots utilise deeper soil layers when penetrating more vertically with closer spacing (Archer and Strauss, 1985; Hunter, 1998b). If there is not enough space to accommodate additional vigour, shaded canopies/vineyards with increasingly lower bud fruitfulness and yield capacity may develop and high labour inputs for pruning, canopy management, and harvesting may be required, whereas grape and wine quality would most likely be inferior (Smart *et al*., 1990).

The purpose of this study was to determine the effects of vine spacing only (with fixed row spacing) on establishment parameters and vegetative and reproductive growth under relatively high potential soil conditions and irrigation. The study focused on vineyard growth sustainability and expected longevity under different terroir conditions.

MATERIALS AND METHODS

1. Experiment layout and practices

Vitis vinifera cv. Shiraz (clone SH 9C)/101-14 Mgt was planted during the spring of 2008 with an approximate row orientation of NNE-SSW (30 °) 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 to 4.5 m, with incremental increases of 30 cm representing 15 treatments (15,000 - 1000 vines/ha). Row spacing was fixed at 2.2 m. Each treatment replicate comprised nine parcels (7.5 m per parcel), and the number of vines per parcel depended on the specific vine spacing. Vines were double cordon-trained on a Vertical Shoot Positioning (VSP) trellis. Four sets of movable foliage wires were used. Each treatment was replicated four times with two buffer rows per treatment.

FIGURE 1. Canopy appearance affected by different plant spacing, Robertson, South Africa.

The total trial surface was approximately 0.9 ha. Irrigation was applied according to crop factors, changing from 0.3 - 0.6 as the season progressed. An average daily ET_0 of 5.0 - 6.7 mm was recorded. A volume of 10 - 28 mm/week of irrigation water was applied, excluding erratic summer rain. Vines were pruned to one-bud spurs for two winters (2010 and 2011), after which two-bud spurs with a 15 cm inter-spur spacing were pruned as from the winter of 2012. Spurs were spaced equally, irrespective of treatment. The number of spurs increased with the length of the cordons. To restrict other cultural practice influences, the vines underwent similar irrigation and fertilisation.

2. Management during establishment

Management labour time was recorded for planting and training of vines, shoot/spur selection, pruning and harvesting. A typical experiment appearance is shown in Figure 1.

3. Vegetative and reproductive growth measurements

For all treatments, the cane mass of all the vines of each replicate was measured in winter and the results expressed on a per vine and per ha basis. Approximately 40 kg of grapes per replicate were harvested for each treatment at each of two ripeness levels (approximately 24 °B and 26 °B, respectively), and the yields calculated based on the number of vines harvested. Shoots (including bunches) were sampled at the two grape ripeness level stages per treatment replicate and used for the determination of vegetative and reproductive growth characteristics. At each ripeness level, five shoots per vine were used to determine total leaf area and primary and secondary shoot leaf areas (by means of a LICOR Model 3100 area meter), number of primary leaves, number of secondary shoots and leaves, primary and secondary shoot lengths, bunch mass and volume, rachis mass and volume, and berry mass and volume. All grape bunches from the five shoots were removed and, after whole bunch measurements had been carried out, were de-berried and the berries well mixed. A sub-sample of 200 berries was then removed to determine berry mass and volume. Bunch, rachis and berry volumes were determined by means of water displacement in a measuring cylinder.

4. Statistical design and methods

The experiment was laid out in a randomised block design with 15 spacing treatments and four replications. The Shapiro-Wilk test verified the normality of the standardised residuals from the model (Shapiro and Wilk, 1965). Levene’s test confirmed homogeneous standard deviations (Levene, 1960). 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. Where applicable, data was then subjected to either the regression procedure (PROC REG), to fit linear and quadratic regressions, or the non-linear regression procedure (PROC NLIN). Join point regression was fitted to the data to describe the changes in trends over vine spacing. Join point regression, also known as change point regression, broken stick or segmented regression, assumes that data can be divided into subsets – each with their own unique linear trend (Hudson, 1966). PROC NLIN was performed to fit more than one line to the data to determine the "join point/s". Outliers were determined using the Shapiro-Wilk test on standardised residuals from the model to verify normality (Shapiro and Wilk, 1965). Outliers were replaced by predicted values of the model. Fisher's least significant difference was calculated at the 5 % level to compare means of the factors (main effects) and factor interaction means (Ott and Longnecker, 2010). A probability level of 5 % was considered significant for all tests.

RESULTS AND DISCUSSION

1. Management during establishment

A decrease in planting density showed clear trends in terms of collective vine purchasing cost, total labour required for planting and young vine-training, and cumulative pruning and harvesting times for the different vine spacing treatments (see Supplementary Material for more details) (Figure 2). In general, labour inputs were in line with those found by Hunter (1998b), but differences were not as pronounced, likely due to the very strict uniform spur spacing applied in this study. The pruning and harvesting values obtained indicate an overall uniform development, implying that similar canopy-related management practices had been carried out, such as shoot positioning, leaf removal, tipping/topping and disease control. While pronounced for closer spacings, responses weakened after approximately 1.8 m spacing. The values for 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, labour accessibility, level of training of the labour force, etc. Furthermore, gross differences would only be valid if all other costs are generalised and standardised. Total production costs need to be considered; i.e., interest, tax, entrepreneurial remuneration, provision for renewal and cash expenditure. Regarding the latter, other cost components, such as direct costs (fertilisers, compost, pesticides, insecticides, herbicides, cover crop seed, repair and binding material), labour (canopy and soil surface 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, and land-, property- and municipal taxes) should also be taken into account. When determining vine spacing, overall sustainability needs to be considered, including costing and marketing of the intended produce.

2. Vegetative parameters

Cane mass per vine and per soil surface area followed an increasing and decreasing trend, respectively, from the narrowest to the widest plant spacing (Figure 3). The cane mass/vine trend corresponded to a decreasing cane mass per shoot length and linear increasing trunk circumference with wider spacing (Figure 4), pointing to opposite responses of the seasonal (also considering technical applications) and perennial growth structures of the vine. The former indicates weaker growth or distributed (diluted) carbon allocation to several spurs and multiple sinks in the vine, which contributed to a more open canopy and various microclimatic and physiological complexities, as discussed in a companion paper (Hunter and Volschenk, 2024).

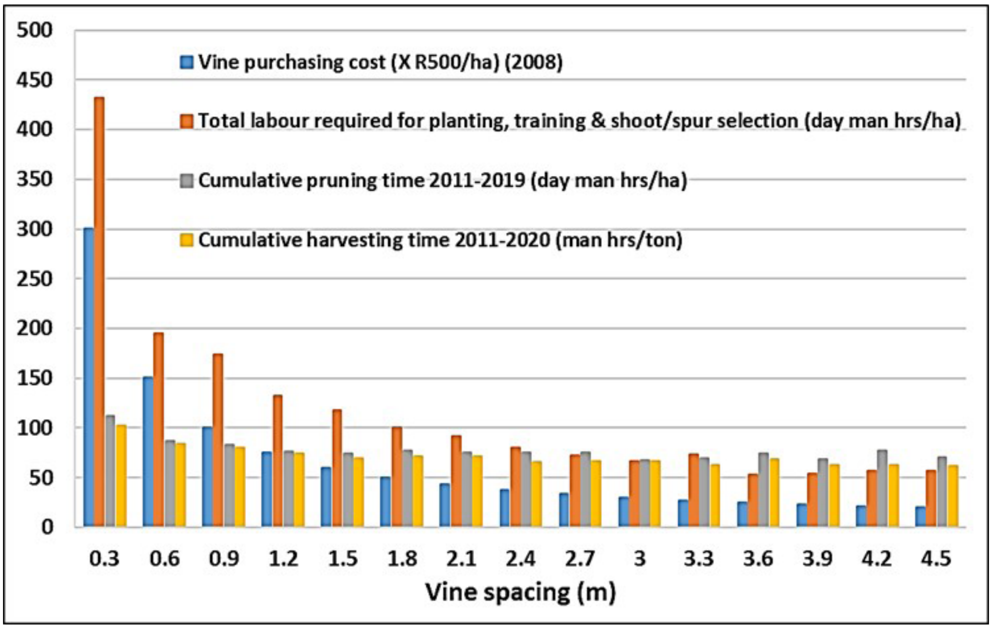

FIGURE 2. Collective figure showing grafted vine purchasing cost (@ R9.93/nursery vine in 2008 - equal to approximately 1 Euro/1.25 US Dollar at the time); total labour required for planting and young vine training (calculated @ 1 day man hour = 8 hrs) (incl. topping, trunk suckering, selection and fixing of cordon arms, shoot removal to select spur positions, cordon extension and bunch removal to 1 bunch/shoot); cumulative pruning time; and cumulative harvesting time for the different vine spacing treatments.

The trunk circumference trend (Figure 4) was in line with the larger root system of the more widely spaced treatments (Hunter and Volschenk, 2024) and indicates collective concentrated growth, through which the vine inherently endeavoured to increase its ability to supply in the extended aboveground vegetative and reproductive growth demand. The decrease in trunk diameter with higher density planting confirms findings in studies on P. noir (Archer and Strauss, 1991) and Citrus (Wheaton *et al*., 1995). Spacing the vines equally and further apart induced an initial almost linear seasonal vegetative reaction per vine, but this response faded beyond approx. 2.1 m (Figure 3). The growth response and increase in spacing increment became increasingly dissimilar, indicating that vine carbon allocation was affected by the distance between vines. The cane mass/ha (Figure 3) agreed with the total number of roots/ha (Hunter and Volschenk, 2024) and confirms the positive relationship between aboveground and subterranean growth, irrespective of spacing (Hunter, 1998b; Archer and Hunter, 2004).

The vegetative growth parameters showed that individual primary and secondary (not shown) leaves were larger with narrower vine spacing, and that leaf size decreased from narrow to wide spacing (see also Hunter, 1998b), with a turning point at around 2.7/3.0 m, after which a slight upward curve occurred (Figure 5). The secondary leaf area/primary shoot showed a decreasing trend with narrow to wide spacing and the primary:secondary leaf area ratio increased with wider spacing (Table 1).

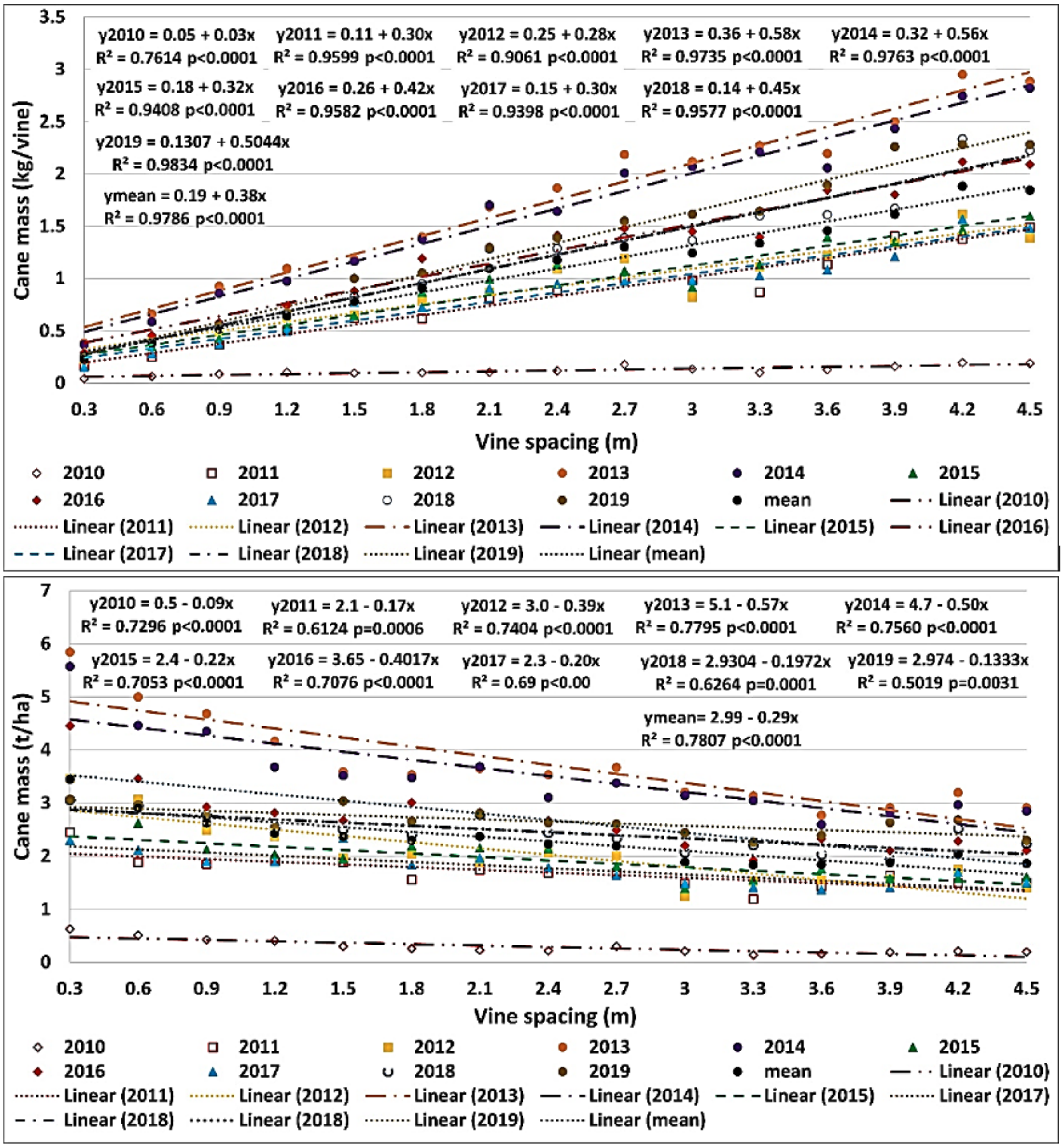

FIGURE 3. Cane mass (per vine, top; per ha, bottom) of Shiraz/101-14 Mgt (2010 - 2019 seasons).

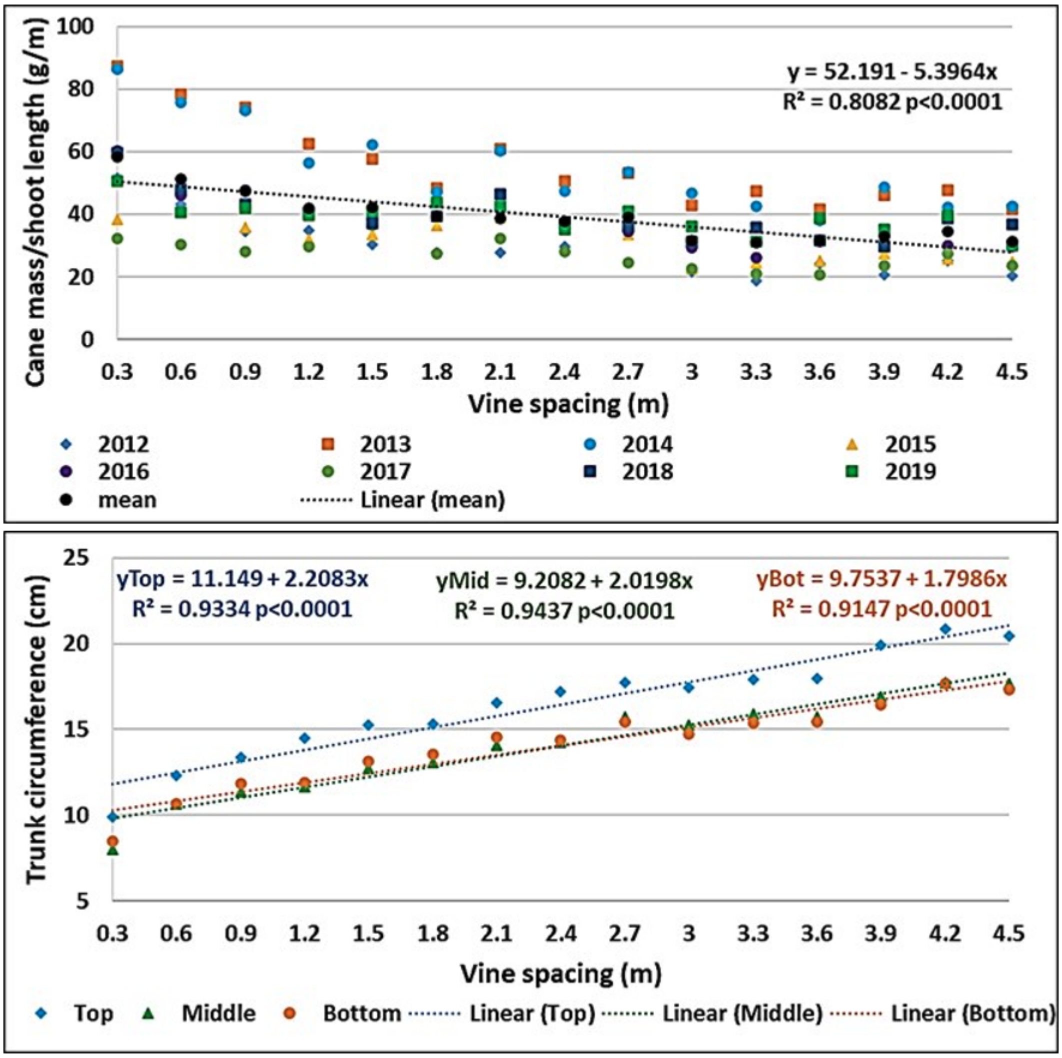

FIGURE 4. Cane mass/shoot length (means 2012 - 2019 seasons) and trunk circumference (means of 2016 - 2019 seasons) of Shiraz/101-14 Mgt.

The vines therefore demonstrated a shift in leaf area and age balance on the shoot, and thus compensatory vegetative growth responses to the physical growth volume confinement under naturally more vigorous growth conditions, which was in competition with grape development and composition, irrespective of plant spacing. The regression lines of the primary leaf area per soil surface (increasing) and the secondary leaf area per soil surface (decreasing) crossed at 1.8 m spacing, but the total leaf area per soil surface area was nonetheless relatively unaffected by vine spacing (Figure 5). However, the more widely spaced treatments were visually observed to have sparser canopies. This was also evident from the increasing canopy PAR with increasing vine spacing and particularly the steeper regression line found in the upper zone of the canopies of these treatments (Hunter and Volschenk, 2024). The poorer light microclimate of the more closely spaced vines and the more open canopies of the more widely spaced treatments, together with water potential and photosynthetic responses (Hunter and Volschenk, 2024), confirmed the physiological and morphological compensatory growth differences of the canopies induced by vine spacing (with similar spur spacing). Plant water deficit generally leads to smaller leaf areas, thicker leaves, higher leaf tissue density and lower hydraulic conductance (not excluding possible embolisms) (Schultz and Matthews, 1993; Lovisolo and Schubert, 1998; Yang *et al*., 2021), all seemingly driven by a lower turgor- and age-induced reduction in elastic and plastic extensibility and deformation, higher canopy temperature, and a decrease in availability of photoassimilates. However, under conditions conducive to sufficient vigour, Hunter and Visser (1990), Candolfi-Vasconcelos and Koblet (1990) and Fournioux (1997) showed opposite compensatory leaf responses (increase in leaf mass and lamina expansion) to applied partial defoliation, which decreased the source:sink relationships, albeit with an improvement in canopy light exposure and photosynthetic activity (Hunter and Visser, 1989). This positively affected grape composition and wine quality (Hunter *et al*., 1995b). A significant role of soil water in root system alteration and aboveground behaviour has been demonstrated in various plant species (Lovisolo *et al*., 2010; Yang *et al*., 2021). A positive correlation between secondary shoot presence, judicious canopy exposure, lower source:sink ratios, and root density/activity has been previously found (Hunter, 2000). A decrease in the number of laterals led to a delay in sugar accumulation.

TABLE 1. Vegetative growth parameters (primary & secondary shoots) at grape ripeness levels 1 (means of 2012 - 2019) and 2 (means of 2015 - 2019) of Shiraz/101-14 Mgt planted to different vine spacing. (Part 1/2)

Ripeness 1													
Vine spacing (m)	Number prim. leaves/ shoot	Prim. leaf mass (g)	Prim. leaf area/ shoot (cm^2)	Prim. shoot length (cm)	Prim. leaf area/ vine (cm^2)	Number sec. shoots/ prim. shoot	Number sec. leaves/ prim. shoot	Sec. leaf area/ prim. shoot (cm^2)	Sec. leaf area/ vine (cm^2)	Total leaf area/ shoot (cm^2)	Total leaf area/ vine (cm^2)	Leaf area Prim.: Sec. ratio	Total leaf area: yield ratio
0.3	9.57	3.43	1528	115.6	6113	8.28	32.23	1862	7448	3390	13561	0.98	20162
0.6	11.15	3.14	1560	115.4	12483	9.21	33.96	1781	14251	3342	26734	1.06	17061
0.9	10.94	2.90	1450	109.1	17398	8.27	29.36	1588	19054	3038	36451	1.02	14528
1.2	11.54	2.96	1560	115.0	24967	8.95	29.75	1563	25005	3123	49972	1.13	12440
1.5	11.99	2.97	1549	112.3	30976	8.99	31.11	1630	32601	3179	63577	1.17	11932
1.8	12.04	2.77	1523	114.9	36551	8.65	29.94	1650	39596	3173	76147	1.04	12293
2.1	11.00	2.95	1462	109.8	40927	8.95	32.21	1747	48909	3208	89836	0.95	13692
2.4	11.45	2.95	1563	114.4	50028	9.64	31.53	1750	56013	3296	105462	1.02	12785
2.7	12.66	2.76	1569	110.7	56469	8.72	29.14	1539	55417	3108	111886	1.20	10814
3.0	13.66	2.60	1621	116.5	64837	9.18	30.81	1510	60420	3131	125256	1.38	12036
3.3	13.74	2.56	1562	120.9	68717	8.70	29.08	1395	61370	2957	130087	1.26	11821
3.6	12.22	2.74	1497	114.6	71839	8.54	26.30	1384	66428	2881	138268	1.27	12278
3.9	13.37	2.66	1584	112.7	82363	8.57	30.59	1426	74173	3001	156027	1.30	11458
4.2	12.52	2.90	1610	115.0	90165	8.63	30.63	1679	94039	3289	184204	1.26	10492
4.5	13.00	2.85	1645	118.3	98679	9.43	31.15	1607	96408	3251	195087	1.21	11934
LSD ($p = 0.05$)	1.72	0.39	156	9.7	6360	1.18	5.67	374	13824	425	17938	0.24	2676
Ave	12.06	2.88	1552	114.3	50167	8.85	30.52	1607	50076	3158	100170	1.15	13048

TABLE 1. Vegetative growth parameters (primary & secondary shoots) at grape ripeness levels 1 (means of 2012 - 2019) and 2 (means of 2015 - 2019) of Shiraz/101-14 Mgt planted to different vine spacing. (Part 2/2)

	Ripeness 2												
Vine spacing (m)	Number prim. leaves/ shoot	Prim. leaf mass (g)	Prim. leaf area/ shoot (cm^2)	Prim. shoot length (cm)	Prim. leaf area/ vine (cm^2)	Number sec. shoots/ prim. shoot	Number sec. leaves/ prim. shoot	Sec. leaf area/ prim. shoot (cm^2)	Sec. leaf area/ vine (cm^2)	Total leaf area/ shoot (cm^2)	Total leaf area/ vine (cm^2)	Leaf area Prim.: Sec. ratio	Total leaf area: yield ratio
0.3	10.68	2.96	1402	107.2	5609	8.19	29.90	1576	6304	2978	11913	0.99	21754
0.6	11.13	2.82	1430	104.7	11438	8.49	26.79	1385	11079	2815	22518	1.14	17300
0.9	11.92	2.81	1476	101.3	17707	8.29	30.12	1513	18151	2988	35858	1.09	15201
1.2	13.07	2.64	1468	98.2	23488	8.31	27.27	1335	21359	2803	44847	1.20	14831
1.5	13.38	2.67	1592	105.0	31842	8.83	29.71	1511	30225	3103	62067	1.17	16477
1.8	11.43	2.75	1398	98.4	33545	8.36	26.14	1268	30439	2666	63984	1.44	14233
2.1	12.02	2.79	1454	94.0	40725	7.86	28.64	1397	39114	2884	80739	1.32	15095
2.4	13.87	2.56	1583	108.2	50656	8.28	28.08	1294	41411	2877	92067	1.37	14824
2.7	14.68	2.64	1682	102.6	60568	9.86	31.20	1616	58168	3298	118736	1.23	16228
3.0	13.04	2.61	1514	104.4	60554	9.36	26.60	1246	49834	2760	110388	1.35	16400
3.3	14.77	2.56	1666	103.5	73298	8.99	30.77	1353	59534	3029	133285	1.34	13167
3.6	13.62	2.62	1594	105.1	76494	9.16	28.84	1310	62875	2904	139369	1.35	15095
3.9	13.60	2.64	1527	101.7	79425	8.78	30.97	1352	70318	2880	149743	1.32	13130
4.2	13.56	2.73	1660	102.6	92961	9.19	28.85	1498	83898	3158	176858	1.24	17090
4.5	13.49	2.65	1570	100.8	94174	8.44	27.32	1325	79484	2894	173658	1.36	14920
LSD ($p = 0.05$)	2.42	0.31	219	10.7	8632	1.27	6.24	306	11114	406	16778	0.33	3300
Ave	12.95	2.70	1534	102.5	50166	8.69	28.75	1399	44146	2936	94402	1.26	15716

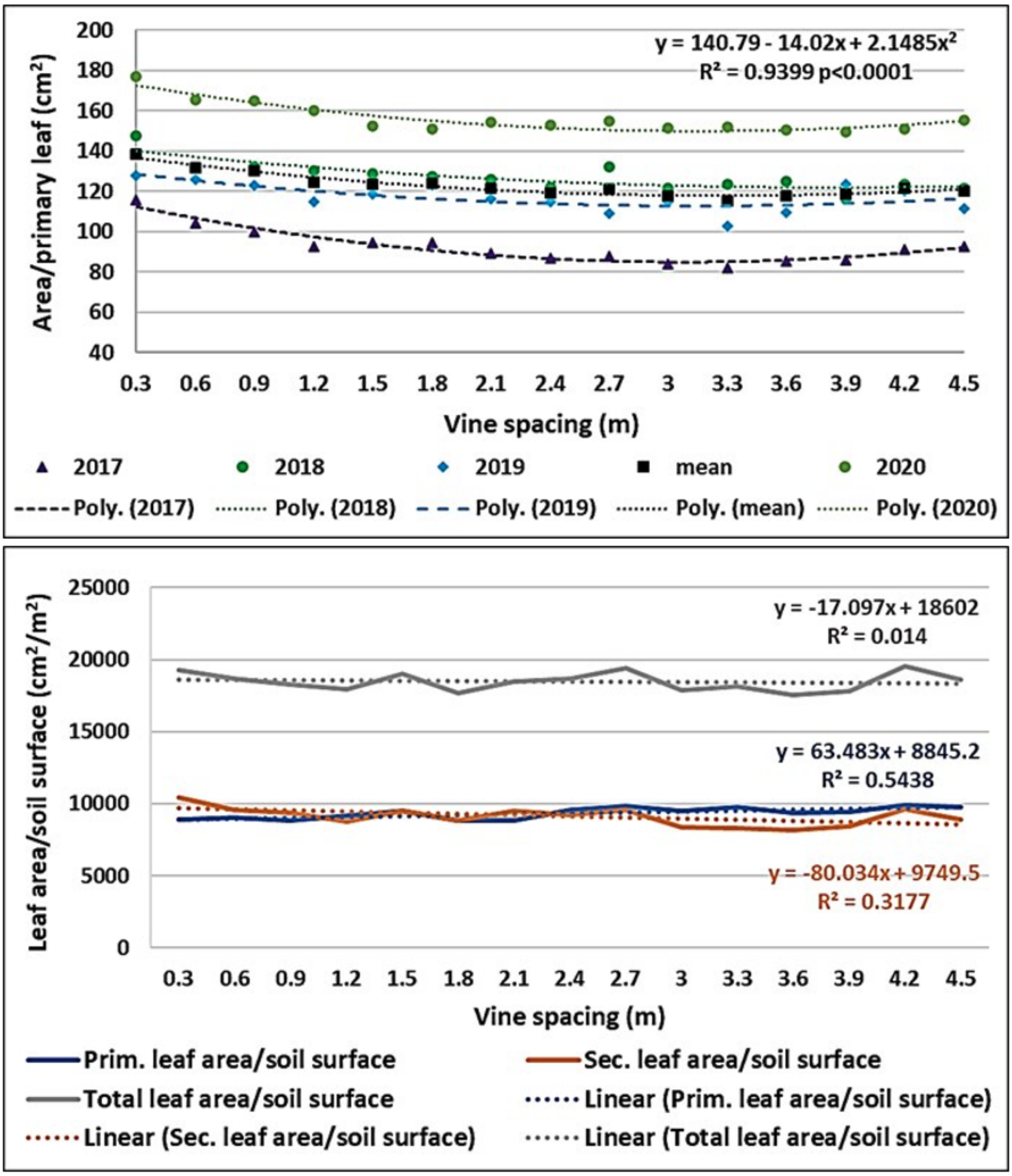

FIGURE 5. Area/primary leaf (2017 - 2020 seasons) and total leaf area/soil surface area (average of measurements at two ripeness levels) (2015 - 2020 seasons) of Shiraz/101-14 Mgt.

3. Reproductive parameters

Although annual yields increased on a per vine and per hectare basis with spacing (from narrow to wide), cumulative yields of the last five years of grapes harvested at the first ripeness level exhibited the highest yield gain, with 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 at the first ripeness level) (Figure 6). A similar pattern emerged when yields were expressed per seasonal water supply (Figure 6). This implies that if vines are fully developed and water supply is not adjusted to the increase in vine spacing and development, increasingly wider spacing of vines would lead to progressively less production per surface area. Similar results have been previously found (Champagnol, 1979, and references therein; Archer & Strauss, 1991; Hunter, 1998b). If irrigation is not adjusted, growth, microclimate and grape composition should be carefully monitored to avoid imbalances. The yield turning point was apparently reached earlier at the first than at the second ripeness level. At the latter ripeness level, a flatter, linearly increasing curve occurred that seemed to stabilise at around 2.7 m spacing, beyond which available space for vine development seemed in discordance with yield obtained per surface area. Yield/ha followed an opposite trend to that of cane mass/ha and the number of roots/ha. Thus, despite the seemingly sufficient response of vegetative growth (canopy and roots) to the narrower spacing, the yields did not react in the same way. As discussed earlier, this impacted the physiological, microclimatic, and vegetative characteristics of particularly the more widely spaced vines.

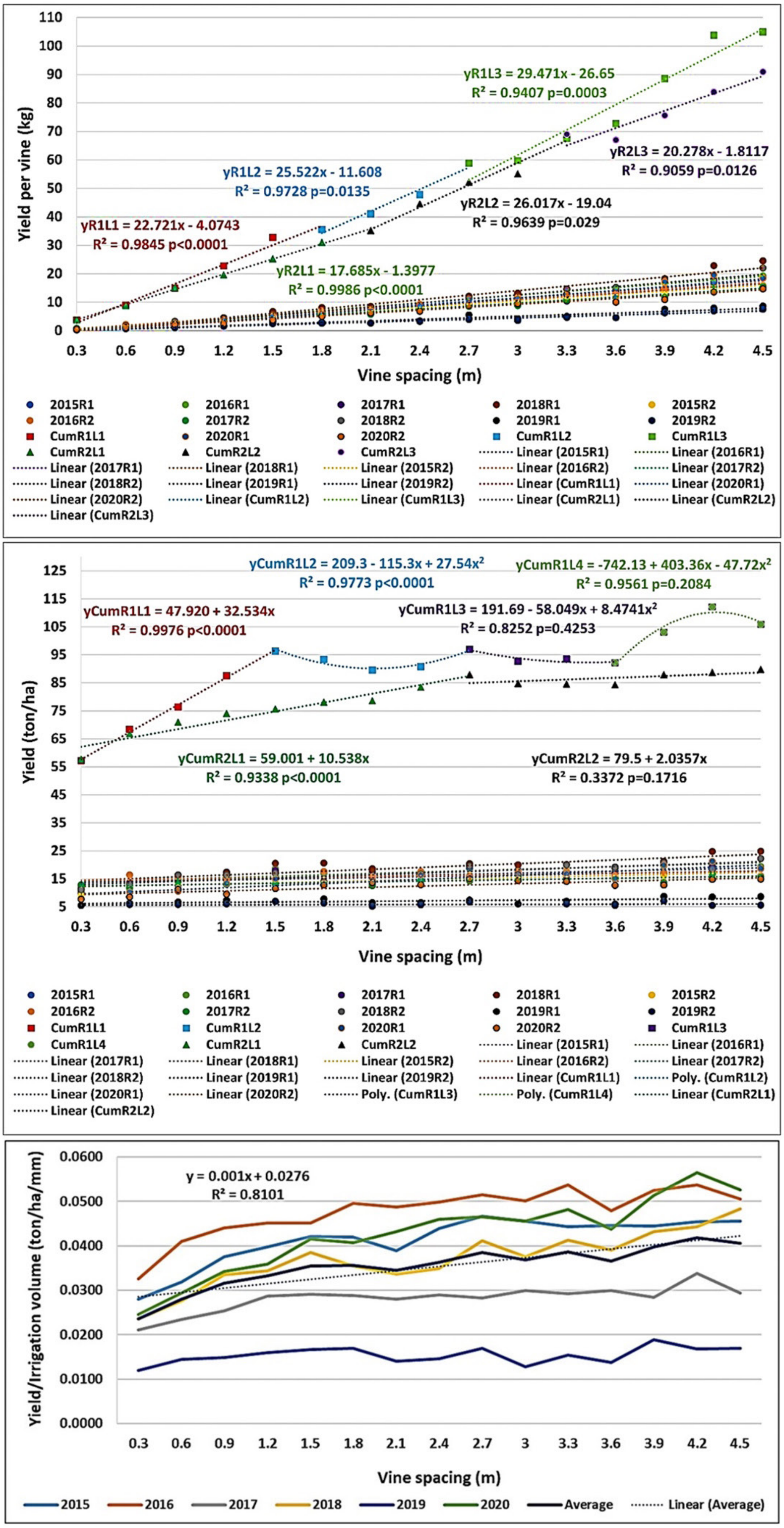

FIGURE 6. Yields per vine and per hectare (annual and cumulative) of consecutive seasons (at two ripeness levels) and yield per irrigation volume (of consecutive seasons - average of two ripeness levels) of Shiraz/101-14 Mgt (2015 - 2020 seasons).

TABLE 2. Reproductive growth parameters at grape ripeness levels 1 and 2 of Shiraz/101-14 Mgt, planted to different vine spacing (means of 2012 - 2019).

Ripeness 1												
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
Ripeness 2												
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

Although berry size showed no marked differences between the plant spacing treatments, yield responses seemed to be linked to fertility, setting, and bunch mass, with increasing trends with narrow to wide spacing treatments, while the bunches of the narrow-spaced vines appeared to be more compact (Table 2). In general, insufficient space for the allocation of buds on a single cordon largely hampers and restricts adjustments in bud numbers and crop load under excessive vegetative growth conditions.

Substantial yield losses occurred with hang time (from first to second harvest); this was evident from the bunch volume, berry mass, berry volume and bunch:rachis volume ratios (Table 2). The significant decrease in bunch width is noteworthy and may indicate that the rachis started to droop between the two harvest dates. Such deformation could be the result of a loss in turgor, generally becoming more prominent in berries with ripening (Carlomagno *et al*., 2018). The decrease in bunch width is a factor that could possibly be used as an indicator of full ripeness. Almost all the parameters decreased between the first and second harvest - this is an aspect that should be considered when grape prices are negotiated between growers and buyers and when wine price points are fixed. The phenomenon of berry shrivelling (as is evident from the decrease in berry mass and berry volume) is commonly found in Shiraz (and often in other varieties), most likely occurring because of continued berry transpiration, sluggish water refill or even termination of water supply to the berry (Hunter *et al*., 2014; Carlomagno *et al*., 2018. Hunter *et al*., 2018). Berries are more sensitive to vine water relations during pre-véraison than during post-véraison (Greenspan *et al*., 1994; Hunter *et al*., 2014), but berry transpiration plays a significant role during both periods, especially during late ripening (Greenspan *et al*., 1994; Greer and Rogiers, 2009).

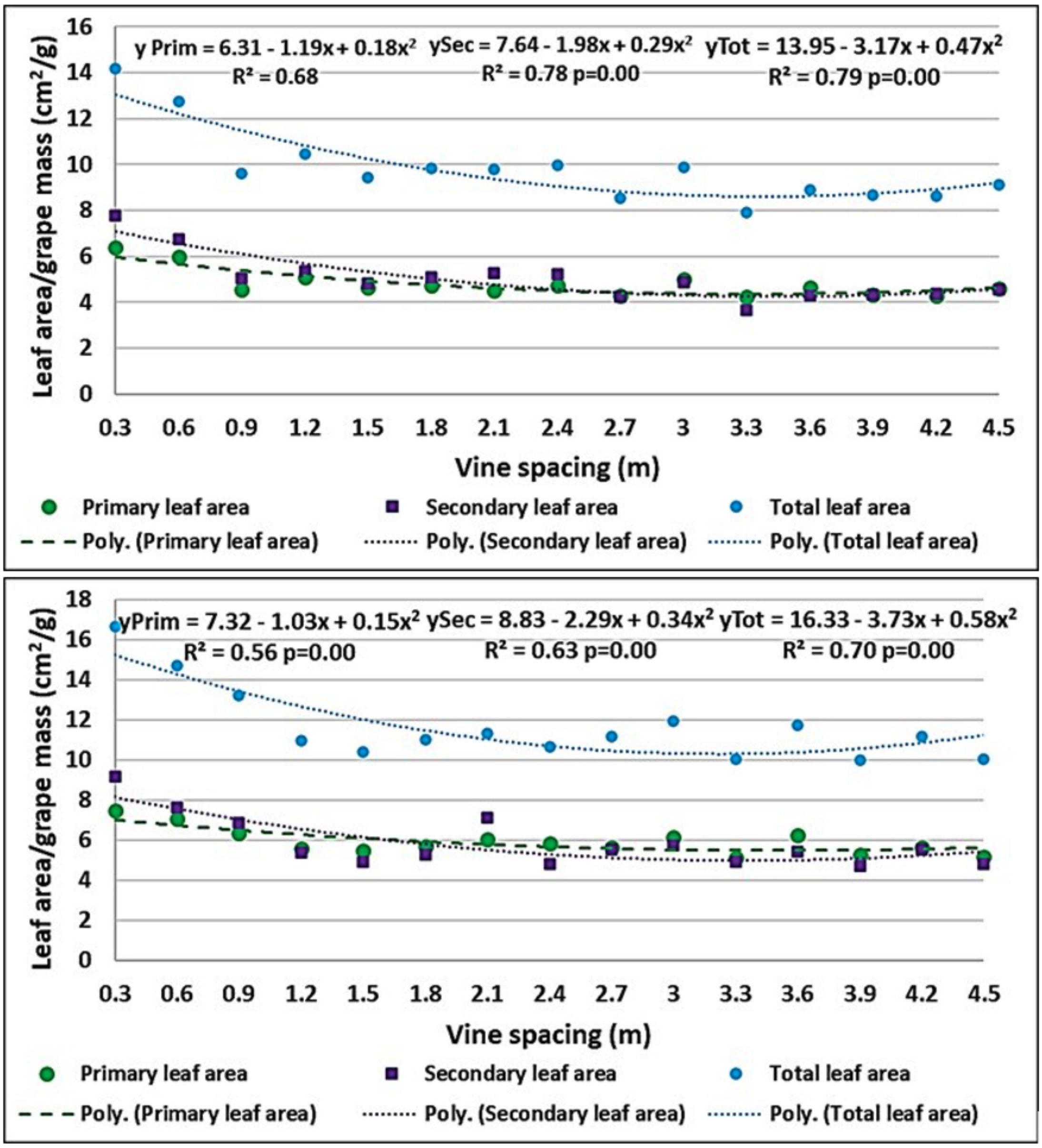

FIGURE 7. Leaf area/grape mass (Ripeness level 1, top; Ripeness level 2, bottom) of Shiraz/101-14 Mgt (means of 2012(R1)/2015(R2) - 2019 seasons).

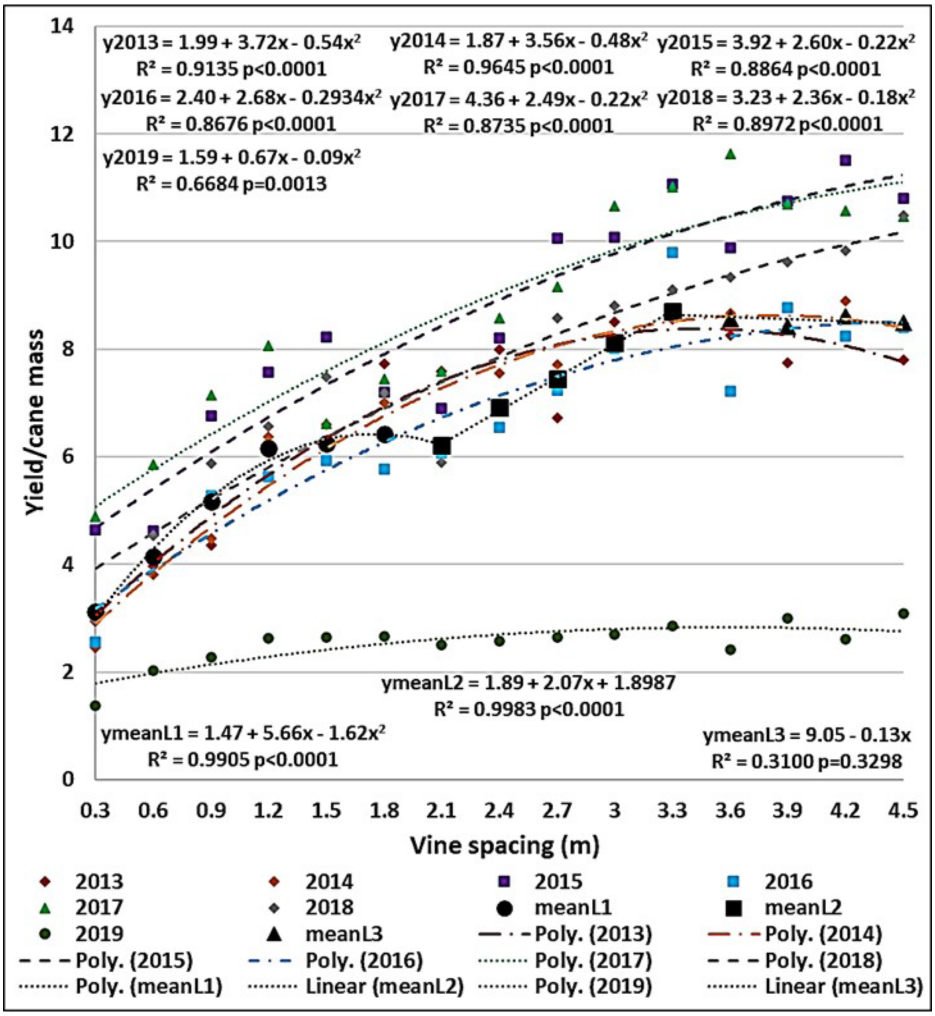

FIGURE 8. Yield/cane mass (calculated from ton/ha - Ravaz) (either from single harvests or an average of two harvests, where applicable) of Shiraz/101-14 Mgt (2013 - 2018 seasons).

At véraison, congruent with an apparent xylem disruption, phloem sap becomes the primary 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 (Greenspan *et al*., 1994). The continuation of berry transpiration and progressive isolation of the berry from vascular support led to the shrinking of the berry and/or solute concentration depending on the physiological activity of the vine, physical dimensions of the canopy and environmental conditions, the latter being very important (Hunter *et al*., 2014). In general, excessive shrivelling of the berry is not considered favourable for obtaining quality grapes and wine (Hunter *et al*., 2014; Carlomagno *et al*., 2018; Hunter *et al*., 2018). Thus, although the loss in grape mass/concentration is more often necessary with hang time, excessive shrivelling of grapes should be avoided by both growers and winemakers to prevent a detrimental effect on grape and wine quality. Differences in yield trends between ripeness levels indicate that treatments with more exposed canopies/less growth per shoot (more widely spaced vines) were generally more prone to yield loss with progressive ripening. Yields per cordon space/length (expressed on a per hectare basis) showed an initial rapid decline with very narrow to approx. 2.4 m spacing, after which a further slight decrease occurred with wider spacing; this trend is reversed when yields per cordon space are expressed on a per vine basis (data not shown). This has significant implications from a plant material cost/establishment point of view.

The total leaf area/vine showed a general stepwise increase from narrowest to widest spacing (Table 1), but total leaf area/grape mass showed a general decreasing trend from narrow to wide spacing with an apparent turning point at around 2.1 m (Figure 7). The higher vine starch depletion or lower starch accumulation that was found in this study with closer spacing (Hunter and Volschenk, 2024) indicates that, with decreasing space between the vines, sucrose export instead of transitory starch formation becomes preferential, as it actively supports seasonal aboveground growth, grape development, and root formation. However, this does not rule out the possibility that the starch accumulation of the more widely spaced vines might have been affected by a stressful physiological status induced by much lower source:sink ratios than those of closely spaced vines. An increase in total leaf area/grape mass at the second versus the first ripeness level indicates a loss in grape mass with hang time (most likely because of berry shrivel (Greer and Rogiers, 2009; Carlomagno *et al*., 2018)) and provides evidence of limited transport to the grapes during this period (Hunter *et al*., 2014). Yield/cane mass (Figure 8) followed an increasing trend from narrow to wide spacing, similar to cane mass/vine (Figure 3) and trunk circumference (Figure 4); a stepwise increasing pattern and a plateau for the widest spacing treatments are recognisable, whereas definite join points appeared at 1.8/2.1 m and at 3.3 m spacing.

4. General

In field experiments and commercial vineyards, seasonal vine behavioural differences or plasticity are to be expected and commonly occur because of variation in growth environments (particularly climatic conditions), as well as changes in cultivation practices and inherent perennial vine physiological adaptations; for example, reproductive growth is greatly impacted by sub-optimal growth balances, unfavourable weather conditions during the previous season (and even before that), and prevailing weather conditions during the seasonal formation of inflorescence primordia and differentiation of male and female flowers, as well as during the flowering/berry set stages. The physiological impact is related to multiple factors linked to *inter alia* seasonal changes in the weather and in pruning, irrigation, nutrition, and canopy management practices. It reflects overall effects on general growth, yield, reserves and root growth, the latter modifying hormone balance during spring and seasonal growth, and thereby governing both vegetative and reproductive development. The exposure of grapevines to prolonged adverse conditions (such as drought conditions, high temperatures, injudicious irrigation and fertilisation programmes and poor seasonal management) may lead to the gradual depletion of reserves in perennial tissues, such as the roots, trunk and cordons. This would affect growth stability over seasons and beyond the normal seasonal plasticity. Furthermore, the consistency of yields, resistance of the vine to unfavourable environmental conditions, and the lifespan of the vine would be deleteriously affected. Inadequate replenishment and growth balance disturbance, which result in annual growth and yield demands not being met, may therefore eventually lead to insufficient resilience of the vine during transient environmental/climatic extremes, thus challenging short- and long-term sustainability objectives.

Following data over a 10-year period, yields appeared to have reached an optimum at around 1.8 m vine spacing under conditions of this experiment. Vegetative (including the root system) and reproductive growth compartments of the vines seemed to become asymptotic, thus not responding in a linear fashion to the increase in space when the double cordons were extended to cover the allocated lateral space. Imbalances were observed when the vine spacing became either narrower or wider: in the former case, the vines showed a good vegetative response (shoot and root growth), but were restricted when utilising the growth potential for reproductive yield; meanwhile, in the latter case, the vines were restricted in terms of vegetative growth, but they utilised the available growth and other relevant impacting factors the most effectively for reproductive yield. Thus, closely spaced vines ended up being slightly under-cropped and widely spaced vines over-cropped. The latter vines would require additional treatment, such as irrigation and fertilisation, in order to remain productive and to maintain grape quality in the long run on VSP trellising. Even for other training/trellis systems (such as bush vines and larger canopies with spur and/or cane pruning), practical cultivation accommodation limitations on aboveground growth quantity, distribution and efficiency would always have a regulating effect on subterranean expansion because of the role of growth balances, and spacing choices may thus not always be favourable for land utilisation and sustainability.

Although it seems possible to increase growth and yield when vines are spaced more widely than the apparent optimum in this study, this may require higher fertilisation and water supply, which in turn would increase growth and production costs. The 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 very wide spacings (plus 1 - 2 winters). Such a scenario does not seem plausible and sustainable in the current producer circumstances, which are characterised by very difficult operational conditions, including: the decreasing availability of water for agricultural use, the increase in direct farming, nutrient and labour costs; a slow return on investment regarding farm gate price points and wine sales; net income challenges; and competitive markets. Although widely spaced vines still carried higher yields than narrower spaced vines on a per vine and surface basis, growth and yields did not increase linearly with vine cordon extension, and the relationship between growth capacity and soil yielding and utilisation became increasingly disrelated. If irrigation and fertilisation were adjusted and shoot growth of widely spaced vines improved (with appropriate and sufficient support wiring for cordon weight, seasonal growth and the crop), it should be possible to obtain higher yields in a higher quality category than in this experiment. This aspect may be justified by the very low graft material purchasing costs and low labour inputs for planting. By contrast, despite the positive effects of such spacing, the high purchasing and establishment costs of the graft material (including labour) required when spacing vines closer than 1.2 m under the favourable growth conditions of this experiment do not seem viable.

The commonly found natural balance between above- and belowground growth interactively determines the activity and expansion of top and root growth, hence affecting the density and extent of horizontal and vertical root distribution, and thus soil water and nutrient absorption capacity (Archer and Strauss, 1985; Archer and Strauss, 1989; Archer and Strauss, 1991; Reynolds *et al*., 1995; Hunter, 1998a; Hunter, 1998b; Archer and Hunter, 2004; Hunter *et al*., 2016; Archer and Saayman, 2018). Viticultural practices should be conducive to both above- and belowground development in order for the explorative extension of the root system to take place (Hunter *et al*., 2016). It is important to take these factors into account in conditions of shallow soil, dryland, limited soil water holding and low rainfall. A prolific and denser root system may be advantageous for water absorption under such circumstances, but there should be sufficient available soil water to maintain turgor and support vegetative growth, grape development and ripening during the entire season, as well as to provide a buffer during occasional heat waves. Hence, planting less and smaller vines per soil surface, and thus the concomitant lower total plant transpirational water loss and soil water extraction, seems plausible and advantageous for water conservation under marginal conditions, but the findings on growth balance behaviour with different plant spacing under low, moderate and high soil fertility, depth and water availability conditions generally does not seem to favour high root density and deep root penetration with wide planting; field conditions would rarely present a limit-free scenario. Although lateral distribution did not seem to be markedly affected by wider spacing, root density and deep penetration of roots were indeed restricted. This would decrease the tolerance of the vine to adverse environmental conditions within and over seasons. Furthermore, the preferred scenario from an agricultural perspective is to increase income per surface area. This results in a combination of lower production costs, optimal soil utilisation per available volume, and higher (or consistent) yield, grape quality and price point (also for the wine), while ensuring an optimal population and the valorisation of land in a sustainable way (Hunter *et al*., 2010; Hunter *et al*., 2016).

The yielding capacity of a soil with natural root restricting/hard layers in the subsoil can be increased by soil amelioration (before planting) and with management practices; e.g., deep ripping, delving, ridging, liming, irrigation, fertilisation, organic mulching and planting cover crops (Saayman, 1982; Christensen *et al*., 1994; Raath and Saayman, 1995; Conradie *et al*., 1996; Fourie *et al*., 2006; Medrano *et al*., 2015; Archer and Saayman, 2018). Cawthon (2002) found that growth and yield increased on a naturally deep soil with wide in-row spacing, and the vines thereby fully compensated on a per hectare basis; however, this was not the case on a shallow soil, which was more suitable for closer vine spacing to maintain yields and obtain full grape ripening. Furthermore, better adaptation of the rootstock to soil characteristics (e.g., lime, salinity, acidity and drought and waterlogging potential) (Conradie, 1983; Southey, 1992) and of the scion to the climatic conditions (particularly the temperature profile) of the allocated land, would increase sustainability under variable and extreme conditions (Van Leeuwen *et al*., 2008; Hunter *et al*., 2010; Hunter *et al*., 2016). Rootstocks and grape varieties that are free from harmful viral diseases (e.g., leaf roll Engelbrecht and Kasdorf, 1990; Petersen and Charles, 1997; Pietersen, 2006) and tolerant to common grapevine pests and fungal diseases (including the various forms of the soil-borne pests phylloxera, phytophthora, margarodes, and nematodes – Loubser, 1978; Marais, 1983; De Klerk, 1985; Loubser, 1988; and grapevine trunk diseases, botrytis, downy mildew and powdery mildew – Bois *et al*., 2017; Mondello *et al*., 2018), would contribute significantly to increasing the plasticity and lifespan of vineyards, particularly under challenging climatic conditions. In addition to the impact of plant density on root development, other viticulture practices e.g., the scion-rootstock combination (Southey, 1992), trellising (Archer *et al*., 1988), pruning levels/bud load (Slavtcheva and Pourtchev, 2003; Hunter *et al*., 2016) and canopy manipulation (Hunter and Le Roux, 1992; Hunter *et al*., 1995b; Hunter and Volschenk, 2001; Hunter *et al*., 2016) also affect the mass and size composition of the root system. Any of the aforementioned factors would most likely lead to an increase in the utilisation/valorisation of the available land and the economic viability of the farming operation. Each terroir would have a vine density optimum depending on the soil conditions, vigour of the graft combination and the numerous environmental and cultivation factors that interact and impact growth and complete utilisation of subterranean and aerial spaces (Shaulis, 1980; Van Leeuwen *et al*., 2008; Hunter *et al*., 2010; Hunter *et al*., 2016; Archer and Saayman, 2018).

Both above- and belowground spaces need to be fully utilised to make the most of the area being planted. For the grapevine, aboveground utilisation is determined by the size and leaf composition/efficiency of the canopy and belowground utilisation by the size and density/efficiency of the root system. The quality of both canopy and root system is important. The primary and secondary leaves of the canopy, and at least the primary, secondary, and tertiary roots in the root system are required for the optimal functioning and support of the grapes. The reserve storage and regenerative ability of both compartments are important for the formation of new leaves and roots, and thus crucial for the survival and yield and quality potential of the grapevine. This is driven by vigour potential that can only be established via the interaction of the canopy and root system. In addition to these factors, the canopy should be continuous, uniform, well-exposed and active in order to obtain high photosynthetic output (and high grape berry functioning/demand) and the root system should allow high absorption and utilisation of deep soil layers in a soil with the appropriate physical and chemical characteristics and drainage. Collectively, these aspects determine the physiological functioning of the grapevine, and its internal carbon distribution, growth microclimate, fertility, and grape development and composition.

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 study. These responses may have resulted, among others, from the unequal development of aboveground and subterranean growth, and thus a disturbance in the capacity of supply and demand bodies, resulting in disproportional distribution, long translocation distances in the widely spaced cordons that may have deleteriously affected flow rates and volumes of nutrient rich sap *via* xylem and phloem conduits, a crop load that may have resulted in imbalanced source:sink relationships per vine, and water (irrigation) and nutrition (fertilisation) that may not have been suitable for all treatments (the latter pointing to possible differential requirements of differently spaced vines). All the above, along with the other practical aforementioned limitations may prevent the proportionate extension of the cordons. Luxurious as well as overly stressful growth conditions should be avoided; instead, conditions conducive to balanced development would minimise any erratic behaviour beyond the normal complexities that grapevines experience in the field from year to year.

Both the root system and canopy are involved in water potential and photosynthetic activity regulation, and the interaction between these two plant compartments may lead to a lack of (expected) differences between the different vine spacings. Vine spacing affects both the above- and belowground compartments of the vine, and therefore induces an array of complex interactive physiological triggers and homeostatic mechanisms. If the development of these compartments is not balanced, the response of the grapevine to environmental factors and cultivation practices will be disrupted, often leading to erratic and unpredictable behaviour, and underperformance. Such conditions would thus not be conducive to the grapevine having a long lifespan and being resilient to environmental challenges, such as those associated with a change in climate.

5. Guidelines/useful observations

Based on the conditions of this study and using all the available data, the following are noteworthy:

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

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

• Vine spacing of less than 1.8 m led to an increase in canopy density and wider spacing to more exposed canopies; both scenarios inducing limitations in physiological activity; i.e., conditions were stressful.

• The most widely spaced vines in particular showed signs of over-cropping and stress, as the known requirements for canopy condition, physiological performance, production, and grape quality were not satisfied. Widely spaced vines (with full in-row space cordon development) would deteriorate further the poorer the growth conditions (e.g., with less water availability and nutrition, and without crop control).

• Natural leaf size responses were induced by changing the distance between vines; spacing narrower than the 1.8 m optimum led to larger leaves.

• The longevity of the widely spaced vines may be affected in the long run; a progressive starch depletion in the permanent vine structure would most likely occur.

• The balance between available space for vine development and yield obtained per surface area appeared to fade when vines were spaced more widely than 1.8 m, especially beyond 2.7 m (approx. 6 m^2/vine; 1684 vines/ha) and up to the maximum in this experiment of 4.5 m (approx. 10 m^2/vine; 1010 vines/ha).

• A 2.1 m (approx. 4.5 m^2/vine; 2165 vines/ha) vine spacing seems feasible, yet maximum, to meet production and grape quality targets, with a 10 – 12 cm^2 leaf area/g grape being obtained, which is a well-tested canopy-grape criterium, the performance of which would still provide a buffer under adverse conditions.

• Under reasonably fertile conditions and water availability, a vine spacing of 1.5 m (approx. 3.5 m^2/vine; 3030 vines/ha) to 1.2 m (approx. 2.5 m^2/vine; 3788 vines/ha) is advisable for inducing a naturally, slightly denser canopy that would provide better protection to grapes under, for example, hot to very hot climatic conditions, and which may naturally increase root density and water and nutrient absorption, without hampering photosynthetic output and grape and wine quality.

• Under similar conditions to those stated above, a vine spacing of 2.1 m (approx. 4.5 m^2/vine; 2165 vines/ha) and even wider (2.4 m) (approx. 5.5 m^2/vine; 1894 vines/ha) may be advisable for cool to cold conditions to allow for a naturally thinner canopy with proper functioning and grape ripening conditions, but at the potential risk of a less favourable, decreased root density; however, in such conditions soil moisture may be better maintained, thus likely decreasing the necessity for high root density.

• Wider spacing should be applied on more fertile and/or deeper soils, and when using more vigorous rootstocks, whereas narrower spacing should be applied on less fertile, poorer and/or shallower soils, and when using more drought-resistant and moderately vigorous rootstocks; the same principle can be applied to higher or lower water availability and more or less fertilisation (although these factors should always be adjusted depending on soil and leaf analysis results, yields and vegetative growth). In all cases, optimum utilisation of the soil potential should be sought, avoiding the risk of under- or over-exploitation of land surface and deterioration of the vines. The drought resistance characteristics of rootstocks and the high temperature resistance of scion varieties are becoming even more important and should be integral to vine spacing and establishment decisions in general. This would also contribute to developing more natural and organic cultivation.

• Training and trellising for VSP would always result in a restricted space if traditional cordon or cane pruning methods are applied. Space for vegetative growth and for carrying the yield would therefore be limited. The options for improving space utilisation, growth balances and yield (under sufficient water and fertilisation supply) would be to divide the cordon or canopy and/or add more buds in the form of spurs/half-length canes/canes; these kinds of interventions are almost always related to the occurrence of more than the usual vigour. Various methods exist to accomplish more balanced growth, but they should be executed with extreme care, meticulous circumspect and judicious management, especially in summer; vigour potential, product objectives and skilful practice are of defining importance. Larger, divided and overhead trellises are costly and challenging to manage, but can accommodate more buds. Vine and row spacing should be adequate for the development of cordons/spurs/canes and allow sufficient, well-distributed and, in particular, continuous, uniform canopies to obtain optimal microclimate to maintain fertility and satisfy requirements for bud burst, efficient leaf area, berry set, and grape development and quality. The goal is to obtain optimal utilisation of subterranean and aerial space of the allocated land, taking into account the impacting abiotic and biotic factors.

- The size of the vine within a specific space and within the population per surface area is dictated by its own genetic capacity (as determined by the scion-rootstock combination), the competing influence of adjacent vines within the population, and the environmental conditions (mostly climate and soil). Further dictating effects are those brought about by vineyard practices, such as soil preparation, fertilisation, irrigation, vine structure development and bud load/pruning. If the spacing is beyond the growth capacity of the graft combination (and induced by other viticulture practices), the available surface area will be under-utilised, and maximum crop and quality potential per surface area will not be attained. Proper utilisation of the surface area in such a case will be reached with closer spacing, but only if it does not lead to shoot/leaf crowding. Spur spacing should be maintained and the vigour of individual shoots monitored along with the microclimate. Furthermore, spacing that is too close in a soil type with a shallow potential root colonisation depth (restrictive soil depth) or a low water retaining capacity would result in a high rate of soil moisture and nutrient exhaustion during the summer season, which would impede the attainment of full canopy output and grape ripeness; this would be exacerbated under dryland cultivation conditions, particularly during seasons with little or no rainfall. In such situations, vines should rather be spaced more widely (though not too widely, due to space utilisation and the relationship between aerial and belowground growth), despite the likely loss in production per surface area; this also applies to bush vines.

- Alleviation of soil restrictive layers before establishment would favour deeper root distribution, environmental tolerance, sustainability, and valorisation of the land. With plant spacing under marginal growth conditions, a fine balance between evaporation (from the soil - disadvantageous) and transpiration (from the vine - advantageous) should be aimed for; a deeper and more drought resistant root system would favour the latter and contribute to resilience, growth and grape quality management possibilities, economic viability, and sustainability. In the case of bush vines or vine-by-post, with limited bud allocation and shoot growth accommodation possibilities, growth balances would still determine aerial and subterranean growth; any change in the growth conditions or structure of any of the two compartments would be reflected in the other, and judicious management would be required to maintain growth, microclimate and fertility for sustainable yield, grape composition, and wine quality.

- Under favourable growth conditions, close planting may result in the crowding and interlacing of the canes, and dense, shaded foliage which may interfere with fertility, setting, bunch growth, sugar accumulation, colouring, and other aspects of fruit ripening and quality parameters. Shading of the soil would to some extent curb evaporation, depending on the row orientation. The control of diseases and insects may be difficult. Viticulture practices, such as canopy management, pruning and harvesting, would be unduly costly. On the other hand, poor growth conditions would lead to open canopies with high radiation in the centre of the canopy and on leaves, most likely resulting in high water loss *via* evapotranspiration and affecting photosynthetic activity of leaves negatively. Although pruning and harvesting would be easier, yields would be lower and the acidity, pH, colour, flavour and general morphology and health of the grapes deleteriously affected, likely resulting in unbalanced and structureless, poor quality wine. Disease control may be more effective, but frugivorous and herbivorous birds, insects and bovids may damage visible hanging grapes before harvest.

The appropriate spacing of vines is a natural way of optimising root colonisation (for absorption of water and minerals), canopy growth and microclimate (for photosynthetic activity), yield and grape composition, while maintaining the fertility and longevity of the vine. Extreme circumspection is thus of the utmost importance when making choices related to terroir and viticultural practices before establishing the vineyard. The results of the present study confirm the necessity of field studies and collection of whole vine information before any recommendations can be made at producer level. They also point to the importance of integrative studies that include climate, soil, and cultivation factors, facilitating the practical application of scientific knowledge.

CONCLUSION

The aim of the study was to provide information regarding the most practical and economic vine spacing under high potential soil conditions, with a focus on finding a balance between the establishment, viticulture practices, production returns, and physiological status and longevity of vines. The reaction of the grapevine to above- and belowground spaces was monitored. Carbon allocation differences between vine spacing treatments were evident in terms of leaf size, trunk circumference, shoot and cane mass, vegetative:reproductive ratios and yield. As spurs were allocated uniformly, canopy microclimate and visual canopy density differences resulted from morphological (shoot size) responses. Trends found for vegetative:reproductive growth relationships seemed to indicate that more widely spaced vines experienced more stress with fully developed vine structure. The confinement and progressive extension of the grapevine structure led to its gradual transition from higher vigour (perhaps mostly root growth/physiology induced) to lower vigour (perhaps mostly canopy structure/physiology induced). This resulted in more widely spaced vines having lower leaf:fruit ratios, which caused an imbalance between increasing spacing, growth, canopy microclimate and yield return.

The results highlight the importance of judicious choices regarding planting density, trellis system, scion-rootstock combination and seasonal cultivation practices (including the planting practice *per se* during the establishment of a new vineyard), such as pruning, canopy management, fertilisation and irrigation. These would all contribute to the establishment of sizeable, proportionate and efficient vines that possess appropriate physiological characteristics for buffering unfavourable environmental or other abiotic/biotic conditions of both transient and perpetual nature, while sustaining productivity. Adherence to the principles of grapevine growing and manipulation/maintenance criteria is important for efficient leaf and root function and the successful outcomes of the selected vine spacing. However, each terroir, along with soil preparation, plant material choices and viticulture practices, will dictate the density of the planting and vineyard uniformity. Making choices requires judicious circumspection, and all the criteria involved in grapevine growing and wine style objectives need to be considered. Once vineyard establishment and vine structure development have been completed, it is imperative that practices concerning vine water relations, nutrition, and growth balances, as well as disease status, be constantly re-assessed and optimised to accommodate seasonal environmental and physiological events.

This study provided solid, extrapolatable information at scientific and practical levels to aid strategic approaches for vine spacing selection from a cost, management, growth and production perspective. It aimed at establishing vine spacing criteria to provide a foundation for the full utilisation and expression of given terroir conditions, and to ensure the sustainable production of high quality grapes and vineyard longevity.

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