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Grapevine physiological response to row orientation-induced spatial radiation and microclimate changes

JJ Kobus Hunter[1], Luigi Tarricone[2], Cornelis Volschenk[1], Christian Giacalone[3], Maria Susete Melo[1] and Roberto Zorer[4]

[1]Agricultural Research Council, ARC Infruitec-Nietvoorbij, Private Bag X5026, Stellenbosch, South Africa
[2]CREA-Council for Agricultural Research and Economics, Research Centre for Viticulture and Enology, Via Casamassima 148, 70010 Turi (BA), Italy
[3]Dipartimento di Scienze Agrarie e Forestali, Università di Palermo - Viale delle Scienze, 90128 Palermo, Italy
[4]Department of Biodiversity and Molecular Ecology, Research and Innovation Centre, Fondazione Edmund Mach, Via E. Mach 1, 38010 San Michele all'Adige, (TN), Italy

*Corresponding author: hunterk@arc.agric.za

ABSTRACT

Terroir factors and vineyard practices largely determine canopy and root system functioning. In this study, changes in soil conditions, multi-level (vertical, horizontal) light interception (quantitative, photographic, schematic, 3D modelled), leaf water potential and photosynthetic activity were measured during the grape ripening period on NS, EW, NE-SW, and NW-SE orientated (Southern Hemisphere) vertically trellised Shiraz grapevine canopies. It was hypothesised that the spatial radiation interception angle and radiation distribution of differently orientated and vertically trained grapevine rows would affect soil conditions and vine physiological activity. Soil water content showed an increase and soil temperature a decreasing gradient with soil depth. In the afternoon, soil layers of EW orientated rows reached their highest temperature. This, along with measured photosynthetic active radiation received by canopies, complimented the diurnally-captured photographic, constructed and 3D modelled images (also schematically) of canopy and soil exposure patterns. The top, bottom and outside of NS canopies mainly received radiation from directly above, from the E and the W; during midday, high radiation was only received from above. The EW rows received the highest radiation component from above and from the N. The NE-SW rows received high levels of radiation from above, from the SE until 10:00, and from the NW from 13:00. A similar profile can be described for NW-SE rows, but with high radiation received from the NE up to 13:00 and from the SW from 16:00. Overall, lowest leaf water potential occurred for NE-SW canopies, followed by those orientated NW-SE, NS and EW. Photosynthetic activity reflected the positive radiation impact of the sun azimuth during the grape ripening period; best overall performance seemed to occur for E and N exposed canopy sides. This was largely driven by the responsiveness of the secondary leaves to radiation. Photosynthetic output decreased from apical to basal canopy zones with low, erratic values in the light-limited canopy centre. The NS and EW orientated canopies generally showed the highest average photosynthesis, while it was lower for the sides facing S, SE and SW. The results provide a better understanding of the physiological functioning of horizontal and vertical leaf layers in differently orientated grapevine canopies, as affected by climatic conditions. The study contributes to the longstanding challenges of capturing the complexity of parallel microclimatic and physiological output of grapevine canopies under open field conditions. The results can be directly applied to the selection of vineyard practices and seasonal management to ensure the attainment of yield, grape composition and wine quality objectives.

KEYWORDS

grapevine row orientation, spatial radiation, canopy microclimate, canopy modelling, leaf water potential, photosynthesis, soil conditions

INTRODUCTION

The geo-morphological complexity of vineyard terroirs has a dictating role in temporal and long term climatic and edaphic conditions, which should be taken into account when making decisions regarding variety and rootstock choices, vineyard trellising, row orientation and plant density for establishment. It has already been demonstrated that grapevine roots respond to soil nutrition and water as well as cultivation practices (Archer and Strauss, 1985; Archer and Strauss, 1989; Archer and Strauss, 1990; Conradie *et al.*, 1996; Hunter, 1998; van Leeuwen *et al.*, 2019). Soil also constitutes a source of warm and cold air and humidity dissipation. Its physical and chemical composition largely controls plant growth by determining water and nutrient release capacity and availability to plant roots, organic matter decomposition and mineralisation, and in particular biological activity (Steenwerth *et al.*, 2008; Hunter *et al.*, 2010; Renouf *et al.*, 2010; Echeverría *et al.*, 2017). The sensitivity of grapevine leaves to sunlight exposure and plant water status means that canopy structure dimensions, geometric shapes, and pruning and foliage management practices are critical if optimal functioning is to be reached (Kriedemann, 1968; Pandey and Farmahan, 1977; Hunter *et al.*, 1988a, Hunter *et al.*, 1988b; Smart *et al.*, 1990; Hunter *et al.*, 1995; Hunter *et al.*, 2004; Hunter *et al.*, 2014a). Together, terroir factors and vineyard practices largely determine the suitability of canopy and root system functioning for product-objective-orientated grape production and wine style.

The photosynthetic output of grapevine canopies has been frequently studied over the years includes different varieties, trellising systems and environmental conditions (Kriedemann, 1968; Pandy and Farmahan, 1977; Hunter and Visser, 1989; Düring, 1991; Chaumont *et al.*, 1994; Hunter *et al.*, 1994; Naor and Wample, 1994; Hunter, 1998; Zufferey *et al.*, 1999). Data sets have mostly been obtained from single leaf measurements using small clip-on chambers to confined surfaces on different leaves distributed in the canopy (Hunter *et al.*, 2014a, and references therein), but whole vine measurements on either single or multiple vines enclosed in large commercially-constructed gas analyser-connected chambers have also been conducted (Poni *et al.*, 2009, and references therein). The latter is argued to present net canopy photosynthetic diurnal and seasonal output, accommodating leaf orientation and inclination, as well as direct, diffuse and reflected radiation, as dictated by growth structure and plasticity. Yet in such atmosphere-controlled conditions the detailed potential or function at individual leaf level is undefined and photosynthetic output merely represents a collective functional outcome. Efforts therefore continue in gaining a better understanding of the proportional differential contributions of micro-environmental factors (light, humidity, air flow, turbulence), phyllotaxy, leaf position, leaf size and leaf age to net photosynthetic potential/capacity; thus going beyond net output from artificially enclosed vines. In terms of the latter, it remains a challenge to create conditions in which field-grown or pot-grown vines function without growth or micro-climate constraints and interactive complications; similarly, it is notoriously difficult to reach ultimate optimal and representative conditions in the field when single leaf measurements are conducted. Furthermore, varying seasonal and diurnal/nocturnal climatic conditions, physiological and growth responses, and management practices that change source:sink relationships, seriously complicate efforts to upscale and relate values obtained at single leaf level to whole plant photosynthetic capacity, during the typically varying temporal and seasonal phenology, and canopy and grape development periods (Hunter, 2000). A grapevine canopy is often still considered as a single, static unit instead of a very dynamic composite foliage unit containing leaves of different ages, sizes, and origins, and which comprises a mixture of source and sink activities that respond to both nocturnal and diurnal conditions. Capturing the complexity of grapevine canopies quantitatively under field conditions with regards to microclimate, leaf morphology and physiological status, and physical constraints by applying quality-controlled methodology, which is precise, calibrated and consistent, remains unsatisfactory and an enormous current and future challenge.

The intricacy of the relationship between single leaf and whole plant carbon balance and water relations has been shown by Medrano *et al.* (2015) in a study focused on plant water-use efficiency. Reviewing various models on stomatal conductance, Damour *et al.* (2010) expressed the relevancy of continued attempts to integrate the complex impact of environmental factors on stomatal regulation and carbon fixation under field conditions, especially considering climate change-related factors, such as high air temperature, intense radiation and drought.

Calibrating a model that used several semi-empirical equations with direct and diffuse radiation as the main factors, Haasbroek *et al.* (2000) found a very good regression when the output was compared with field measurements of photosynthesis of Cabernet Sauvignon on a slanting trellis. Using three-dimensional and radiative transfer modelling approaches to simulate canopy light microclimate efficiencies of two cultivars (Syrah, Grenache) trained to different trellising systems (Vertical shoot positioned, Gobelet, Bilateral free cordon) with accompanying shoot orientations (partially wired and free), genotypic growth and shoot architecture (along with vigour) emerged as strong impacting factors (Louarn *et al.*, 2008). Results thus highlighted the difficulty in integrating genotypic behaviour and requirements with climate parameters and objectives related to viticultural and oenological performance.

It is plausible to attempt simulations of optimal radiative transfer through a grapevine canopy absorption, emission and scattering medium, which is extremely heterogeneous in architecture, soil-climate sensitivity, shoot growth, spatial definition, and other turbulent intra-microclimatic conditions (temperature, humidity, wind) and which is notably subjected to the interfering effects of neighbouring grapevine bodies, and practical manipulation. However, it involves a magnitude of assumptions and difficulties, despite there being some ostensibly successful simplified individual cases. Furthermore, the reproduction of modelled gas exchange output would be further compromised if the complex dynamics of morpho-physiological responses, source:sink activity and carbon partitioning of the various vegetative-reproductive entities (including the root system) inside the grapevine body are ignored or not fully elucidated (Haasbroek *et al.*, 2000; Hunter, 2000; Fourcaud *et al.*, 2008; Hunter *et al.*, 2010, Hunter *et al.*, 2016; Prieto *et al.*, 2012; Prieto *et al.*, 2019). Despite intensive efforts, structural-functional growth simulations seem far from elucidated to a point where common application and practice have become acceptable, especially for the grapevine of which growth, yield and product quality are dictated by a multitude of impacting factors, such as soil, climate, various cultivation practices and wine quality objectives. Under field conditions, these factors are barely separable; therefore, not only are they major research challenges, but they also provide the opportunity to understand and demonstrate integrative relationships at practical level, which can be applied to optimise the use of available resources.

In this study, it is hypothesised that the spatial radiation angle and radiation distribution of differently orientated, vertically trained grapevine rows affect vineyard soil conditions, (multi-level) canopy photosynthetically active radiation, leaf water potential and leaf photosynthetic activity. Measurements were temporally conducted under field conditions in the grape ripening period of the growth season. The assessments were supplemented by diurnal photographic images, schematic reconstructions and simple canopy 3D modelling to provide clear representations of the canopies and spatial radiation patterns in the field.

MATERIALS AND METHODS

1. Vineyard

Shiraz(clone SH 9C)/101-14 Mgt was planted during 2003 to four row orientations (treatments), i.e. North-South, East-West, North-East-South-West, and North-West-South-East, which were replicated on a flat site of approximately 3 ha with uniform clayey loam soil at the Robertson Experiment Farm of the Agricultural Research Council (ARC) Infruitec-Nietvoorbij Institute for Deciduous Fruit, Vines and Wine in the Breede River Valley, Robertson (33°49’35’’ Latitude S/19°52’53’’ Longitude E/159 m a.s.l.), South Africa (Southern Hemisphere). Vines were spaced at a fixed distance of 1.8 x 2.7 m, cordon trained, and pruned to two bud spurs, spaced approximately 14 cm apart. Vertical shoot-positioned canopies of an average height of 1.2 m (from cordon to top, and with cordon height of 0.7 m) (Hunter *et al.*, 2017) had approximately four leaf layers (from side to side) and were uniformly managed (Figure 1). Vines were only shoot positioned and topped, both actions being performed on an average of three times a year. Primary and secondary shoots were positioned between four sets of movable wires. A cover crop (rye) was sown after harvest and killed before budding. Vines were irrigated on a weekly basis at a volume of 14 mm. Irrigation took place during the season’s period of highest evaporative demand, due to the low winter rainfall in the region, which averages 150-300 mm per annum (Hunter *et al.*, 2016). Irrigation was done according to the regional crop factor and ET_0 values (obtained from the automatic weather station close to the vineyard). Overall, the annual management of the vines was done as similar as possible and close to commercial conditions in the field.

2. Macroclimate (temperature and wind speed)

A detailed description of the main meteorological parameters, according to the different row orientations, is reported in Hunter *et al.* (2016). Ambient temperature and wind speed of the two days of measurements in different seasons (04/03/2010 and 08/03/2011) were calculated from hourly climatic data obtained from an automatic weather station (part of the weather station network of the ARC Institute for Soil, Climate and Water; the South African Weather Service is a member of the World Meteorological Organisation and complies with international meteorological standards), located approximately 200 m from the experimental vineyard at Robertson Experiment Farm.

3. Canopy light microclimate measurements and sun/shade digital and schematic patterns

The photosynthetic photon flux density (PPFD over a wavelength range of 400-700 nm) (µmol/m^2/s) was determined during the grape ripening period by means of four PAR (photosynthetically active radiation) line quantum sensors (LI-191R, LI-COR, Lincoln, Nebraska, USA), each measuring 180° and fixed together in such a manner that light interception was measured along the canopy in four directions (upwards, downwards, sideways; Figure 2). It was measured immediately next to (at a distance of less than 5 cm away from the canopy wall) and in the centre (inside) of the basal, middle and apical zones, of the canopy; on top of the canopy; and at the bottom of the canopy below the cordon. Ambient PAR was measured in the row approximately 30 cm higher than the canopy. Each PAR value represents incoming light, directed by a 1 m (L) x 12.7 mm (W) quartz rod under a diffuser to a single filtered silicon photodiode (LI-COR Biosciences). An infinite number of spectral sensing points over the 1 m sensing area are therefore integrated and averaged into a single value. For each position, the integrated output of each line quantum sensor was digitally displayed on four channels of a MCSystems 120-04EX data logger and manually recorded. These measurements were taken under clear sky conditions at 08:00, 10:00, 13:00, 16:00, and 18:00. At the same time points, digital camera photographs of sun and shade patterns of the canopies were taken down the rows of the different row orientations. Furthermore, schematic patterns of sun/shade patterns of the differently orientated rows were constructed based on measured distances of sun/shade ground patterns at the time points mentioned above.

4 Canopy modelling

The Google SketchUp Make 2017 CAD software (Trimble Inc., 935 Stewart Drive, Sunnyvale, CA 94085 USA) was used to compile simplified three-dimensional canopy models of the sun/shade patterns of the canopies on 4 March. The software allows 3-D drawings to be created with extreme simplicity. The single vine model was created according to the measurements performed in the vineyard and stated in the vineyard description. In particular, the canopy shape is represented by two symmetric arcs with a total height of 1.2 m and a maximum thickness of 30 cm. The double cordon height was set at 0.7 m above ground, with a total length of 1.8 m. Rows were created by multiple duplication of the

FIGURE 1. Example of a typical post-véraison canopy of Shiraz planted in four row orientations.

single vine model, spaced to a fixed distance of 1.8 m between vines and 2.7 m between rows. The NE-SW and NW-SE plots were rotated 45° after the creation of the parallel rows, since it is much easier to rotate all the rows together, rather than to move the single elements in oblique directions. The software also allows the 3D-scene to be geo-located and an aerial map image to be added as a background, thus simplifying the spatial match between model and reality. Finally, hourly shading patterns for the sampling date (2010-03-04) were generated using the «Shadows» tool and saved as 2-dimensional images. The SunHours Plugin of the same software was used to create images of radiation intensity gradients and accumulated diurnal number of hours of exposure of the soil on the same day.

5. Soil water and temperature measurements

The soil water content and temperature were determined during the grape ripening period directly below the vines and in three positions across the work row (centre of the row and mid-way between the centre and the two adjacent vine rows) and in three depth layers: 0–30 cm, 30–60 cm and 60– 0 cm. The measurements across the work row were averaged per depth in order to obtain a value across the work row. Soil samples were taken with an auger and, after weighing, dried for 72 hrs in an oven with constant temperature set to 80 °C. The samples were then cooled and weighed, and their water content calculated. The temperature of the soil in the different layers was measured by means of a hand-held thermometer (ETI 2202, Electronic Temperature Instruments Ltd, Worthing, West Sussex, UK), fitted with a probe that was slid down the hole (after removing the sample for soil water measurement), ensuring that the probe was in contact with the soil at the bottom of the hole for each depth. Holes were made and measurements taken in the morning (10:00) and in the afternoon (16:00).

6. Physiological measurements

The photosynthetic activity (µmol/m^2/s) (P_n) was determined at ambient solar radiation, air temperature and humidity in the morning (10:00), at mid-day (13:00) and in the afternoon (16:00), using an open system portable photosynthesis meter (Model LCA2/DL2, The Analytical

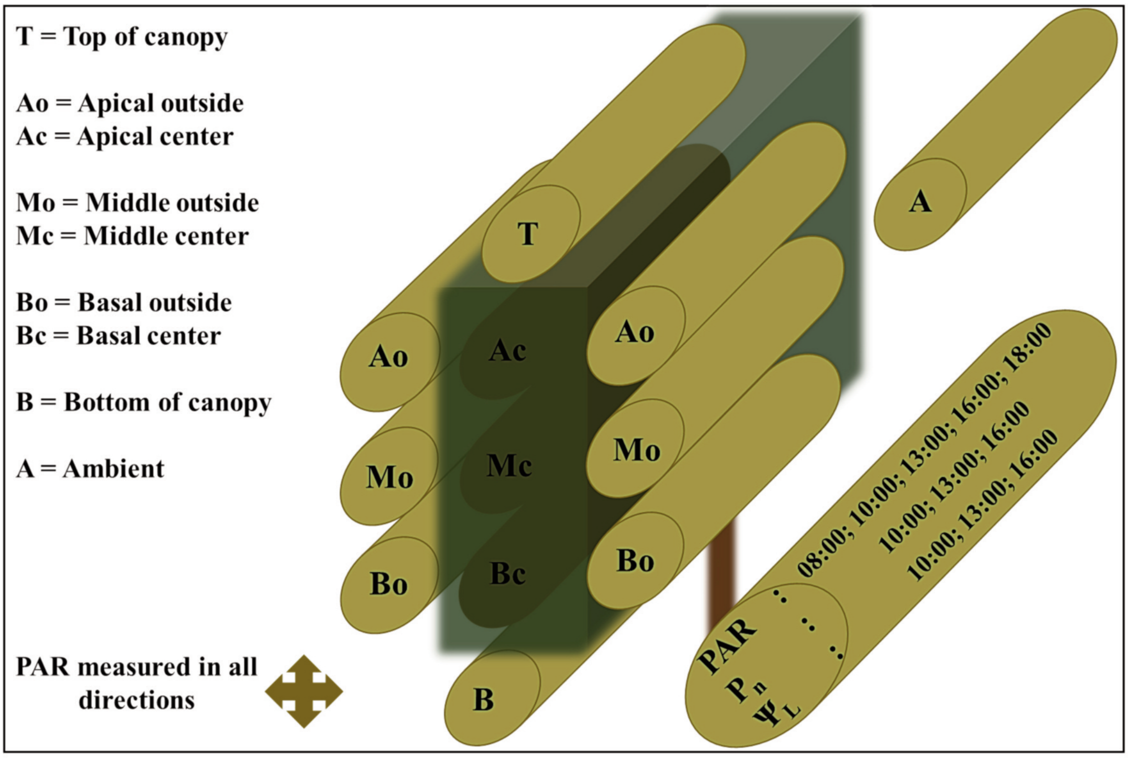

FIGURE 2. Schematic representation of the photosynthetically active radiation (PAR), photosynthesis (Pn) and leaf water potential (ΨL) measurements taken post-véraison in the Shiraz vineyard planted in four row orientations.

Development Co., Ltd., Hoddesdon, England), as specified in Hunter and Visser (1988b) and in Hunter and Visser (1989) (Figure 2). Leaf water potential (–kPa) (Ψ_L) measurements were conducted in a similar way to the P_n measurements, using two non-commercial precision-manufactured and pressure- and flow-calibrated Scholander pressure chambers (Scholander *et al.*, 1965). The measurements of P_n (one leaf) and Ψ_L (one leaf) were done on undisturbed primary and secondary leaves, which were naturally positioned, orientated and exposed. The orientation and positioning of the leaves were not disturbed during the measurement of P_n. At each time point, all measurements were done on outer rim leaves (on each side of the canopy), and on inner leaves from the centre of the canopy; these were performed in the apical, middle and basal zones of the canopy.

All of the described measurements and photographs were taken approximately 6 weeks after véraison (~ 80 % berry colouring) at an average of 23 °Balling (23 g/100mL) berry soluble solid content and were completed within an hour per time point.

7. Statistics

The full experimental layout comprised a randomised design with four vineyard row orientations and five replicates per orientation, each confined to a separate vineyard block with surface area of approximately 800 m². Statistically, replicated blocks were uniform in vegetative growth, as shown in a previous paper (Hunter *et al.*, 2017). Canopy physiological measurements, as well as soil water content and temperature measurements were conducted under open sky conditions approximately six weeks after véraison. These were carried out on one day and on one replication per treatment for two consecutive seasons. The photosynthetic and water potential measurements were done on one leaf per position per time point. The day on which the measurements were done was chosen for the following reasons: the canopy management practices were completed; the canopies were established with stable leaf age compilation and primary and secondary shoots which had stopped growing, and are thus representative of the canopy conditions generally found during this period; the crop load and quantitative source:sink ratio could be assumed as being stable; it was in the middle of the normal ripening period for this site; the ripeness level of the grapes was

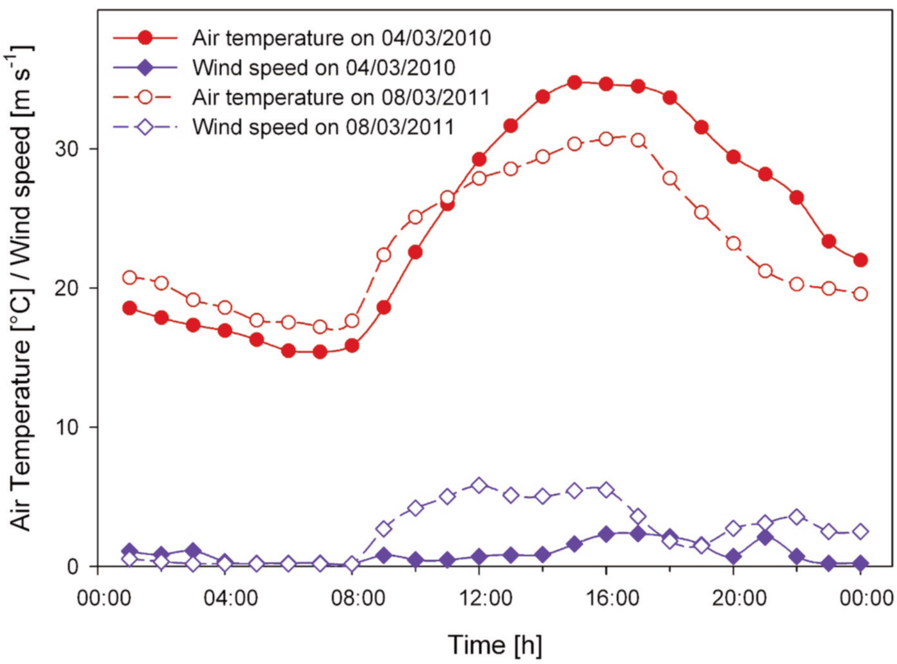

FIGURE 3. Temperature and wind speed on the days of measuring in the vertically trellised Shiraz/101-14 Mgt vineyard planted to four different row orientations.

TABLE 1. Photosynthetically active radiation, measured in different positions in the canopies of Shiraz/101-14 Mgt planted in four different row orientations (measurements taken on 04/03/2010).

Row orien	Can side	Measure direction	Photosynthetically active radiation (µmol/m²/s)																	
			Basal zone of canopy						Middle zone of canopy						Apical zone of canopy					
			08:00	10:00	13:00	16:00	18:00	Ave	08:00	10:00	13:00	16:00	18:00	Ave	08:00	10:00	13:00	16:00	18:00	Ave
NS	E	Up	81	733	36	3	7	**172**	246	375	73	8	51	**106**	366	345	125	12	51	**180**
		Down	3	54	12	21	2	**18**	35	28	14	15	2	**19**	34	34	18	29	6	**24**
		E	112	1190	91	6	24	**285**	1398	670	82	9	37	**439**	1152	1019	105	30	65	**474**
		W	2	4	2	41	2	**10**	2	5	5	61	63	**27**	5	5	10	68	9	**19**
	W	Up	33	16	15	326	12	**80**	39	41	22	687	95	**177**	61	50	181	938	100	**266**
		Down	2	9	20	51	3	**17**	2	6	9	42	20	**16**	78	9	11	47	29	**35**
		E	2	22	2	3	1	**6**	11	16	2	5	2	**7**	5	33	4	6	4	**10**
		W	35	40	97	1175	63	**282**	41	60	91	1102	1045	**468**	47	71	123	1276	754	**454**
	Cntr	Up	25	82	6	28	6	**28**	25	18	9	83	8	**29**	311	32	8	70	6	**76**
		Down	5	15	6	19	2	**9**	26	14	5	12	1	**12**	3	12	8	22	9	**20**
		E	60	191	9	8	4	**54**	414	112	15	8	8	**111**	478	28	24	18	8	**216**
		W	8	8	15	125	13	**34**	15	23	20	313	8	**76**	25	29	17	540	80	**34**
		Ave	**31**	**197**	**26**	**150**	**12**	**83**	**169**	**114**	**29**	**195**	**112**	**124**	**214**	**139**	**53**	**255**	**93**	**151**
EW	N	Up	51	328	663	567	12	**324**	10	730	463	209	9	**284**	340	551	1254	825	30	**600**
		Down	10	28	51	40	5	**27**	6	32	39	18	5	**20**	29	34	42	28	6	**28**
		S	2	6	15	8	1	**6**	2	6	13	6	2	**6**	22	15	39	31	8	**23**
		N	57	170	515	346	46	**227**	48	542	590	184	43	**281**	122	507	747	230	68	**335**
	S	Up	25	24	25	24	13	**22**	8	50	74	22	25	**36**	35	145	424	47	39	**138**
		Down	8	14	12	12	6	**10**	6	15	15	12	10	**12**	9	29	21	21	9	**18**
		S	82	90	108	82	58	**84**	65	84	108	84	80	**84**	99	125	138	110	95	**113**
		N	2	3	3	2	2	**2**	6	29	24	8	2	**14**	9	37	32	12	3	**19**
	Cntr	Up	10	18	61	10	3	**20**	10	73	59	13	5	**32**	36	235	290	152	22	**147**
		Down	3	10	9	10	2	**7**	5	14	12	8	2	**8**	6	10	18	9	5	**10**
		S	4	22	13	8	9	**11**	8	24	33	16	18	**20**	22	43	52	39	22	**36**
		N	15	63	41	18	3	**28**	29	85	103	17	6	**48**	48	164	151	24	30	**83**
		Ave	**22**	**65**	**126**	**94**	**13**	**64**	**17**	**140**	**128**	**50**	**17**	**70**	**65**	**158**	**267**	**127**	**28**	**129**
NE-SW	NW	Up	15	12	652	484	64	**245**	27	48	662	294	137	**234**	76	304	1520	724	194	**564**
		Down	9	18	64	42	6	**28**	5	6	40	43	25	**24**	9	25	29	58	23	**29**
		SE	6	4	9	6	2	**5**	26	15	13	13	4	**14**	48	20	33	35	6	**28**
		NW	30	78	583	816	134	**328**	55	82	195	734	568	**327**	71	119	699	1190	691	**554**
	SE	Up	223	19	30	41	12	**65**	137	188	53	58	38	**95**	311	192	417	148	47	**223**
		Down	12	32	10	6	2	**12**	36	26	20	8	3	**19**	29	40	21	21	6	**23**
		SE	336	125	84	54	28	**125**	871	176	95	84	48	**255**	674	153	120	103	60	**222**
		NW	3	0	2	8	2	**3**	5	8	13	44	21	**18**	18	24	69	99	63	**55**
	Cntr	Up	44	18	68	44	24	**40**	25	39	246	172	16	**100**	81	70	406	215	21	**159**
		Down	3	15	28	10	3	**12**	15	14	29	9	8	**15**	25	15	25	18	18	**20**
		SE	18	39	13	11	6	**17**	163	80	18	24	8	**59**	225	63	58	58	9	**83**
		NW	12	17	57	130	91	**61**	21	30	266	114	55	**97**	55	61	253	185	179	**147**
		Ave	**59**	**31**	**133**	**138**	**31**	**79**	**115**	**59**	**138**	**133**	**78**	**105**	**135**	**91**	**304**	**238**	**110**	**175**
NW-SE	NE	Up	144	700	45	9	6	**181**	279	605	450	15	15	**273**	319	726	1484	117	42	**538**
		Down	32	40	45	17	2	**27**	54	42	28	6	2	**26**	53	58	29	10	47	**39**
		NE	544	538	225	5	20	**266**	1077	1041	458	69	37	**536**	1201	1470	548	105	56	**676**
		SW	3	9	3	3	2	**4**	5	9	8	3	6	**6**	10	21	48	29	8	**23**
	SW	Up	16	9	41	76	25	**33**	56	229	33	149	38	**101**	106	132	408	585	97	**266**
		Down	2	9	17	28	3	**12**	8	12	21	21	32	**19**	12	15	25	26	29	**21**
		NE	4	4	2	2	2	**3**	41	108	9	8	8	**35**	360	69	73	20	4	**105**
		SW	38	51	108	156	80	**87**	55	60	94	213	616	**208**	71	103	130	548	633	**297**
	Cntr	Up	68	79	16	25	22	**42**	102	259	24	51	68	**101**	464	195	308	77	94	**228**
		Down	5	10	18	1	2	**7**	18	20	12	8	3	**12**	25	17	23	14	10	**18**
		NE	107	125	35	16	6	**58**	189	924	45	26	9	**239**	675	292	82	35	28	**222**
		SW	9	15	5	12	61	**20**	27	17	10	32	91	**35**	35	40	61	96	255	**97**
		Ave	**81**	**132**	**47**	**29**	**19**	**62**	**159**	**277**	**99**	**50**	**77**	**133**	**278**	**262**	**268**	**139**	**109**	**211**
			Top of canopy						Bottom of canopy						Outside/Ambient PAR					
NS		Up	450	669	1244	315	152	**566**	450	71	105	81	12	**144**	-	1299	1899	1085	320	**1151**
		Down	14	9	10	36	8	**15**	14	97	56	55	3	**45**	-	65	141	56	62	**81**
		E	499	259	43	24	30	**171**	499	705	20	34	2	**252**	-	1447	90	71	52	**415**
		W	24	61	125	1281	415	**381**	24	52	49	535	46	**141**	-	97	212	1286	1113	**677**
		Ave	**247**	**250**	**356**	**414**	**151**	**284**	**247**	**231**	**58**	**176**	**16**	**146**	**-**	**727**	**586**	**625**	**387**	**581**
EW		Up	181	2136	1618	1039	262	**1047**	3	16	3	3	2	**5**	748	1490	1899	1045	230	**1082**
		Down	3	14	9	10	5	**8**	45	75	95	56	14	**57**	91	117	119	75	23	**85**
		S	30	101	118	78	129	**91**	22	50	48	37	13	**34**	114	116	114	97	76	**103**
		N	38	224	396	360	26	**209**	27	63	58	58	21	**45**	222	675	854	419	74	**449**
		Ave	**63**	**619**	**535**	**372**	**105**	**339**	**24**	**51**	**51**	**39**	**12**	**35**	**294**	**600**	**747**	**409**	**101**	**430**
NE-SW		Up	664	923	1777	1126	194	**937**	32	6.1	15	19	3	**15**	745	1488	1803	1074	279	**1078**
		Down	17	26	31	36	14	**25**	31	54	117	62	5	**54**	62	119	116	48	9	**71**
		SE	495	148	71	78	35	**165**	242	45	58	24	4	**75**	849	347	103	108	67	**295**
		NW	65	77	728	1144	659	**535**	29	26	255	43	24	**75**	86	92	944	1328	580	**606**
		Ave	**310**	**294**	**652**	**596**	**226**	**415**	**84**	**33**	**111**	**37**	**9**	**55**	**436**	**512**	**742**	**640**	**234**	**512**
NW-SE		Up	867	1129	1852	833	155	**967**	81	5	8	2	0	**19**	742	1354	1861	1144	212	**1063**
		Down	15	14	26	12	12	**16**	15	97	89	70	3	**55**	31	64	139	108	8	**70**
		NE	561	501	561	82	52	**351**	341	67	91	20	6	**105**	1393	1522	630	91	56	**738**
		SW	85	88	114	288	517	**218**	18	38	29	32	2	**24**	105	94	100	655	630	**317**
		Ave	**382**	**433**	**638**	**304**	**184**	**388**	**114**	**52**	**54**	**31**	**3**	**51**	**568**	**759**	**683**	**500**	**226**	**547**

Row orien = row orientation; Can side = canopy side; Cntr = centre of canopy; Ave = average

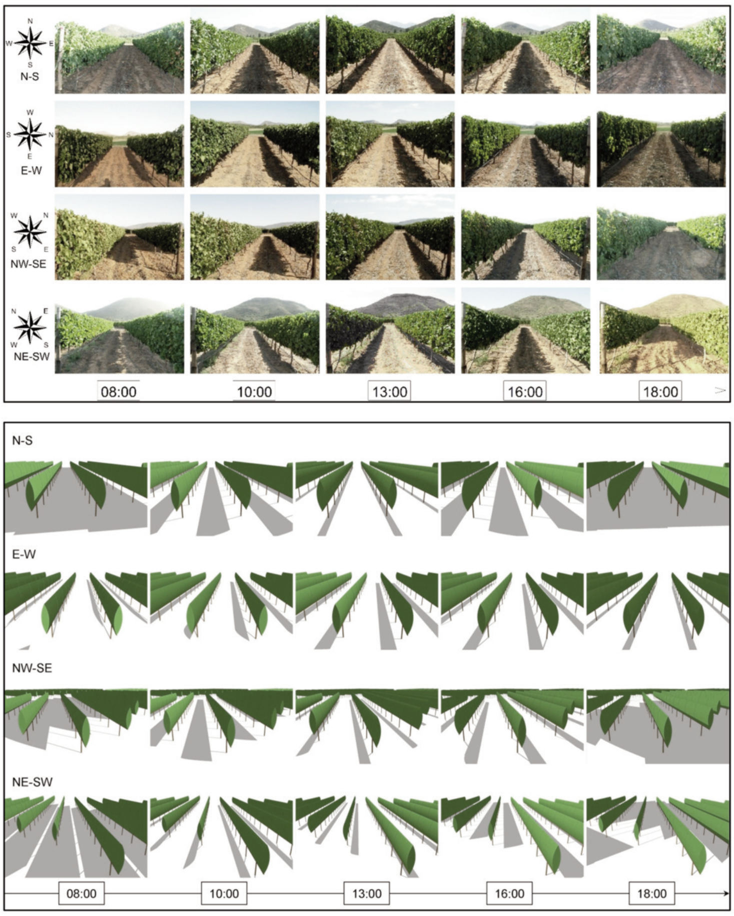

FIGURE 4. Photographs (Top) and simplified 3-D canopy modelled images (Bottom) of the sun/shade patterns of vertically trellised Shiraz/101-14 Mgt planted in four different row orientations at the ARC Robertson Experiment Farm on 4 March (photographs taken during grape ripening on 04/03/2010).

approximately 23 °B; it was possible to make a sound judgement of the quantitative and qualitative ability of the canopy to support the grapes until full ripeness. As statistically similar trends were found for the two seasons, average values of the two days of measurement in the 2009/10 and 2010/11 seasons are presented in this paper. Canopy PAR measurements, photographs and sun/shade distance measurements were taken in one season only, due to similar soil, canopy and ambient conditions, as well as vineyard management, during the two years of the experiment (and based on more than 10 years of experimental set-up). The magnitude of detail, time required for measurements and number of measurements per time point during the day did not allow more replications to be measured. Where applicable, analysis of variance was performed using SAS version 9.2 (SAS, 2012). The Shapiro-Wilk test was performed to test for non-normality (Shapiro and Wilk, 1965). Student's t-Least Significant Difference was calculated at the 5 % significance level to compare treatment means (Ott, 1998).

RESULTS

1. Temperature and wind speed

The ambient temperature and wind speed of the two days of measurements during two seasons are shown in Figure 3. The respective temperatures reached 30-35 °C and largely fluctuated according to the wind speed, which reached maxima of approximately 4-6 m/s. These conditions can be considered to be representative of variation on a typical summer's day on the terroir where the study was carried out (Hunter and Bonnardot, 2011; Hunter *et al.*, 2016).

2. Radiation patterns

Sun/shade photographs (showing depth and inclination of the incoming light) and photosynthetic active radiation (PAR) measurements showed complimentary trends. The sun/shade photographs, taken down the rows of the different row orientations during the late grape ripening period (on the day of microclimate and physiological measurements in the first season of the experiment), are shown in Figure 4; corresponding PAR values are shown in Table 1. These light patterns are complimented by schematic shade patterns (Figure 5).

Simplified 3-D modelled images of canopy (Figure 4) and soil exposure (radiation intensity and duration) (Figure 6) corresponded almost perfectly with the photographs and field-measured schematic representations, thus confirming that the sun/shade patterns of the vertically trellised vineyard are affected by row orientation. From early morning (08:00) to late afternoon (18:00), the light patterns of the *NS orientated canopies* clearly show movement of the sun position in the sky over the canopies and the partial sunray-blocking effects of adjacent vine rows. High direct radiation occurred in the basal canopy zone on the E canopy side only at 10:00 (received from above and E); in the middle zone at 08:00 (received from E) and 10:00 (received from above and E); and in the apical zone at 08:00 and 10:00 (both times received from above and E); in all cases, the major light component was received from the E. On the W side of the canopy, high radiation in

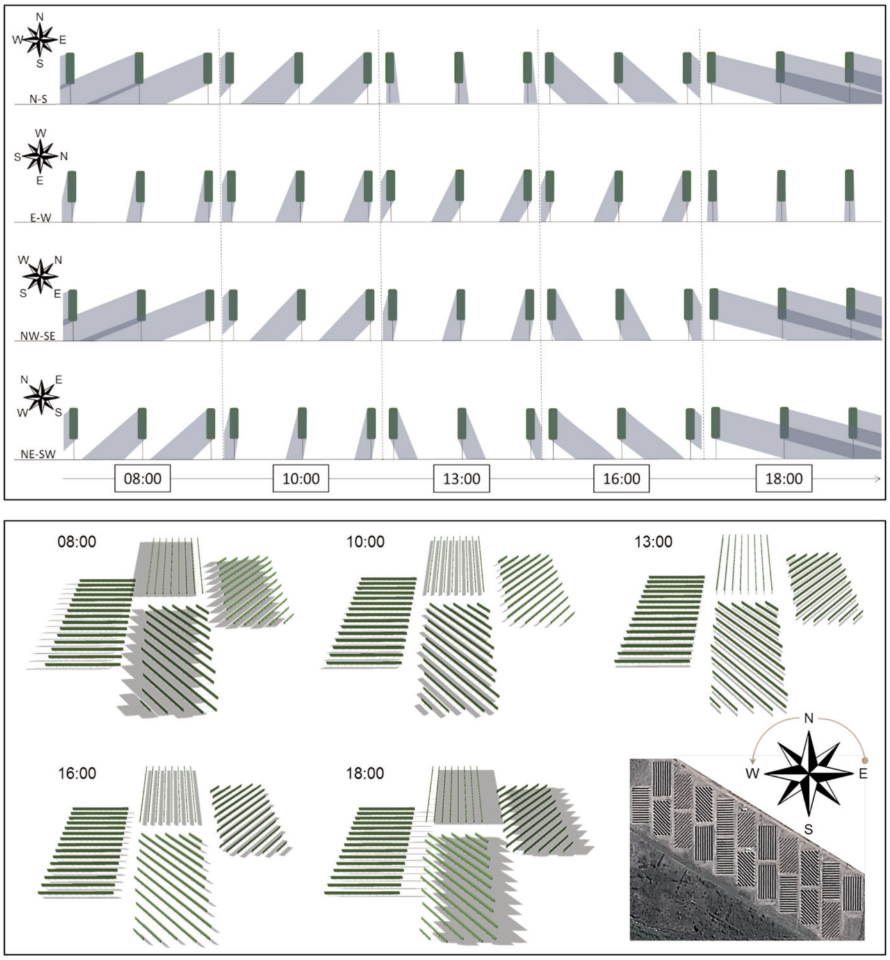

FIGURE 5. Schematic representation (Top) and simplified perspective view of 3-D canopy modelled images (and the vineyard site in the bottom right-hand corner) (Bottom) of the sun/shade patterns of vertically trellised Shiraz/101-14 Mgt planted in four different row orientations at the ARC Robertson Experiment Farm on 4 March (schematic representations compiled based on distances of sun/shade ground patterns measured at ground level on 04/03/2010).

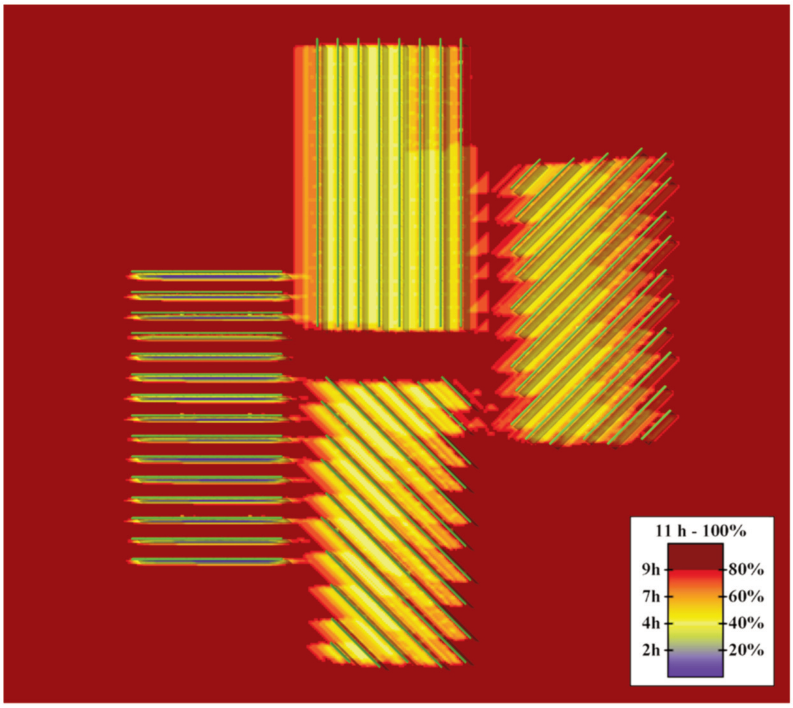

FIGURE 6. Simplified 3-D canopy modelled images of the soil radiation exposure intensity and duration (accumulated diurnal sun hours) in vertically trellised Shiraz/101-14 Mgt planted in four different row orientations at the ARC Robertson Experiment Farm on 04/03/2010.

the basal zone was only received at 16:00 from above and W; in the middle zone at 16:00 from above and W, and at 18:00 from the W; and in the apical zone at 16:00 from above and W, and at 18:00 from the W. In parallel to the above, the central part of the canopy was penetrated by higher levels of light during early morning from the E and during the afternoon from the W, whereas the canopy interior was largely shaded during midday as the sun moved over the canopy from E to W. From late morning to afternoon, the light patterns of the *EW orientated canopies* mainly showed a dominating radiation effect on the N canopy side, from above, and in the apical part of the canopy. The central part of the canopy was largely shaded, except for the apical zone that was penetrated by a reasonable amount of radiation from the N and from above. Except for early morning (up to 10:00), the *NE-SW orientated canopies* mainly received high radiation on the NW canopy wall (especially from 13:00) and from above. On the SE side, high radiation was also received during early morning (08:00), after which it faded towards late afternoon. Radiation was also evident from above, especially in the apical zone of the canopy. A similar pattern occurred in the centre of the canopy. The light pattern of the *NW-SE orientated canopies* was dominated by radiation on the NE canopy wall, especially up to 13:00, thus showing a diurnal and almost mirror image of that of the NE-SW orientation. Early to late afternoon radiation was dominant on the SW side, and radiation from above increased in the higher parts of the canopy. Except for late afternoon, when high levels of radiation were received from the SW, the central part of the canopy mainly received radiation from the NE during the morning (up to 10:00), together with reasonable levels of light from above. The *outside (ambient) PAR* was intense in the morning until13:00. For the NS orientation, the top, bottom and outside of the canopy mainly received radiation from directly above, as well from the E in the morning and the W in the afternoon; during midday, high radiation was only received from above the canopy. The EW rows received the highest radiation component from above in particular, as well as from the N. For the NE-SW orientation, high levels of radiation were also received from above, as well as from the SE in the morning (up to 10:00) and NW in the afternoon (from 13:00); whereas a similar pattern occurred for the NW-SE orientation, but with high levels of radiation received from the NE in the morning (up to 13:00) and the SW in the afternoon (from 16:00).

3. Soil conditions

In general, the soil water content increased, whereas the soil temperature followed a decreasing gradient with depth (Table 2). The soil water content directly below the vine, as well as in the work row, mostly decreased from morning to afternoon in all layers. The soil temperature generally increased in the two top layers and decreased in the bottom layer from mid-morning to late afternoon.

4. Leaf water potential

The leaf water potential (Ψ_L) results are shown in Table 3. In general, the primary Ψ_{PL} decreased noticeably from morning to afternoon for all canopy sides and in all canopy zones (apical, middle, basal). For the EW orientated rows, this trend was not clear and Ψ_{PL} showed more stability in the centre of the canopies. The secondary leaves of the NS orientated canopies showed a general recuperation of water status during mid-day, but the lowest values were recorded in the afternoon. Those of the EW, NE-SW and NW-SE treatments mostly decreased towards the afternoon. Relatively stable secondary Ψ_{SL} occurred in the centre of the EW orientated canopies. The lowest Ψ_{PL} and Ψ_{SL} were generally recorded for the NE-SW and the highest for the EW orientated canopies. Overall, leaves in the apical, middle and basal zones of the canopies showed highest Ψ_L when canopies were EW orientated (-1199 kPa), followed by those orientated NS (-1273 kPa), NW-SE (-1404 kPa), and NE-SW (-1476 kPa); whereas for all row orientations, Ψ_L was lowest in the centre of canopies, in the same decreasing order. Canopy sides displayed overall Ψ_L in the following decreasing trend: S, N, W, E, SW, NE, SE, NW.

5. Photosynthetic activity

In accordance with the sun path from E to W, primary and secondary leaf photosynthetic activity (P_n) of the NS orientated canopies showed opposite diurnal trends for the two canopy sides from morning to afternoon, decreasing on the E side and increasing on the W side, but always displaying higher values in the morning on the E side than in the afternoon on the W side (Table 4). Photosynthetic output decreased from the apical to the basal part of the canopy. Values were very low and erratic in the centre of the canopy in both basal and middle zones. Leaves on the N side of the EW orientated canopies showed much higher P_n than those on the S side. The inclination of the sun favoured penetration from and exposure of the N side during this period. Leaves in the centre of the EW canopies showed generally higher P_n than those of the NS orientated canopies. Leaves on the SE of the NE-SW orientated canopies only displayed higher P_n than those on the NW side in the morning. As in the case of the NS

Table 2. Soil water content and temperature of Shiraz/101-14 Mgt planted in four different row orientations (average of measurements on 04/03/2010 and 08/03/2011).

Row orien	Soil depth layer (cm)	Soil water content (%)					Soil temperature (°C)				
		Below vine		In row		Ave	Below vine		In row		Ave
		10:00	16:00	10:00	16:00		10:00	16:00	10:00	16:00	
NS	0-30	10.22ab	9.12abc	9.47a	7.97a	**9.20abc**	28.40abc	30.05bcde	28.80ab	31.02ab	**29.57bc**
	30-60	9.54ab	9.41ab	9.64a	8.58a	**9.29ab**	27.45bcd	28.05ef	29.15a	29.85abcd	**28.63cdef**
	60-90	10.35a	9.66a	10.08a	9.04a	**9.78a**	27.30bcd	26.95f	29.15a	27.08d	**27.62f**
	Ave	**10.04A**	**9.40A**	**9.73A**	**8.53A**	**9.42A**	**27.72BC**	**28.35B**	**29.03A**	**29.32AB**	**28.61A**
EW	0-30	8.99ab	8.74ab	8.59a	7.88a	**8.55bcd**	29.80a	32.90a	28.48ab	31.90a	**30.77a**
	30-60	9.56ab	8.83bc	7.91a	7.39a	**8.42cd**	28.90ab	30.75abc	28.75ab	30.65abc	**29.76ab**
	60-90	9.45ab	8.89bc	8.72a	8.34a	**8.85bcd**	28.75ab	28.70cdef	28.87ab	28.00cd	**28.58def**
	Ave	**9.33A**	**8.82B**	**8.41AB**	**7.87A**	**8.61A**	**29.15A**	**30.78A**	**28.70A**	**30.18A**	**29.70A**
NE-SW	0-30	8.63b	8.48cd	7.81a	8.08a	**8.25d**	25.75d	30.05bcde	28.48ab	29.15abcd	**28.36def**
	30-60	9.31ab	7.99d	8.04a	7.46a	**8.20d**	26.15cd	28.20ef	29.17a	28.15bcd	**27.92ef**
	60-90	9.98ab	9.25ab	9.57a	8.45a	**9.31ab**	27.90abcd	27.45f	29.45a	27.45d	**28.06def**
	Ave	**9.31A**	**8.57B**	**8.47AB**	**8.00A**	**8.59A**	**26.60C**	**28.57B**	**29.03A**	**28.25B**	**28.11A**
NW-SE	0-30	9.71ab	8.72bcd	8.03a	8.27a	**8.68bcd**	28.75ab	32.00ab	26.85b	30.72abc	**29.58bc**
	30-60	9.89ab	8.69bcd	7.72a	7.96a	**8.57bcd**	28.80ab	30.50cde	27.70ab	29.60abcd	**29.15bcd**
	60-90	9.23ab	8.46cd	8.19a	8.68a	**8.64bcd**	29.10ab	28.45def	29.85a	27.88cd	**28.82bcde**
	Ave	**9.61A**	**8.63B**	**7.98B**	**8.30A**	**8.63A**	**28.88AB**	**30.32A**	**28.13A**	**29.40AB**	**29.18A**

Mean values with the same small letter in a column do not differ (p≤0.10); Mean values with the same capital letter in a column do not differ (p≤0.10). Row orien = row orientation; Ave = average.

orientated canopies, P_n of all leaves in the centre of these canopies was very low in the middle and basal zones. The P_n on the NE side of NW-SE canopies decreased from morning to afternoon, whereas that of leaves on the SW side generally increased, but seemed to decrease over midday. The P_n values in the centre of these canopies were extremely low. Generally, secondary leaves showed higher P_n output than primary leaves. Sides facing S, SE and SW displayed lower average P_n. The higher overall P_n of the NS and EW row orientations also corresponded to higher water retention in the canopies (Table 3). Overall, leaves in the apical, middle and basal zones of the canopies showed highest P_n when canopies were NS (3.00) and EW (2.99) orientated, followed by those orientated NW-SE (2.17) and NE-SW (1.77); whereas for all row orientations the P_n was lowest in the centre of canopies, in the decreasing order of EW, NW-SE, NS, and NE-SW. Canopy sides displayed overall P_n in the following decreasing trend: N, E, W, NE, NW, SW, SE, S.

6. Water-use efficiency

The water-use efficiency (ratio of P_n and transpiration) (WUE) results showed consistently highest values in the morning and lowest values in the centre of canopies, irrespective of the row orientation (Table 5). The apical, middle and basal leaves also differed significantly in a decreasing order. Although the overall WUE did not differ significantly between row orientations, the canopy sides responded to the row orientations and showed the following apparently decreasing trend: N, NE, NW, E, W, SE, SW, S. The latter three canopy sides therefore performed poorly with respect to P_n and WUE.

DISCUSSION

The upper values of both ambient temperature and wind speed were mostly on the limit in terms of suitability of field climatic conditions for photosynthetic activity, restricting limits being higher than 35 °C and direct velocity of 4 m/s, respectively, onto the leaves (Kriedemann, 1968; Freeman *et al.*, 1982; Hamilton, 1989; Hunter and Bonnardot, 2011; Hochberg *et al.*, 2015). However, these conditions are generally affected by the vineyard row orientation and are therefore

TABLE 3. Leaf water potential of the canopies of Shiraz/101-14 Mgt planted in four different row orientations (average of measurements on 04/03/2010 and 08/03/2011).

Row	Can side	Leaf																					
		Apical	Middle		Basal	Grand																	
		Primary	Secondary		Primary	Secondary		Primary	Secondary		Ave												
		10:00	13:00	16:00	10:00	13:00	16:00	Ave	10:00	13:00	16:00	10:00	13:00	16:00	Ave	10:00	13:00	16:00	10:00	13:00	16:00	Ave	
NS	E	1175ab	1163cd	1650ab	1550a	1300ab	1600abc	1406abcd	1175abc	1125cde	1625abc	1550a	1125bc	1488ab	1348abcd	1225a	1225abcde	1538ab	1425a	1000cd	1500abcd	1319abcd	1358abc
	W	1250ab	1268abcd	1513bcd	1250a	1268ab	1600abc	1358bcde	925c	1195bcde	1485abcd	1040a	1173abc	1513ab	1222cdef	1248a	1000cde	1525ab	1250a	1238abcd	1525abcd	1298bcde	1293abc
	Cntr	1100ab	1113d	1365de	1238a	1180b	1575abc	1262e	945bc	925e	1350bcd	1075a	950c	1413abc	1110ef	1038a	888e	1300bc	1200a	863d	1500abcd	1131ef	1168bc
	Ave	1175C	1181C	1509B	1346A	1249B	1592A	1342B	1015A	1082B	1487A	1222A	1083B	1471AB	1226B	1170A	1038B	1454AB	1292A	1033B	1508AB	1249B	1273BC
EW	N	1200ab	1300abcd	1425cde	1250a	1350ab	1550abc	1346cde	1150abc	1250bcde	1375abcd	1025a	1275abc	1400abc	1246cde	1025a	1225abcde	1325bc	1075a	1225abcd	1425bcd	1217cdef	1269abc
	S	1160ab	1250bcd	1425cde	1195a	1360ab	1290bc	1280de	1020bc	1075de	1250de	1105a	1400abc	1325bc	1196def	1075a	1050bcde	1300bc	1050a	1110bcd	1300cd	1148def	1208abc
	Cntr	1050b	1413abcd	1325e	1300a	1338ab	1250c	1279de	1025bc	1013de	963e	1025a	1150abc	1063c	1040f	1150a	950de	1000c	1000a	950d	1213d	1044f	1121c
	Ave	1137C	1321BC	1392C	1248A	1349AB	1363B	1302B	1065A	1113B	1196B	1052A	1275AB	1263B	1160B	1083A	1075B	1208B	1042A	1095B	1313B	1136C	1199C
NE-SW	NW	1500a	1575a	1625ab	1400a	1613ab	1638ab	1558a	1350ab	1550ab	1700a	1450a	1600a	1563ab	1535a	1200a	1388ab	1675ab	1375a	1575a	1638abc	1475a	1523a
	SE	1320ab	1550ab	1725a	1238a	1550ab	1675a	1510ab	1163abc	1640a	1650ab	1280a	1425ab	1750a	1485ab	1143a	1475a	1810a	1150a	1525a	1800ab	1484a	1493ab
	Cntr	1300ab	1488ab	1525bcd	1525a	1513ab	1588abc	1490abc	1075abc	1338abcd	1313cd	1425a	1413ab	1500ab	1344bcd	1475a	1325abcd	1338bc	1425a	1400ab	1463abcd	1404ab	1413abc
	Ave	1373A	1538A	1625A	1388A	1558A	1633A	1519A	1196A	1509A	1554A	1385A	1479A	1604A	1455A	1273A	1396A	1608A	1317A	1500A	1633A	1454A	1476A
NW-SE	NE	1500a	1450abc	1563abc	1500a	1563ab	1538abc	1519ab	1475a	1450abc	1488abcd	1500a	1200abc	1250bc	1394abc	1425a	1475a	1438abc	1475a	1350abc	1388cd	1425ab	1446abc
	SW	1123ab	1475ab	1500bcde	1220a	1725a	1575abc	1436abcd	1075abc	1325abcd	1500abcd	1180a	1350abc	1525ab	1326bcd	1255a	1400ab	1475ab	1095a	1475ab	1825a	1421ab	1394abc
	Cntr	1230ab	1375c	1600abc	1383a	1438ab	1375abc	1400abcde	1145abc	1375abcd	1550abcd	1198a	1400abc	1525ab	1365abcd	1160a	1350abc	1450ab	1173a	1545a	1400cd	1346abc	1371abc
	Ave	1284B	1433	1554AB	1368A	1575A	1496AB	1452A	1232A	1383A	1513A	1293A	1317AB	1433AB	1362A	1280A	1408A	1454AB	1248A	1457A	1538AB	1397A	1404AB
LSD Can side	417	310	186	527	483	369	162	422	365	333	809	457	397	190	499	386	444	553	389	392	176	336	
LSD Row orien	241	179	107	304	279	213	81	244	211	192	467	264	229	96	288	223	257	319	224	227	92	194	

Mean values with the same small letter in a column do not differ (p≤0.10); Mean values with the same capital letter in a column do not differ (p ≤ 0.10). Row orien = row orientation; Can side = canopy side; Cntr = centre of canopy; Ave = average.

variable throughout the day (Hunter *et al.*, 2016).

The canopy radiation interception patterns of the respective row orientations were very different and are comparable to the general meso- and microclimate patterns reported by Hunter *et al.* (2016) and Zorer *et al.* (2017). Briefly, the photographic, schematic and modelled patterns and the PAR measurement observations showed that the NS vine rows received low radiation in the early morning and late afternoon and were sunlit on the E wall in the morning, straight on top of the canopy during mid-day, and on the W wall in the afternoon. Sunrays were therefore largely blocked by the adjacent vine rows early morning and late afternoon on the E and W sides respectively. Grape bunches were diffused sunlit or shaded, concomitant to these patterns. The EW orientated rows had a sunlit N side, whereas the S side was largely shaded; grape bunches of these rows were therefore predominantly illuminated from the N and received less sun than those of the NS row orientation. The sun/shade patterns of the NW-SE and NE-SW orientations were almost mirrored diurnally, canopies of both row orientations being illuminated during the morning; however, the former orientation switched sunlit walls later in the day than the latter orientation. The former was therefore exposed to a longer period of morning-incoming sunrays, whereas the latter was exposed to a longer period of afternoon-incoming sunrays.

The radiation that is reflected from the soil into and around the canopy may change according to soil type and colour (e.g., clay *versus* calcareous *versus* sandy soils) and in combination with different soil covers or mulches. These factors affect surface colour, as well as thermal storage in the soil and thermal conductivity from soil to atmosphere, canopy and grapes (Hunter, 1998), which in turn are affected by the cordon and canopy height, canopy density and inter-row spacing. Furthermore, all of these sunlight/shade patterns changed slightly with the ecliptic changes as the growth season progressed from budding to full grape ripeness, for example, the canopy walls of the EW orientated rows were more equally illuminated during the green berry period of the growth season, whereas the still developing canopies of all row orientations permitted higher penetration of sunlight during the same period.

TABLE 4. Photosynthetic activity of the canopies of Shiraz/101-14 Mgt planted in four different row orientations (average of measurements on 04/03/2010 and 08/03/2011).

Row	Can side	Photosynthetic																					
		Apical	Middle		Basal	Grand																	
		Primary	Secondary		Primary			Primary															
		10:00	**13:00**	**16:00**	**10:00**	**13:00**	**16:00**	**Ave**	**10:00**	**13:00**	**16:00**	**10:00**	**13:00**	**16:00**	**Ave**	**10:00**	**13:00**	**16:00**	**10:00**	**13:00**	**16:00**	**Ave**	
NS	E	9.46ab	2.08cd	2.02cde	12.22a	5.66ab	0.29e	**5.28b**	10.49a	1.93c	1.09cd	7.39ab	3.41bc	0.64c	**4.16b**	6.31ab	2.26bc	0.74c	9.13a	4.59b	0.16c	**3.83b**	**4,43b**
	W	2.90de	1.64cd	9.02a	2.84cd	4.38bc	8.47a	**4.87b**	0.58de	4.29b	7.70a	1.57d	3.14bc	7.04a	**4.05b**	1.15c	3.20ab	5.41a	0.92c	1.79bcd	6.71a	**3.19bc**	**4,04bc**
	Cntr	1.93de	1.63cd	0.00e	2.55cd	0.23e	0.81de	**1.19f**	0.36de	0.00d	0.16cd	0.55d	0.08d	0.15c	**0.22f**	0.71c	0.00d	0.00c	0.44c	0.00d	0.00c	**0.20f**	**0,54g**
	Ave	**4.76A**	**1.78AB**	**3.68A**	**5.87A**	**3.42AB**	**3.19A**	**3.78A**	**3.81A**	**2.07AB**	**2.98A**	**3.17A**	**2.21A**	**2.61A**	**2.81A**	**2.72A**	**1.82A**	**2.05A**	**3.50A**	**2.12AB**	**2.29A**	**2.42AB**	**3,00A**
EW	N	11.31a	6.17a	4.75b	7.60b	7.38a	7.19a	**7.40a**	8.78a	7.10a	4.59b	8.60a	7.17a	4.00b	**6.71a**	7.48a	4.59a	3.61b	7.07ab	7.83a	4.36b	**5.82a**	**6,64a**
	S	2.79de	1.06cd	1.42cde	2.09cd	1.90de	1.59cde	**1.81def**	4.18bc	1.51cd	0.39cd	2.56cd	1.21cd	0.81c	**1.77de**	2.22c	1.61bcd	0.17c	2.39c	0.76d	0.01c	**1.24e**	**1,59f**
	Cntr	0.51de	0.21d	0.99de	3.20cd	3.19cd	0.29e	**1.39ef**	0.53de	0.37cd	0.00d	1.59d	0.59d	0.29c	**0.57f**	0.80c	0.00d	0.00c	0.23c	0.40d	0.00c	**0.24f**	**0,73g**
	Ave	**4.87A**	**2.48A**	**2.38AB**	**4.28AB**	**4.16A**	**3.02A**	**3.50A**	**4.49A**	**2.99A**	**1.66B**	**4.25A**	**2.99A**	**1.70B**	**3.02A**	**3.50A**	**2.07A**	**1.26AB**	**3.23A**	**2.99A**	**1.46A**	**2.44A**	**2,99A**
NE-SW	NW	3.86cd	4.66ab	2.07cde	1.57cd	4.47bc	4.01bc	**3.44c**	2.80bc	2.06c	1.14c	3.39bcd	4.13b	3.01b	**2.75c**	1.67c	1.78bcd	1.10c	2.09c	3.73bc	1.37c	**1.95de**	**2,71d**
	SE	7.02bc	0.90cd	0.64de	5.28bc	1.25de	1.06de	**2.69cd**	3.67bc	0.70cd	0.52cd	4.11abcd	0.83d	0.08c	**1.65e**	3.66bc	0.60cd	0.50c	4.98b	1.20cd	0.32c	**1.87de**	**2,07ef**
	Cntr	1.00de	0.78cd	0.85de	0.69d	1.30de	2.21bcde	**1.14f**	0.55de	0.00d	0.17cd	0.19d	0.14d	0.07c	**0.19f**	0.76c	0.00d	0.00c	0.74c	0.00d	0.00c	**0.25f**	**0,52g**
	Ave	**3.96A**	**2.11AB**	**1.19B**	**2.51B**	**2.34B**	**2.42A**	**2.42B**	**2.34B**	**0.92C**	**0.61C**	**2.56A**	**1.70A**	**1.05B**	**1.52B**	**2.03A**	**0.79AB**	**0.53B**	**2.60A**	**1.64AB**	**0.56B**	**1.36C**	**1,77B**
NW-SE	NE	8.53ab	2.44bc	2.90bcd	8.06ab	4.68bc	3.12bcd	**4.95b**	4.84b	1.80c	0.18cd	6.70abc	3.22bc	1.11c	**2.97c**	7.15a	1.32bcd	0.52c	6.06b	1.72bcd	0.07c	**2.80cd**	**3,58c**
	SW	1.56de	0.92cd	3.68bc	1.71cd	2.01de	4.24b	**2.35cde**	2.31cd	1.43cd	3.84b	2.61cd	1.89bcd	4.06b	**2.69cd**	1.57c	0.28cd	3.21b	1.46c	1.33cd	4.65c	**2.08de**	**2,37de**
	Cntr	0.38e	0.00d	1.53cde	4.21bcd	1.72de	0.53e	**1.39ef**	0.23e	0.00d	0.15cd	0.51d	0.13d	0.00c	**0.17f**	0.53c	0.00d	0.00c	0.00c	0.00d	0.00c	**0.09f**	**0,55g**
	Ave	**3.49A**	**1.12B**	**2.70A**	**4.66AB**	**2.80B**	**2.62A**	**2.90AB**	**2.46B**	**1.08BC**	**1.40B**	**3.27A**	**1.75A**	**1.69B**	**1.95B**	**3.08A**	**0.53B**	**1.24AB**	**2.51A**	**1.02B**	**1.57A**	**1.66BC**	**2,17B**
LSD		3,37	2,22	2,29	4,37	1,95	2,55	1,11	2,05	1,74	1,09	4.50	2,27	1,53	0,97	3,23	2,24	1,5	2.50	2,95	1,39	0,94	0.58

Variations in the atmosphere that result in the scattering and transmission of solar radiation during the growth season were a constant factor determining the direct and diffuse radiation components reaching the canopies (Jones and Rotenberg, 2011). The composition of sunlight reaching the interior of the canopies (and proportional number or portions of bunches) also most likely changes from a ratio of preferred higher short:long wavelengths (Red:Far-red radiation) to the less preferred higher long:short wavelengths as the growth season progresses and the volume and density of the canopy continue to increase (Smart, 1987). This has implications for photo-morphogenesis and the activity of many enzymes involved in the photosynthetic process and secondary compound formation, *via* the effect on phytochrome (Mitrakos and Shropshire, 1972; Smart, 1987). The results only reflect the photosynthetically active region of the incoming solar short wave radiation (380–710 nm) that comprises 21–46 % of energy, 4 % of ultra-violet (290–380 nm) and 50–70 % of near infrared (710–4 000 nm); therefore, radiation may have further impacted the energy, radiation and temperature regulation (and heat storage) of the canopy to incoming solar energy (Ross, 1981; Jones and Rotenberg, 2011). The different canopy sides are fully or proportionally exposed at different times of the day. Therefore, the thermal (long wave or infra-red between 3000–4000 nm and 100000 nm) radiation portion (release of energy) from the canopy bodies also dynamically changed diurnally, which may have led to differences in energy balances (radiative transfer, sensible heat transfer, latent heat transfer, and transfer to or from storage) of the differently orientated canopies. Nocturnal energy exchange is affected. The energy balance fluxes of the canopies changed according to the soil-vineyard-atmosphere continuum, irrespective of row orientation, but were dominated by the radiative fluxes onto and through the canopies.

On a practical level, the height, homogeneousness and density of the canopy walls affected the extent of exposure/shading of the different canopy sections (from bottom to top; e.g., bunch exposure timing and duration) and the soil. This is qualified by the spatial distribution of the incoming light, which is affected by the orientation of the row. In a broader sense, different latitudes also affect the sun path and thus the inclination and energy level of the incoming radiation. The latitude is taken into

TABLE 5. Water-use efficiency of an average of primary and secondary leaves in the canopies of Shiraz/101-14 Mgt planted in four different row orientations (average of measurements on 04/03/2010 and 08/03/2011).

Row orien	Can side	Water-use efficiency (Photosynthesis/Transpiration - mmol/mole H_2O)												
		Apical				Middle				Basal				Grand
		10:00	13:00	16:00	Ave	10:00	13:00	16:00	Ave	10:00	13:00	16:00	Ave	
NS	E	2,14a	0,74abc	0,22ef	**1,04abc**	2,09a	0,63abcd	0,23cd	**0,98b**	1,92a	0,61abcd	0.14cd	**0.89ab**	**0.97b**
	W	0,72c	0,76abc	1,53a	**1,00bc**	0,31f	0,94abc	1,36a	**0,87bc**	0,31c	0,82abc	1,18a	**0.77bc**	**0,88b**
	Cntr	0,70c	0,24c	0,13f	**0,36e**	0,24f	0,03d	0,04d	**0,10e**	0,21c	0,01d	0,00d	**0.07d**	**0,18d**
	Ave	**1,19A**	**0,58A**	**0,63A**	**0,80A**	**0,88A**	**0,53A**	**0,54A**	**0,65A**	**0,81A**	**0,48A**	**0,44A**	**0.58A**	**0,68A**
EW	N	2,01a	1,24a	1,17ab	**1,47a**	2,03ab	1,33a	1,09ab	**1,48a**	1,88a	1,22a	0,96ab	**1.35a**	**1,44a**
	S	0,61c	0,35c	0,41cdef	**0,45de**	0,99cde	0,44bcd	0,22cd	**0,55cd**	0,74bc	0,35bcd	0,08d	**0.39cd**	**0,46cd**
	Cntr	0,48c	0,51bc	0,29def	**0,43de**	0,45ef	0,25cd	0,07d	**0,26de**	0,27c	0,07cd	0,01d	**0.12d**	**0,27d**
	Ave	**1,03A**	**0,70A**	**0,62A**	**0,79A**	**1,16A**	**0,68A**	**0,46A**	**0,76A**	**0,96A**	**0,55A**	**0,35A**	**0.62A**	**0,72A**
NE-SW	NW	1,11bc	1,23a	1,01abcd	**1,12abc**	1,05cde	1,08ab	0,72bc	**0,95b**	1,04b	1,00ab	0,58bc	**0.87abc**	**0,98b**
	SE	1,74ab	0,47bc	0,40cdef	**0,87bcd**	1,42bcd	0,52bcd	0,21cd	**0,72bc**	1,69a	0,53abcd	0,27cd	**0.83bc**	**0,81bc**
	Cntr	0,38c	0,63abc	0,47bcdef	**0,49de**	0,31f	0,03d	0,07d	**0,14e**	0,49bc	0,00d	0,00d	**0.16d**	**0,26d**
	Ave	**1,07A**	**0,78A**	**0,63A**	**0,83A**	**0,93A**	**0,54A**	**0,34A**	**0,60A**	**1,07A**	**0,51A**	**0,28A**	**0.62A**	**0,68A**
NW-SE	NE	2,00a	1,02ab	0,94abcde	**1,32ab**	1,59abc	0,91abc	0,38cd	**0,96b**	1,82a	0,71abcd	0,24cd	**0.92ab**	**1,07ab**
	SW	0,41c	0,47bc	1,14abc	**0,67cde**	0,96de	0,52bcd	1,21ab	**0,90bc**	0,53bc	0,34bcd	1,22a	**0.70bc**	**0,76bc**
	Cntr	0,66c	0,26c	0,46bcdef	**0,46de**	0,23f	0,08d	0,06d	**0,12e**	0,15c	0,00d	0,00d	**0.05d**	**0,21d**
	Ave	**1,02A**	**0,58A**	**0,85A**	**0,82A**	**0,93A**	**0,51A**	**0,55A**	**0,66A**	**0,83A**	**0,35A**	**0,49A**	**0.56A**	**0,68A**
LSD Grand Ave		**1,08a(i)**	**0,66c(i)**	**0,68c(i)**	**0,81A(i)***	**0,97ab(i)**	**0,56cd**	**0,47de(i)**	**0,67B(i)***	**0,92b(i)**	**0,47de(i)**	**0,39e(i)**	**0,59C(i)***	**0,69c(i)**
LSD sides		0.83	0.67	0.74	0.47	0.61	0.71	0.57	0.37	0.60	0.80	0.48	0.50	0.39
LSD row orientation		0.48	0.39	0.43	0.27	0.35	0.41	0.33	0.21	0.35	0.46	0.28	0.80	0.22

Mean values with the same small letter in a column do not differ significantly (p≤0.05). Mean values with the same capital letter in a column do not differ (p ≤ 0.05). Mean values with the same letters merged with (i) within the "Grand Ave" row do not differ (p=0.05). Row orien = row orientation; Can side = canopy side; Cntr = centre of canopy; Ave = average.

account in the 3D modelling approach that was used in this study.

Al-Kayssi *et al.* (1990) found that solar energy absorption and the heat storage capacity of soil both increase as water content increases, but in the present study, such responses were not found to be consistent in the different soil layers. Water fluctuation in the different soil volumes most likely mainly resulted from the surface area between the rows being exposed to sun, a generally higher concentration of roots directly below the vines (Hunter, 1998), and a high evaporative demand on the canopy (affecting leaf vapour pressure deficits) on the day of measurement. The soil in the experimental vineyard was accepted as being uniform with similar bulk density (which was determined before establishing the vineyard, following which the same management actions were applied between the rows). The latter *per se* is therefore unlikely to have affected the thermal diffusivity of the soil (thermal diffusivity = ratio of thermal conductivity:volumetric heat capacity), and thus the results as found. The temperature fluxes in the top soil layers generally paralleled the increase in ambient temperature, whereas the temperature variation (amplitude) generally faded with soil depth. In the afternoon, all soil layers of the EW orientated rows reached the highest temperature values - most probably due to the larger and continuously exposed inter-row surfaces - in comparison to those of the other row orientations (as also confirmed by the canopy sun/shade photographs, schematic presentations and 3D modelling of canopy sun/shade patterns and the intensity and duration of soil surface exposure); this corresponded to lower soil water contents between the rows in the afternoon.

The results of this study fit the general positive relationship which has been found between air temperature and soil temperature, due to the effect of energy balances at ground surface level (Zheng *et al.*, 1993; Wu and Nofziger, 1999). The larger and longer inter-row exposed area in vineyards with EW row orientation (Figure 6) may have led to higher thermal radiation and dampening from the soil, which may have affected the temperature of the canopy-body (Jones and Rotenberg, 2011). It is conceivable that the radiation climate, atmospheric conditions and soil conditions, along with the architecture, morphology and orientation of the different canopies, affected canopy heat fluxes and absorption, reflection, transmission and emittance of radiation. Under normal field conditions, this may never be a steady state condition, but rather a dynamic system, as impacting factors, such as wind fluxes and clouds, will always induce resistance (impediment) or stimulation in the morphologically and physiologically active canopy bodies.

The Ψ_L results show that radiative energy has induced changes at soil, canopy and physiological levels, which complimentarily affected plant water relations by driving a general decrease from the morning to the afternoon for all row orientations. The highest Ψ_{PL} and Ψ_{SL} values that were measured for the EW orientated canopies are in agreement with those found by Hunter *et al.* (2016), but seem to contrast with the apparent higher depletion of soil water contents and higher soil temperatures found in the EW orientated rows in the afternoon. Medrano *et al.* (2015) also showed the complexity of water relations in grapevine canopies and the difficulty in upscaling from leaf to canopy level under field conditions on a diurnal and seasonal basis, reflecting the effects of leaf position, light interception, canopy density, soil water conditions and additionally, night transpiration and respiratory losses.

Photosynthetic activity of all the leaves in the canopy was clearly affected by the inclination of the sun, as demonstrated by the much higher P_n of the N versus S canopy sides. This was also found by Hunter *et al.* (2016). The differences in P_n amongst canopy sides may be due to stomatal movements responding to intrinsic physiological inter-relationships and diurnal below- and above-ground environmental impact. Reduced P_n in the afternoon has also been previously found under different field conditions (Hunter *et al.*, 1994; Haasbroek *et al.*, 2000), and over-estimations with leaf gas exchange models are common under ample sunlight conditions in the afternoon, indicating photo-inhibition (Prieto *et al.*, 2012). The lower afternoon P_n may have been driven by a combination of high radiation intensity, lower Ψ_L, and increasing ambient temperatures, peaking at around 15:00 to 17:00 at 30–35 °C on the days of measurement in this study. The preceding diurnal carbon assimilation, as clearly demonstrated by Hunter *et al.* (1994), may also have benefitted the canopy as a whole, irrespective of side. Feedback inhibition may well have been a restricting physiological response to further high P_n rates in the afternoon, but under field conditions, the existence of carbon partitioning into photosynthesising reproductive and perennial (including root) tissues renders this physiological mechanism more complex than just a simple regulation by starch and/or sucrose build-up (Hunter *et al.*, 1994, Hunter *et al.*, 1995). The preference for transitory starch accumulation instead of sucrose export from the leaves during the day changes in favour of the former, especially during late season. Furthermore, soil water content decreased from 10:00 until 16:00, whereas the temperature in the top soil layer (0–60 cm) increased. These conditions may have increased the impact of radiative (ultraviolet, visible and infra-red) energy and soil emittance on leaf temperature; the normal evaporation cooling mechanism of the leaves for optimum activity may thus have been inefficient for leaf temperature regulation and energy balance control (Jones and Rotenberg, 2011). Altogether, these conditions may also have triggered a restricting stomatal control signal from the roots and in the leaves in the afternoon, most likely involving abscisic acid (Lovisolo *et al.*, 2002; Patakas *et al.*, 2005; Hunter *et al.*, 2014a).

The general decrease in photosynthetic output from the apical to the basal part of the canopy was also found by Hunter and Visser (1989) and Hunter *et al.* (1994). The low erratic values measured in the interior of the canopy in both basal and middle zones are to be expected, due to the commonly occurring lower light conditions in these zones that limit P_n. However, these leaves clearly responded positively to light exposure from the basal to the apical zone, although they were mostly sheltered from direct radiation. In addition, higher overall P_n in, for example, the NS and EW row orientations also corresponded to higher water retention in the canopies. These results confirm the importance of canopy age, light exposure and water potential in the driving of grapevine functioning.

Given the above, results indicate a cumulative physiological impact on temporal status. This also emerged from intensive WUE measurements on various genotypes, showing the significant effects of leaf position, light interception and water balances (Medrano *et al.*, 2015). The results are in agreement with those found for the same variety under different (Novello and Hunter, 2004) and similar (Hunter *et al.*, 2016) growth conditions. However, the WUE results are not in agreement with the findings of Medrano *et al.* (2015), who found the highest values at midday, relatively high values in the centre of the canopy, and no specific trend for different leaf positions; these discrepancies may have resulted from differences in growth conditions. The results clearly display an interaction between the trellising system, row orientation and growth (including vigour and accommodation of the shoots). This was also shown in modelling approaches with different cultivars and trellising system configurations (Louarn *et al.*, 2008), confirming the difficulty in integrating climate, genotype and practices in order to reach the product objectives of yield and quality.

The WUE results in this study point to a complex whole plant internal regulation of output, despite the agreeable trends found between the different physiological parameters and radiation. Overall, the results reflect the positive impact of the azimuth and penetration of the sun into the canopy on P_n during the ripening period. The P_n performance of canopy sides during this period seem mostly driven by the presence and responsiveness of secondary leaves, confirmed in this study by their generally higher P_n output than that of primary leaves. The measurements were taken during the latter part of the ripening period when secondary leaves were generally younger and more responsive to environmental changes (see also Hunter *et al.*, 2014). These leaves have an increasingly important role in supplying and transporting sucrose, as well as in supporting further formation of secondary compounds inside the bunches during the course of ripening (Allen and Lacey, 1993; Marais *et al.*, 1999; Hunter and Ruffner, 2001; Ojeda *et al.*, 2002). They may also be assumed to be less sensitive to abiotic influences on the plant, compared to primary leaves. Patakas *et al.* (1997) found that the capability for osmo-regulation was almost the same in mature and immature leaves, but the elasticity of cell walls, and thus the ability to maintain positive cell turgor, decreased with age. Younger secondary leaves may therefore have increased isohydric behaviour (active stomatal regulation of transpiration – Naor and Wample, 1994; Escalona *et al.*, 2002), which may contribute to a better ability to buffer the impact of unfavourable environmental conditions (e.g., high temperatures and low soil water contents) on grape development and ripening (Hunter, 2000; Hunter *et al.*, 2004; Novello and Hunter, 2004; Hunter *et al.*, 2014a, 2014b). In addition to water management (and appropriate fertilisation programmes), it is important for the initiation and development of secondary leaves to be stimulated pre-véraison by judicious canopy management in order to maintain canopy photosynthetic capacity and to increase the potential of the canopy to support and protect the grapes when adverse environmental conditions are experienced during the ripening period (Hunter, 2000). In this experimental vineyard, the primary:secondary leaf area ratio during this period was calculated to be 0.85; the final canopy and leaf exposure dimensions measured over a 7-year period between treatments have been found to be similar (data presented in Hunter *et al.*, 2017). The contribution of secondary leaves to total canopy photosynthetic output was thus substantially higher than that of primary leaves during ripening, even when excluding smaller (apical) leaves (on both primary and secondary shoots) that may have still been displaying sink-behaviour (and despite the fact that active growth had already halted).

Under any circumstances, the water status of soil and plant is critical for their maintenance, restriction or stimulation of growth and survival, and thus for attaining product objectives (Hunter *et al.*, 2014a, Hunter *et al.*, 2014b). In addition, as Ψ and P_n of the leaves are sensitive to sun exposure, the latitude (e.g., Southern *versus* Northern grape growing countries) and concomitant ecliptic changes during the growth season affect the response and output of the canopy, relative to the vineyard row orientation. For example, Zufferey *et al.* (1999) found that the net diurnal photosynthesis of Chasselas leaves on S exposed canopy sides of EW orientated rows in the Northern hemisphere was highest during the whole growth season, in comparison to the N side found in this study. Moutinho-Pereira *et al.* (2003) found a higher photosynthetic rate for Touriga Nacional leaves on the NE side of NW-SE orientated rows in the morning, while that of leaves on the SW side was reduced in the afternoon due to stomatal and non-stomatal restrictions.

In general, the integrated photosynthetic output of the canopy and the metabolic activity of the vine can be further improved by timely and properly executed canopy management in order to stimulate the development of source-behaving secondary leaf availability during the grape ripening period and accommodating all leaves in such a way that they satisfy the dual foliage functioning objective; i.e., to reach the maximum *physiological* potential for supplying to the grapes, and at the same time to fulfil the *physical* role of protecting the grape bunches against over-exposure to the sun (Kriedemann, 1968; Pandey and Farmahan, 1977; Hunter *et al.*, 1988a, 1988b; Smart *et al.*, 1990; Hunter *et al.*, 1994; Hunter *et al.*, 1995; Hunter, 2000; Hunter *et al.*, 2004; Poni *et al.*, 2009; Chorti *et al.*, 2010; Hulands *et al.*, 2014; Hunter *et al.*, 2016; Zorer *et al.*, 2017). The terroir environmental conditions (specifically: orographic, edaphic and climatic) largely determine the balance between these two objectives. Such conditions may range from extreme cool conditions, in which thin canopies and almost full grape exposure may be required, to extreme hot conditions, in which partial protection of the grapes by the leaves would be favourable for yield and disease-free grape ripening to achieve optimum ripeness; for the latter, it is critical to understand and manage the interplay between grape exposure and ripeness level (between under- and over-ripe) in both environmental scenarios.

In the present study, direct and diffused radiation interception was measured in the canopy layers of the different row orientations. The diffused radiation component of the EW row orientation was hampered by the vertical shoots and their topping, as well as the sun path from E to W over the top of the canopy. However, a shift towards direct exposure of the N side occurred as the growth season progressed. Nonetheless, an EW row orientation would provide more protection to grapes in especially hot climatic conditions (particularly on the S side, in the Southern hemisphere), whereas it may most likely be too shaded in cool conditions (particularly for red grapes). In contrast, the NS orientation resulted in a larger direct radiation component because of the (almost) perpendicular angle of incidence of the sun in the morning on the E side and in the afternoon on the W side; however, grapes were diffusedly shaded over the (critical) midday period. The diffused radiation component was largest, and direct radiation component smallest, for the NW-SE and NE-SW orientations, the major difference being that the former received higher levels of incidence in the morning on the NE side and the latter received higher levels of incidence in the afternoon on the NW side; in general, slightly more radiation was intercepted by the NW-SE orientation. Despite the diffused radiation, the central canopy zones of both of these row orientations were better exposed than those of the NS and EW orientations. Several studies have already shown that it is best to be cautious when there is the possibility of direct radiation on the grapes (especially in hot climates), as this may have deleterious consequences (Smart *et al.*, 1990; Allen and Lacey, 1993; Hunter *et al.*, 2004; Tarara *et al.*, 2008; Chorti *et al.*, 2010; Hulands *et al.*, 2014), such as high pulp temperatures, bunch rot, poor skin colouring, low titratable acidity, high pH and loss of flavour. Diffused radiation is thus generally preferred for grape and wine quality, although a shift towards a larger direct radiation portion may benefit the grapes in cool to cold conditions. Evidently, the heterogeneous ripening of grapes exposed on the two sides of vertical canopies of differently orientated rows can occur under any management conditions, and intra-bunch compositional differences can be expected. The level of impact of the differential conditions induced by a specific row orientation could naturally be determined by the terroir conditions, sensitivity of the variety-rootstock combination, and the objectives regarding yields as well as grape and wine quality. Although the effects of over- and under-exposure of grapes on composition and wine quality are relatively well-known, the specific implications of the intensity and duration of direct and diffused radiation at different times of the day and growth season have still not been elucidated and present a major challenge under field conditions.

A number of integrated factors drive the functional response of the grapevine canopy to radiation at any given time: continuous adaptation to or compensation for temporal changes in the root system (responding to the biotic and abiotic soil environment and aboveground growth and maintenance demands from vegetative and reproductive organs); water relation status (as affected by evaporative demands and internal physiological requirements and mechanisms); biochemical status and responsiveness, which may lead to an unsaturated, temporally saturated or fully saturated plant substrate or enzyme reaction status (according to the combined impact of diurnal/nocturnal environmental conditions and physiological processes in aboveground and belowground organs); general leaf age composition (source-sink status ratios and levels) and exposure of the canopy, as affected by the seasonal growth progression, physiological senescence, and physical leaf loss or abscission, either as a result of manipulation, environmental stress or because of the normal perennial cycle (Hunter, 2000). The energy balances and seasonal dynamics of physiological parameters (such as carbon assimilation and distribution, and water relations) can therefore be affected by the specific location, environmental conditions and long- and short-term cultivation practices to which the grapevines are exposed and which could impact aspects such as vigour potential and bud fertility. Bearing this in mind, the yield of the NS orientated vines was highest, followed by that of the NW-SE, EW and NE-SW orientated vines (Hunter *et al.*, 2017), despite the results indicating higher plant water retention of the EW orientated vines and similar overall average photosynthetic activity to that of the NS orientated vines. The NS orientated vines also had the most stable yields over the seven consecutive years of monitoring (Hunter *et al.*, 2017). The yields were differentially affected by canopy orientation and the ripeness level of the grapes when harvested. Total yield losses of 17 % occurred over the measuring period, from a ripeness level of approximately 23 °Balling (total soluble solids) to approximately 27 °B. In affecting spatial and temporal leaf and grape bunch exposure (Hunter *et al.*, 2016; Zorer *et al.*, 2017) and carbon allocation (Hunter *et al.*, 2017), row orientation clearly has a critical role in the extent to which objectives related to physiological output and yield (as well as grape and wine quality) can be reached; it is important to be judicious when considering canopy (micro)climatic exposure and vineyard practices during both pre- and post-véraison periods to favour the maintenance and formation of compounds in the berries (Bois *et al.*, 2008; Hunter *et al.*, 2010; Hunter and Bonnardot, 2011; Hunter *et al.*, 2014b; Hunter *et al.*, 2016). High photosynthetic activity (sucrose availability) during the pre-véraison period contribute to primary and secondary compound pool availability in the berries when the ripening period starts, whereas it will largely buffer a decrease in organic acid (conversion to salt forms and metabolism) and an increase in pH during the post-véraison period. This favours further development and accumulation of the secondary compound pool required for quality grape composition and wine (Iland, 1987; Patrick, 1997; Riou, 1998; Hunter, 2000; Hunter and Ruffner, 2001; Ojeda *et al.*, 2002; Hunter *et al.*, 2004; Hunter and Bonnardot, 2011).

Choice of row orientation is therefore more complicated than merely selecting the highest or lowest water potential and photosynthetic output; it must also take into account terroir- and management-related factors, as well as other (viticultural) factors, such as bud fertility, yield, health and composition of grapes, and wine quality objectives. Furthermore, the radiation patterns of the differently orientated canopies change according to the ecliptic changes as the growth season progresses from bud break to full grape ripeness. Along with growth and source:sink dynamics in the canopy (Hunter, 2000) and canopy height, density and seasonal practices, the intensity and duration of exposure/shade can induce temporal and seasonal (including cumulative) differential leaf responses and have an effect on canopy functioning and grape development and ripening. This should all be considered at a commercial level, taking into account grape and wine product objectives. Judiciously chosen practices and careful management are therefore necessary to avoid risks and obtain the full value of a long-term cultivation practice, such as vineyard row orientation.

Results of this study provide evidence of the interaction between environmental impact factors (especially radiation), genotype growth characteristics and physiological response mechanisms and control, and cultivation practices. This detailed study on light microclimate and a variety of individual leaves under common field cultivation conditions may lay a better foundation for the up- and downscaling to, and understanding of, the light conditions, photosynthesis and leaf water potential of whole plants and differently orientated and managed canopies. A broad image of the horizontal and vertical functional layers in the canopies has been obtained, which can also be used to predict potential canopy physiological output under different terroir conditions, whether by means of quantitative observations or modelling. Such output is affected by grapevine growth and manipulation (by means of, e.g., pruning, shoot topping, leaf thinning), canopy geometric shape, space and composition (primary and secondary shoot number and lengths; shoot internode lengths and distribution; wired or free hanging shoots and their orientation; leaf size, distribution, age and morphology), inter-row spacing, and radiation inclination, penetration, efficiency, sufficiency and consistency. These are all in turn largely affected by the direction of the grapevine rows, terroir conditions and management practices (thus affecting vine-to-vine uniformity and continuity). Site specific conditions (orography; soil fertility, depth, water holding capacity and drainage; rainfall; macro- and meso-climate) are therefore critical to the establishment of practical and functional vineyard row orientations, defining the extent to which grapevine morphological development and physiological output related to yield, grape composition and wine quality will be favoured.

This study contributes to better understanding the complexity of interrelationships between the microclimate, water status and photosynthesis of leaves in canopies affected by vineyard row orientation within specific terroir conditions. Data on leaf water potential showed that EW vineyard row orientation resulted in the highest overall water retention in the canopy, despite lower afternoon soil water contents and higher soil temperatures. In general, the NE-SW orientation showed the lowest overall water potential in the canopy. The water retention of leaves in the centre of the canopies tended to be the highest, while photosynthesis was at its lowest, with output being clearly limited by the light blocking effect of the leaves on the outer rim of the canopy. Photosynthetic activity reflected the positive impact of the sun azimuth during the ripening period in the Southern Hemisphere; leaves on the E- and N-exposed canopy sides were evidently superior during this period, mostly been driven by the presence and responsiveness of secondary leaves. Results confirmed the need for management actions that will ensure the presence of secondary shoots with younger leaves in the canopy in order to maintain the carbohydrate pool, supply carbohydrate to bunches and reserve compartments, sustain grape ripening, and protect bunches from over-exposure. Concomitantly, the study clarified the differential importance of leaves in differently orientated canopies and the requirement for judicious exposure.

This comprehensive and novel study contributed to the hitherto demanding challenge of capturing the physiological complexity of grapevine canopies under field environmental conditions. The knowledge acquired will be of great value in facilitating the selection of grapevine row orientation, row and plant spacing, irrigation and fertilisation, as well as canopy management practices at commercial level for different soil and climatic conditions. The sun/shade patterns could assist in obtaining very clear visualisations and judgements of the intensity and duration of exposure of the grapes in grapevine rows, and the expected concomitant morphological-chemical implications for any product objective. This should be considered in existing and future vineyard planting per terroir, and according to grape and wine product objectives of the vineyard, to guarantee uncompromised and sustainable fertility and yield, healthy grapes, and manageable and predictable grape composition.

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