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Effects of canopy architecture and microclimate on grapevine health in two training systems

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Summary

Semi minimal pruned hedge (SMPH) is a time and cost saving grapevine training system, which is becoming more and more popular in German viticulture. In this study we compared the canopy architecture and its effect on the microclimate of SMPH trained grapevines with those of plants trained in vertical shoot positioning (VSP). We detected a 3 % points higher humidity and a 0.9 °C lower mean temperature within the complex canopy architecture of SMPH trained vines compared to VSP. Moreover, we investigated the influence of the differing microclimate, canopy and bunch architecture, as well as berry skin characteristics of the two training systems on the incidence of the major fungal grapevine diseases Downy Mildew, Powdery Mildew and Botrytis Bunch Rot, as well as on the occurrence and damage of the invasive insect pest *Drosophila suzukii*. We demonstrate that SMPH trained vines can be more susceptible to Downy Mildew and Powdery Mildew than VSP trained vines. The incidence of Botrytis Bunch Rot can be higher in the latter system, even if berry skin characteristics are the same in both training systems. We trapped a higher number of *D. suzukii* in SMPH canopies, however no increased berry damage was observed. Based on our results we recommend a more adapted plant protection regime for SMPH trained vines due to their higher susceptibility to the major fungal diseases. Furthermore, we propose a combination of SMPH and fungal resistant grapevine cultivars, e.g. 'Reberger', to achieve a more competitive, environmentally friendly and high quality grapevine production.

K e y w o r d s : training system; plant architecture; Powdery Mildew; Downy Mildew; *Drosophila suzukii*; *Vitis vinifera* ssp. *vinifera*; PIWI; viticulture.

Introduction

Traditionally, grapevine in Germany is cultivated in the vertical shoot positioning (VSP) system, which is typical for cool climates. This type of grapevine training enables farmers to manage grape yield and quality by controlling the number of buds and their optimal distribution in the trellis (Jackson 1996). However, the farmer has to undertake a time consuming winter pruning and wire positioning during the season, which causes high labor costs (Clingeleffer 1993). In order to reduce the costs of manual labor, a novel training method called semi minimal pruned hedge (SMPH) was introduced. The mechanization of pruning, which is the basis of SMPH, in combination with the omission of wire positioning, reduces labor costs to a minimum (Clingeleffer 1993). This makes SMPH a highly efficient and competitive grapevine production system, which is easily applicable by grapevine growers.

Cultivation of grapevines in SMPH affects plant physiology and as a consequence plant morphology. Compared to VSP, bunches of SMPH trained plants weigh less and have a more loose architecture, due to the fact that they consist of fewer and smaller berries (Intrieri *et al.* 2011). Despite smaller bunches, the number of inflorescences and bunches per plant is elevated in minimal pruned grapevines and thus the yield per plant is enhanced in contrast to the traditional training system (Clingeleffer and Possingham 1987, Wolf *et al.* 2003). The average leaf size in SMPH is smaller than in VSP vines (Sommer *et al.* 1993), but the total leaf number per vine and hence the total leaf area (m^2/m of row) is higher if the grapevines are minimally pruned (Clingeleffer and Posingham 1987, Schmid and Schultz 2000, Intrieri *et al.* 2001). We expect that these vast differences in canopy architecture between SMPH and VSP affect the grapevine microclimate. Because of the increased leaf volume SMPH canopies should show poor air movement and less light penetration. We therefore expect a lower temperature and a higher humidity in SMPH canopies than in the less voluminous VSP canopies.

European grapevine, *Vitis vinifera*, is threatened by several pests. Fungal diseases such as Downy Mildew (DM, caused by *Plasmopara viticola*), Powdery Mildew (PM, caused by *Erysiphe necator*) and Botrytis Bunch Rot (BR, caused by *Botrytis cinerea*) are the most destructive. Their development and spreading in the vineyard can be influenced by canopy management. Since disease progress of DM and BR is facilitated by a warm and moist climate, training systems which increase air movement and light

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penetration are beneficial for controlling these pathogens in the vineyard (Coombe and Dry 1992). Canopy management during the season such as leaf removal in the bunch zone can additionally reduce wetness and improve light penetration, creating an environment which is less favorable for PM and BR (Gubler *et al.* 1987, Austin and Wilcox 2011). In addition, characteristics of the berry skin, e.g. thickness of the berry skin and of the cuticle, are described as further important traits influencing susceptibility against BR (Commenil *et al.* 1997, Gabler *et al.* 2003, Becker and Knoche 2012a, b, Herzog *et al.* 2015).

We expect a higher incidence of DM in SMPH because of the elevated humidity and reduced light penetration in the canopy compared to VSP. Concerning *Botrytis* we assume a decreased rate of BR in SMPH panels as result of the loose bunch architecture. Furthermore we expect the incidence of PM to be elevated in SMPH panels, due to the more favorable microclimate and reduced light penetration (Gadoury *et al.* 2012).

Drosophila suzukii (Matsumura, Diptera: Drosophilidae), also known as spotted wing drosophila (SWD) is a pest insect native to Asia which has recently spread to the Americas and Europe (Cini *et al.* 2012). In contrast to the common fruit fly *Drosophila melanogaster* which is attracted by overripe or rotten fruit, SWD prefers ripening or ripe red fruit. It may penetrate intact fruit skin with its serrated ovipositor and deposit eggs inside the fruit (Lee *et al.*, 2011). However, laboratory experiments revealed that artificially damaged berries are more attractive for the fly than intact ones (Ioriatti *et al.* 2015, Jarausch *et al.* 2017). SWD damage can be both direct through larval feeding and indirect, since oviposition leaves the fruit skin damaged and susceptible to secondary pathogens such as bacteria and fungi (Ioriatti *et al.* 2015). SWD has a wide range of host plants including blueberries, strawberries, cherries, and plums, as well as grapevine (Rouzes *et al.* 2012, Bellamy *et al.* 2013). Since SWD prefers humid conditions on a large as well as on a smaller scale (Hauser *et al.* 2009; Tochen *et al.* 2016) we hypothesize that more flies can be trapped in SMPH panels with their more voluminous canopy than in VSP. As a result of the higher density of SWD we expect a higher infestation rate of grapes in SMPH than in VSP trained grapevines. In addition to the microclimate, the characteristics of the grape skin might further influence the damage by SWD on berries. Thicker and more resilient skin might reduce the egg laying success of SWD females in SMPH trained grapevines (Ioratti *et al.* 2015).

Material and Methods

Plant material and cultivation practices: For this study the *Vitis vinifera ssp. vinifera* cultivars 'Chardonnay' (planted 2008) and 'Reberger' (planted 2001) were used. Vines were planted at the experimental vineyards of Geilweilerhof located at Siebeldingen, Germany (N 49°21.747, E 8°04.678). Since 2013, half of the rows of each cultivar were pruned mechanically and thereby converted to the SMPH system. Inter-row distance is 2 m and grapevine spacing is 1 m. For pest control plants were treated with an organic plant protection regime consisting of wettable sulphur (AgroStulln, Stulln, Germany), Funguran progress (Spiess-Urania, Hamburg, Germany) and Vitisan (Biofa, Münsingen, Germany). Pesticides were applied fortnightly, 12 times during the season. In 2017 conventional pesticides (Polyram WG, Enervin, Vivando; BASF SE, Ludwigshafen, Germany) were used in the first three plant protection applications, because of the severe plant damage caused by *P. viticola* und *E. necator* in the previous year. After flowering both panels, SMPH and VSP, were pruned mechanically.

All experiments and measurements were performed during the growing season 2016 and 2017. Phenological development of grapevines was determined using the BBCH scale according to Lorenz *et al.* (1995).

Canopy architecture: To compare the canopy architecture six main characters were chosen and analyzed for each cultivar and training system: (1) the number and distribution of shoots at bud burst (BBCH 10) was evaluated in four random 50 cm wide canopy sections, divided into five horizontal zones (Fig. S1 suppl. data); (2) based on this scheme the number and distribution of inflorescences/bunches at the phenological stages flowering (BBCH 65), pea size (BBCH 75) and veraison (BBCH 81) was determined; (3) for calculation of the leaf area index (LAI) all leaves from four random 50 cm wide canopy sections were removed and measured with a leaf area meter (Modell 3100 area meter, Li-COR, Lincoln, Nebrasca, USA); (4) fifty randomly selected leaves were measured to calculate the average leaf size; (5) the canopy volume was calculated as the product of canopy height [m] x canopy width [m] x 10.000 m², divided by the inter-row distance [m] (Siegfried and Sacchelli 2005). LAI, average leaf size, and canopy volume were also determined at flowering (BBCH 65), pea size (BBCH 75) and veraison (BBCH 81); (6) weight [g], length [cm] and width [cm] of ten randomly selected bunches were recorded as indicator for bunch architecture. Additionally, average berry number and size [mm] of 10 berries per bunch was measured. Bunch architecture was evaluated at ripening (BBCH 89). Data were analyzed using t tests in R (R Core Team, 2013).

Berry skin characteristics: Physical and morphological berry skin characteristics were determined of 'Reberger' (VSP and SMPH) at ripening stage (BBCH 89) and before harvest. First, impedance of the berry cuticle was measured at room temperature by using the I-Sensor from 30 berries per training system, 17 % Brix and relative impedance Z_{rel} was calculated according to Herzog *et al.* (2015).

The TA.XT Texture analyzer (Stable Micro System, Godalming, Surrey, UK) was used to evaluate the penetration resistance of berries by mean of maximum break force [N] and skin break energy [mJ]. Settings were used according to Letaief *et al.* (2008). For each training system 50 berries were randomly harvested. Results were recorded with software Exponent Lite Express (Stable Micro System, Godalming, Surrey, UK) results were recorded.

The thickness of berry skin was measured using light microscopy in order to detect morphological differences between SMPH and VSP berries. Skin sections of 20 frozen berries were cut from the side and sliced into 6-8 µm thick discs with a cryomicrotome (Micro HM 525, Thermo Scientific, Waltham, Massachusetts, USA). 15 skin slices per berry were then fixed on a protein glycerol coated object plate and stained in an Astra Blue solution. Using Leica Application Suite 4.3 and a Leica DM 4000 B light microscope (Leica Microsystems GmbH, Wetzlar, Germany) under 100-fold magnification, the thickness of the berry skins was determined. All means were compared using t tests in R (R Core Team, 2013).

Microclimate: Temperature and relative humidity in the grapevine canopy were recorded with Tinytag Plus 2 data loggers (Gemini Data Logger Ltd, Chichester, UK). Three loggers per training system and variety were positioned 150 cm above ground in the canopy at random locations in the vineyard. Microclimate measurements were started when three leaves were visible (BBCH 13) and ended by the time of ripening (BBCH 89) with a recording interval of 1 h. For adjustment and reading of the loggers as well as for data evaluation the Tinytag Explorer Software (Gemini Data Logger Ltd) was used. Local climate data including mean temperature, total rainfall and leaf wetness were obtained from the institute DLR Rhineland-Palatinate (www.am.rlp.de). For statistical evaluation of the mean values a permutation test with the program R was performed (R Core Team 2013).

Assessment of fungal diseases: Monitoring of fungal grapevine diseases was done according to the European and Mediterranean Plant Protection Organization (EPPO) guidelines: *Plasmopara viticola* (PP 1/31(3)), *Erysiphe necator* (PP 1/4(4)), *Botrytis cinerea* (PP 1/17(3)). For each training system and variety 100 grape bunches were screened and rated for disease symptoms of the particular fungal pathogen. The score ranged from 0 % (no symptoms) to 100 % (symptoms on the whole bunch) with a scaling interval of 10 %. Additionally, a scoring of 5 % was added to the ranking for the assessment of minimal symptoms. With this method we determined both incidence rate and level. For statistical evaluation Fisher's exact test for the incidence rate and Kruskal-Wallis test for the incidence level was performed with the program R (R Core Team 2013).

Spotted wing drosophila (SWD): Trap design and evaluation: During the season the occurrence of SWD in the two training systems was evaluated from BBCH 83 to BBCH 89 in the variety 'Reberger'. SWD appears almost exclusively on red varieties, which is why the white 'Chardonnay' variety was not sampled for this experiment (Saguez *et al.* 2013). Three traps per training system were randomly distributed in the canopy and analyzed weekly for four weeks. A trap consisted of a 500 mL clear plastic drinking vessel with lid. The vessel was manipulated in the upper third by affixing a red tape and drilling 15 holes with a diameter of 1 mm into it. As trapping liquid we used 100 mL of a 1:1 mixture of water and unfiltered cider vinegar plus a drop of wetting agent (Tween® 20, Sigma-Aldrich, Munich, Germany). *Drosophila suzukii* flies were counted through a stereomicroscope (Zeiss, Jena, Germany). Statistical analysis was done using t test in R (Core team, 2013).

SWD: Berry infestation rate: Between BBCH 83 to 89, 50 intact berries per training system were collected weekly from random vines and different bunches within the 'Reberger' variety to evaluate the infestation rate. Oviposition of SWD was observed under a stereomicroscope (Zeiss) and the number of eggs per 50 berries was counted. Data was analyzed using t tests in R (R Core Team 2013).

Results

Canopy architecture: In Tab. 1 all investigated characteristics of the canopy architecture for 2016 (a) and 2017 (b) are listed (the complete Table including a comparison of the different trellis zones can be seen in Tab. S1, suppl. data). The number of shoots per 0.5 m was significantly higher in SMPH panels than in VSP panels in both years: Eight to 15 times for 'Chardonnay' and six to eleven times for 'Reberger'. We also noticed differences in shoot distribution between the two training systems. While the majority of the shoots were found in the upper zones (Tab. S1, 3-5) in the SMPH trellis, shoots in the VSP trellis were almost completely restricted to the lower zones (Tab. S1, 1-2) and virtually equally distributed.

A similar result was observed for the number of inflorescences/bunches per 0.5 m. In 2016 and 2017 at BBCH 65 the total amount of inflorescences in the 'Chardonnay' field was two to four times higher for SMPH compared to VSP and three to six times higher in the 'Reberger' field. The majority of SMPH inflorescences/bunches were located in the higher zones (Tab. S1, 4 and 5). In the VSP panel the inflorescences/bunches were most frequently found in zone two and three.

For 'Chardonnay' the LAI and the canopy volume were at least 1.5 times higher in the SMPH than in the VSP panel during the complete seasons of both experimental years, except for BBCH 75 in 2017 (Tab. 1). In the 'Reberger' variety both parameters showed significant differences between the training systems the entire season of 2017. In 'Chardonnay', leaves of VSP plants were 1.5 times bigger than leaves from SMPH plants at all phenological stages. For 'Reberger' this was only the case at BBCH 75 in 2016 and at BBCH 65 in 2017.

Regarding bunch architecture, all investigated characteristics, weight, length, width, number of berries and mean berry size, were significantly higher for VSP bunches compared to SMPH bunches in both years and cultivars, except for 'Reberger' in 2016. For 'Chardonnay' the differences in bunch architecture between the two training systems are clearer in 2017 than in the previous year.

Berry skin characteristics: No significant differences were detected between the two training systems in terms of investigated berry skin characteristics, *i.e.* impedance of the cuticle, maximum break force, skin break energy and berry skin thickness (Tab. S2, suppl. data).

Microclimate: The evaluation of microclimate as a function of the training system showed significant differences between SMPH and VSP, predominantly in the 'Chardonnay' field in 2016 (Tab. 2, a). In the first year of the study, increased leaf wetness was measured in BBCH 13-71 and 83-89 due to rainfall and morning dew, respectively. At this time the relative humidity in the SMPH canopy was significantly higher and the temperature lower compared to VSP canopies. This was also the case for 'Reberger', but

Table 1

Canopy architecture characteristics of the two grapevine varieties 'Chardonnay' and 'Reberger' as a function of training system, 2016 (a) and 2017 (b). T test; $*P < 0.05$, $**P < 0.001$

a)

2016	BBCH	Chardonnay			Reberger		
		SMPH	VSP		SMPH	VSP	
Number of shoots [per 0.5 m]	10	68.3 ± 9.6	8.3 ± 1.3	**	44.4 ± 6.9	6.5 ± 1.8	**
Number of inflorescences/bunches [per 0.5 m]	65	40.0 ± 5.9	9.0 ± 0.8	**	30.0 ± 7.9	9.3 ± 3.1	*
	75	19.0 ± 7.7	9.5 ± 3.7	n.s.	25.0 ± 11.5	7.8 ± 3.1	n.s.
	81	11.5 ± 2.4	7.5 ± 3.7	n.s.	10.3 ± 3.8	9.5 ± 5.8	n.s.
LAI	65	4.7 ± 0.7	1.0 ± 0.1	**	2.6 ± 1.0	1.2 ± 0.1	n.s.
	75	2.8 ± 0.2	1.7 ± 0.3	*	2.6 ± 0.5	1.9 ± 0.4	n.s.
	81	3.1 ± 0.3	1.8 ± 0.4	*	3.2 ± 0.5	1.9 ± 0.6	*
Average leaf size [cm²]	65	65.9 ± 6.6	106.7 ± 11.7	*	87.3 ± 4.2	107.4 ± 36.6	n.s.
	75	59.3 ± 3.1	85.0 ± 10.2	*	70.9 ± 4.6	119.5 ± 13.7	**
	81	51.2 ± 3.9	74.4 ± 5.8	**	76.0 ± 13.6	99.5 ± 2.6	n.s.
Canopy volume [m³]	65	47046.0 ± 6770.8	9945.5 ± 1122.6	**	25884.4 ± 10246.0	12094.6 ± 728.5	n.s.
	75	28041.6 ± 2350.2	17234.5 ± 3139.9	*	26322.2 ± 4797.8	18604.0 ± 3796.0	n.s.
	81	31120.9 ± 2787.9	17986.3 ± 3139.9	**	31812.4 ± 4608.5	19209.8 ± 5902.6	*
Bunch weight [g]	89	96.5 ± 37.3	152.3 ± 40.0	*	126.7 ± 27.1	182.6 ± 69.0	*
Bunch length [cm]	89	11.2 ± 2.0	12.9 ± 1.1	*	11.3 ± 2.5	13.3 ± 3.3	n.s.
Bunch width [cm]	89	6.9 ± 1.3	8.7 ± 1.8	*	8.7 ± 1.9	9.6 ± 1.1	n.s.
Berry number per bunch	89	78.1 ± 26.9	110.1 ± 27.5	*	71.3 ± 17.1	85.6 ± 24.1	n.s.
Ø berry size [mm]	89	12.0 ± 1.0	12.4 ± 1.0	*	14.2 ± 1.2	14.2 ± 1.3	n.s.

b)

2017	BBCH	Chardonnay			Reberger		
		SMPH	VSP		SMPH	VSP	
Number of shoots [per 0.5 m]	10	150.0 ± 14.4	10.0 ± 1.2	**	101.0 ± 11.3	9 ± 0.8	**
Number of inflorescences/bunches [per 0.5 m]	65	18.5 ± 6.5	9.8 ± 2.2	n.s.	52.0 ± 15.4	8.0 ± 2.1	*
	75	19.0 ± 7.5	9.0 ± 0.8	*	18.0 ± 8.0	7.8 ± 3.0	n.s.
	81	12.3 ± 4.5	9.8 ± 2.2	n.s.	27.5 ± 6.4	7.0 ± 1.6	n.s.
LAI	65	3.5 ± 0.4	1.1 ± 0.3	**	3.7 ± 0.3	0.8 ± 0.1	**
	75	3.0 ± 0.3	2.6 ± 0.5	n.s.	2.6 ± 0.5	1.5 ± 0.5	*
	81	3.5 ± 0.7	2.1 ± 0.4	*	4.0 ± 0.6	2.1 ± 0.2	*
Average leaf size [cm²]	65	60.4 ± 5.7	105.3 ± 6.7	**	68.1 ± 10.6	98.8 ± 8.4	*
	75	60.7 ± 6.9	76.2 ± 8.7	*	79.7 ± 16.2	95.0 ± 9.8	n.s.
	81	63.4 ± 3.6	96.8 ± 5.6	**	84.0 ± 10.2	96.9 ± 7.7	n.s.
Canopy volume [m³]	65	35039.0 ± 4414.3	10726.4 ± 2860.0	**	36713.1 ± 3465.7	8288.9 ± 1196.5	**
	75	30205.5 ± 3148.3	25861.5 ± 4969.6	n.s.	26167.3 ± 5174.9	15326.1 ± 5108.7	*
	81	34957.6 ± 6964.7	20611.1 ± 4041.3	*	40488.8 ± 6456.3	20934.6 ± 1851.5	*
Bunch weight [g]	89	76.2 ± 34.8	163.7 ± 33.0	**	101.4 ± 35.7	257.7 ± 83.5	**
Bunch length [cm]	89	8.7 ± 2.6	12.0 ± 1.4	*	10.9 ± 2.3	14.7 ± 2.2	*
Bunch width [cm]	89	6.9 ± 1.7	8.9 ± 1.6	*	6.9 ± 1.7	8.9 ± 1.6	*
Berry number per bunch	89	57.8 ± 23.7	125.1 ± 26.8	**	56.0 ± 20.5	134.1 ± 45.5	**
Ø berry size [mm]	89	12.2 ± 1.0	13.2 ± 1.3	**	12.8 ± 2.0	15.3 ± 1.7	**

only at BBCH 13-71. However, in 2017 (Tab. 2, b), when the leaf wetness only reached a maximum of 29.0 % in spite of intense rainfall, minor differences in the canopy microclimate between the two training systems were noted.

A more detailed look on the canopy microclimate during the course of the day revealed that the relative humidity in the SMPH canopy is up to 20 % points higher compared to VSP after a rain event, while the temperature in the two training systems may differ by up to 3 °C (Fig. 2 b, 2nd d, 12:00 h). Similar results could also be observed during morning dew (Fig. 2a and b, 3rd d, 7:00 h). These observations were made in both trial vineyards, 'Chardonnay' and 'Reberger'.

F u n g a l d i s e a s e s : At the first DM assessment in 2016, when young fruits begin to swell (BBCH 71), 25 % of the VSP and 48 % of the SMPH bunches in the 'Chardonnay' trial field were infected with *P. viticola* (Tab. 3). The mean incidence level for SMPH reached 19.3% and was significantly higher compared to VSP with 2.9 %. At beginning of veraison, 92 % of the SMPH bunches and almost all examined VSP bunches showed DM symptoms. The incidence level was 43.3 % for SMPH and 37.7 % for VSP. No significant differences between the two training system could be observed at the second DM assessment.

Similar results were observed in the 'Reberger' field. In the beginning of the DM infection process, at BBCH 71, 48 % of the SMPH and 28 % of the VSP bunches showed symptoms. With incidence levels of 13.3 % for SMPH and 3.8 % for VSP, a significant difference between the training

Table 2

Local and micro climate during different phenological stages in the trial fields 'Chardonnay' and 'Reberger' as a function of grapevine training system, 2016 (a) and 2017 (b). Except for "total rainfall" all parameters are mean values. Permutation test; $*P < 0.05$, $**P < 0.001$

a)

2016	local climate				Chardonnay			Reberger		
BBCH	Temperature [°C]	total rainfall [mm]	leaf wetness [%]	Microclimate	SMPH	VSP		SMPH	VSP	
13-71	17.4	131.4	49.1	Relative humidity [%]	83.4 ± 17.5	80.5 ± 19.7	**	83.3 ± 16.7	80.0 ± 20.4	**
				Temperature [°C]	18.2 ± 5.3	18.7 ± 5.7	*	17.9 ± 4.8	18.8 ± 6.0	**
71-83	19.8	63.1	28.8	Relative humidity [%]	75.4 ± 19.6	72.7 ± 20.2	*	74.7 ± 74.7	74.3 ± 19.9	n.s.
				Temperature [°C]	20.7 ± 5.8	20.9 ± 5.0	n.s.	20.4 ± 5.5	20.5 ± 5.6	n.s.
83-89	18.3	32.6	44.6	Relative humidity [%]	77.9 ± 18.8	74.8 ± 20.5	**	75.2 ± 21.0	75.4 ± 21.0	n.s.
				Temperature [°C]	18.8 ± 6.1	19.3 ± 5.5	*	19.1 ± 7.0	18.9 ± 6.7	n.s.

b)

2017	local climate				Chardonnay			Reberger		
BBCH	Temperature [°C]	total rainfall [mm]	leaf wetness [%]	Microclimate	SMPH	VSP		SMPH	VSP	
13-71	18.8	74.8	19.7	Relative humidity [%]	69.6 ± 21.1	67.7 ± 22.4	n.s.	68.9 ± 21.4	68.1 ± 20.5	n.s.
				Temperature [°C]	19.6 ± 6.8	20.2 ± 7.2	n.s.	19.5 ± 6.6	20.4 ± 7.3	*
71-83	20.7	65.6	23.0	Relative humidity [%]	73.1 ± 20.4	71.7 ± 20.4	n.s.	72.9 ± 20.1	73.6 ± 19.7	n.s.
				Temperature [°C]	21.3 ± 5.9	21.5 ± 5.9	n.s.	21.1 ± 5.6	21.5 ± 5.9	n.s.
83-89	17.1	145.2	29.0	Relative humidity [%]	78.7 ± 18.1	76.8 ± 18.8	*	77.3 ± 18.3	78.1 ± 17.9	n.s.
				Temperature [°C]	19.0 ± 4.9	19.3 ± 5.2	n.s.	19.1 ± 4.8	19.5 ± 5.1	n.s.

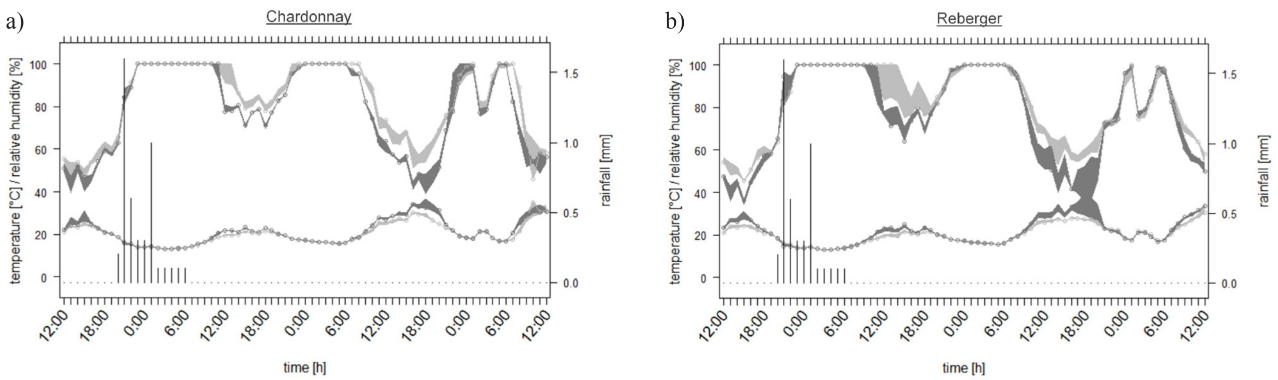

Fig. 2: 72 h recording section of the microclimate data from 20th to 23th of June 2016 in the two trial fields 'Chardonnay' (**a**) and 'Reberger' (**b**) as a function of grapevine training system SMPH (bright) and VSP (dark). Relative humidity is shown in the upper lines, temperature in the lower lines. Black columns represent rainfall [mm].

systems could be noticed at this point of plant development. At BBCH 83 an increase of infection pressure was evident in both experimental panels, which led to disease symptom in 96 % of the sampled SMPH and 100 % of the VSP bunches. In the SMPH panel the mean infection level was 46.5 % and for VSP 45.2 %, resulting in no significant differences between the training systems. The assessment results for DM in 2017 revealed no infection in either of the both experimental fields during the whole season.

In the 'Chardonnay' trial field in 2016 78 % SMPH and 76 % VSP bunches were infected with PM at the beginning of ripening (BBCH 83). The mean incidence level was 22.2 % for SMPH and 25.8 % for VSP. At BBCH stage 85 when the berries started to soften, 97 % of the SMPH bunches and all tested VSP bunches showed symptoms of *E. necator*. Additionally, an increase in the infection level occurred. Both training systems had a similar mean value of about 62.5 %. In the subsequent year 29 % more infected bunches were found in the SMPH panel than in the VSP at BBCH 83. The incidence level was three times higher for infected SMPH bunches compared to the VSP bunches. At the second PM assessment the number of infected bunches was almost equal in both training systems. However, the incidence level was still significantly higher in the SMPH panel.

During the whole season 2016 and 2017 no or only minimal PM symptoms could be observed in the trial field of the grapevine cultivar 'Reberger'. For 2016 no severe Botrytis infection could be noticed in either of the both grapevine cultivars until ripening (BBCH 89). Only 3 % of the SMPH and 5 % of the VSP bunches in the 'Chardonnay' field showed slight symptoms of BR and all examined 'Reberger' bunches were free of BR. In 2017 significant differences between the two training systems regarding BR infection could be noticed, at least in the 'Chardonnay' field.

Table 3

Assessment results for the fungal grapevine diseases Downy Mildew, Powdery Mildew and Botrytis Bunch Rot as a function of grapevine training system, 2016 (a) and 2017 (b). Statistical analysis was done with Fisher's exact test for the incidence rate and Kruskal-Wallis test for the incidence level; *P < 0.05, **P < 0.001

a)			Chardonnay			Reberger		
2016	BBCH	Incidence	SMPH	VSP		SMPH	VSP	
Downy Mildew	71	rate [%]	48	25	**	48	28	**
	71	level [%]	19.3 ± 26.7	2.9 ± 6.4	**	13.3 ± 22.4	3.8 ± 8.2	**
	83	rate [%]	92	99	n.s.	96	100	n.s.
	83	level [%]	43.3 ± 37.6	37.7 ± 27.2	n.s.	46.5 ± 35.8	45.2 ± 33.3	n.s.
Powdery Mildew	83	rate [%]	78	76	n.s.	0	0	n.s.
	83	level [%]	22.2 ± 23.0	25.8 ± 27.7	n.s.	0 ± 0	0 ± 0	n.s.
	85	rate [%]	97	100	n.s.	0	0	n.s.
	85	level [%]	63.3 ± 29.0	62.1 ± 31.4	n.s.	0 ± 0	0 ± 0	n.s.
Botrytis Bunch Rot	89	rate [%]	3	5	n.s.	0	0	n.s.
	89	level [%]	0.2 ± 1.2	0.6 ± 3.0	n.s.	0 ± 0	0 ± 0	n.s.
b)			Chardonnay			Reberger		
2017	BBCH	Incidence	SMPH	VSP		SMPH	VSP	
Downy Mildew	71	rate [%]	0	0	n.s.	0	0	n.s.
	71	level [%]	0 ± 0	0 ± 0	n.s.	0 ± 0	0 ± 0	n.s.
	83	rate [%]	0	0	n.s.	0	0	n.s.
	83	level [%]	0 ± 0	0 ± 0	n.s.	0 ± 0	0 ± 0	n.s.
Powdery Mildew	83	rate [%]	77	48	**	3	2	n.s.
	83	level [%]	18.2 ± 23.0	6.4 ± 12.0	**	0.3 ± 2.1	0.3 ± 2.1	n.s.
	85	rate [%]	98	94	n.s.	0	0	n.s.
	85	level [%]	47.4 ± 27.9	36.5 ± 29.3	*	0 ± 0	0 ± 0	n.s.
Botrytis Bunch Rot	89	rate [%]	11	42	**	6	11	n.s.
	89	level [%]	1.8 ± 8.0	8.7 ± 14.4	**	0.4 ± 1.5	2.6 ± 10.5	n.s.

Here, 42 % of the monitored VSP and 11 % of the SMPH bunches showed BR symptoms. The incidence level was almost five times higher in the VSP panel compared to the SMPH. Also in the 'Reberger' field BR symptoms could be observed, but the incidence rate as well as the incidence level was quite low with no significant differences between both training systems.

Drosophila suzukii: In both seasons the mean number of *D. suzukii* flies was up to two times higher in SMPH compared to VSP trained grapevine (Tab. 4). However, only in 2017 this difference is significant. Despite this striking difference we did not observe a higher number of eggs on intact SMPH grape berries. In both panels the number of detected eggs on grapevine berries was marginal over the two seasons and no differences between the training systems were observed.

Discussion

The aim of this study was to compare two training systems, SMPH and VSP, with regard to canopy architecture, berry skin characteristics, microclimate and the influence of those factors on incidence of common fungal grapevine pathogens as well as the damage caused by the invasive insect pest *Drosophila suzukii* in German viticulture. We found that the large amount of leaves produced by SMPH trained plants create a bigger and denser canopy structure than VSP trained plants, even if the leaves of the latter are larger in size. SMPH bunches showed a looser structure than VSP bunches, due to a smaller architecture, a reduced number of berries and smaller sized fruits. These findings are in line with other studies, which compared the morphology of minimal and intensely pruned grapevines (CLINGELEFFER and POSSINGHAM 1987, SCHMID and SCHULTZ 2000, SOMMER *et al.* 1993, WOLF *et al.* 2003, INTRIERI *et al.* 2011). The analyses of canopy architecture in the different trellis zones demonstrate that the plant vigor in the SMPH system is mainly located in the upper zones (3-5), while in the VSP system it is restricted to the lower zones (1-2), perhaps because of the apical dominance (JACKSON 1996).

These differences in plant morphology between the two training system have a clear effect on the microclimate in the canopy. SMPH canopies dry much slower and need several

Table 4

Number of trapped SWD flies in SMPH and VSP trained 'Reberger' vineyards (mean value, n = 12 traps). Counted *D. suzukii* eggs on 50 randomly selected SMPH and VSP berries with intact skin (mean value, n = 4 runs). Results from 2016 (a) and 2017 (b) are shown. T test; *P < 0.05, **P < 0.001

		SMPH	VSP	
a)	2016	SMPH	VSP	
	mean no. of trapped *D. suzukii* flies	31.3 ± 18.7	20.5 ± 20.2	n.s.
	mean number of eggs per 50 berries	2.3 ± 3.3	0.5 ± 1.0	n.s.
b)	2017	SMPH	VSP	
	mean no. of trapped *D. suzukii* flies	10.3 ± 6.6	4.8 ± 2.6	*
	mean number of eggs per 50 berries	0.8 ± 1.0	1.0 ± 1.2	n.s.

hours longer after rain or morning dew to achieve a similar humidity level as VSP canopies. Local weather increased leaf wetness and lead to a higher relative humidity, but lower temperature in SMPH canopies compared to VSP canopies. This is clearer for 'Chardonnay' than for 'Reberger', probably because of the hillside location of the latter. The dense leaf structure of the SMPH plants prevents sunlight from reaching the inside of the canopy, thus the moisture takes longer to evaporate. Additionally, air movement is reduced, which also impedes the canopy from drying.

Under certain climate conditions with high leaf wetness, as observed in 2016, we found SMPH trained grapevines more susceptible to DM than VSP trained, for 'Chardonnay' and 'Reberger'. However, in the second assessment no significant differences between the two training systems were found. This is probably caused by a considerable decline of SMPH inflorescences/bunches caused by DM, which are not included in the assessment made at BBCH 83. *Plasmopara viticola*, the causal agent of DM, needs an environment rich in moisture for successful infection and spreading (Blaeser and Weltzien 1978, 1979). It is possible that the slower drying of the SMPH canopies provides an extended time frame for *P. viticola* to successfully infect grapevine tissue after rain or morning dew.

SMPH bunches were more sensitive to PM infection than VSP bunches in 'Chardonnay' in 2017. The results of Austin *et al.* (2011) demonstrate that training systems showing a high light penetration in the fruit zone are less susceptible to PM, due to sunlight exposure of the pathogen and improved pesticide deposition. According to this assumption, VSP should be the more robust training system, since the SMPH bunches are more often located within the dense leaf canopy. This was only the case in 2017. In the previous year no differences in PM incidence between the two training systems could be observed. Since the infection pressure of DM and PM reached an extraordinary high level in 2016, the first three plant protection applications in 2017 were performed with conventional pesticides to achieve a profound cleaning effect of the plants against the pathogens. It is possible that the use of these pesticides maintained a better protection shield for VSP trained vines than minimal pruned vines, due to the enhanced accessibility of the VSP bunches.

Because of the *E. necator* resistance gene *Ren3* located in the genome of the grapevine variety 'Reberger' no or very few PM symptoms could be observed during the study of this work (Zendler *et al.* 2017).

In this study, differences between SMPH and VSP regarding their susceptibility against BR could only be noticed in the 'Chardonnay' field in 2017. Bunches from minimal pruned vines with their loose bunch structure were less susceptible to BR compared to the densely packed bunches from cane pruned vines, which tend to burst and open the gates for BR infection, which is in consensus with Ashley *et al.* 2006. Also Emmett *et al.* (1995) reported that the bunch architecture of minimally pruned vines is usually characterized by a smaller and less compact structure, which promotes robustness against BR. However, in 2016 no differences between the training systems could be noted. An explanation for these inconsistent results could be the influence of DM on bunch architecture in 2016. In this year the heavy DM epidemic demolished many berries in the trial fields, creating loose bunch structures in both training systems, SMPH and VSP.

As expected we found significantly more SWD in the SMPH trained than in the VSP trained panels, but the difference was only significant in 2017. SWD prefers shady and humid microhabitats, even within a single plant species (Diepenbrock and Burrack 2017). In this experiment, a high number of captured SWD did not correspond with a high incidence of SWD damage to the grapes. It appears that *D. suzukii* uses the grapevine as a habitat, but does not necessarily use grapes as a substrate for oviposition. Despite their wide host range, grapevine does not seem to be a preferred host for SWD. In laboratory studies only very few eggs were laid on grape berries and those eggs had very slow developmental rates as well as a low survivorship to the adult stage (Bellamy *et al.* 2013, Jarausch *et al.* 2017, Maiguashca *et al.* 2010, Lee *et al.* 2011, Poyet *et al.* 2015). The small numbers of eggs that we could find in both trial years on grape berries confirms that grapevine appears to be a low quality host for SWD. The resistance of fruit skin to penetration has been previously discussed as a factor driving oviposition in SWD (Lee *at al.* 2011, Burrack *et al.* 2013). Ioratti *et al.* (2015) reported that oviposition by *D. suzukii* increases with decreasing penetration force. Since the two training systems did not influence the grape skin characteristics significantly, we cannot directly confirm their results.

In conclusion, SMPH trained grapevines were more susceptible to DM and PM compared to VSP trained vines, possibly due to differences in canopy microclimate. The incidence of BR in contrast was higher for VSP vines showing a more compact bunch architecture. Regarding SWD, a higher activity was noticed in SMPH canopies. However, the number of damaged berries was the same in both training system. Because of the higher susceptibility of SMPH against the two major fungal grapevine diseases a plant protection regime specifically adapted to this new training system should be established. The benefit of fungus resistant cultivars such as 'Reberger' will be particularly high in SMPH vines, enabling winegrowers to combine advantages of SMPH with the economic and environmental benefits of reduced fungicide applications.

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