applied sciences

MDPI

Article

Semi-Minimal-Pruned Hedge (SMPH) as a Climate Change Adaptation Strategy: Impact of Different Yield Regulation Approaches on Vegetative and Generative Development, Maturity Progress and Grape Quality in Riesling

Jan Schäfer [1,*], Matthias Friedel [1], Daniel Molitor [2] and Manfred Stoll [1]

1 Department of General and Organic Viticulture, Hochschule Geisenheim University, Von-Lade-Strasse 1, 65366 Geisenheim, Germany; matthias.friedel@hs-gm.de (M.F.); manfred.stoll@hs-gm.de (M.S.)
2 Environmental Research and Innovation (ERIN) Department, Luxembourg Institute of Science and Technology, LIST, 41, rue du Brill, 4422 Belvaux, Luxembourg; daniel.molitor@list.lu
* Correspondence: jan.schaefer@hs-gm.de; Tel.: +49-6722-502-161

Abstract: The training system Semi-Minimal-Pruned Hedge (SMPH) blends features of traditional Vertical Shoot Positioning-type (VSP) trellising systems with the concept of minimal pruning. While saving labor, this training system results in relatively high crop load and a poor leaf area to fruit weight-ratio (LFR), and thus, needs to be able to ripen grapes in a cool to moderate climate. For these reasons the impact of yield regulation strategies, including (i) shoot thinning (Darwin-Rotor), (ii) biotechnological thinning (Gibberellic acid), and (iii) bunch thinning (harvest machine) were trialed in a three year study at Geisenheim, Germany between 2017 and 2019 using Riesling (*Vitis vinifera* L.). The average yield per vine in SMPH (5.34 ± 1.10 kg) was 61.1% higher with a narrower LFR (14.01 $cm^2\ g^{-1}$), compared with VSP (3.32 ± 1.02 kg, LFR: 16.99 $cm^2\ g^{-1}$). The yield was successfully reduced and LFR simultaneously increased with shoot thinning (−33.1%, LFR: 19.04 $cm^2\ g^{-1}$), biotechnological thinning (−18.3%, LFR: 16.69 $cm^2\ g^{-1}$) and bunch thinning (−37.3%, LFR: 21.49 $cm^2\ g^{-1}$). Ripening was delayed in SMPH. On average, two maturity thresholds (14.1 °Brix and 18.2 °Brix) were achieved 129 GDD (seven days according to the recorded daily mean temperatures, respectively) and 269 GDD (16 days) later in non-thinned SMPH, compared to VSP. All thinning treatments accelerated maturity progress ranging from 27 GDD (two days) to 58 GDD (three days) for 14.1 °Brix and 59 GDD (three days) to 105 GDD (six days) for 18.2 °Brix. Apart from immediate benefits on the economic efficiency, the adaption of the leaf area to fruit weight ratio using SMPH holds high potential to, (i) produce grapes targeting specific wine profiles and/or (ii) reducing the velocity of ripening under conditions of climatic change.

Keywords: SMPH; training systems; climate change; crop thinning; maturity progress; maturity delay; velocity of ripening; primary fruit components

Citation: Schäfer, J.; Friedel, M.; Molitor, D.; Stoll, M. Semi-Minimal-Pruned Hedge (SMPH) as a Climate Change Adaptation Strategy: Impact of Different Yield Regulation Approaches on Vegetative and Generative Development, Maturity Progress and Grape Quality in Riesling. *Appl. Sci.* **2021**, *11*, 3304. https://doi.org/10.3390/app11083304

Received: 5 March 2021
Accepted: 29 March 2021
Published: 7 April 2021

1. Introduction

Modern viticulture is challenged from various sides. On the one hand, labor shortages and a trend towards larger winery sizes create the demand for increased mechanization and automatisation of vineyard and winery tasks. On the other hand, climate change threatens traditional forms of viticulture. A general tendency in German viticulture was reported by Stock et al. [1] and indicates a northbound shift of viticultural areas, as well as an ascent to higher elevations and an acceleration of all phenological phases due to increasing temperatures. Jones et al. [2] predict a global average increase in growing season temperature of 2 °C during the first half of the 21st century with different magnitude for specific wine regions, i.e., a possible shift into another climate maturity type. Changes in average season temperature (Northern Hemisphere: Apr-Oct; Southern Hemisphere: Oct-Apr) show a high variability but seem to be less pronounced in cool climate regions, i.e., Rhine valley showing an average warming of 1.51 °C [2]. Generally, phenological stages, such as bud break, flowering and veraison are projected to occur earlier in the year in European viticulture [3,4]. Duchêne and Schneider [5] report an earlier bud break, which might increase the risk of spring frost damages in grapevines in some regions. Flowering is projected to occur 15 days earlier by mid of the 21st century and 30 days until the end of 21st century in Bordeaux [6]. Moreover, temperature increases have already advanced the onset of ripening since the 1980's and are expected to advance veraison up to 30 days in the future European viticulture (2041–2070) under the predicted conditions of climate change [3]. Duchêne et al. [7] report that future ripening of grapes could occur under higher temperatures due to earlier veraison. An earlier ripening period will expose the ripening grapes to higher temperatures [4], and lead to a higher degree of alcohol, a lower concentration of organic acids, especially malic acid, and to changes in the aroma composition of wines [8]. This may ultimately impact on the typicity of regional wine profiles. The earlier onset of ripening will also lead to an increased pressure of fungal infections by *Botrytis cinerea* or other pathogens during the ripening phase. Optimum temperature for *B. cinerea* infection has been reported at 20.8 °C [9], well-above the temperature prevailing during grape ripening in cool to moderate climates. Several approaches have been proposed to counteract these climate change-related effects. The spraying of buds with oil or the painting of stems with white chalk has been reported to delay bud break [10]. Late pruning [11] and double pruning have been described to delay phenological development and delay ripening [12–14]. Moreover, the application of anti-transpirant agents to the canopy has also been shown to be successful in delaying phenological development and sugar accumulation in the grapes [15]. Boettcher et al. [16] delayed ripening by pre-veraison auxin applications on bunches. The manipulation of leaf area to fruit weight-ratio has been tested at various phenological stages. Whereas, leaf removal, prior to flowering, reduced the yield, and hence, promoted sugar accumulation [17], leaf removal after flowering, and after veraison [18,19], delayed ripening substantially. Another way to modify leaf area to fruit weight-ratio, and thus, delay ripening is through the vine training system. The grapevine training system, known as Semi-Minimal-Pruned Hedge (SMPH) has first been described by Intrieri et al. [20]. Whereas, machine pruned systems, trained to a VSP-type trellis, have been reported much earlier under the name of hedge pruning or box pruning [21]. SMPH is a vine training system, which blends features of traditional VSP-type trellising systems with the concept of minimal pruning. Vines are mechanically pruned in winter to a hedge shape of the trellis system using a normal grapevine hedger saving approximately 60 to 70 labor hours per hectare. Compared to cane pruning, SMPH has a much higher bud load and shoot number per meter of canopy [20]. The yield in SMPH is higher compared to VSP and consists of a higher number of loose bunches with a lower number of berries and a lower berry weight [20]. While, Intrieri et al. [20] found no differences in sugar accumulation between VSP and SMPH, experiments in cool to moderate climates like Germany, Luxembourg or Austria have shown that the onset of ripening, as well as maturity are delayed in SMPH trained grapevines [22]. The fact that ripening is delayed and bunches are less compact in SMPH, compared to VSP, makes the system suitable in counteracting the increased infection pressure by *B. cinerea* and the loss of grape quality due to warm conditions during the ripening phase. While, the system has been well-established in central European viticulture practice, there is a lack of experimentation with this system concerning long-term yield stability and vine capacity overload, potentially leading to a loss of product quality and yield breakdown [22–24].

The aim of this study was to investigate different crop thinning strategies in SMPH training system and the impact on (i) phenological development, (ii) maturity progress, as well as on (iii) long-term yield stability and hence grape quality. Two mechanical and one biotechnological thinning strategies were considered. Moreover, the potential of the training system SMPH to counteract the challenges of climate change were investigated and compared to the widely spread training system VSP. In this context, the central research question was whether SMPH is an adequate strategy in postponing the harvest date, while maintaining fruit quality and wine profile under changing climatic conditions.

2. Materials and Methods

2.1. Experimental Vineyard Design and Thinning Treatments

All experiments were performed with Riesling (*Vitis vinifera* L.) grafted on SO4 rootstock in a vineyard site located at the Rheingau region (Germany: 49°59′30.8″ N, 7°56′54.1″ E) and managed by Hochschule Geisenheim University (HGU) between 2017 and 2019. The vineyard was planted in 1998 with an inter and intra row distance of 2 m × 1.2 m (vine density: 4167 vines/ha) and a row azimuth of 160°. Conversion to Semi-Minimal-Pruned Hedge training system was conducted in 2012. Three different thinning treatments were investigated considering two mechanical and one biotechnological thinning strategy. Mechanical shoot thinning was applied using the Darwin-Rotor (SMPH ST; Fruit Tec Maschinenbau, Markdorf, Germany) with horizontally rotating strings. Additionally, a second mechanical thinning strategy, which pursued bunch thinning, was performed with a harvest machine (SMPH BT; Grapeliner SF200, ERO, Niederkumbd, Germany) at berry pea size (E-L number 31; [25]). As biotechnological thinning strategy, the plant growth regulator Gibberellic acid (SMPH GA; Gibb 3, Plantan GmbH Buchholz i. d. Nordheide, Germany) was applied at a concentration of 50 ppm during flowering (E-L number 21). The treatments were established in three replicates, each represented by one row (field repetition). All three thinning treatments were compared to standard practice in VSP and a SMPH non-thinned control. Thinning treatments and annual adjustments are presented in Table 1.

Table 1. Mechanical and biotechnological thinning treatments and corresponding thinning adjustments for cv. Riesling in SMPH between the years 2017 and 2019.

	Mechanical				Biotechnological		
Parameters	Darwin-Rotor	Harvest machine			Gibberellic acid		
Treatment abbreviations	SMPH ST	SMPH BT			SMPH GA		
Thinning target (organ)	Shoots	Bunches			Inflorescences/Blossom		
Time	2–3 leaves separated	Pea size stage of fruit development			Flowering, 30% caps off		
Phenological stage (E-L number)	9	31			21		
Thinning target (intensity)	40–50%	40–50%			50 ppm		
Application	East side of canopy	Both sides of canopy			Both sides of canopy		
Adjustments	2017–2019	2017	2018	2019	2017	2018	2019
Hydraulic oil [L]	20		-			-	
Mechanical thinning frequency [beats min^{-1}]	-	380	355	365		-	
Velocity [km h^{-1}]	4		3			4	

2.2. Phenological Monitoring and Assessment of Phenological Progress Curves

Phenological development was monitored bi-weekly using the modified E-L system of Coombe [25] until pre-veraison (E-L number: 33). Fifty-one organs per field replicate were considered for the determination of the E-L number. Phenological progress was modelled by curve fitting of sigmoidal function type $f(a,b,w,x)$: $y = a/(1 + e^{-((x-w)/b)})$ according to Molitor et al. [22] to empiric data of phenological monitoring. Whereas, y represents the E-L number, a is the maximum of the curve, x indicates the growing degree day, w is the inflection point and b describes the slope factor of the curve in the inflection point. The cumulative growing degree days (GDD) were calculated according to Parker et al. [26] with a base temperature of 0 °C starting on 1st of March. Phenological differences in days were obtained by determining the day of the year (DOY) for each treatment in the seasons respectively at which calculated GDD for reaching full bloom (E-L number: 23) and pre-veraison (E-L number: 33) were reached.

2.3. Vegetative and Generative Parameters

The vegetative and generative parameters were assessed during growing season 2018 and 2019.

2.3.1. Number of Shoots, Shoot Length, Shoot Diameter and Leaf Area per Shoot

Shoot number was counted for one linear meter of canopy per field replicate. Shoot length was analyzed on twelve randomly sampled shoots post trimming. Diameter was measured with a caliper above the first node. For the evaluation of leaf area per shoot, twelve shoots were randomly sampled from both sides of the canopy. Leaf area was measured in the laboratory using a leaf area meter (LI-3100C Area Meter, LI-COR® Inc., Nebraska, NE, USA).

2.3.2. Number of Nodes, Budburst Rate and Inflorescences per Shoot

The number of nodes were counted on one-year old canes for one meter of linear canopy per field replicate. Count inflorescences per shoot was obtained by the quotient of inflorescences per meter and shoots per linear meter of canopy prior to flowering. Budburst rate was calculated from the quotient of shoots and nodes per linear meter.

2.4. Leaf Area and Leaf Area to Fruit Weight-Ratio

An indirect measure of leaf area (LA) was determined by non-destructive measurements of the leaf area index (LAI) using the LAI-2200 Plant Canopy Analyzer (PCA; LAI-2200, LI-COR® Inc., Nebraska, NE, USA). Measurements were conducted frequently during growing season between 2017 and 2019. The LAI of three transects per treatment was measured using protocol SFC (sensor facing the canopy with eight B-readings). Readings were recorded along a diagonal transect including eight vines on each side at sunset. A physical cap was used to limit the azimuthal field-of-view to 45°. The conversion of LAI to LA per meter canopy was conducted using the empirical calibration equation ($y = 1.1684x - 0.1809$) according to Doering et al. [27] for same canopy architecture. For the determination of leaf area to fruit weight-ratio (LFR) LA per meter canopy was obtained at beginning of August. Fruit weight per vine was determined at harvest and converted into fruit weight per linear meter canopy. Due to sour rot infections in 2017, LFR was assessed by gravimetric analysis of manual harvested bunches and leaves (without petioles) of three linear meter of canopy for each treatment. Leaf area per gram leaves was calculated by the quotient of measured LA (LI-3100C Area Meter, LI-COR® Inc., Nebraska, NE, USA) and leaf weight of approximately 10% sampled leaves. Finally, the leaf area per meter was extrapolated with leaf area per gram leaves and total weight of leaves per meter.

2.5. Assessment of Maturity Progress

Maturity monitoring was conducted bi-weekly on a 100-berry sample taken from all field replicates randomly from both sides of the canopy starting at veraison until harvest. Berries were crushed and pressed for five minutes at one bar with a sample press (Longarone 85, Tafec, Norderstedt, Germany). The juice was clarified by centrifugation (5430R, Eppendorf, Hamburg, Germany) for 5 min at 7830 rpm and analyzed by FT-MIR spectroscopy. Maturity progress was modelled by curve fitting of sigmoidal function type $f(a,b,x,w)$: $y = a/(1 + e^{-((x-w)/b)})$ according to Molitor et al. [22] to empiric data of maturity monitoring. Whereas, y represents °Brix, a is the maximum of the curve, x indicates the growing degree day, w is the inflection point and b describes the slope factor of the curve in the inflection point. The cumulative growing degree days (GDD) were calculated according to Parker et al. [26] with a base temperature of 0 °C starting on 1st of March. Differences in maturity progress between the treatments were determined by the differences in calculated GDD for reaching the legal threshold of °Brix for quality categories of quality wine of origin (Riesling: 14.1 °Brix) and cabinet wine (Riesling: 18.2 °Brix) in the Rheingau wine region, Germany, respectively. Maturity differences in days were obtained by determining the day of the year (DOY) for each treatment in the season respectively at which GDD for corresponding brix thresholds were achieved. The concentration of primary amino-acids was determined according to the N-OPA procedure of Dukes and Butzke [28].

2.6. Bunch Architecture

Six bunches per field replicate were randomly sampled from both sides of the canopy prior to harvest. Bunch weight, rachis weight and total berry weight (manually removal from rachis) was determined by weighing with precision scale (2100 G LCD, Satorius). Single berry weight was calculated by total berry weight per bunch divided by number of berries per bunch. Rachis to bunch weight-ratio was determined to describe bunch compactness.

2.7. Botrytis cinerea Monitoring

Monitoring for *B. cinerea* severity and incidence was conducted during ripening period in 2017, and prior to harvest in 2017 and 2019. No data could be obtained in 2018 due to missing disease infections. For each field replicate, 100 bunches from both sides of the canopy were observed randomly. Data was recorded in percent using the European Plant Protection Organization (EPPO) guideline PP1/17, which classifies visually observed disease severities in seven classes (0%, 1–5%, 6–10%, 11–25%, 26–50%, 51–75%, 76–100%).

2.8. Quantification of Yield and Analytical Parameters

Harvest was conducted by harvest machine in all treatments. In 2017, selective manual harvest had to be conducted in VSP, due to sour rot infection. Yield was determined without rachis weight. Harvest dates were scheduled by technical maturity and grape sanitary status. Grapes were harvested in bins and quantified for each field replicate and treatment separately by weighing. Yield per vine was calculated by dividing the total yield by the number of vines of each field replicate. Yield per hectare was than extrapolated considering the planting density. Grape juice was clarified by centrifugation (5430R, Eppendorf, Hamburg, Germany) for 5 min. at 7830 rpm and analyzed by FT-MIR spectroscopy.

2.9. Statistical Analysis and Data Visualization

Statistical analysis and data visualization were conducted with open source software R and JASP. Assumption checks for data normal distribution of residuals was evaluated with Shapiro-Wilk Test. Homogeneity of variances was tested according to Levene's Test (center = median). In case of normal distribution and homogeneity of variances a two-factorial (treatment and vintage) ANOVA was applied followed by Tukey HSD test ($\alpha = 0.05$) for pairwise comparisons. Non-parametric Kruskal-Wallis Test was applied for one-factorial and Scheirer Ray Hare-Test for two-factorial analysis to data that were not normally distributed and/or homogenous. Statistically significant differences between the treatments were evaluated with Dunn's pairwise comparisons using R package FSA [29]. For correlations between empiric data and calculated data of phenology and maturity progress, Pearson's coefficient of correlation was determined. Principal component analysis (PCA) was done with R package stats and princomp function on autoscaled data. Percentage data of *B. cinerea* evaluation was subjected to arcsine transformation prior to statistical analysis. Budburst rate was evaluated with a generalized linear model and poisson regression.

3. Results

3.1. Vegetative and Generative Parameters

The SMPH training system was generally characterized by higher nodes and shoot number, but shorter shoot length, as well as less inflorescences and lower leaf area per shoot compared to VSP (Table 2). The average number of nodes was 20 times higher in SMPH resulting in 10 times higher number of shoots per meter, due to a significantly lower bud burst-rate compared to VSP (Table 2). Due to the high number of shoots per meter of canopy in SMPH, the average shoot length was only a quarter, compared to VSP trained vines with 36% lower shoot diameter, 87% lower leaf area per shoot and one third as much inflorescences per meter canopy. Across three seasons average number of shoots per meter were reduced by 31.8% by means of shoot thinning resulting in an increase in shoot length (+35%), leaf area per shoot (+50%), and thus, leaf area to fruit weight-ratio. Although all thinning treatments did not significantly affect shoot length, leaf area per shoot and number of inflorescences, increasing values referred to the non-thinned SMPH were observed (Table 2). Given the higher shoot number in SMPH, average leaf area per meter of canopy before trimming was 1.6 to 2.0 times higher compared to VSP (Table 2). Growth was enhanced by Gibberellic acid and bunch thinning treatments due to a lower crop load in subsequent vintages, compared to SMPH, resulting in a higher leaf area (LA) during the growing period of 2018 and 2019 (Figure S1). The average LA was 78.4% higher in SMPH, 83.2% in SMPH GA, 100.6% in SMPH BT and 58.1% in SMPH ST compared to VSP (Table 2). The effect of trimming on LA was higher for SMPH training system. Average LA reduction ranged from −30.2% (±4.1) for SMPH ST, −33.2% (±1.8) for SMPH, −37.2% (±5.7) for SMPH GA and −38.0% (±3.2) for SMPH BT, while LA in VSP was reduced by 13.7% (±6.2) in VSP. Trimming minimized the discrepancy in LA between the two training systems. The average LA in SMPH after trimming was only 1.3 to 1.4 times higher than in VSP (Table 2).

Table 2. Mean values and standard deviation (±SD) of vegetative and generative parameters of cv. Riesling trained in VSP and SMPH training system with shoot thinning (SMPH ST), biotechnological thinning (SMPH GA) and bunch thinning (SMPH BT) across the years 2017–2019. Different letters between the treatments indicate significant differences.

	Treatment					*p*-Values		
Parameter	**VSP**	**SMPH**	**SMPH GA**	**SMPH BT**	**SMPH ST**	**Vintage**	**Treatment**	**Vintage * Treatment**
Nodes per meter	17.65 **b** ± 2.57	360.61 **a** ± 75.76	399.89 **a** ± 102.52	374.83 **a** ± 87.15	350.72 **a** ± 89.93	***p* < 0.001**	***p* < 0.001**	***p* = 0.007**
Shoots per meter	17.98 **c** ± 2.76	181.17 **a** ± 13.81	177.11 **a** ± 23.70	182.50 **a** ± 31.09	123.56 **b** ± 14.49	***p* < 0.001**	***p* < 0.001**	***p* < 0.001**
Shoot length [cm]	137.90 **a** ± 7.05	32.81 **b** ± 9.93	36.26 **b** ± 7.49	38.02 **b** ± 10.27	44.31 **b** ± 7.02	***p* = 0.335**	***p* < 0.001**	***p* = 0.796**
Inflorescences per shoot	1.89 **a** ± 0.53	0.59 **b** ± 0.12	0.52 **b** ± 0.13	0.65 **b** ± 0.19	0.75 **b** ± 0.18	***p* = 0.351**	***p* = 0.002**	***p* = 0.405**
Inflorescences per meter	32.78 **b** ± 3.61	109.17 **a** ± 25.50	98.94 **a** ± 30.68	120.06 **a** ± 25.94	94.17 **a** ± 31.40	***p* = 0.997**	***p* < 0.001**	***p* = 0.668**
Bud burst rate [%]	101.91 **a** ± 7.03	51.30 **bc** ± 14.92	44.29 **c** ± 13.86	48.69 **b** ± 17.46	64.14 **b** ± 9.71	***p* = 0.348**	***p* < 0.001**	***p* < 0.001**
Leaf area per shoot [cm^2]	4284.31 **a** ± 389.94	548.31 **b** ± 110.94	554.63 **b** ± 171.34	642.91 **b** ± 137.13	824.83 **b** ± 321.03	***p* = 0.728**	***p* < 0.001**	***p* = 0.097**
LA/m canopy [m^2] before trimming	4.89 **c** ± 0.60	8.72 **ab** ± 1.61	8.96 **ab** ± 1.43	9.81 **a** ± 1.10	7.73 **b** ± 1.28	***p* < 0.001**	***p* < 0.001**	***p* = 0.570**
LA/m canopy [m^2] after trimming	4.22 **c** ± 0.30	5.83 **ab** ± 0.85	5.63 **ab** ± 0.50	6.08 **a** ± 0.54	5.39 **b** ± 0.65	***p* < 0.001**	***p* < 0.001**	***p* = 0.545**
Leaf area to fruit weight-ratio [cm^2 g^{-1}]	16.99 **bc** ± 4.82	14.01 **c** ± 3.35	16.69 **bc** ± 6.48	21.49 **a** ± 4.24	19.04 **ab** ± 3.76	***p* < 0.001**	***p* < 0.001**	***p* = 0.003**

3.2. Leaf Area to Fruit Weight-Ratio

A narrower leaf area to fruit weight-ratio (LFR) was observed in 2017 and 2019 for SMPH compared to VSP (Figure S2). Although, statistically significant differences were not detected between the two training systems. All thinning treatments led to a wider LFR compared to SMPH with exception of SMPH GA in 2017 (Figure S2). These observations were significant in 2018 for bunch thinning treatment ($p = 0.002$). Across three vintages, both mechanical thinning strategies showed a significant wider LFR referred to SMPH. Moreover, a significant higher LFR was achieved with SMPH BT, compared to VSP (Table 2). Biotechnological thinning with Gibberellic acid did not significantly affect LFR.

3.3. Phenology

Full bloom occurred after 1197 GDD (DOY 159) and pre-veraison (E-L number 33) was reached after 2112 GDD (DOY 203) on average between 2017 and 2019 in VSP training system (Table S1). SMPH showed a delay of 41 GDD (2 days) for reaching full bloom and 93 GDD (4 days) pre-veraison. In both mechanical thinning treatments full bloom occurred earlier than in SMPH. The delay to VSP decreased to 28 GDD (1 day) with bunch thinning and 32 GDD (1 day) with shoot thinning. Pre-veraison, a delay of 35 GDD (2 days) was determined with biotechnological thinning compared to the non-thinned SMPH. Pre-veraison was calculated the earliest of all SMPH treatments with SMPH ST (2193 GDD) and the delay to VSP was reduced to 81 GDD (4 days). Mechanical bunch thinning slowed down phenological development resulting in a delay about 139 GDD (6 days) at pre-veraison. The results of GDD and DOY are presented for full bloom and pre-veraison (Table S1).

3.4. Maturity Progress

VSP showed a faster velocity of ripening compared to all SMPH treatments (Figure 1) resulting in a higher brix value at a given GDD. Through all thinning treatments, maturity progress was accelerated and the delay in ripening reduced.

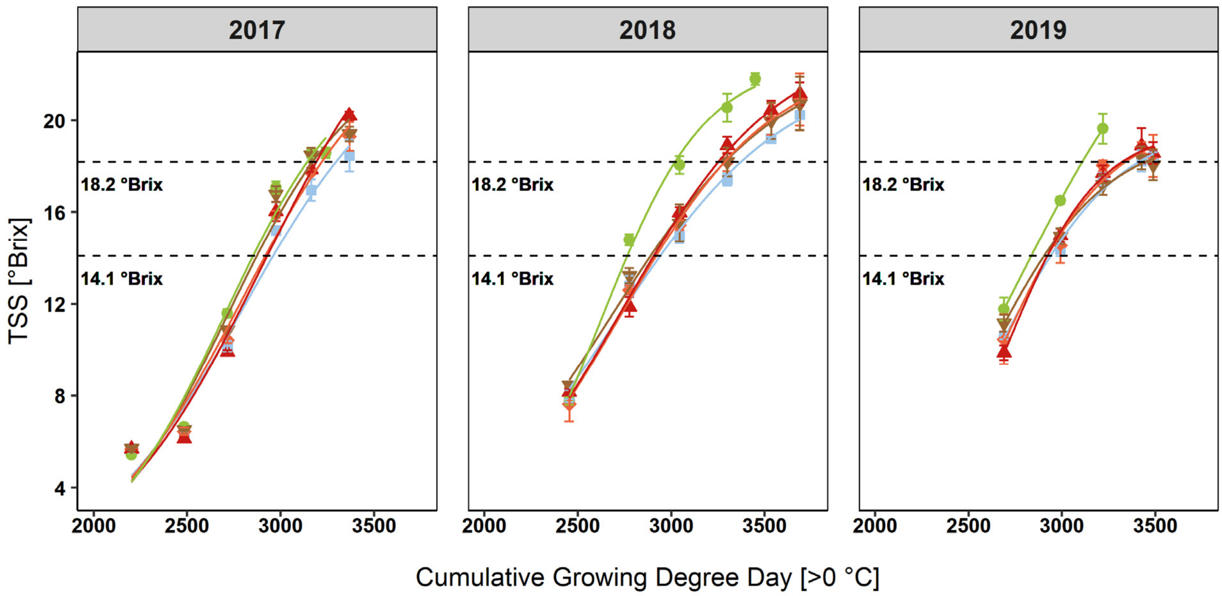

Figure 1. Maturity progress and thresholds of two German wine categories (14.1 °Brix and 18.2 °Brix): Total soluble solids (TSS) plotted against cumulative growing degree days in Vertical Shoot Positioning (VSP ●) and Semi-Minimal-Pruned Hedge (SMPH) training system with non-thinned control (SMPH ■), shoot thinning (SMPH ST ▼), biotechnological thinning (SMPH GA ♦) and bunch thinning using a harvester (SMPH BT ▲) of cv. Riesling between 2017 and 2019. Shapes indicate empirical observed data, lines represent calculated progress according to sigmoidal equation type $y = a/(1 + e^{-((x-w)/b)})$. Error bars are representing ±SD.

On average VSP required 2818 GDD (DOY 236) reaching the legal threshold of TSS (Riesling: 14.1 °Brix) for the category of quality wine of origin at Rheingau valley (Table S2). For the SMPH, a delay of 129 GDD (7 days) was determined. Whereas, thinning accelerated maturity progress. Across three vintages the delay to VSP was reduced to 71 GDD (3 days) by shoot thinning, 101 GDD (5 days) by bunch thinning and 102 (5 days) by biotechnological thinning. Reducing yield caused an earlier ripening (14.1 °Brix) in SMPH ST (58 GDD; 3 days), SMPH BT (28 GDD; 2 days) and SMPH GA (27 GDD; 2 days) compared to non-thinned SMPH.

The threshold of TSS for the category of cabinet wine quality (Riesling: 18.2 °Brix) was reached on average 269 GDD (16 days) later in SMPH (3358 GDD; DOY 268) compared to VSP (3089 GDD; DOY 251) (Table S2). Across three vintages, the delay to VSP was reduced to 164 GDD (10 days) by bunch thinning, 191 GDD (12 days) by biotechnological thinning and 210 GDD (13 days) using shoot thinning. Compared to the non-thinned SMPH 18.2 °Brix was reached earlier in SMPH BT (105 GDD; 6 days), SMPH GA (78 GDD; 4 days) and SMPH ST (59 GDD; 3 days).

GDD and DOY for both wine categories (14.1 °Brix and 18.2 °Brix) and all treatments as well as years respectively are presented in Table S2.

3.4.1. Maturity at Harvest of VSP

Since maturity was reached earlier in VSP, ripening parameters were recorded for all treatments shortly prior to harvest of VSP. At this time values of TSS, reducing sugar and extract were significantly lower in SMPH than in VSP (Table S3). All means of thinning increased TSS, reducing sugars and extract significantly, but concentrations were still significantly lower compared to values of VSP. Compared to VSP, mean value of reducing sugar across three seasons was 14.5% lower in SMPH, while thinning increased sugar concentration about 4.8% in SMPH ST, 5.7% in SMPH GA and 6.6% in SMPH BT, compared to SMPH. No significant difference in total acidity (TA) was determined between all SMPH treatments and VSP, but on average, higher values were observed for SMPH and SMPH GA. While, SMPH BT and SMPH ST showed lower mean values compared to VSP. TA was significantly decreased by bunch and shoot thinning (−7.2% and −7.5%) compared to SMPH. A significant difference between the two training systems was detected for tartaric acid, with 10% higher values in SMPH, 7% in SMPH BT and 5% in SMPH GA. Compared to VSP, lower values of malic acid were determined for SMPH GA (−2.5%), SMPH (−3.8%), SMPH ST (−10.4%) and SMPH BT (−14.6%). These observations were significant for SMPH BT and SMPH ST while SMPH GA did not significantly differ, compared to VSP. N-OPA concentration was significantly lower to VSP in all SMPH treatments except for bunch thinning.

3.4.2. Maturity at Harvest of VSP and SMPH

As harvest occurred later in SMPH training system, maturity parameters were analyzed right before harvest on a hundred-berry sample for each training system separately. Berry composition of SMPH treatments was analyzed 9 days (2017), 19 days (2018) and 20 days (2019) later than in VSP training system. Across three seasons significantly lower values for reducing sugars (−5.6%), extract (−5.3%) and °Brix (−4.9%) was detected in SMPH, compared to VSP. All three thinning treatments increased respective values to a level of VSP (Table S4). Bunch thinning increased sugar concentration (+6%), followed by biotechnological thinning (+3.2%) and shoot thinning (+2.3%). Compared to VSP, higher values of tartaric acid (+4.6%) and significantly lower values of malic acid (−23.1%) were determined for SMPH, resulting in a significantly lower total acidity (TA). Compared to SMPH, the thinning treatments SMPH GA and SMPH ST showed lower values for malic and tartaric acid and hence lower values for TA across three seasons. SMPH BT decreased malic acid by 18% compared to SMPH and 37% compared to VSP resulting in a significantly lower total acidity. By extending the ripening period in SMPH training system, pH-value did not differ and thinning showed no impact. On average across three seasons, no significant difference in N-OPA concentration was detected between all treatments right before harvest. However, a higher assimilable nitrogen concentration (+12% N-OPA referred to VSP and SMPH) was observed with bunch thinning.

3.5. Bunch Architecture and Botrytis cinerea Susceptibility

3.5.1. Bunch Architecture

VSP was related to higher values for rachis weight, single berry weight and more berries per bunch, and hence, higher bunch weights, compared to SMPH training system (Figure 2). Shoot thinning increased bunch weight, while bunch thinning showed the opposite effect. Gibberellic acid and bunch thinning treatments were characterized by a higher rachis to bunch weight-ratio with smaller single berry weights, and thus, a looser bunch architecture was obtained. Whereas, shoot thinning resulted in a more compact bunch architecture.

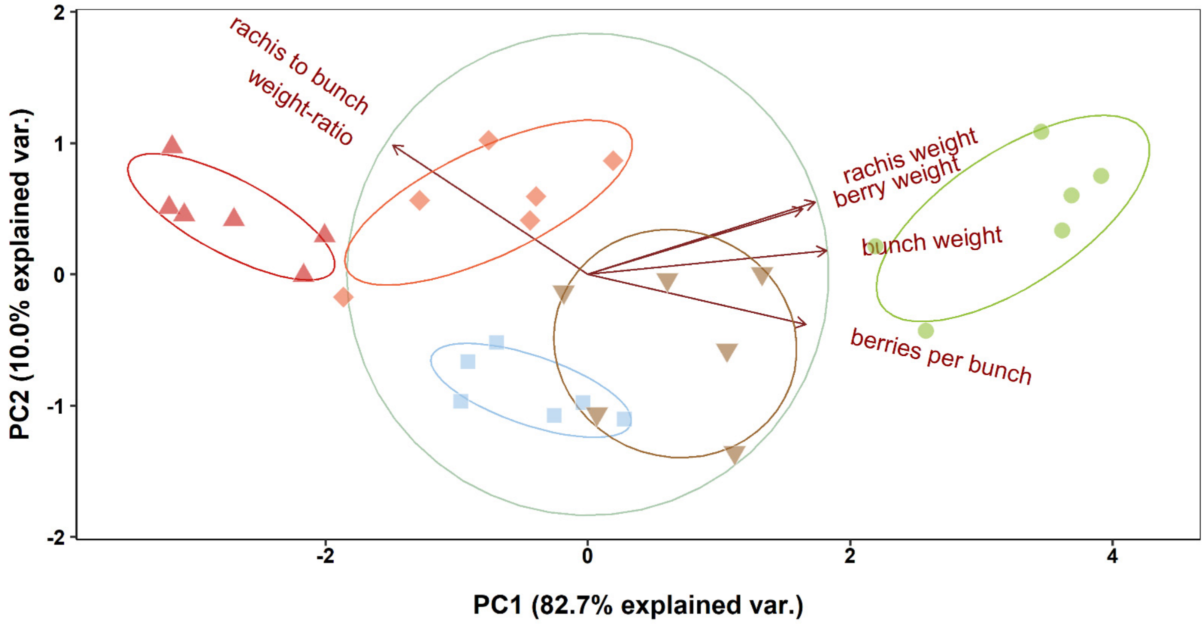

Figure 2. PCA-Biplot of bunch architecture for cv. Riesling trained in Vertical Shoot Positioning (VSP •) and Semi-Minimal-Pruned Hedge (SMPH) with non-thinned control (SMPH ■), shoot thinning (SMPH ST ▼), biotechnological thinning (SMPH GA ♦) and bunch thinning using a harvester (SMPH BT ▲). Length and distance of arrows within correlation circle represent correlation to principle components and between variables respectively. Data was recorded prior to harvest in 2018 and 2019.

On average, a 35.1% lower single berry weight was recorded for SMPH, compared to VSP. Berry weight increased about 10% by means of shoot and biotechnological thinning and decreased about 27.4% with bunch thinning compared to SMPH. A significantly lower rachis weight was detected for all SMPH treatments compared to VSP ($p < 0.001$). Across two seasons rachis weight in SMPH was significantly lower (−51.4%), compared to VSP. Through shoot thinning rachis weight significantly increased by 35.6%, compared to SMPH. An increased rachis weight was observed in SMPH GA (+23.5%) while rachis weight decreased in SMPH BT (−18.4%), but not significantly. On average, 30.2% less berries per bunch were recorded for SMPH compared to VSP. Berries per bunch decreased in SMPH GA (−13.5%) and SMPH BT (−27.5%), but increased with SMPH ST (22%) referred to SMPH. Compared to VSP a significant lower bunch weight was detected for all SMPH treatments ($p < 0.001$). Average bunch weight in SMPH was significantly lower (−54.3%) compared to VSP. In terms of SMPH BT, bunch weight significantly decreased about 44.1% and increased about 33.4% with SMPH ST compared to SMPH. SMPH GA and SMPH BT increased rachis to bunch weight-ratio by 26.0% (6.25%, ±0.41) and 45.9% (7.23%, ±0.39) respectively compared to SMPH and 33.83%, to 54.89%, respectively compared to VSP ($p < 0.001$). To validate the rachis to bunch weight-ratio as a parameter for bunch compactness, the coefficient for determination of rachis to bunch weight-ratio and *B. cinerea* infections in SMPH training system was determined in 2019 with $R^2 = 0.67$ for severity and $R^2 = 0.86$ for incidence (n = 12).

3.5.2. *Botrytis cinerea* Susceptibility during Ripening

In 2017, an incidence for *B. cinerea* of 92.0% with a severity of 18.5% was detected for VSP at harvest (Figure 3). At the same time SMPH training system showed a 24.0% lower incidence with 6.6% lower severity. By means of thinning using Gibberellic acid *B. cinerea* incidence and severity decreased about 19.0%, and 7.6%, respectively, compared to the non-thinned SMPH. Similar values for susceptibility could be observed for bunch thinning. The incidence of *B. cinerea* increased by 9.5% and severity by 6.4% in SMPH ST compared to SMPH. At the time of *B. cinerea* evaluation maturity was advanced in VSP (18.58 °Brix, ±0.21) and SMPH ST (18.49 °Brix, ±0.31). Whereas, maturity was delayed in SMPH BT (17.85 °Brix, ±0.08), SMPH GA (17.75 °Brix, ±0.11) and SMPH (16.96 °Brix, ±0.47).

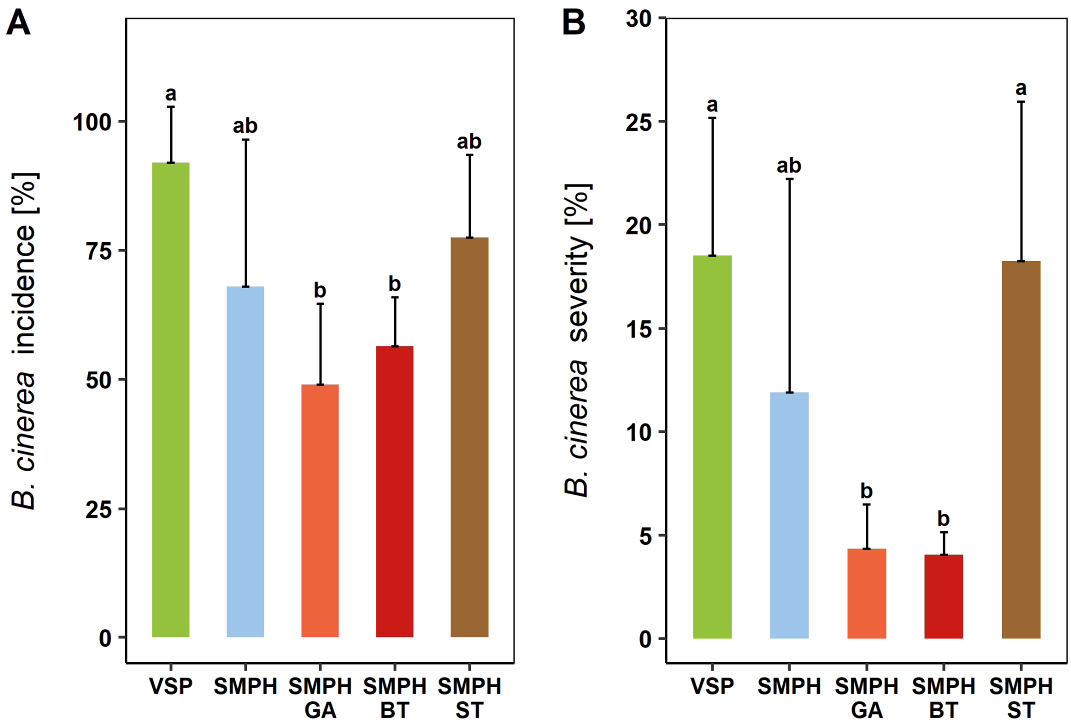

Figure 3. Mean values of incidence (**A**) and severity (**B**) of *Botrytis cinerea* infections [%] for cv. Riesling trained in Vertical Shoot Positioning (VSP ■) and Semi-Minimal-Pruned Hedge (SMPH) with non-thinned control (SMPH ■), shoot thinning (SMPH ST ■), biotechnological thinning (SMPH GA ■) and bunch thinning using a harvester (SMPH BT ■) during ripening progress on 22nd of September in 2017. Different letters indicate statistically significant differences between the treatments with $p = 0.017$ for incidence and $p = 0.008$ for severity. Error bars are representing ±SD.

3.5.3. *Botrytis cinerea* Incidence and Severity at Harvest

As harvest in SMPH training system occurred later than in VSP, *B. cinerea* infections were assessed 13 days later in 2017 and 21 days later in 2019. Generally, high *B. cinerea* infections occurred in 2017. At the postponed harvest date, incidence was higher in SMPH training system than in VSP. In SMPH BT incidence was significantly reduced, but did not show the differences with VSP at a postponed harvest date of three weeks in 2019 (Figure 4A). On average, no significant differences in incidence were detected between all SMPH treatments and VSP at harvest except for SMPH ST ($p = 0.005$). Shoot thinning had a 21.5% higher incidence compared to VSP and 3.6% compared to SMPH. *B. cinerea* incidence decreased about 2.5% in SMPH GA and 12.5% using SMPH BT.

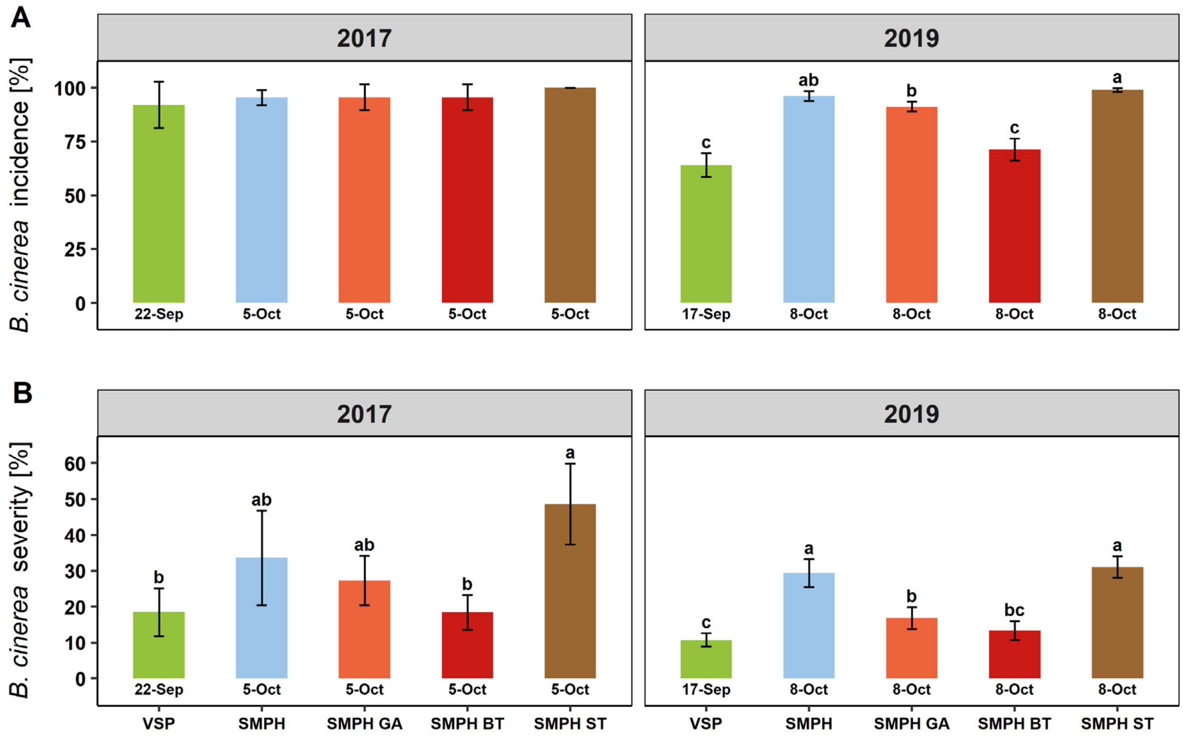

Figure 4. Mean values of incidence (**A**) and severity (**B**) of *Botrytis cinerea* infections [%] for cv. Riesling trained in Vertical Shoot Positioning (VSP ■) and Semi-Minimal-Pruned Hedge (SMPH) with non-thinned control (SMPH ■), shoot thinning (SMPH ST ■), biotechnological thinning (SMPH GA ■) and bunch thinning using a harvester (SMPH BT ■) at harvest in season 2017 and 2019. Evaluation for SMPH was conducted 13 days later than for VSP in 2017 and 21 days later in 2019. Different letters within vintages indicate statistically significant differences between the treatments. Incidence: 2017: p = 0.146, 2019: $p < 0.001$. Severity: 2017: p = 0.002, 2019: $p < 0.001$. Error bars are representing ±SD.

At the later harvest date, *B. cinerea* severity was higher in SMPH training system compared to VSP in 2017 and 2019. SMPH BT and SMPH GA decreased severity in both years. Whereas, SMPH ST increased severity (Figure 4B). Average severity was significantly higher in SMPH and SMPH ST compared to VSP at the postponed harvest dates across 2017 and 2019. SMPH GA and SMPH BT did not differ significantly from VSP. *B. cinerea* severity decreased by 9.4% using SMPH GA and 15.6% in SMPH BT whereas SMPH ST increased severity by 8.4%, compared to SMPH. Significant differences to SMPH were determined for SMPH BT ($p < 0.001$).

3.6. Crop Level, Thinning Performance and Grape Juice Composition

3.6.1. Crop Level

Across three years, VSP training system had the lowest yield of all treatments. On average, crop load in SMPH was about 61% higher compared to VSP (Table 3). Compared to SMPH, in SMPH ST, SMPH GA and SMPH BT yield was reduced by 33.1%, 18.3% and 37.3% respectively. Best thinning performance was observed for SMPH ST and SMPH BT between 2017 and 2019. On average, both treatments reduced yield to a crop load level of VSP. As crop level did alternate annually (alternate bearing), interaction effects in vintage and treatment occurred for almost all grape juice parameters. Effect of alternate bearing was examined by coefficient of variation between 2017 and 2019, which was highest for SMPH GA (37%), SMPH ST (36%) and VSP (34%). Lowest coefficient of variation was calculated for SMPH and SMPH BT (22%) and hence showed less alternate bearing (Table S5).

Table 3. Mean values and standard deviation (SD) of cv. Riesling grape juice parameters in VSP and SMPH training system with different thinning treatments across the years 2017–2019 (±SD). Different letters between the treatments indicate significant differences.

	Treatment					*p*-Values		
Parameter	**VSP**	**SMPH**	**SMPH GA**	**SMPH BT**	**SMPH ST**	**Vintage**	**Treatment**	**Vintage * Treatment**
Yield [t ha^{-1}]	13.82 **c** ± 4.25	22.27 **a** ± 4.60	18.19 **b** ± 6.24	13.96 **c** ± 2.80	14.89 **c** ± 5.22	***p* < 0.001**	***p* < 0.001**	***p* < 0.001**
Yield per vine [kg]	3.32 **c** ± 1.02	5.34 **a** ± 1.10	4.37 **b** ± 1.50	3.35 **c** ± 0.67	3.57 **c** ± 1.25	***p* < 0.001**	***p* < 0.001**	***p* < 0.001**
Total soluble solids [°Brix]	21.56 ± 1.33	20.48 ± 0.81	21.02 ± 0.55	21.57 ± 1.05	21.16 ± 1.32	***p* = 0.001**	***p* = 0.295**	***p* = 0.011**
Reducing sugars [g L^{-1}]	210.31 ± 15.72	198.02 ± 8.57	204.44 ± 5.99	210.86 ± 11.61	206.06 ± 14.97	***p* = 0.002**	***p* = 0.263**	***p* = 0.008**
Extract [g L^{-1}]	234.23 ± 15.38	221.76 ± 9.43	227.98 ± 6.30	234.37 ± 12.11	229.59 ± 15.25	***p* = 0.001**	***p* = 0.295**	***p* = 0.011**
Total acidity [g L^{-1}]	12.43 ± 3.55	10.53 ± 2.53	10.64 ± 2.99	9.68 ± 2.75	10.27 ± 2.92	***p* < 0.001**	***p* = 0.491**	***p* = 0.999**
Tartaric acid [g L^{-1}]	6.49 **a** ± 1.94	6.11 **b** ± 1.13	5.85 **c** ± 1.28	5.78 **c** ± 1.04	5.98 **bc** ± 1.18	***p* < 0.001**	***p* < 0.001**	***p* < 0.001**
Malic acid [g L^{-1}]	6.38 ± 2.30	5.02 ± 2.08	5.33 ± 2.19	4.61 ± 2.03	4.99 ± 2.22	***p* < 0.001**	***p* = 0.298**	***p* = 0.9996**
Tartaric to Malic ratio	1.09 ± 0.29	1.42 ± 0.68	1.24 ± 0.48	1.47 ± 0.64	1.41 ± 0.66	***p* < 0.001**	***p* = 0.533**	***p* = 0.576**
TSS to TA ratio	1.90 **d** ± 0.66	2.03 **c** ± 0.43	2.11 **bc** ± 0.55	2.40 **a** ± 0.70	2.19 **b** ± 0.53	***p* < 0.001**	***p* < 0.001**	***p* < 0.001**
pH-value	3.08 ± 0.23	3.09 ± 0.08	3.05 ± 0.09	3.11 ± 0.09	3.17 ± 0.10	***p* < 0.001**	***p* = 0.206**	***p* = 0.024**
N-OPA [mg L^{-1}]	93.11 **b** ± 28.02	92.11 **b** ± 11.87	94.88 **ab** ± 11.62	103.56 **a** ± 12.09	93.22 **b** ± 8.48	***p* < 0.001**	***p* = 0.0108**	***p* < 0.001**

3.6.2. Grape Juice Composition

Even though the ripening period was extended in SMPH training systems compared to VSP, TSS did not differ significantly between the two training systems in 2017 and 2018 (Figure 5B). Due to persistent precipitation during the extended ripening period of SMPH in 2019, significant lower TSS were detected compared with VSP. A negative correlation between °Brix and yield was determined among the SMPH treatments with correlation coefficients −0.92 (2017), −0.79 (2018) and −0.65 (2019), and hence, resulting in higher TSS with thinning. Significant higher Brix values compared to SMPH were found in 2017 for SMPH ST and in 2019 for SMPH BT ($p < 0.001$). Nevertheless, on average across three vintages, no significant differences in TSS (°Brix) were found, and reducing sugar and extract at harvest occurred between the two training systems and all thinning treatments (Table 3). Lowest values for sugar concentration was observed for SMPH, which was 5.8% lower than in VSP. Compared to the non-thinned SMPH sugar concentration increased about 3.2% in SMPH GA, 4.1% in SMPH ST and 6.5% in SMPH BT thinning treatment. Across three vintages a lower total acidity (TA) compared to VSP was recorded for SMPH (−15.3%). Shoot thinning as well as bunch thinning seem to decrease TA, ranging from −2.5% and −8.1% respectively while SMPH GA showed no notable differences referred to the non-thinned SMPH. On average, tartaric acid concentrations were significantly lower in SMPH (−5.8%), SMPH ST (−7.9%), SMPH GA (−9.8%) and SMPH BT (−11%). The later harvest date in SMPH training system resulted in similar mean values for N-OPA at a simultaneously higher crop level, compared with VSP. When bunch thinning caused the same crop level compared to VSP the N-OPA concentration increased significantly (12.4%).

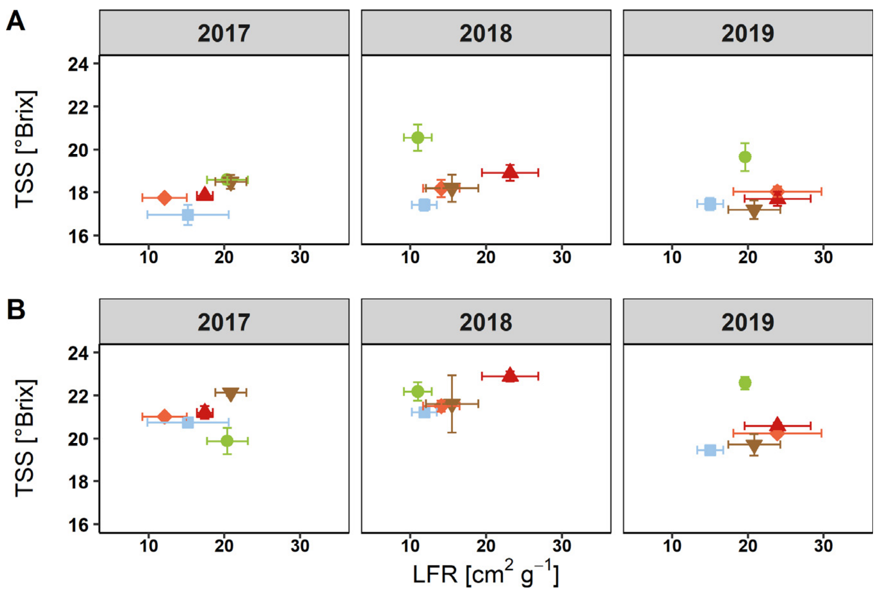

Figure 5. Total soluble solids (TSS) during ripening period (**A**) and at harvest (**B**) in relation to leaf area to fruit weight-ratio (cm^2 g^{-1}) for cv. Riesling trained in Vertical Shoot Positioning (VSP ●) and Semi-Minimal-Pruned Hedge (SMPH) with non-thinned control (SMPH ■), shoot thinning (SMPH ST ▼), biotechnological thinning (SMPH GA ♦) and bunch thinning using a harvester (SMPH BT ▲) in the years 2017–2019. Error bars are representing ±SD.

4. Discussion

The aim of the present study was to evaluate the SMPH training system and thinning approaches as potential adaptation strategies for climate change in a cool-to-moderate climatic region. In addition to their benefits in complete viticultural mechanization, vines grown in SMPH training system have been reported to display several features that might benefit wine quality under global warming [22,24,30]. These include a delay of phenological stages, and thus, ripening in cooler periods, and an improved bunch architecture, both contributing to a reduced *B. cinerea* susceptibility of ripening grape bunches. In addition, ripening under moderate climate conditions may help preserve the typicity of terroir wines, originating from cool to moderate climatic regions, as significantly high temperatures negatively impact organic acids [2,31], and particularly varietal aroma compounds of cv. Riesling [32,33].

4.1. Vegetative and Generative Development

Despite the physiologically self-regulating bud burst mechanism in SMPH [20], growth of SMPH vines was elevated, due to a high bud load, resulting in more shoots. Hence, more bunches and a higher total leaf area per meter of row. This confirmed the results of previous studies under warm and moderate climate conditions [20,22]. Intrieri et al. [20] detected a lower bud burst rate in SMPH, ranging from 49% to 62% depending on canopy height, which is in agreement with our results. Sprayings with gibberellic acid led to decreased bud fertility, and consequently, less inflorescences in minimal pruning trials of Weyand et al. [34]. Although a trend to a lower bud fertility (data not shown), a lower bud burst rate and less inflorescences were observed in SMPH GA, we could not confirm these results statistically. Conversely, SMPH ST seemed to increase bud burst rate, but SMPH BT did not affect bud burst.

Generally, the development of the total leaf area in SMPH was earlier, compared to VSP, due to the higher amount of shoots and wider distribution across the entire trellis system. This needs to be considered in the plant protection strategy, e.g., via an adaptation of the pesticide dose per ha, since the target leaf area and the total number of bunches were higher in SMPH, compared to VSP. SMPH showed a higher overall photosynthetic capacity [20], and higher yield, which increased water consumption through transpiration. Since the risk of dry summers increase under future climate change scenarios [5], irrigation might be considered in SMPH as drought related leaf abscission was observed in 2018.

Average total leaf area as well as leaf area per shoot was increased in SMPH BT in subsequent vintages, indicating that yield reduction by bunch thinning improved growth. Shoot thinning induced a growth compensation effect. While, total leaf area after shoot thinning was 20% to 32% lower, compared to SMPH in May 2018, and 2019 respectively, only marginal differences were detected in August (−2% to −3%). The observed growth compensation effect using SMPH ST increased primary shoot length, shoot diameter, bunch weight and leaf area per shoot, which is in accordance with findings of Naor et al. [35]. The first trimming event drastically reduced total leaf area in SMPH with considerable effect on source-sink relation, i.e., LFR. Usually, a LFR of 16 to 22 $cm^2\ g^{-1}$ is required to ripen grapes in cooler climates of Germany, whereas a LFR of 8–12 $cm^2\ g^{-1}$ is appropriate for warmer climates [36]. Our results revealed, that LFRs obtained with SMPH (ranging from 11.8 to 15.2 $cm^2\ g^{-1}$) were sufficient to achieve the legal threshold of different wine categories of quality wine of origin for cv. Riesling at delayed harvest dates.

In the trials of Parker et al. [37], as in the present study, yield reduction elevated LFRs in all thinning treatments and accelerated maturity progress. Since SMPH ST reduced both, shoots, as well as inflorescences, and bunch weight increased, the higher leaf area per shoot has contributed to an elevated LFR. We conclude that the delayed ripening in SMPH is predominantly caused by the reduction in leaves (source) as yield (sink) remained high in SMPH. These findings are in line with several authors [38,39] who delayed ripening with different canopy sizes. Therefore, altering the extent of trimming, and hence, manipulating LFR via leaf area reduction might be an additional measure to affect maturity progress in SMPH.

4.2. Phenological Development and Maturity Progress

Projections of Stock et al. [1] forecast an earlier bud break (−11 days), begin of flowering (−11 days) and veraison (−3 days) for the 2050s at Geisenheim, Germany compared to the 1990s. Our long-term phenological data (not shown) for cv. Riesling trained in VSP indicates an earlier bud break (−6 days; DOY 111), full bloom (−7 days; DOY 163) and veraison (−8 days; DOY 223) on average over the last 20 years (2001–2020) compared to the period 1991 to 2000. In the present study, full bloom occurred 4 days (DOY 159) earlier in VSP compared to the average between 2001 and 2020, which confirmed the projections in Stock et al. [1]. In contrast, SMPH treatments delayed full bloom by 1 to 2 days, showing a slight trend for advanced phenological development with mechanical thinning treatments (i.e., SMPH ST and SMPH BT).

The delay in maturity progress was more evident. For all SMPH treatments a delay in ripening was observed compared to VSP, which is in accordance with other cool-climate studies on SMPH [22]. On average, we observed a delay in attaining specific TSS levels (14.2 °Brix and 18.1 °Brix) between seven days to 16 days in SMPH, compared to VSP. Similarly, Zheng et al. [40] delayed a target TSS of 22 °Brix by 17 days with minimal pruning. The determined delay in ripening with SMPH might compensate (at least partly) the observed and projected earlier maturation period under warmer condition [4], which was caused by climate change. Negative temperature-based impacts on fruit composition, i.e., low acidity, high alcohol [2,41] and detrimental TDN (1,1,6-trimethyl1,2-dihydronaphtalene) concentrations [32,33,42,43], highlight the importance in shifting veraison and ripening to a period with moderate temperatures to preserve wine typicity. While TSS do not directly represent wine typicity, the present results demonstrate the suitability of SMPH as one potential part of a climate change adaptation strategy. Analyses on sensorial wine profiles of wines vinified, based on the present trials, are ongoing and will be published in an additional paper.

The harvest was conducted 10 days (2017), 20 days (2018) and 22 days (2019) later in SMPH, compared to VSP with the goal to yield similar juice TSS. As discussed earlier, the delayed sugar accumulation seems to be related to the elevated yield level, increased biomass production and lower LFR in SMPH training system compared to VSP. The fact that all thinning treatments effectively accelerated ripening within SMPH strengthens this hypothesis. Although the response of SMPH sugar accumulation to yield level was nearly linear in 2017 and 2018 and based on the manipulation of LFR, the ratio of LFR to Brix was lower in VSP in the dry season of 2018 (Figure 5A), indicating a more efficient carbohydrate assimilation.

4.3. Bunch Architecture and Botrytis cinerea Susceptibility

Bunch architecture plays an important role in controlling bunch rot diseases, and in particular, *B. cinerea*. Several studies report a higher susceptibility of compact clusters to bunch rot [22,23,44]. Since berries in compact bunches are densely packed and cuticular membrane thickness decreases, while berry growth is ongoing [45], the bunch rot risk increased as *B. cinerea* susceptibility was found to be negatively correlated with the impedance of berry cuticle and its waxes [46]. Therefore, a loose bunch architecture is one of the mayor preventive measures in viticulture to reduce *B. cinerea* susceptibility and hence maintain grape quality. Several viticultural management strategies, including delayed winter pruning [11], late first shoot topping [47], bunch-zone defoliation [48,49] or application of Gibberellic acid [50] are known to reduce bunch compactness and enhance resistance against bunch rot. In this study, SMPH indicates a lower rachis weight, lower single berry weight and less berries per bunch, resulting in a lower bunch weight compared to VSP, and thereby confirming previous studies of Intrieri et al. [20]. Moreover, Molitor et al. [22] observed a lower bunch density index (i.e., less compact bunches) in SMPH compared to VSP. In this study, a higher ratio of rachis weight to bunch weight was correlated with a lower *B. cinerea* susceptibility in SMPH training system, and thus, considered as an index for bunch compactness. Relying on this index differences in bunch compactness was not significant between VSP, SMPH and SMPH ST. Whereas, SMPH BT and SMPH GA resulted in less compact bunches.

Thinning treatments modified the bunch architecture. The smallest berries were found in SMPH BT. During bunch thinning, larger berries were selectively removed from the bunches and a slower berry growth was observed during the onset of growth stage III (data not shown), leading to a substantial reduction of berry size at harvest. We assume that this might be due to a shock related reduction of growth processes caused by the mechanical forces during bunch thinning using a harvester. SMPH BT increased the rachis to bunch weight-ratio due to smaller and less berries per bunch, and thus, led to a looser bunch architecture.

The increased berry size in SMPH GA and SMPH ST can be explained by the yield component compensation principle: SMPH GA had larger berries than SMPH due to reduced berry number per bunch at equal bunch numbers per meter of canopy, which is in accordance with results of Hed et al. [50,51] and Weyand and Schultz [34]. SMPH ST, with a significantly reduced bunch number (i.e., shoot), compared to SMPH, had a greater number and larger berries per bunch, confirming the results of Wang et al. [52]. In their study, the magnitude of the berry size compensation effect (16%) was larger than in our study (10%), which might be explained by the fact that the vines in the present trial were not irrigated, or by the generally lower shoot number in their trial. SMPH also affected the kinetics of bunch rot infection. Bunch rot infection occurred earlier in VSP compared to SMPH, possibly due to a slower ripening and improved bunch architecture in SMPH as mentioned earlier. When harvest was conducted in VSP, bunch rot infection was significantly elevated, compared to SMPH.

These differences disappeared or were even reversed, when *B. cinerea* incidence and severity were compared at commercial harvest in 2017 and 2019 (no *B. cinerea* infections occurred in 2018). This might be related to a longer period between veraison and harvest in all SMPH treatments compared to VSP, in which initial *B. cinerea* infections had more time and GDD to spread. While, Kraus et al. [23] found a higher average humidity in

SMPH canopy compared to VSP, we did not detect differences in relative humidity between the non-defoliated bunch zone of VSP and the canopy of SMPH during ripening from 15 August to the harvesting of VSP. However, relative humidity increased by approximately 10% points within the SMPH canopy in the extended ripening period of SMPH compared to the ripening period of VSP (Table S6). These changes in relative humidity might explain higher *B. cinerea* infections with SMPH at delayed harvest dates, since maturity levels did not differ significantly.

Thinning treatments that led to an additional improvement of bunch architecture (i.e., SMPH GA, likewise in the trials of Hed et al. [50], and SMPH BT) led to a deceleration of *B. cinerea* infection. This effect was most evident with SMPH BT. In contrast, shoot thinning (SMPH ST) led to an accelerated *B. cinerea* infection, compared with SMPH, probably due to an advanced maturity level and more compact bunches.

4.4. Alternate Bearing and Thinning Performance

Excessive yields in minimal pruning systems have been reported to cause severe losses in yield in the subsequent vintage [53,54]. Intrieri et al. [54] concluded that excessive yield, and an insufficient effective leaf area during bud induction and differentiation in the previous season, contribute to low bud fruitfulness. Therefore, crop thinning in SMPH is strongly recommended to avoid losses and extreme variability in fruit quality, caused by excessive yield and seasonal yield fluctuations (alternate bearing), which occurs especially in the first two seasons after conversion from VSP to SMPH [4,30,53,55]. In previous studies, Friedel et al. [30] observed cultivar-dependent alternate bearing effects in SMPH. While, high coefficients of variation (CV) for yield were determined with the fungus-tolerant cv. Regent and cv. Rondo within the first three years after conversion from VSP to SMPH (Schäfer et al. *unpublished*), cv. Riesling was less affected by alternate bearing. Moreover, the trials revealed that the general effect of alternate bearing is less pronounced within cv. Riesling trained in SMPH than trained in VSP, confirming the results in the present study. In contrast, data obtained from a study on SMPH by Molitor et al. [4] indicates more pronounced alternate bearing with cv. Pinot blanc trained in SMPH compared to VSP, which matches the results for cv. Regent and cv. Rondo of Friedel et al. [30]. Both investigations demonstrated that mechanical bunch thinning in the seasons after conversion to SMPH is an appropriate strategy to minimize quality losses through alternate bearing.

Nevertheless, in the present study, all thinning strategies successfully and efficiently reduced yield, accelerated ripening and increased TSS, confirming the commonly known yield/quality relationship. Mechanical shoot thinning with Darwin-rotor is a new yield reduction strategy for SMPH and was first investigated for viticulture in the present study. Our trials demonstrated good performance of SMPH ST, in terms of yield reduction. However, since the application is conducted long before fruit set, it is difficult to predict the desired thinning extent and crop level. Moreover, it has to be considered that early shoot thinning with SMPH ST led to compensation effects, which might increase the risk of bunch rot.

4.5. Grape Juice Composition at Harvest

Jones et al. [2] modeled an optimum growing season average temperature for high quality white wines, originating from Rhine Valley of 15.6 °C. The average growing season temperature at Geisenheim across the vintages 2017 to 2019 (16.7 °C) exceeded the optimum temperatures by 1.1 °C. Similarly, projections made by Duchêne et al. [7] forecast an increase in temperature during ripening by 1 °C in the period 2010 to 2040, and even by 6.3 °C in the period 2073 to 2099, compared to years with favorable sugar accumulation for cv. Riesling between 1976–2008 in Alsace, France. However, high average daily temperatures were recorded in the bunch zone of VSP (2018: 19.2 °C; 2019: 19 °C) and in the canopy of SMPH (2018: 19.4 °C; 2019: 19.1 °C) during ripening period of VSP beginning from 15th of August until 19th and 17th of September in 2018 and 2019 respectively (Table S6). Although leaves shaded bunch zone of VSP and data logger were positioned approximately 30 cm higher in the SMPH canopy, temperature differences were marginal higher in SMPH (+0.1 °C to +0.2 °C). Interestingly, average temperatures in the extended ripening period of SMPH (2018: 24th of September–10th of October; 2019: 18th of September–9th of October.) were 6.5 °C (2018) to 7.1 °C (2019) lower, revealing that ripening at least partly occurred under moderate temperatures in SMPH. Nevertheless, VSP and SMPH yielded comparable TSS concentration, while commercial harvest was conducted 10 days (2017), 20 days (2018) and 22 days (2019) later in SMPH, compared to VSP.

All thinning treatments increased grape juice sugar accumulation during ripening, but the treatment effects were not as clear in the harvested juice. This may be due to the fact that *B. cinerea* incidence and severity differed among treatments in 2017 and 2019. In 2018, where no bunch rot was observed, grape juice TSS in SMPH were linearly correlated to yield, with SMPH BT increasing TSS by about 1.7 °Brix at 47.6% yield reduction, compared to SMPH. The grape juice of SMPH trained vines generally showed a higher TSS to TA ratio than that of VSP trained vines, and a higher tartaric to malic acid ratio. High TSS to TA ratios were determined by Kliewer and Dokoozlian [56] in high cropping table grapes of Thompson Seedless cultivar. Moreover, Parker et al. [37] concluded that higher TSS to TA ratios in the presence of higher yield was due to a lower TA relative to a target TSS during ripening. Since tartaric acid and malic acid accumulation is dependent on carbon sources as well as glucose [57], lower TA could be explained by limited carbon sources (leaves) in response to trimming and/or leaf removal after fruit set. Assuming that TSS accumulation is not affected by leaf removal, due to a compensation response, resulting in an increase in photosynthetic activity and mobilization of reserve carbohydrates [17,58], TSS to TA ratio is consequently increased. Conversely, Parker et al. [37,38] found decreased TSS to TA ratios by manipulating leaf area to fruit weight ratio through leaf and crop removal, as well as lower canopy height (−30% to −60%), predominantly caused by reduced TSS accumulation. The higher tartaric to malic acid ratio in SMPH may be explained by the higher light exposure of SMPH bunches, which increased the berry temperature, leading to an accelerated respiration of malic acid, as well as smaller berry size, which intrinsically led to an elevated tartaric to malic acid ratio in Riesling [58]. Low concentrations of malate were also related to low water status pre-veraison by Matthews and Anderson [59]. Presuming that water use is higher in SMPH, due to a significantly higher leaf area, and thus, higher transpiration by leaves compared to VSP, tartaric to malic acid ratio might be further negatively impacted through lower malic acid concentration caused by water deficit under warmer/hot climate conditions, as observed in vintage 2018 and 2019. At the beginning of ripeness measurements in SMPH BT showed higher tartaric and lower malic concentration, and hence, a higher tartaric to malic acid ratio compared to all other treatments. This was probably due to reduced photosynthesis activity after thinning. N-OPA was unaffected by training system but increased by SMPH BT, indicating that SMPH does not negatively affect N-supply of the grapes.

5. Conclusions

The results of this study showed that SMPH provides several approaches to counteract the challenges of climate change in moderate climate regions with sufficient water availability. If weather conditions are not considered a risk factor, the date of harvest can be postponed about three weeks while still maintaining analytical grape parameters on a comparable level, as in VSP. Full bloom and pre-veraison occurred later in SMPH compared to VSP, and ripening was slower. Depending on the targeted wine profile, SMPH under several thinning practices provided the opportunity to, either achieve lower TSS with a higher degree of organic acids, or postpone the date of harvest by maintaining grape quality compared to VSP. In terms of thinning measures in SMPH, maturity progress can be accelerated, leading to an increase in TSS and a decrease in bunch rot susceptibility. Under changing climatic conditions, effective thinning measures to reduce crop load and increase TSS might need to be reconsidered.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/app11083304/s1: Figure S1: Development of leaf area, Figure S2: Leaf area to fruit weight-ratio, Table S1: Phenological timings and treatment deviation, Table S2: Ripening timings and treatment deviation for target TSS, Table S3: Maturity parameters during ripening, Table S4: Maturity parameters at harvest, Table S5: Yield parameters, Table S6: Microclimate.

Author Contributions: Conceptualization, J.S., M.F., M.S.; methodology, J.S., M.F. and M.S.; formal analysis, J.S., M.F.; investigation, J.S., M.F.; resources, J.S., M.F., M.S., D.M.; data curation, J.S. and M.F.; writing—original draft preparation, J.S., M.F., M.S., D.M.; writing—review and editing, J.S., M.F., M.S., D.M.; visualization, J.S.; supervision, M.S. and D.M.; project administration, J.S., M.F. and M.S.; All authors have read and agreed to the published version of the manuscript.

Funding: The German Federal Ministry of Education and Research (BMBF) funded this research.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We acknowledge the financial support by the BMBF (Federal Ministry of Education and Research) of the project NoViSys [Novel viticulture systems for sustainable production and products project; number 031A349G]. Furthermore, we acknowledge the technical and laboratory team of the Department of General and Organic Viticulture and the Department of Beverage Technology of Geisenheim University for their indispensable help in conducting the experiments and supporting the analyses.

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

References

1. Stock, M.; Badeck, F.; Gerstengarbe, F.-W.; Hoppmann, D.; Kartschall, T.; Oesterle, H.; Werner, P.C.; Wodinski, M. *Perspectives of the Climatic Change until 2050 for the Viticulture in Germany (Climate 2050): Final Report of the FDW Project—Climate 2050*, 106th ed.; Gerstengarb, F.-W., Ed.; Potsdam Institute for Climate Impact Research (PIK): Potsdam, Germany, 2007.
2. Jones, G.V.; White, M.A.; Cooper, O.R.; Storchmann, K. Climate change and global wine quality. *Clim. Chang.* **2005**, *73*, 319–343. [CrossRef]
3. Fraga, H.; Cortázar-Atauri, I.G.; Malheiro, A.C.; Santos, J.A. Modelling climate change impacts on viticultural yield, phenology and stress conditions in Europe. *Glob. Chang. Biol.* **2016**, *22*, 3774–3788. [CrossRef]
4. Molitor, D.; Junk, J. Climate change is implicating a two-fold impact on air temperature increase in the ripening period under the conditions of the luxembourgish grapegrowing region. *OENO One* **2019**, *53*, 409–422. [CrossRef]
5. Duchêne, E.; Schneider, C. Grapevine and climatic changes: A glance at the situation in Alsace. *Agron. Sustain. Dev.* **2005**, *25*, 93–99. [CrossRef]
6. Van Leeuwen, C.; Darriet, P. The impact of climate change on viticulture and wine quality. *J. Wine Econ.* **2016**, *11*, 150–167. [CrossRef]
7. Duchêne, E.; Huard, F.; Dumas, V.; Schneider, C.; Merdinoglu, D. The challenge of adapting grapevine varieties to climate change. *Clim. Res.* **2010**, *41*, 193–204. [CrossRef]
8. Santos, J.A.; Fraga, H.; Malheiro, A.C.; Moutinho-Pereira, J.; Dinis, L.-T.; Correia, C.; Moriondo, M.; Leolini, L.; Dibari, C.; Costafreda-Aumedes, S.; et al. A review of the potential climate change impacts and adaptation options for european viticulture. *Appl. Sci.* **2020**, *10*, 3092. [CrossRef]
9. Nair, N.G.; Allen, R.N. Infection of grape flowers and berries by *Botrytis cinerea* as a function of time and temperature. *Mycol. Res.* **1993**, *97*, 1012–1014. [CrossRef]
10. Poling, E.B. Spring cold injury to winegrapes and protection strategies and methods. *Horts* **2008**, *43*, 1652–1662. [CrossRef]
11. Silvestroni, O.; Lanari, V.; Lattanzi, T.; Palliotti, A. Delaying winter pruning, after pre-pruning, alters budburst, leaf area, photosynthesis, yield and berry composition in Sangiovese (*Vitis vinifera* L.). *Aust. J. Grape Wine Res.* **2018**, *24*, 478–486. [CrossRef]
12. Moran, M.; Petrie, P.; Sadras, V. Effects of late pruning and elevated temperature on phenology, yield components, and berry traits in Shiraz. *Am. J. Enol. Vitic.* **2019**, *70*, 9–18. [CrossRef]
13. Martinez De Toda, F.; García, J.; Balda, P. Preliminary results on forcing vine regrowth to delay ripening to a cooler period. *Vitis J. Grapevine Res.* **2019**, *58*, 17–22.
14. Palliotti, A.; Frioni, T.; Tombesi, S.; Sabbatini, P.; Cruz-Castillo, J.G.; Lanari, V.; Silvestroni, O.; Gatti, M.; Poni, S. Double-pruning grapevines as a management tool to delay berry ripening and control yield. *Am. J. Enol. Vitic.* **2017**, *68*, 412–421. [CrossRef]
15. Gatti, M.; Galbignani, M.; Garavani, A.; Bernizzoni, F.; Tombesi, S.; Palliotti, A.; Poni, S. Manipulation of ripening via antitranspirants in cv. Barbera (*Vitis vinifera* L.). *Aust. J. Grape Wine Res.* **2016**, *22*, 245–255. [CrossRef]

16. Boettcher, C.; Harvey, K.; Forde, C.G.; Boss, P.K.; Davies, C. Auxin treatment of pre-veraison grape (*Vitis vinifera* L.) berries both delays ripening and increases the synchronicity of sugar accumulation. *Aust. J. Grape Wine Res.* **2011**, *17*, 1–8. [CrossRef]
17. Poni, S.; Casalini, L.; Bernizzoni, F.; Civardi, S.; Intrieri, C. Effects of early defoliation on shoot photosynthesis, yield components, and grape composition. *Am. J. Enol. Vitic.* **2006**, *57*, 397–407.
18. Poni, S.; Gatti, M.; Bernizzoni, F.; Civardi, S.; Bobeica, N.; Magnanini, E.; Palliotti, A. Late leaf removal aimed at delaying ripening in cv. Sangiovese: Physiological assessment and vine performance. *Aust. J. Grape Wine Res.* **2013**, *19*, 378–387. [CrossRef]
19. Palliotti, A.; Panara, F.; Silvestroni, O.; Lanari, V.; Sabbatini, P.; Howell, G.S.; Gatti, M.; Poni, S. Influence of mechanical postveraison leaf removal apical to the cluster zone on delay of fruit ripening in Sangiovese (*Vitis vinifera* L.) grapevines. *Aust. J. Grape Wine Res.* **2013**, *19*, 369–377. [CrossRef]
20. Intrieri, C.; Filippetti, I.; Allegro, G.; Valentini, G.; Pastore, C.; Colucci, E. The Semi-Minimal-Pruned Hedge: A novel mechanized grapevine training system. *Am. J. Enol. Vitic.* **2011**, *62*, 312–318. [CrossRef]
21. Lopes, C.; Melicias, J.; Aleixo, A.; Laureano, O.; Castro, R. Effect of mechanical hedge pruning on growth, yield and quality of Cabernet Sauvignon grapevines. *Acta Hortic.* **2000**, *526*, 261–268. [CrossRef]
22. Molitor, D.; Schultz, M.; Mannes, R.; Pallez-Barthel, M.; Hoffmann, L.; Beyer, M. Semi-Minimal Pruned Hedge: A potential climate change adaptation strategy in viticulture. *Agronomy* **2019**, *9*, 173. [CrossRef]
23. Kraus, C.; Pennington, T.; Herzog, K.; Hecht, A.; Fischer, M.; Voegele, R.T.; Hoffmann, C.; Töpfer, R.; Kicherer, A. Effects of canopy architecture and microclimate on grapevine health in two training systems. *Vitis J. Grapevine Res.* **2018**, *57*, 53–60.
24. Walg, O.; Blätz, M.; Friedel, M. Minimalschnitt im Spalier–eine wirksame Möglichkeit zur Spätfrostprävention. *Dtsch. Weinbau-Jahrb.* **2019**, *2018*, 76–85.
25. Coombe, B.G. Growth stages of the grapevine: Adoption of a system for identifying grapevine growth stages. *Aust. J. Grape Wine Res.* **1995**, *1*, 104–110. [CrossRef]
26. Parker, A.K.; Cortázar-Atauri, I.G.; Leeuwen, C.; Chuine, I. General phenological model to characterise the timing of flowering and veraison of *Vitis vinifera* L. *Aust. J. Grape Wine Res.* **2011**, *17*, 206–216. [CrossRef]
27. Doering, J.; Stoll, M.; Kauer, R.; Frisch, M.; Tittmann, S. Indirect estimation of leaf area index in VSP-trained grapevines using plant area index. *Am. J. Enol. Vitic.* **2014**, *65*, 153–158. [CrossRef]
28. Dukes, B.C.; Butzke, C.E. Rapid determination of primary amino acids in grape juice using an o-phthaldialdehyde/N-acetyl-L-cysteine spectrophotometric assay. *Am. J. Enol. Vitic.* **1998**, *49*, 125–134.
29. Ogle, D.H.; Wheeler, P.; Dinno, A. FSA: Fisheries Stock Analysis. R package version 0.8.31. 2020. Available online: https://github.com/droglenc/FSA (accessed on 17 November 2020).
30. Friedel, M.; Schäfer, J.; Blätz, M.; Stoll, M.; Walg, O. Minimal-invasiv?: Long-term study on SMPH. *Dtsch. Weinbau* **2018**, *12*, 28–32.
31. Sweetman, C.; Sadras, V.O.; Hancock, R.D.; Soole, K.L.; Ford, C.M. Metabolic effects of elevated temperature on organic acid degradation in ripening *Vitis vinifera* fruit. *J. Exp. Bot.* **2014**, *65*, 5975–5988. [CrossRef]
32. Pons, A.; Allamy, L.; Schüttler, A.; Rauhut, D.; Thibon, C.; Darriet, P. What is the expected impact of climate change on wine aroma compounds and their precursors in grape? *OENO One* **2017**, *51*, 141–146. [CrossRef]
33. Marais, J.; van Wyk, C.J.; Rapp, A. Effect of storage time, temperature and region on the levels of 1,1,6-trimethyl-1,2-dihydronaphthalene and other volatiles, and on quality of Weisser Riesling wines. *S. Afr. J. Enol. Vitic.* **1992**, *13*, 33–44.
34. Weyand, K.M.; Schultz, H.R. Regulating yield and wine quality of minimal prunning systems through the application of gibberellic acid. *OENO One* **2006**, *40*, 151–163. [CrossRef]
35. Naor, A.; Gal, Y.; Bravdo, B. Shoot and cluster thinning influence vegetative growth, fruit yield, and wine quality of Sauvignon blanc grapevines. *J. Am. Soc. Hort. Sci.* **2002**, *127*, 628–634. [CrossRef]
36. Müller, E. *Weinbau*, 3rd ed.; Kadisch, E., Müller, E., Eds.; Ulmer: Stuttgart, Germany, 2008.
37. Parker, A.K.; Hofmann, R.W.; van Leeuwen, C.; McLachlan, A.; Trought, M. Manipulating the leaf area to fruit mass ratio alters the synchrony of total soluble solids accumulation and titratable acidity of grape berries. *Aust. J. Grape Wine Res.* **2015**, *21*, 266–276. [CrossRef]
38. Parker, A.K.; Raw, V.; Martin, D.; Haycock, S.; Sherman, E.; Trought, M.C.T. Reduced grapevine canopy size post-flowering via mechanical trimming alters ripening and yield of 'Pinot noir'. *Vitis J. Grapevine Res.* **2016**, *55*, 1–9.
39. Stoll, M.; Lafontaine, M.; Schultz, H.R. Possibilities to reduce the velocity of berry maturation through various leaf area to fruit ratio modifications in *Vitis vinifera* L. *Progrès Agric. Vitic.* **2010**, *127*, 68–71.
40. Zheng, W.; Del Galdo, V.; García, J.; Balda, P.; Martínez de Toda, F. Use of minimal pruning to delay fruit maturity and improve berry composition under climate change. *Am. J. Enol. Vitic.* **2017**, *68*, 136–140. [CrossRef]
41. Hofmann, M.; Stoll, M.; Schultz, H.R. Klimawandel und Weinbau. *Geogr. Rundsch.* **2016**, *3*, 20–26.
42. Schüttler, A.; Guthier, C.; Stoll, M.; Darriet, P.; Rauhut, D. Impact of grape cluster defoliation on TDN potential in cool climate Riesling wines. *Biol. Web Conf.* **2015**, *5*, 010061-3. [CrossRef]
43. Yuan, F.; Feng, H.; Qian, M.C. C13-norisoprenoids in grape and wine affected by different canopy management. In *Advances in Wine Research*; Ebeler, S.B., Sacks, G., Vidal, S., Winterhalter, P., Eds.; American Chemical Society: Washington, DC, USA, 2015; pp. 147–160.
44. Molitor, D.; Baus, O.; Hoffmann, L.; Beyer, M. Meteorological conditions determine the thermal-temporal position of the annual *Botrytis* bunch rot epidemic on *Vitis vinifera* L. cv. Riesling grapes. *OENO One* **2016**, *50*, 231–244. [CrossRef]

45. Becker, T.; Knoche, M. Deposition, strain, and microcracking of the cuticle in developing 'Riesling' grape berries. *Vitis J. Grapevine Res.* **2012**, *51*, 1–6.
46. Herzog, K.; Wind, R.; Töpfer, R. Impedance of the grape berry cuticle as a novel phenotypic trait to estimate resistance to *Botrytis cinerea*. *Sensors* **2015**, *15*, 12498–12512. [CrossRef] [PubMed]
47. Molitor, D.; Baron, N.; Sauerwein, T.; André, C.M.; Kicherer, A.; Döring, J.; Stoll, M.; Beyer, M.; Hoffmann, L.; Evers, D. Postponing first shoot topping reduces grape cluster compactness and delays bunch rot epidemic. *Am. J. Enol. Vitic.* **2015**, *66*, 164–176. [CrossRef]
48. Molitor, D.; Behr, M.; Fischer, S.; Hoffmann, L.; Evers, D. Timing of cluster-zone leaf removal and its impact on canopy morphology, cluster structure and bunch rot susceptibility of grapes. *OENO One* **2011**, *45*, 149–159. [CrossRef]
49. Intrieri, C.; Filippetti, I.; Allegro, G.; Centinari, M.; Poni, S. Early defoliation (hand vs mechanical) for improved crop control and grape composition in Sangiovese (*Vitis vinifera* L.). *Aust. J. Grape Wine Res.* **2008**, *14*, 25–32. [CrossRef]
50. Hed, B.; Centinari, M. Gibberellin application improved bunch rot control of Vignoles grape, but response to mechanical defoliation aried between training systems. *Plant Dis.* **2021**, *105*, 339–345. [CrossRef]
51. Hed, B.; Ngugi, H.K.; Travis, J.W. Use of gibberellic acid for management of bunch rot on Chardonnay and Vignoles grape. *Plant Dis.* **2011**, *95*, 269–278. [CrossRef]
52. Wang, X.; De Bei, R.; Fuentes, S.; Collins, C. Influence of canopy management practices on canopy architecture and reproductive performance of Semillon and Shiraz grapevines in a hot climate. *Am. J. Enol. Vitic.* **2019**, *70*, 360–372. [CrossRef]
53. Clingeleffer, P.R. Plant management research: Status and what it can offer to address challenges and limitations. *Aust. J. Grape Wine Res.* **2010**, *16*, 25–32. [CrossRef]
54. Intrieri, C.; Poni, S.; Lia, G.; Del Gomez Campo, M. Vine performance and leaf physiology of conventionally and minimally pruned Sangiovese grapevines. *Vitis* **2001**, *40*, 123–130.
55. Schiefer, H.-C.; Thim, G. Dem Minimalschnitt auf der Spur: Veränderung von Menge und Güte. *Dtsch. Weinmag.* **2020**, *26*, 28–31.
56. Kliewer, W.M.; Dokoozlian, N.K. Leaf area/crop weight ratios of grapevines: Influence on fruit composition and wine quality. *Am. J. Enol. Vitic.* **2005**, *56*, 170–181.
57. Ollat, N.; Gaudillere, J.P. The effect of limiting leaf area during stage I of berry growth on development and composition of berries of *Vitis vinifera* L. cv. Cabernet Sauvignon. *Am. J. Enol. Vitic.* **1998**, *49*, 251–258.
58. Friedel, M.; Stoll, M.; Patz, C.D.; Will, F.; Dietrich, H. Impact of light exposure on fruit composition of white 'Riesling' grape berries (*Vitis vinifera* L.). *Vitis* **2015**, *54*, 107–116.
59. Matthews, M.A.; Anderson, M.M. Fruit ripening in *Vitis vinifera* L.: Responses to seasonal water deficits. *Am. J. Enol. Vitic.* **1988**, *39*, 313–320.