

Hochschule Geisenheim University

and

Justus Liebig University Giessen

Faculty 09 - Agricultural Sciences, Nutritional Sciences, and Environmental Management

Comparison of terraced and steep slope vineyards emphasizing the impact of an altered viticultural system regarding physiology, health status and distinctive berry quality parameters of the grapevine

Submitted in fulfilment of the requirements for the degree

Doktor der Agrarwissenschaften (Dr. agr.)

Submitted by

Timo Strack

Born: 17th May 1991

in Baden-Baden, Germany

Geisenheim, December 2022

This thesis was accepted on 14th July 2023 as a doctoral dissertation in fulfilment of the requirements for the degree “Doktor der Agrarwissenschaften (Dr. agr.)” by Hochschule Geisenheim University and the Faculty 09 - Agricultural Sciences, Nutritional Sciences, and Environmental Management of Justus Liebig University Giessen.

Examination Committee:

Supervisor and Reviewer:	Prof. Dr. Manfred Stoll, Hochschule Geisenheim University
2nd Reviewer:	Prof. Dr. Christoph Müller, Justus Liebig University Giessen
3rd Reviewer:	Prof. Dr. Astrid Forneck, University of Natural Resources and Life Sciences Vienna
1st Examiner:	Prof. Dr. Sylvia Schnell, Justus Liebig University Giessen
2nd Examiner:	Prof. Dr. Ilona Leyer, Hochschule Geisenheim University
Head of the Committee:	Prof. Dr. Simone Loose, Hochschule Geisenheim University

Selbstständigkeitserklärung

„Ich erkläre: Ich habe die vorgelegte Dissertation selbständig und ohne unerlaubte fremde Hilfe und nur mit den Hilfen angefertigt, die ich in der Dissertation angegeben habe. Alle Textstellen, die wörtlich oder sinngemäß aus veröffentlichten Schriften entnommen sind, und alle Angaben, die auf mündlichen Auskünften beruhen, sind als solche kenntlich gemacht. Bei den von mir durchgeführten und in der Dissertation erwähnten Untersuchungen habe ich die Grundsätze guter wissenschaftlicher Praxis, wie sie in den Satzungen der Hochschule Geisenheim und der Justus-Liebig-Universität Gießen zur Sicherung guter wissenschaftlicher Praxis niedergelegt sind, eingehalten.

§ 16 (2) Promotionsordnung der Hochschule Geisenheim (2018)

Declaration of authorship

“I declare that this thesis has been composed solely by myself, without the unpermitted aid of others, except where explicitly stated in the text. All text passages taken in letter or in spirit from published writings and all information based on oral statements are clearly referenced as such. I have adhered to the principles of good scientific practice as laid down in the Statutes of Hochschule Geisenheim University and Justus Liebig University Gießen to ensure good scientific practice in the studies I have carried out and which are referred to as such in the doctoral thesis.”

§ 16 (2) doctoral regulations Hochschule Geisenheim University (2018)

Geisenheim, den 16.12.2023

Contents

Summary	IV
Zusammenfassung.....	VI
Chapter I: General introduction.....	1
1.1 Particularities of steep slope viticulture	3
1.2 Steep slope vineyard transformation to terraces.....	4
1.3 The effects of terrace construction on soil conditions.....	8
1.4 The influence of vineyard row orientation on the grapevine	10
1.4.1 The impact of row orientation on the grapevine microclimate	11
1.4.2 The impact of row orientation on the grapevine performance and health.....	13
1.4.3 Effect of row orientation on berry composition of the grapevine	14
1.5 General objectives	16
Chapter II: Impact of steep slope management system and row orientation on canopy microclimate. Comparing terraces to downslope vineyards.....	19
Chapter III: Implication of Row Orientation Changes on Fruit Parameters of <i>Vitis vinifera</i> L. cv. Riesling in Steep Slope Vineyards	35
Chapter IV: Soil water dynamics and drought stress response of <i>Vitis vinifera</i> L. in steep slope vineyard systems	53
Chapter V: General Discussion	66
5.1 Vineyard terracing is a useful tool to mitigate weather extremes	66
5.2 Vineyard terracing alters the composition of grapevine berries.....	73
5.3 Vineyard terracing comprises the chance of precipitation retention, but bares the risk of drought stress in the early years of grapevine establishment	76
5.4 Concluding remarks	80
References	81

List of Figures

Figure 1. A two-month old modern vineyard terrace. Vineyard transformation and vine planting was conducted in April 2021. Embankment cover crop seeds were sown in May 2021. Picture was taken in June 2021 at the Assmannshäuser Höllenberg in the Rheingau wine-growing region (Germany). The yellow auxiliary line displays the stair-like character of the transformed hill side.

..... 3

Figure 2. Locations of experimental sites (squares) and reference weather stations (triangles) along Rhine River. The two treatments (C and T) were in next possible proximity to each other. Numeration of sites: 1 = GM = Geisenheimer Rothenberg; 2 = RB = Rüdesheimer Berg Rottland; 3 = AS = Assmannshäuser Höllenberg; 4 = LB = Lorcher Bodental; 5 = LS = Lorcher Sesselberg; 6 = LE = Lorcher Eisersgrube; 7 = K = Kauber Burg Gutenfels. Map data source: Google Maps Platform..... 16

Figure 3. Shoot growth rate (cm GDD^{-1}) per measurement date (DOY) of the year 2021 for the sites GM, LE, LS and RB. Lines represent the fitted polynomial trend for each treatment (solid lines = control (C); dashed lines = terraced vineyards (T)), the boxplots indicate data variability. The flowering date of C is highlighted by an arrow and an annotation (E-L 23). Unpublished data.

..... 70

Figure 4. Principal component analysis of the years 2019 to 2021. (A) Score plot of individuals. Dots represent individual samples and dot colour indicates bunch exposition. Big dots show the mean of sample group, ellipses represent 95% confidence interval. (B) Loadings plot of variables. Black labels show analysed berry parameters (concentrations). Green labels represent supplementary quantitative data. BW = berry weight, LLN = leaf layer number, PIC = percentage of interior clusters, PIL = percentage of interior leaves ($_f$ = flowering, $_o$ = onset of ripening, $_h$ = harvest-ripe), LSF = bunch zone radiation energy interception, GABA = γ -aminobutyric acid, gal = galactoside, glc = glucoside, rut = rutinoside, GRP = grape reaction product, Kmp = kaempferol, Que = quercetin..... 74

Figure 5. Impact of a heavy precipitation event (25 mm in one hour) on the vineyard soil after a hot and dry period on the 24th of June 2022 at the Geisenheimer Rothenberg. The downslope planted vineyard showed an enormous loss of soil (left), while no surface soil erosion could be observed in the terraced treatment (right).

78

List of Tables

Table 1. Theoretical calculations of the embankment geometry (height and width) in relation to the initial vineyard slope, the distance between rows and varying inclination of the embankment according to Jörger et al. (2008a)..... 6

Table 2. Geometric parameters and planting information of the vineyard sites (GM = Geisenheimer Rothenberg; RB = Rüdesheimer Berg Rottland; AS = Assmannshäuser Höllenberg; LE = Lorcher Eisersgrube; LS = Lorcher Sesselberg; K = Kauber Burg Gutenfels) and treatments (C = control, downslope planted vineyard; T = terraced vineyard). Due to non-complete data records of the initial plantations differences in clones of the varieties were not taken into account.

..... 17

Table 3. Results of the multifactorial analysis of variance (ANOVA) for the difference in the response of different quality-determining berry parameters per gram berry weight to the factors 'Exposition', 'Vintage', 'Site' and the interaction between 'Site' and 'Treatment'..... 75

List of abbreviations

ANOVA	Analysis of variance
AS	Assmannshäuser Höllenberg
BW	Berry weight
C	Control (downslope planted vineyard)
cv	Cultivar
DOY	Day of the year
GABA	γ -aminobutyric acid
gal	Galactoside
GDD	Growing degree days
glc	Glucoside
GM	Geisenheimer Rothenberg
GRP	Grape reaction product
K	Kauber Burg Gutenfels
Kmp	Kaempferol
LB	Lorcher Bodental
LE	Lorcher Eisersgrube
LLN	Leaf layer number
LS	Lorcher Sesselberg
LSF	Light sensitive films
PAR	Photosynthetically active radiation
PIC	Percentage interior clusters
PIL	Percentage interior leaves
Que	Quercetin
RB	Rüdesheimer Berg Rottland
rut	Rutinoside
SOC	Soil organic carbon
SWC	Soil water content
T	Terraced vineyard system
TDN	1,1,6-trimethyl-1,2-dihydronaphthalene
WUE	Water use efficiency

Summary

Historically and under cooler climate conditions, steep slope vineyards yielded best quality wines and highest reputation, due to their distinctive light microclimate, especially pronounced at the end of the ripening period. Today, German steep slope viticulture is facing major challenges. The cultivation of steep vineyard sites is costly. Compared to fully-mechanized vineyards, steep slope vineyards are labour-intensive and strenuous to manage, they produce less yield and are at higher risk of the adverse effects of a changing climate.

The modern vineyard terracing may be a viable alternative to the current cultivation method of downslope planted grapevines. The terrace platforms lead along the contour line of the hill and allow a higher degree of vineyard mechanization. The flat terrace platforms reduce surface runoff and allow for greater infiltration of precipitation, thus reducing or preventing runoff of the fertile vineyard soil and enhance the retention of precipitation in the soil.

In the present work, the effects of the transformation of vineyards planted downslope to modern vineyard terraces on microclimatic parameters, soil water dynamics and, finally, on the vegetative and generative performance of the grapevine were investigated. The experimental sites, comprising a vineyard planted downslope and a modern terrace, were selected with regard to their spatial proximity to one another and the comparability of the planting material with each other and monitored over a period of two to four years.

The change in the radiation distribution and the heat balance became apparent due to the inherent row orientation change by vineyard terracing, leading to an alteration of distinctive fruit quality parameters. The concentrations of polyphenols and amino acids in the berries were highly related to the amount of received solar radiation. Vineyard terraces were able to mitigate weather extremes. However, younger vines planted at the outer end of the terrace platform showed high drought stress responses across all experimental years. However, this lessened as the vine age progressed.

The modern terracing of steep slope vineyards proved to be an appropriate tool for high-quality grape production. Additionally, the potential for promoting biodiversity through a sustainable management of the terrace embankments complements the overall positive

findings of the present work. In the near future, the challenge to increase the competitiveness of young vines grown at steep slope vineyards to accompanying plants needs to be solved by means of viticultural, technical or breeding measures.

Zusammenfassung

In der Vergangenheit trugen Weine aus Steilstlagen zu einem maßgeblichen Teil zur Reputation deutscher Spitzenweine im nationalen und internationalen Vertrieb bei. Die historischen Weinlagen prägten die Kulturlandschaft und deren Entwicklung. Der deutsche Steillagenweinbau steht jedoch vor großen Herausforderungen. Bereits in den letzten Jahrzehnten wurde die Bewirtschaftung eines großen Teils steiler Weinbergsflächen aufgegeben. Die Gründe hierfür sind vielfältig. Die im Vergleich zu direktzugfähigen Weinbergen in der Ebene kostenaufwendigere Kultivierung von Steillagen geht mit einer höheren körperlichen Belastung und einem zusätzlich höheren Unfallrisiko einher. Für viele Nachwuchskräfte ist die Arbeit im Steillagenweinberg daher wenig attraktiv; für viele praktizierende Betriebe zu teuer. Doch auch der allgegenwärtige Klimawandel wirkt auf die flachgründigen Steillagen mit geringen Bodenaufgaben unter zukünftig länger andauernden Trockenperioden, einer höheren Verdunstung und generell unregelmäßigeren, jedoch häufiger werdenden Starkniederschlagsereignissen, negativ auf die Ertragsstabilität und die allgemeine Traubenqualität ein. Dies betrifft vor allem die stark sonnenexponierten, flachgründigen Südhänge steiler Weinbergslagen.

Die moderne Querterrassierung von Weinbergen stellt eine mögliche Alternative zur gegenwärtigen Bewirtschaftung von Reben in der Falllinie dar. Die hangparallele Zeilenführung auf Terrassenplattformen lässt nicht nur einen höheren Grad der Weinbergsmechanisierung zu. Die ebenen Terrassenflächen können den Oberflächenabfluss verringern und erlauben eine höhere Infiltration von Niederschlägen, so dass eine Abschwemmung des fruchtbaren Weinbergsbodens reduziert oder verhindert und das Wasser im Boden besser zurückgehalten werden kann.

In der vorliegenden Arbeit wurde untersucht welche Auswirkungen die Umstrukturierung von Falllinienweinbergen zu hangparallel verlaufenden Querterrassen auf mikroklimatische Parameter, die Bodenwasserdynamik und letztlich auf die vegetative und generative Leistung der Rebe hat. Die bis zu sieben untersuchten Weinbergspaare, bestehend aus Falllinienweinberg und Querterrasse, wurden entlang des unteren Rheingaus und des oberen Mittelrheintals hinsichtlich ihrer räumlichen Nähe zueinander und der Vergleichbarkeit des Pflanzguts untereinander ausgewählt und über einen Zeitraum von zwei bis vier Jahren begleitet.

Es konnte gezeigt werden, dass eine durch die Weinbergstransformation orthogonal zur ursprünglich in Falllinie verlaufenden Zeilenorientierung in einer Veränderung der Strahlungsverteilung und des Wärmehaushalts resultiert. Querterrassen konnten Wetterextreme abschwächen und bewiesen eine für den Reifeabschluss begünstigte Besonnung der Traubenzone. Dies zeigte sich deutlich in der Unterscheidbarkeit der Gehalte qualitätsbestimmender

Traubeninhaltsstoffe, wie zum Beispiel Polyphenole und Aminosäuren. Jüngere Reben, die am äußeren Ende der Terrassenplattform gepflanzt wurden, wiesen über alle Versuchsjahre hinweg hohe Trockenstressreaktionen auf. Dies milderte sich jedoch mit fortschreitendem Rebalter ab. Die Querterrassierung von Steillagenweinbergen erwies sich als probates Mittel zur Erzeugung hochwertigen Traubenmaterials. Zudem ergänzt das Potential zur Förderung der Artenvielfalt durch eine nachhaltige Bewirtschaftung der Terrassenböschungen die als insgesamt positiv zu wertenden Versuchsergebnisse der vorliegenden Arbeit. Einzig die Herausforderung der zügigen Etablierung bzw. Konkurrenzfähigkeit von Jungreben im Steillagenweinberg stellt nach wie vor eine Schwierigkeit dar, die es mit weinbaulichen, technischen oder züchterischen Maßnahmen zu lösen gilt.

Chapter I: General introduction

The cultivation of grapevine (*Vitis vinifera* L.) has been practiced by advanced civilisations for several thousands of years (McGovern et al., 1996). Since then, the grape has become one of the economically most important fruit crop (Alston and Sambucci, 2019), while, to date, vineyards covering an area of approximately 7.34 Mha worldwide (OIV, 2022). Historically, and under cooler climate conditions, the production of grapes, not only for winemaking, but also for dietary purpose, was only possible, since the nutritional requirements of the grapevine are generally lower in comparison to vital crops important for human consumption (Löhnertz, 1988). In the past, viticulture was conducted on nutrient-poor soils, e.g. at shallow and stony sites of hills and mountains, where no direct competition to staple food production existed (van Leeuwen and Seguin, 2006), but light conditions for grape-ripening were favourable. Ever since, people have awarded a special significance to steep slope viticulture as well.

For viticulturists, working on steep slopes is physically demanding and the soil as well as the plants have to stand challenging weather conditions (e.g. heavy rains, winds and intense solar radiation). To reduce physical strains, but also to retain precipitation water on site, and thereby prevent fertile soil from erosion, people have built terraces in various designs since ancient times (Tarolli et al., 2014). Those terraces have to be adequately stabilized to prevent collapses and to guarantee a safe workplace (Crosta et al., 2003; Pijl et al., 2020).

Oftentimes, dry-stone wall terraces were built to facilitate the work in, *inter alia*, German steep slope vineyards of, for example, the Moselle or Ahr valley, at the Neckar or along the Rhine. These terraces shaped scenic landscapes and supported biodiversity due to the diversification of the landscape until the recent past (Petit et al., 2012; Assandri et al., 2016). The disadvantages of this elaborate handicraft are the high expenses for building and maintaining them as well as the impracticability of using heavy machinery for the vineyard management in the frequently small-scaled and difficult to access vineyard plots. Today, this cultural legacy is mainly preserved by public subsidies, although vineyard terraces are acknowledged for their special contribution to the world heritage, e.g. in the Austrian Wachau wine-growing region (UNESCO, 2000).

In the course of several vineyard consolidation procedures over the last decades in Germany, the dry-stone walls were removed from the vineyards and single-vine training systems and/or the whole vineyard row orientation changed from planting vines along the contour line of the hill to a plantation and trellising of grapevines down the slope gradient. The aim of this enormous procedure was the economization through an increase in the efficiency in grape production by a higher degree of mechanization (e.g. via rope and winch systems). The reduction of manual labour

by rope-pulled machines decreases the cost disadvantage from manual vineyard management at steep sites compared to flat vineyard management by approximately 20 % (Strub and Mueller Loose, 2021). However, the investment costs for the specialised machines add to the financial budget of the wine estate. Additionally, rope-pulled machines have to pass every vineyard alley twice. Thus, there is a reduced efficiency in certain management practices, since the rope has to be winded up before moving the machine to the next row pending in cultivation. Furthermore, this system requires an appropriate infrastructure (i.e. sufficiently wide and paved access paths) and may not contribute to the solution of the soil erosion issue.

At the end of the 19th century, the efforts in vineyard management at steep slopes were almost equal compared to flat wine-growing areas due to the lack of mechanization. The quality advantage of grapes grown on steep slopes was reduced or made obsolete with every further development of technical innovations of self-propelled, tractor-drawn or tractor-mounted machines (Schrieck, 2016), even with the introduction of technical solutions explicitly created for steep slope viticulture (e.g. rope and winch systems).

The introduction of biologically stabilized, i.e. cover cropped, terraces began in Switzerland during the late 1960s using heavy machinery (the so called ‘Menzi-Muck’) and is still a common method for hill-side terracing (Siegfried et al., 2011). However, due to management and grape quality reasons the original system of multi-row terraces built on broad terraces was soon adjusted to small width terraces (approximately 1 m). These could be cultivated by hand and single axle machines; a system that is still popular in alpine wine-growing areas, due to new options in mechanisation (e.g. the Vitrac®) and the reduction of unexploited vineyard area (Hafner and Sinn, 2015). In earlier times, the vineyard area was the limiting factor of production. Despite the concerns of considerable losses in vineyard area (Stumm, 1985), a new method was used to create single-row vineyard terraces in the Ortenau wine-growing region (Baden, Germany; Königer, 1988) from the late 1970s onward. This innovation allowed narrow track tractors to pass and to cultivate the vineyard terraces more cost-efficiently (Jörger et al., 2008b).

This modern kind of vineyard terraces is constructed via a ‘cut and fill’ procedure: a caterpillar levels the first platform along the contour of the hill and compacts the soil in this process. An excavator forms the embankment with the tilting bucket. The caterpillar then uses the excavated soil to build the next terrace. The embankments are stabilized immediately by sowing a cover crop mixture afterwards, ideally comprising regional wildflower and grass seeds (Wersebeckmann et al., 2022). A single row of grapevines is then planted at an approximately 0.3 m distance from the edge of the platform (Figure 1).



Figure 1. A two-month old modern vineyard terrace. Vineyard transformation and vine planting was conducted in April 2021. Embankment cover crop seeds were sown in May 2021. Picture was taken in June 2021 at the Assmannshäuser Höllenberg in the Rheingau wine-growing region (Germany). The yellow auxiliary line displays the stair-like character of the transformed hill side.

This type of terrace combines the benefit of a higher degree in mechanisation, due to a broad, levelled platform suitable for narrow track tractors with the advantage of an increased infiltration of water as an effective measure of precipitation retention, thus erosion prevention. Economically, the main advantage arises from the length of the alleys and the reduced number of turning manoeuvres.

1.1 Particularities of steep slope viticulture

The German Wine Regulation § 34b (issued at 1st September 1995, recasted at the 21st April 2009) acknowledges the special characteristic of steep slope vineyard systems and specifies a vineyard as ‘steep’ or ‘terraced’, if the (initial) hill slope is not less than 30 %, and regarding the latter, the vineyard comprises a reinforcement by walls or cover cropped embankments, i.e. either a physical or a biological stabilization. Traditionally, the German wine promotion also highlighted the particularity of German steep slope vineyards due to its favourable microclimatic conditions during the late phase of berry ripening. Historically, when temperatures for grape-ripening were oftentimes sub-optimal at higher latitudes (e.g. 50°N), particular topographical conditions were required to fulfil the thermal needs of the grapevine to achieve grape berry maturity and to yield high quality grapes for prestigious wines (Hellman, 2003).

For example, in the middle of September, when the sun altitude becomes lower at the 50°N latitude, the amount of radiation at a 20° (approximately 36 %) inclined south-facing slope can be +129 % higher compared to a flat vineyard site (Hoppmann et al., 2017). Sechrist (2012) described the historical prevalence of the grapevine at the *Rheinlands*, i.e. the wine-growing regions along the Rhine river and its tributaries (Moselle, Main and Nahe), and highlights in particular, the suitability of the late-ripening (thus in terms of climate conditions rather demanding) Riesling grapevine cultivar in this regard. Inclined surfaces, in particular in South and South-West exposition, receive a higher amount of solar radiation (van Leeuwen, 2009). This extra amount of solar energy fulfilled the grapevine's requirement of a minimum 12 °C, frost-free, growing season temperature (Jones et al., 2012).

However, the well-irradiated steep vineyard sites, which once yielded prestigious wines, suffer under high production costs nowadays and furthermore, are competing with wines that can be produced 0.42 € L⁻¹ to 0.86 € L⁻¹ less expensively at fully-mechanized flat terrain vineyards (Strub and Mueller Loose, 2021). Additionally, there is also a decline in the consumers' knowledge of and appreciation for the formerly valued, but now unprofitable steep slope vineyard wines (Loose et al., 2017). The high costs of steep slope vineyard management led to a decline in steep slope vineyard area, which is strenuous to cultivate (Job and Murphy, 2006). For example, in the wine-growing regions of the Middle-Rhine valley and the Moselle, the steep slope vineyard area declined by 20 % to 30 % between 1999 and 2015 (Strub and Loose, 2016).

1.2 Steep slope vineyard transformation to terraces

For the successful creation of vineyard terraces, the (hydro-)geological conditions have to be considered. Drainage systems or the proper canalization of precipitation water shall be implemented, where necessary, to avoid waterlogging or gully erosion. The construction of vineyard terraces requires a minimum soil depth of 0.6 to 1 m to ensure a sufficient amount of soil mass for the formation of the terrace platform. Therefore, consulting the appropriate state agency, e.g. the Hessian Agency for Nature Conservation, Environment and Geology, before the planning and the construction of a terraced vineyard begins, may provide useful information about the suitability and stability of the terrain for the building of a vineyard terrace. The knowledge about the soil particle size distribution, the soil depth, the potential location of slide areas or underground watercourses of the site may prevent from a later collapse of the newly build terrace system (Wehinger and Spies, 2008).

The exact design of a modern vineyard terrace cannot be planned in the final detail in advance, since the construction depends on the given terrain structure. The machine operator of the

caterpillar carves the terrace steps by experience only, led by the natural shape of the hill. To successfully convert a vineyard into a terrace, the vineyard transformation has to be conducted in the early months of spring. From February to May an adequate soil moisture content can be guaranteed for soil compaction purpose. Additionally, the risk of frost, which may be detrimental to the terrace stability due to the development of soil cracks, is reduced as spring progresses. Warm spring temperatures additionally benefit the germination of the cover crop grasses and shrubs to rapidly establish a biological embankment stabilization.

Modern terraces are constructed for the purpose of mechanisation. Thus, the overall width of the terrace platform has to be a minimum of 2.1 m to use commonly available equipment for grapevine cultivation. Smaller platforms do not allow the use of narrow track tractors, they would require special machines or, in general, they limit the use of machinery. Consequently, the natural slope angle of the hill and the aspired platform width determine the terrace geometry, particularly, the height and the slope of the terrace embankments. Depending on the soil type, the exposition, the prevailing weather conditions and the degree of stabilization, vineyard terraces can be formed at slopes of 35 % to 60 %. The use of narrow track tractors or tracked vehicles, may be possible to an extent of 60 % slope, but require optimal soil conditions, i.e. dry soil, which may guarantee a good traction between tractor tire and soil. However, the risk of accidents increases with slope and even rope-pulled machines are not risk-free (Böhme, 2003).

In some cases, driveable terraces are built without fulfilling the static design criteria, i.e. with too high and too steep embankments. Oftentimes, the inclination of the embankments is therefore >100 %, which reduces the loss in vineyard area, but bares the risk of embankment instabilities. The friction angle of the soil of steep embankment slopes may be lower than the embankment angle. This may lead to soil slips and damages of the plants and the trellis system (Ramos et al., 2007). However, there is long-term experience on steep terrace embankments (inclinations >120 %; Porten and Treis, 2008), which highlights the importance of the individual soil and climate conditions for the successful transformation of vineyard terraces at the respective site.

Anyhow, the planting density is lower in terraced vineyards compared to vineyards planted down the slope. More specifically, the loss of vineyard area increases with the initial slope of the hill, since the embankment size (height and width) increases (Table 1).

Table 1. Theoretical calculations of the embankment geometry (height and width) in relation to the initial vineyard slope, the distance between rows and varying inclination of the embankment according to Jörger et al. (2008a).

Assumed vineyard metrics		Embankment parameters		
Initial slope (%)	Row width (cm)	Height (cm)	Inclination (%)	Width (cm)
35	400	140	100/110/120	140/127/117
40	400	160	100/110/120	160/145/133
45	400	180	100/110/120	180/164/150
50	400	200	100/110/120	200/182/167
55	400	220	100/110/120	220/200/183
60	400	240	100/110/120	240/218/200

Ultimately, the planting density in terraced vineyards may result in 2'800 to 3'500 vines per hectare or higher, depending on the initial hill slope (Porten and Treis, 2008).

In every second vine row, a turning plate of four to six meters (depending on machinery) has to be built and a cross-path can be useful for more efficient traffic. Additionally, if the slope of the terrain displays a high variation, the creation of short inter-rows may be necessary, which will cause a further loss in cultivatable vineyard area. Furthermore, the length of the newly created vine rows has to be considered to reduce turning manoeuvres. The machine use efficiency can be enhanced by row lengths of at least 60 m and may be optimized by a row length of 100 m and longer. To increase the number of grapevines per hectare, oftentimes narrow inter-vine distances, of approximately 0.6 to 0.7 m, are chosen to counter the potential loss in planting area.

The cost for trellising is lower compared to vineyards planted downslope (Porten and Hermen, 2022). Furthermore, subsidies for the restructuring of steep slope vineyards to terraces and the planting of the grapevines and the embankment cover crops approximately cover the cost for the heavy soil work, which is necessary for the construction of the vineyard terrace. The costs for the vineyard transformation depend on the site characteristics, and thus the construction effort can vary between 10'000 to 20'000 € ha⁻¹. The additional cost for cover cropping the terrace embankment may range between 2'000 and 4'000 € ha⁻¹.

Depending on the competent federal state of Germany the level of subsidisation, which is provided by direct payments, i.e. the first pillar of the common agricultural policy of the European Union, for a vineyard transformation to a terrace varies from 18'000 € ha⁻¹ (Baden-

Wuerttemberg¹) to 24'000 € ha⁻¹ (Hesse², Rhineland-Palatinate³ and Bavaria⁴). However, additional investment cost may be necessary for the acquisition of an embankment mower system.

The maintenance of the embankment requires a little extra workload of approximately 3 h ha⁻¹ to 8 h ha⁻¹ (Jörger et al., 2008a; Becker et al., 2017). However, vineyard terraces are limited to the use of multi-row machinery (e.g. sprayer for plant protection or hedging machines) and further require a pivoting arm for the device pole. Additionally, mechanical weed control may be difficult, due to narrow planting distances of the grapevines and due to the risk of damages at the edge of the terrace platform. Nevertheless, plough discs are also common to control under-vine weed growth in vineyard terraces, but the mode of action is single-sided. Lately, different weed brush models have been developed for the usage in modern terrace vineyard systems, which show satisfiable results to reduce or to renounce herbicides.

The replacing of single grapevines in existing terrace systems or even the uprooting and replanting of a whole terraced vineyard is feasible without damaging the edge of the terrace platform. During the procedure of a clearing of vineyard terraces, a potential re-levelling of the platform can be conducted by a rotary harrow or an excavator (Benz, 2022). The positive long-term experiences (>40 years) of commercial wineries and grape producers attest the suitability of terraces as a viable alternative for steep slope viticulture.

The terracing of steep slope vineyards is capable of lowering the cost for trellising and the reduction of working hours, but is limited by a reduced yield per hectare (Porten and Hermen, 2022). However, the terrace transformation is a useful solution to maintain valuable vineyard sites, where steep slope viticulture is economically unviable and where vineyards are therefore getting abandoned. Jörger et al. (2008b) lists several reasons in favour of the construction of (modern) terraces. Compared to steep slope vineyards, the work safety increases, while physical strains during the vineyard management (measured by pulse and blood lactate) decreases. Furthermore, important tasks of vineyard cultivation can be better performed on time. In addition to a potential increase in water retention and higher soil volume for root colonialization per plant, the prevention from soil erosion is mentioned as well. It is also stated, that the terrace embankments provide a habitat for xerothermophil plant and animal species and further, that the

¹ <https://foerderung.landwirtschaft-bw.de/pb/,Lde/Startseite/Foerderungswegweiser/Umstrukturierung+Rebflaechen>.

² <https://rp-darmstadt.hessen.de/umwelt-und-energie/landwirtschaft-fischerei-und-weinbau/weinbau/foerderung>.

³ https://mwv1w.rlp.de/fileadmin/mwkel/Abteilung_9_Weinbau/Weinbau/Dokumente/Umstrukturierung/Merkblatt_Teil_1_Stand_11052022.pdf.

⁴ <https://www.foerderdatenbank.de/FDB/Content/DE/Foerderprogramm/Land/Bayern/programm-zur-staerkung-des-weinbaus-teil-a.html>.

management system of modern vineyard terraces contributes to the preservation of cultural landscape comprising best vineyard locations (Jörger et al., 2008b; Porten and Hermen, 2022).

In short, modern terracing may be a viable solution to improve the costs of steep slope vineyard management, to prevent valuable agricultural area from abandonment, thus preserving the local history, the socio-culture and the jobs in traditional wine-growing regions. Furthermore, environmental benefits of a reduced erosion risk or the increase of structural elements in the landscape promote biodiversity in flora and fauna.

The most apparent result of the transformation of steep slope vineyards to terraces is the shape of the vineyard, i.e. the stair-like character including a change in row orientation (Figure 1). The intensive earthmoving results in altered soil conditions. The change in row orientation, by terracing, further affects the vineyard soil characteristics and various microclimate parameters, hence it affects the grapevine performance and, finally, a variety of berry quality parameters as well as the grapevine health status.

1.3 The effects of terrace construction on soil conditions

The construction of terraces can be considered as one of the most apparent anthropogenic intrusion on terrain morphology (Cots-Folch et al., 2006; Tarolli et al., 2014). The modification of hillsides considerably changes the soil chemical and physical properties. Ramos et al. (2007a) showed, that by the action of terracing and land levelling severe changes compared to the initial vineyard soil (or fallow) occur. In the course of terrace construction, deeper soil layers are displaced to the top, thus affecting the gravel size distribution, the soil pH and it further causes a shift of the soil organic matter from the top to the bottom (Ramos et al., 2007a). Michalsky (1976) describes, that the relocation of organic matter and soil nutrients, during the process of vineyard terracing, is equivalent to the relocation of the top soil and that the distribution of the soil pore volume is heavily influenced by potential preliminary bulldozer work. Soil movement by heavy machines and its compaction during the process of terrace construction may negatively affect the hydraulic conductivity, the water availability to the plant and the aggregate stability. Eventually, the soil's bulk density is likely to be increased due to terracing action (Cots-Folch et al., 2006). Chen et al. (2020) confirmed, that in the first five years after the terrace construction a detrimental impact on the soil structure, e.g. loss of carbon, occurs. However, after six years, terraces would be able to promote the build-up of soil organic content (SOC), which may also increase the water-holding capacity, may further improve additional soil physical parameters and may also benefit the plant's health. Hereby, the cultivated crop significantly influences the soil organic carbon sequestration, e.g. 38 % in orchards (Chen et al., 2020). Archaeologic studies of buried terrace

forms from the Bronze Age in the northeast of England showed, that terraces are able to conserve the topsoil-derived organic carbon better compared to non-terraced soils. This was linked to the prevailing environmental conditions, which led to lower microbial mineralisation rates, and a higher C:N ratio in the 'fill' part of the terrace (Zhao et al., 2021). Michalsky (1976) displayed, that different parts of the terrace show different soil temperatures, i.e. the soil of the terrace embankment was warmer than the platform soil. However, the soil warming in 25 cm and 50 cm depth of downslope planted vineyards was in general higher compared to terraces (Michalsky, 1976).

The construction of terraces and its, positive as well as negative, effects on the hydrological processes has been subject of several studies. On the one hand, terraces reduce the slope and the length of hillsides and the flat platforms comprise an increased soil volume, that favours the infiltration of precipitation in the same way as the reduction of runoff. On the other hand, a big focus has been put on soil erosion events in terraced vineyards, on its causes, but also on recommendations for an improvement in soil conservation (Tarolli et al., 2014; Arnáez et al., 2015; Pijl et al., 2019; Pijl et al., 2021). Collectively, Ramos and Porta (1997), Ramos et al. (2007b) and Camera et al. (2018) showed, that poorly maintained terraces bare the risk of gully and rill erosion, landslides or the collapse of dry-stone walls, when exposed to heavy rainfall events. The soil loss in terraces fortified by vegetation is quantified up to $10.95 \text{ Mg ha}^{-1} \text{ y}^{-1}$, which only makes up for approximately a third of the amount of the annual erosion compared to a downslope planted vineyard (Bagagiolo et al., 2018; Pijl et al., 2020). However, the degree of mechanisation (Pijl et al., 2019) and vegetation cover (Bagagiolo et al., 2018; Rodrigo-Comino et al., 2019) as well as the arrangement of cross-paths and of access roads strongly influence the amount of soil particle movement and surface runoff (Tarolli et al., 2015). Additionally, Ramos et al. (2007b) showed, that with an increase in the height of the terrace embankment, the mass movement increases exponentially. Effective measures to reduce erosion are the construction of well-built terrace systems to reduce flow velocity and to guarantee the proper drainage of precipitation water. This may include structural installations like sediment traps and the implementation of cover crops, as well as an site- and weather-adapted vineyard management regime (Pijl et al., 2020).

Grapevines planted at the external edge of the terrace, i.e. the valley-facing side of the platform, gain a higher soil volume compared to vines planted downslope, since the 'cut and fill' procedure shifts the soil mass to the front section of the platform (Cucchiaro et al., 2021). The increase in soil volume and the levelling may also increase water storage capacity of the vineyard soil. However, the evaporation of the terrace embankments may account for about one-third of the

water loss of the terrace (Lü et al., 2009), resulting from a high sun-exposed surface, which requires cover crop for stabilization, additionally competing with the grapevine. For this reason, Michalsky (1976) observed, that vineyards planted downslope had slightly higher soil moisture values compared to the terraced treatments. By modelling the soil water content (SWC) of a double-rowed terrace and a downslope planted vineyard Oliveira (2001) calculated a slightly higher SWC in the downslope planted vineyard system (+28 mm during flowering and +10 mm during véraison) compared to the terraced treatment. From véraison to harvest, the two systems evaluated did not differ in SWC (Oliveira, 2001). However, by comparing different designs of steep slope vineyard systems in northern Italy, Pijl et al. (2022) awarded ‘contour terracing’, which is equal to modern terraces, as the system which showed the highest potential of retaining soil water on the site. The system, of ‘contour’ or modern terracing, comprising narrow platform widths, has the benefit of rather small embankments between two vine rows planted along the contour of the hill, thus the reduction of evapotranspiration due to grapevine canopies which would provide shade to the terrace platform and, depending on the platform width, to the embankment behind (Pijl et al., 2022).

By a slight incline of the platform, either toward or away from the uphill side, it is possible to lead precipitation water either towards the grapevine at the edge of the platform or to the foot of the embankment. The benefit of water accumulation at the hill-side of the platform may be the retention of water and the slow drainage into the platform as well as the incentive for the grapevine to grow away from the highly exposed embankment. In longer terms, this may reduce water and nutrient competition to the embankment cover crop, but also bares the risk of surface runoff, if the soil is not capable to retain higher amounts of precipitation. The desirable development of an evasive grapevine root growth pattern could be also achieved with a subsoil irrigation system located at the foot of the embankment or drainage channels (Smart et al., 2006). Complementary, an inclination towards the valley may increase the risk of soil erosion and embankment failures (Crosta et al., 2003; Tarolli et al., 2015; Pijl et al., 2020). Furthermore, the risk of late-frost damage on the grapevine might be increased. Even though, the katabatic flow of cold wind down the slope may be supported by a valley-facing inclination, grapevines planted at the edge of the terrace platform and tall-growing embankment vegetation may act like semi-natural impediments, which may hold back the cold air and lead to damage on young grapevine shoots (Evans, 2000).

1.4 The influence of vineyard row orientation on the grapevine

Compared to the initial direction of the vineyard rows (planted down the slope), terraces are planted approximately orthogonal, i.e. along the contour of the hill. This means, that a vineyard transformation to a terrace always implies a change in the row alignment. At the northern

hemisphere, vineyards are usually located on south-facing hills. Therefore, the row orientation of a downslope planted vineyard is N-S and the row orientation changes during the terrace transformation process to an E-W direction. If the original downslope orientation of a vineyard is NE-SW, then the terrace alignment will be in NW-SE direction. Of course, due to orographic heterogeneities or a customization in favour of an improved work management, some degree in variation of the row alignment may be possible.

Presently, information about the impact of row orientation changes in steep slope terrain is rare. However, the impact of row orientation changes on the grapevine microclimate, the grapevine performance and the health status as well as on a range of fruit quality-determining parameters has been elaboratively studied in vineyards located on plane land.

1.4.1 The impact of row orientation on the grapevine microclimate

The canopy microclimate is defined as the interaction of the soil, the climate and the viticultural decisions, which are affecting the exposure of foliage and the fruit of the grapevine (Smart et al., 1985). The distance between the soil and the shoot tip is significantly influenced by the solar radiation, which has a direct impact on the air temperature and the (relative air) humidity in and around the grapevine canopy, which comprises a section of approximately 2 m in a common German vineyard systems (Hoppmann et al., 2017).

Hunter et al. (2016) described the light microclimate in a row orientation-trial comprising N-S, E-W, NE-SW and NW-SE alignment in a flat vineyard in South Africa. Within the progress of a developing canopy, the photosynthetically active radiation (PAR) was lowest in the bunch zone of grapevines planted in E-W orientation. However, the share of the total radiation reflected from the soil during the late ripening period was highest in the bunch zone of this E-W row orientation compared to the others (Hunter et al., 2016). Row orientations shifted by 45° and 315° (NE-SW and NW-SE, respectively) showed irradiation peaks either in the afternoon or in the morning, while in the N-S row orientation canopy sides were balanced illuminated during the course of the day (Hunter et al., 2016).

The N-S row orientation has long been recommended to viticulturists for the purpose of a more symmetrically, thus a more efficient capture of the sunlight (Smart, 1973; Hunter et al., 2016; Zorer et al., 2017), which should guarantee optimal photosynthesis and ensure a more even ripening of the berries, despite an intensified afternoon radiation. Campos et al. (2017) further highlighted the advantage of the N-S and the NE-SW row directions at the latitudes 40°N and 50°N regarding assimilation efficiency. The PAR absorption of those two row orientations, namely of the E- and the NE-side of the canopy, was significantly higher during the morning

hours compared to the canopy sides of the E-W and NW-SE alignment of the vines (Campos et al., 2017).

The E-W oriented vine rows show the most unbalanced distribution of sunlight, since one side of the canopy is shaded for almost the whole day, thus only receiving a small amount of (indirect) irradiation, while the other side is being directly radiated constantly from morning until evening (Hunter et al., 2020). This may result in large differences in temperatures between the canopy sides and the irradiated soil during the ripening period (Wang et al., 2022). The NE-SW and the NW-SE row orientations showed similar, but mirrored values of incoming radiation, more specifically a diurnal variation in the radiation patterns of UV-A, UV-B and PAR, for the respective canopy sides of the two row orientations (Grifoni et al., 2008; Hunter et al., 2020).

The sun irradiation is linked to (leaf and berry) surface heating, which can be reproduced by shading experiments (Reshef et al., 2018). Friedel (2018) recorded the highest sunburn incidences on berries on the W-side of a N-S oriented vineyard within a row orientation trial in Geisenheim, Germany. Maximum temperatures recorded on the W-side of this vineyard setup reached a higher temperature of approximately 15 °C (i.e. 43 °C_{max}) during the afternoon of an early September day compared to the E-side of the canopy (Friedel et al., 2012). The sunlit side of the E-W oriented grapevine canopy (the S-side in vineyards of the northern hemisphere) is exposed to sunlight most of the day, thus showing the highest daily mean temperatures; but the highest maximum temperatures occur on the W-side of the N-S oriented vineyard rows (Gambetta et al., 2020b). Lately, other row orientations than N-S, namely the E-W and the NW-SE or at least adaptive means, have been recommended to winegrowers in warm to hot and sunny climates at the southern hemisphere to prevent losses in yield and quality caused by berry heating due to intense sun irradiation (Dry, 2009).

A distinct microclimate evolves under sunny conditions with wind speed smaller 2 m s⁻¹ (Horney, 1975). Wind additionally affects performance, growth and berry quality of the grapevine, directly and indirectly, e.g. by mechanical perturbation of the shoots or the cooling and drying of soil and leaves (Jagoutz, 2004; Tarara et al., 2005). Depending on the prevailing wind direction, the vines may be sheltered by neighbour rows, as shown by Heilman et al. (1994). Depending on planting density and vineyard row orientation the reduction in wind speed would affect the energy balance (Heilman et al., 1994), thus the evapotranspiration of a vineyard (Galleguillos et al., 2011). Hunter et al. (2016) recorded different wind velocities under different row orientations and development stages of the grapevine and highlighted the importance of row orientation considerations regarding prevailing winds to the vegetative grapevine development, the yield and the berry health. Complementarily, despite higher wind velocity, the E-W orientated rows tended to have

higher relative air humidity during morning periods, compared to the other row orientation treatments (Hunter et al., 2016).

Low relative air temperature affects assimilation negatively and reduces leaf growth (Keller, 2020). High humidity (i.e. >90 %) may be conducive for the development of fungal diseases like *Plasmopara viticola* (downy mildew) or *Botrytis cinerea* (grey rot), two major threats in grape production (Mohr, 2012).

1.4.2 The impact of row orientation on the grapevine performance and health

Altered microclimatic conditions, i.e. irradiation, temperature, relative air humidity and wind profiles, may result in an altered grapevine development and the susceptibility to biotic and abiotic stressors. As described previously, canopy sides that receive sudden and excessive amounts of direct sun irradiation may suffer from a higher sunburn incidence of clusters. However, leaf characteristics are also affected by different light regimes.

On a SW-exposed canopy in the Douro wine region, Moutinho-Pereira et al. (2003) showed the adaption of well-exposed leaves of *V. vinifera* cv. Touriga Nacional to sunlight by a higher specific leaf weight and lower leaf contents of chlorophyll and carbohydrates. In a Brazilian vineyard, significantly higher leaf starch and a tendency to higher contents of chlorophyll were found in N-S oriented grapevine rows compared to E-W aligned vines. Additionally, higher pruning wood and cluster weights in the N-S oriented vineyard, but no difference in the yield per vine was detected compared to the E-W orientation (Souza et al., 2019). The factor of row orientation showed an effect on the dry matter of leaves and canes of spur-pruned Sangiovese canopies in Italy, but did not affect vines trained in a free cordon management system (Intrieri et al., 1999). Contrarily to the Brazilian study, E-W planted vines were more vigorous compared to the N-S oriented vines; however, no distinction was made between canopy sides in the results presented (Intrieri et al., 1999). Likewise, the E-W aligned vineyard rows in a South African vineyard tended to show the highest vigour compared to other row orientations (namely N-S, NE-SW and NW-SE). In particular, the shaded side of the E-W canopy had the biggest leaf mass of primary and secondary shoots as well as the highest berry mass and berry volume (Hunter et al., 2017). But in general, differences in vegetative growth parameters between canopy sides and row orientations were small (Hunter et al., 2017).

In the same South African vineyard, located on the southern hemisphere, the leaf water use efficiency (WUE; calculated as the ratio of the rate of assimilation to the rate of transpiration) was the highest on the during the day well-exposed canopy sides, i.e. N, NE, NW and E (Hunter et al., 2016; Hunter et al., 2020). Inconsistent results were found for potted grapevines. A row

orientation trial comprising potted Chardonnay plants, which were grown in a plastic chamber in Italy, showed, that during the mid of the day the N-S oriented vines benefited from a reduced transpiration, thus an increased WUE (Intrieri et al., 1998). However, it could not be generalized that a N-S row orientation would improve WUE. Because contrarily, potted *V. vinifera* cvs. Bobal and Verdejo arranged in an E-W orientation displayed a lower relative water use per canopy area and day compared to the N-S oriented plants (Buesa et al., 2017). Here, the WUE was calculated by the ratio of yield to the plant's water consumption, therefore no direct comparison to the Italian study can be made. However, a tendency of a higher yield to water use ratio was shown for the E-W positioned vines, which was explained by a higher photosynthesis and transpiration rate of the N-S aligned vines during the afternoon (Buesa et al., 2017).

A limitation in water affects photosynthesis negatively. Regarding the water availability, the vines of the E-W oriented vineyard rows experienced less drought stress compared to the N-S, NE-SW and NW-SE oriented treatments (Hunter et al., 2016), although higher soil temperatures and a faster depletion of SWC were observed in the South African study under semi-arid conditions (Hunter et al., 2020).

1.4.3 Effect of row orientation on berry composition of the grapevine

The composition of a grapevine berry is affected by its position at the cluster and the canopy, thus its exposure to the environment, e.g. sun irradiation (Pieri et al., 2016; Reshef et al., 2017; Reshef et al., 2019). During the day, the irradiation intensities influence the ambient temperature as well as the berry temperature, which may modify the fruit metabolism, thus a variety of berry quality-determining parameters, e.g. sugars, organic acids and secondary metabolites. Additionally, during the grapevine growing season light conditions are altered by seasonal changes and spatial variations due to the canopy development. Several studies focused on the analysis of grapevine berry concerning the comparison of different row orientations or different canopy sides of vineyards planted on plane land.

The impact of the cluster position on the composition of Welschriesling grapes was analysed in a Chinese study. Lu et al. (2021) found a lower content of total soluble solids and a lower berry weight in berries positioned on the W-side of the canopy, compared to the E-side. Furthermore, the amount of total skin flavonols and the abundance of aroma compounds in the juice was less in berries located on the western side of the canopy compared to those ripened on the east-facing side (Lu et al., 2021). In the same study, cluster location as well as row orientation comparisons were conducted on Cabernet Sauvignon berries. Berries located on the W-side of the canopy showed a higher total titratable acidity, and higher amounts of herbaceous aroma compounds

compared to the E-side of the canopy. Regarding the row orientation, total soluble solids, flavanols and C6/C9 aroma compounds were significantly higher in the E-W oriented vine rows compared to those aligned in N-S direction.

Likewise, Wang et al. (2022) investigated a higher diversity in the volatile aroma compounds in another E-W oriented vineyard in China compared to grapevines planted in N-S orientation. However, the technological maturity was more advanced in the N-S oriented rows, since berries were riper regarding sugars, total titratable acidity and flavonoids, e.g. acylated anthocyanins.

The influence of row orientation on Shiraz berries, juice and wine composition was the subject of an investigation in a South African long-term row orientation trial. The studies conducted took different stages of ripening into consideration, which showed varying impact on quality-determining fruit parameters. To sum up, the NE-SW and NW-SE row orientations as well as the canopy sides which received moderate light and accumulated less heat during the day, especially in the afternoon hours, grew the most favourable grapes for wine-making purposes (Hunter and Volschenk, 2017; Hunter et al., 2021; Minnaar et al., 2021).

The composition of Riesling grapes in the Rheingau wine-growing region, Germany, was investigated by Friedel (2018). It was shown, that well-exposed berries were lower in flavanols, amino acid nitrogen, malate and total titratable acidity, but higher in flavonols and monoterpenes (Friedel et al., 2016). Furthermore, sun-exposed leaves had higher content of nitrogen, phosphorous and calcium compared to leaves grown on the shaded side of the canopy (Friedel, 2018).

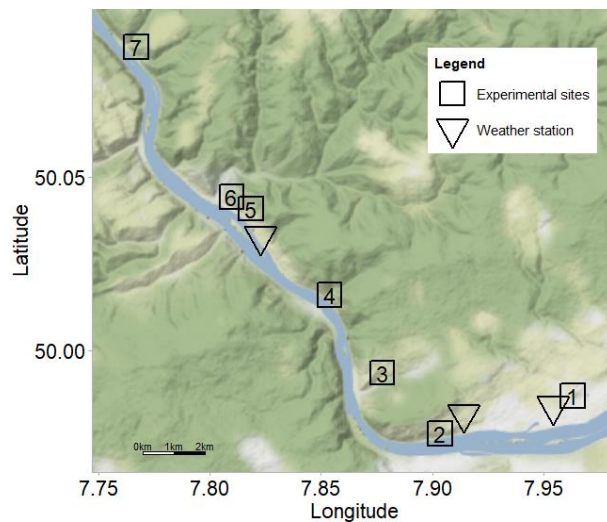
The studies mentioned investigated row orientation characteristics on flat vineyard sites. Therefore, not all findings may be directly transferred to row orientation changes on steep slopes, i.e. terraces, since the vineyard geometry and the (solar) energy input differ substantially between flat and steep slope sites. Most of the row orientation experiments depicted above were conducted on red grape varieties, displayed divergent growing conditions (i.e. a high elevation or a tropical climate) or where located at the southern hemisphere.

To the best of the authors knowledge, there is currently no peer-reviewed study available, which covers the broad range of the topic of row orientation changes on steep slopes, i.e. the impact of terracing on the microclimate, the grapevine's vegetative and generative performance and its fruit composition. Even though modern terraces were subject of vivid discussions in the past fifty years and many benefits are attributed to this steep slope management system, there is still little holistic literature available, hence many questions on important viticultural issues still remain unanswered.

1.5 General objectives

This doctoral thesis aimed to investigate the effects of a management system change in steep slope vineyards. At first, the impact of the changes in vineyard geometry, due to the formation of modern terraces, on i) the microclimate, ii) the soil water dynamics and iii) its effects on the grapevine's vegetative and generative performance was examined by comparing, *inter alia*, the effect of the inherent row orientation change of the respective management system studied. Secondly, the divergent microclimatic effects of different canopy sides of a row orientation are subject of the work presented here.

The experimental design comprised seven vineyard pairs (Figure 2), each consisting of a vineyard according to the standard cultivation method of vines planted downslope (control, C) and a terraced vineyard system (T). The vineyards were located in the Rheingau and the Middle Rhine wine-growing regions, Germany. Three *V. vinifera* L. cultivars were included in the study (Cabernet Sauvignon, Pinot Noir and Riesling; Table 2).



The vineyards were maintained by six commercial wineries, which were following their own vineyard management schemes. However, applied means were in accordance to the Code of Good Agricultural Practice. Differences in the vineyard management between treatments

Figure 2. Locations of experimental sites (squares) and reference weather stations (triangles) along Rhine River. The two treatments (C and T) were in next possible proximity to each other. Numeration of sites: 1 = GM = Geisenheimer Rothenberg; 2 = RB = Rudesheimer Berg Rottland; 3 = AS = Assmannshäuser Höllenberg; 4 = LB = Lorcher Bodental; 5 = LS = Lorcher Sesselberg; 6 = LE = Lorcher Eisersgrube; 7 = K = Kauber Burg Gutenfels. Map data source: Google Maps Platform.

are partly owed to the cultivation system itself. The selection criteria of the experimental sites were the next possible proximity of the two treatments (namely the downslope planted vineyards and the terraced vineyards) to each other and the same planting material (variety and rootstock) in both of the treatments at one site.

During the experimental years, all vineyard management practices and experimental realizations were made under a close consultation with the managers of the respective wineries.

Table 2. Geometric parameters and planting information of the vineyard sites (GM = Geisenheimer Rothenberg; RB = Rudesheimer Berg Rottland; AS = Assmannshäuser Höllenberg; LE = Lorcher Eisersgrube; LS = Lorcher Sesselberg; K = Kauber Burg Gutenfels) and treatments (C = control, downslope planted vineyard; T = terraced vineyard). Due to non-complete data records of the initial plantations differences in clones of the varieties were not taken into account.

Site	Treatment	Vineyard characteristics								Embankment geometry			Planting information		
		Row orientation	Exposition	Slope	Alley width (m)	Planting distance (m)	Planting density*	Distance to crown (m)	Platform width (m)	Length (m)	Height (m)	Width (m)	Variety	Rootstock	Year of planting
GM	C	N-S	S	36 %	1.40	1.00	7143	-	-	-	-	-	White Riesling	5C, 3309C	1971
	T	E-W	S	36 %	2.00	0.70	3968	0.30	2.30	1.20	1.50	1.18	White Riesling	5C	1974
RB	C	N-S	S	40 %	2.00	1.00	5000	-	-	-	-	-	Cabernet Sauvignon	SO4	2012
	T	E-W	S	50 %	2.00	0.70	3663	0.30	2.30	2.60	2.00	1.13	Cabernet Sauvignon	SO4	2012
AS	C	N-S	S	40 %	1.80	1.00	5556	-	-	-	-	-	Pinot Noir	unknown	1993
	T	E-W	S	46 %	2.30	0.70	3663	0.30	2.60	2.30	1.50	1.2	Pinot Noir	Börner	2013
LE	C	NE-SW	SW	40 %	2.00	1.10	4545	-	-	-	-	-	White Riesling	Börner	2008
	T	NW-SE	SW	45 %	2.30	0.60	4762	0.30	2.60	2.10	1.60	1.41	White Riesling	Börner	2013
LS	C	NE-SW	SW	40 %	2.00	1.20	4167	-	-	-	-	-	White Riesling	Börner	2001
	T	NW-SE	SW	40 %	1.80	0.70	3861	0.30	2.10	1.90	1.50	1.27	White Riesling	Börner	2008
K	C	NE-SW	SW	60 %	1.40	0.80	8929	-	-	-	-	-	Pinot Noir	SO4	2008
	T	NE-SE	SW	36 %	1.50	0.90	4274	0.00	1.50	1.80	1.20	1.21	Pinot Noir	SO4	2008

*The planting density (vines ha⁻¹) is a theoretical estimation calculated by the distance of the vineyard rows × the distance between the single grapevines

Consequently, the following studies presented do not correspond to a meticulously prepared experimental design, but represent an investigation under conditions of common viticultural practice. However, the experiments were set up with the objective of a comparative analysis between the management systems. So, the evaluations conducted were applied with the aim of a general description of the two steep slope management systems.

Under these considerations, the following hypotheses were tested in the set framework:

H_I: Vineyard terracing affects the canopy microclimate and leads to lower temperature parameters and a more favourable canopy irradiation (Chapter 2).

H_{II}: The change in row orientation by vineyard terracing affects the irradiation of the bunch zone, thus improves the berry composition and reduces the incidence of sunburn damage of *Vitis vinifera* L. cv. Riesling (Chapter 3).

H_{III}: Vineyard terracing improves the retention of precipitation, resulting in a higher water availability, thus a lower drought stress response (Chapter 4).

Depending on the research question and the feasibility of data acquisition, a selection of the experimental vineyards was conducted at various sites (Figure 2). All seven vineyard pairs were chosen for the characterisation of the microclimate of the two steep slope vineyard systems (Strack et al., 2021). Whereas only the Riesling vineyard sites (1, 5 and 6) were selected to investigate the impact of row orientation changes and grapevine canopy sides on the composition of the grapes (Strack and Stoll, 2021). For the investigation of the soil water dynamics and the observation of drought stress response, the vineyard pairs 1, 2, 5 and 6 were used (Strack and Stoll, 2022).

For further information regarding the vineyard setup, the material and the methods, the reader may be referred to the respective following Chapters II – IV.

Chapter II: Impact of steep slope management system and row orientation on canopy microclimate. Comparing terraces to downslope vineyards

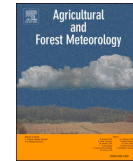
This chapter has been published as:

Strack, T.; Schmidt, D.; Stoll, M. (2021). Impact of steep slope management system and row orientation on canopy microclimate. Comparing terraces to downslope vineyards. *Agric. For. Meteorol.* 2021, 307, 108515. <https://doi.org/10.1016/j.agrformet.2021.108515>.

Author Contributions

Conceptualization: T.S. & M.S.
Data curation: T.S. & D.S.
Formal analysis: T.S. & D.S.
Funding acquisition: M.S.
Investigation: T.S.
Methodology: T.S. & M.S.
Project administration: M.S.
Resources: M.S.
Supervision: M.S.
Validation: M.S.
Visualization: D.S.
Writing – original draft: T.S.
Writing – review & editing: M.S. & D.S.

All authors have read and agreed to the published version of the manuscript.



Impact of steep slope management system and row orientation on canopy microclimate. Comparing terraces to downslope vineyards

Timo Strack^{a,*}, Dominik Schmidt^b, Manfred Stoll^a

^a Department of General and Organic Viticulture, Hochschule Geisenheim University, Von-Lade Straße 1, Geisenheim 65366, Germany

^b Department of Modeling and Systems Analysis, Hochschule Geisenheim University, Von-Lade-Straße 1, Geisenheim 65366, Germany

ARTICLE INFO

Keywords:

Canopy temperature
Radiation interception
Terraced vineyard
Bayesian linear mixed effect model

ABSTRACT

Historically and under cooler climate conditions, steep slope vineyards yielded best quality wines and highest reputation, due to their distinctive microclimate, especially during ripening period. Nevertheless, steep slope vineyard sites primarily suffer from reduced competitiveness leading to abandonment, thus a loss of valuable vineyard sites. The aim of this work was to investigate differences in microclimatic conditions between different steep slope vineyard management systems and row orientations. Records of inner canopy microclimatic parameters were taken over two consecutive vegetation periods including seven vineyard pairs. A Bayesian mixed effect model was used to properly account for the complexity of the conducted experiment. Additionally, irradiation and canopy surface temperature data was compared. Grapevines planted downslope (control) exhibited a more even light distribution on canopy sides. Contrarily, at terraced vineyard sites canopy sides showed big differences regarding light interception, also affecting diurnal canopy surface temperature. Differences in N-S/E-W row orientation comparison were more pronounced compared to vineyard pairs aligned NE-SW/NW-SE. Night temperatures were slightly higher in terraced vineyards, while daily mean and maximum temperature and temperature amplitude were higher in vineyard rows planted in line of the greatest slope. While a treatment effect was not always clearly visible, an impact of row orientation on temperature microclimate was observed. Differences between treatments may become more pronounced under projected climate change conditions with consequences on physiological processes, thus grapevine performance influencing berry composition.

1. Introduction

Vineyard microclimate is described by solar radiation, temperature, humidity as well as wind speed. Those meteorological variables determine fruit composition and latter wine profile, hence play a crucial role in steep slope viticulture. Historically and under cooler temperature conditions grape maturity was only achieved on climatically favourable steep slope sites where grapevines did not compete with arable crops on plain fertile fields (Petit et al., 2012). Topography (i.e. altitude, slope inclination and exposure) significantly influences the distribution of direct sunlight and wind, affecting temperature and humidity of the canopy (de Ressaiguier et al., 2020). The energy input in a vineyard during the growing season increases with slope, especially in S and SW exposition. Notably during the late ripening phase in autumn when solar altitude is low, steep slope vineyards receive up to 30 to 40 % more solar energy, compared to flat vineyards (Hoppmann et al., 2017; Jagoutz, 2005), amending the aroma profile of the berries. In addition to solar

radiation and temperature, water availability also has a major influence on grapevine performance in steep slopes (Hoppmann and Schaller, 1981). Still, higher amounts of solar radiation lead to an increase in potential evaporation, which, in combination with shallow soils, may lead to a higher risk of water deficit (Hofmann et al., 2014). For S-facing steep slopes with an angle of 30° the mean daily potential evaporation can be higher by 0.5-0.8 mm/day during the vegetation period compared to flat vineyards (Hofmann and Schultz, 2015). In addition, steep slope viticulture suffers competitive disadvantages. On the one hand, soil depth and field capacity are usually low at steep terrain leading to a higher susceptibility to stress, further decreasing yield. On the other hand production costs are generally higher compared to fully-mechanized flat vineyard sites (Strub et al., 2020). A decline in steep slope vineyard area can already be observed in German grape growing regions, i.e. approximately 30 % in the Mosel region over the last thirty years (Stoll and Schultz, 2021). The abandonment of xero-thermic steep slope cultivation sites, mainly caused by economic

* Corresponding author.

E-mail address: timo.strack@hs-gm.de (T. Strack).

<https://doi.org/10.1016/j.agrformet.2021.108515>

Received 15 April 2021; Accepted 6 June 2021

0168-1923/© 2021 Elsevier B.V. All rights reserved.

reasons, does not only mean a loss of historically important vineyard area and of sites of highest biodiversity value (Maixner et al., 2012), but also affects the aesthetic appearance of mountainous regions and their local socio-culture, thus magnifying economic issues for regions heavily dependent on tourism (Job and Murphy, 2006). Concepts of keeping steep slope viticulture economically viable include the formation of terraces (Strub and Mueller Loose, 2021). Since the early 1970s the suitability of grapevine cultivation for wine production on terraces has been evaluated. Results were not always unambiguous, since soil type and texture, the exposition and slope inclination mainly affect the ability to convert into terraces (Michalsky, 1976). Even though terraced vineyards bear a lower risk of erosion and may better hold back precipitation, especially young vines prior to full adaptation planted on terraces may suffer from the competition for water due to higher evapotranspiration, resulting from a higher exposed surface of the embankments, which further requires cover crop to stabilize the small slope (Preuschen, 1977). However, changing row orientation is an effective measure for manipulating microclimatic conditions on a long-term base. A change in row alignment in flat terrain is known to alter microclimatic parameters affecting grapevine, namely incident solar radiation and photosynthetic active radiation (Campos et al., 2017; Grifoni et al., 2008; Hunter et al., 2020) which influences grapevine organ temperatures (Friedel, 2018), it alters the wind flow (Tarara et al., 2005) as well as the relative air humidity in the bunch zone (Hunter et al., 2016).

Today, a modern kind of vineyard terraces is being constructed via a 'cut and fill' procedure: a caterpillar levels the first platform along the contour of the hill and compacts the soil in this process. An excavator forms the embankment with the tilting bucket. The caterpillar then uses the excavated soil to build the next terrace. The embankments are stabilized immediately by sowing a grass mixture afterwards. A single row of vines is planted at 0.3 m distance from the edge of the platform.

The objective of this study was to compare the microclimatic conditions of steep slope vineyards aligned downslope versus terraces to gain a better insight in the complex interaction of grapevine performance.

2. Materials and methods

Seven vineyard pairs, each consisting of a vineyard according to the standard cultivation method of vines planted downslope (control, C) and a terraced vineyard system (T) were selected along the Rhine River to characterize microclimatic conditions of grapevine canopy. The experimental sites are located in the Rheingau and Middle Rhine valley wine growing region in Germany (see Fig. 1).

2.1. Site description and experimental design

The maximum linear distance of the experimental sites is approximately 18 km. In consideration of the limited number of terraced vineyards in the region vineyard pairs were selected by two criteria: variety and the next possible proximity of the two different managed treatments to each other. Vineyard pairs shared the same *Vitis vinifera* L. cultivar. The vines of both treatments were all trained using vertical shoot positioning (VSP), with a single guyot comprising 6-8 buds per m². Row spacing ranged from 1.4 m to 2 m among the control treatments, depending on vineyard age and feasibility to mechanization. Vine space ranged from 1.2 m² to 2.2 m². Since geometry of terraced vineyards (T) is mainly affected by topography (i.e. hill slope and length, soil depth and structure) and type of mechanization, the geometrical parameters differed (see Table 1).

2.2. Mesoclimatic conditions

Vegetation period temperatures of 2019 and 2020 were above average compared to the three-decade average of 1981-2010 (Table S1 and Fig. S1). In 2019 growing season started with hot and dry weather

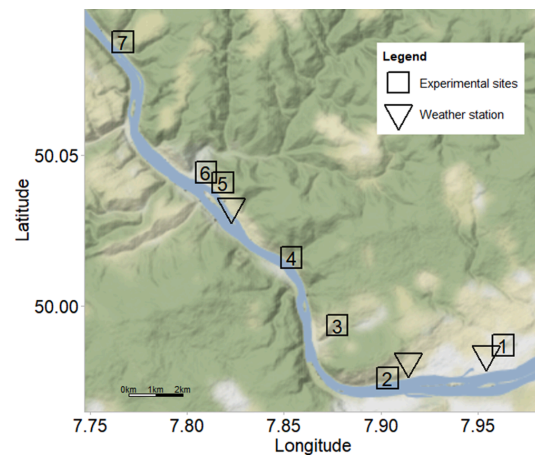


Fig. 1. Locations of experimental sites (squares) and reference weather stations (triangles) along Rhine River. The two treatments (C and T) were in next possible proximity. Numeration of sites: 1 = GM = Geisenheimer Rothenberg; 2 = RB = Rüdesheimer Berg Rottland; 3 = AS = Assmannshäuser Höllenberg; 4 = LB = Lorcher Bodental; 5 = LS = Lorcher Sesselberg; 6 = LE = Lorcher Eisersgrube; 7 = K = Kauber Burg Gutenfels. Map data source: Google Maps Platform.

conditions from April to October (2.6°C higher compared to the long-term average) little amount of rain fell since July 2018 (rainfall deficit of -13.5 %; sunshine hour surplus of 28 %). In 2019 rainfall was 13.3 % less compared to the long-term average and had an increase of 19 % in sunshine hours. When compared to the long-term average, in 2020 precipitation was 23 % less, while the amount of sunshine hours increased by 21 %. Each month showed warmer mean temperatures compared to the long-term average, except the month of May, both in 2019 and 2020. For 2019 and 2020 there was an annual temperature increase of 1.3°C and 1.7°C, respectively. In general, bud burst was about one week advanced in 2019 and about two weeks earlier in 2020 (DOY 102), being the second earliest bud burst date for Riesling since the beginning of weather records (1955) in the Rheingau grape growing region (data source: Regierungspräsidium Darmstadt, Dezernat Weinbau, Eltville). Flowering was only two days in advance in 2019, but two weeks earlier in 2020. Temperatures in June and July were higher in 2019 compared to 2020 (+2.7°C and +0.9°C, respectively), but spring and autumn months showed higher average temperatures in 2020 (April +1.6°C, May +1.4°C, September +1.4°C). Data from the three weather stations 'Hochschule', 'Rüdesheim' and 'Lorch' were used and linked to the seven sites based on local proximity as follows: Hochschule = GM; Rüdesheim = RB, AS; Lorch = K, LE, LS, LB.

3. Assessment of microclimatic parameters

3.1. Inner canopy physical parameters & statistical approach

During the vegetation period of 2019 and 2020 three data loggers (EL-USB-2; Lascar Electronics Ltd., Wiltshire, UK) per site and treatment recorded air temperature (°C) and relative air humidity (%) in five minute intervals at bunch zone height (approx. 1 m above ground). Prior to the experiment the measuring accuracy was evaluated by comparing the temperature data measured in a controlled environment at 15°C, 30°C and 40°C. Mean variance among tested sensors was 0.06°C with a maximum variance of 0.28°C for temperature and 2.61 and 4.79 % for the variance of relative humidity records. According to manufacturer specifications measurement accuracy of the sensor was ±0.5°C and ±3.5 %, repeatability was ±0.2°C and ±0.2 % for temperature and

Table 1
Geometric parameters and planting information of the vineyard sites.

Site	Treatment	Row orientation	Exposition	Initial slope	Alley width (m)	Vineyard characteristics		Platform		Embankment		Planting information	
						Planting distance (m)	Planting density* (vines/ha)	Distance to crown (m)	Width (m)	Length (m)	Height (m)	Width (m)	Variety
AS	C	N-S	S	40%	1.8	1	5556	-	-	-	-	Pinot Noir	1993
AS	T	E-W	S	46%	2.3	0.7	3663	0.3	2.6	2.3	1.7	Pinot Noir	2013
GM	C	N-S	S	36%	1.4	1	7143	-	-	-	-	Riesling	1971
GM	T	E-W	S	36%	2	0.7	3968	0.3	2.3	1.2	1.5	Riesling	1974
K	C	NE-SW	SW	60%	1.4	0.8	8929	0.8	-	-	-	Pinot Noir	2008
K	T	NW-SE	SW	36%	1.5	0.9	4274	0	1.5	1.8	1.2	Pinot Noir	2008
LB	C	NE-SW	SW	32%	1.6	0.8	7813	-	-	-	-	Pinot Noir	2008
LB	T	NW-SE	SW	38%	2.1	0.6	4630	0.3	2.4	2	1.6	Pinot Noir	2010
LE	C	NE-SW	SW	40%	2	1.1	4545	-	-	-	-	Riesling	2008
LE	T	NW-SE	SW	45%	2.3	0.6	4762	0.3	2.6	2.1	1.6	Riesling	2013
LS	C	NE-SW	SW	40%	2	1.2	4167	-	-	-	-	Riesling	2001
LS	T	NW-SE	SW	40%	1.8	0.7	3861	0.3	2.1	1.9	1.5	Riesling	2008
RB	C	N-S	S	40%	2	1	5000	-	-	-	-	Cabernet Sauvignon	2012
RB	T	E-W	S	50%	2	0.7	3663	0.3	2.3	2.6	2	Cabernet Sauvignon	2012

* Theoretical planting density at terraced vineyards calculated by row distance × vine distance; excluding turning plate and other technical necessities.

relative humidity, respectively. Data from local weather stations close to the study sites were used to assign global radiation and wind speed data to each site.

To compare the different row orientations, the median of each logger triplet was used to represent a single vineyard at each date. The difference of daily climatic parameters between C and T was calculated for each observation site. Since low global radiation and/or higher wind speeds affect possible differences in within-canopy measurements, data was split into subsets based on local wind speed × global radiation measurements. Intervals of 2 ms⁻¹ and 1.5 kWhm⁻² for daily average wind speed and daily sum of global radiation were used. Table 2 shows the observation dates per subset. Statistical analysis was only conducted for all subsets of wind speed × global-radiation with at least 50 observations (Table 2, bold letters).

For each subset a robust Bayesian linear mixed effect model with Student-t likelihood was set up. The factors row orientation-pair, season and year and their interactions were modelled as fixed effects while controlling for random effects and repeated measures by dates and sites. Furthermore, the model controls for heteroscedasticity between seasons, indicated by higher variability in summer and autumn, compared to spring. If a subset did not contain data for all factor levels, for instance, when higher global radiation values were only monitored in summer and autumn, the missing factor levels were dropped from the model. The models use weakly informative priors and run with four chains each with 4000 iterations including a warm-up of 2000 iterations, summing up to a total of 8000 post-warmup samples available for posterior predictions. Quality and convergence of the models were verified visually by comparing the posterior distributions with the data and monitoring of well-mixedness from trace plots of the Markov chains. Quantitative checks included controlling a Rhat measure of below 1.01 (Vehtari et al., 2020) and assuring the ratios of effective sample size (bulk and tail) to the total sample size to be consistently above 0.1 for all model parameters. In addition, the length of the Markov chains guaranteed adequate multivariate effective sample sizes (Flegal et al., 2020) for a Monte Carlo standard error of below 5 % for all models (Vats et al., 2019). Inference is then based on posterior model predictions for all fixed effect combinations only, estimating the median temperature and relative humidity difference between C and T, as well as the 50 and 89 % highest density intervals (HDI). In addition, the one-sided probability (later referred to as “probabilities” or “P”) was estimated to see if the difference is positive or negative (i.e. > 0 or < 0) or whether the difference is larger than 0.5 or lower than -0.5 for temperature as well as larger than 3.5 or lower than -3.5 for relative humidity. The latter thresholds are based on the measurement resolution of the loggers. Similar to median and the highest density intervals, these probabilities are also based on the posterior predicted differences, and represent the proportion (%) of differences above or below the given threshold. All analyses were performed within the R environment (v3.6.3 (2020-02-29)). Data management and aggregation was conducted with the *data.table* package (v.1.13.2 (Dowle and Srinivasan, 2020)). For the Bayesian statistical analysis *brms* (v2.14.0 (Bürkner, 2017, 2018)) was used. Model convergence was supported by the *mcmcse* package (v1.4-1), that estimates necessary effective sample sizes for multivariate MCMC models

Table 2

Number of observations of wind speed × global radiation combinations of 2019 and 2020 vegetation periods. Bold numbers (> 50) indicate subsets used for Bayesian statistical analysis.

global radiation (Whm ⁻²)	wind speed (ms ⁻¹)		
	(0,2]	(2,4]	(4,6]
(0,1.5e+03]	276	13	0
(1.5+e03,3e+03]	430	26	0
(3e+03,4.5e+03]	451	34	0
(4.5e+03,6e+03]	649	54	0
(6e+03,7.5e+03]	504	48	12
(7.5e+03,9e+03]	267	30	0

(Flegal et al., 2020)). Visualizations are based on *ggplot2* (version 3.3.3 (Wickham, 2016)).

3.2. Canopy surface parameters

Measurements of bunch zone light energy interception and canopy surface temperature were conducted at three major grapevine growth stages (flowering [E-L 23], onset of ripening [E-L 35] and berries harvest-ripe [E-L 38]), according to Coombe (1995)). Four of the seven vineyard pairs were selected for measurements of canopy characteristics, taking the different row orientations of the treatments (N-S, E-W, NE-SW, NW-SE) into account. In general, sunny and clear conditions were preferred for conducting the trial for better comparability.

3.2.1. Cumulated relative global radiation measurements

A grid (1 m × 0.3 m) equipped with fifteen photosensitive films (OptoLeaf R-3D, Taisei-Environmental & Landscape Group, Tokyo, Japan) was placed in front of both canopy sides, sunlit and shaded, at bunch zone height (0.7 m to 1 m) at all experimental sites in 2019 and 2020 during same time intervals. The dyed triacetyl cellulose strips with a maximum absorbance at 521 nm were placed vertically in the frames. The light sensitive films were attached to and collected from the grid after sunset to prevent further fading of the dye. The use of the photosensitive films has been previously evaluated as a simple and accurate method for the characterization of bunch zone light exposure (Bon-tempo et al., 2018). From a weather station of Hochschule Geisenheim University (49°98'4" N; 07°95'44" E) global radiation data was obtained. At this weather station and for calibration purposes two horizontally mounted photosensitive films were detached three times a day (08:00, 14:00, 20:00 CET) and dye fading was measured using a photometer (D-Meter RYO-470, Taisei-Environmental & Landscape Group, Tokyo, Japan). The fading values were plotted against cumulated global radiation data. The obtained regression equation was used to determine a site-specific calibration to convert the fading rate of the light sensitive films into a cumulated relative amount of global solar radiation (Whm^{-2}). Calibration curves were created for each measurement period in 2019 and 2020. Individual calibrations showed a very good fit ($R^2 > 0.97$) and a good comparability to manufacturers fading rate formula. Although the objects of investigation were different within a site, where similar radiation intensities are present, output data was normalized by dividing the respective sum of global radiation for the measurement period to account for differences in exposition time (two to four days, depending on the fading pace) between periods.

3.2.2. Canopy surface temperature measurements

In 2020 infrared radiometer sensors (Model SI-431-SS, Apogee, Logan, UT USA) were used to record canopy surface temperature over a period of 24 hours, parallel to the radiation measurements mentioned above. The sensors (ultra-narrow field of view, 14° half angle), were placed at the same height and distance of each canopy side of a vineyard pair to obtain comparable measuring surfaces. Considering different leaf area at the phenological stage of E-L 23, E-L 35 and E-L 38 (i.e. 0.3 m², 0.8 m² and 0.8 m², respectively), sensor readings were taken at three times. The radiometers were connected to a CR300 data logger (Campbell Scientific, Logan, UT USA) for a continuous recording of data in two second-intervals. Although not all sites could be measured simultaneously, within-site measurements were always conducted at the same date. To consider similar time frames between sites a 24 h-time duration was extracted starting at 02:00 am for each sensor. Due to different measurement dates between sites only exploratory data analysis was conducted. Differences between sunlit and shaded sides were compared within a vineyard and differences between similar sides (shaded, sunlit) of different treatments (C, T) were compared within a site. Additionally, to compare average surface temperatures of C and T canopies, the mean temperature of the sunlit and shaded side of a canopy was calculated for each time point.

3.3. Assessment of phenology and vegetative growth

Phenological records were generated at all seven vineyard pairs. For shoot length measurements a reduced number of sites, as in 3.3, were chosen.

3.3.1. Phenological observations

Grapevine growth stages being assessed included budburst (E-L 4) and flowering (E-L 23), according to the modified E-L system (Coombe, 1995). For budburst fifty randomly selected vines per vineyard were scored, recording each bud status along the cane. For flowering the status of one hundred inflorescences per vineyard were scored on randomly selected vines. The onset of ripening was determined measuring total soluble solids (TTS) > 5 °Brix by a handheld refractometer (HRKL32, Krüss, Hamburg, Germany).

3.3.2. Shoot growth measurements

For shoot growth measurements three buds on six vines per vineyard were tagged at budburst. Buds were selected at the base, the middle and the second last position of the cane. Shoot growth was assessed weekly by measuring from the bud's base to the shoot tip.

4. Results

4.1. Inner canopy temperatures

After splitting the data into subsets representing different combinations of daily sums of global radiation with wind speed, the following results were detected for differences in median of the analysed parameters T_{min} , T_{mean} , T_{max} , and T_{amp} . In Figs. 2 to 4 and S2, posterior predicted probabilities (P) of absolute differences are categorized in (i) differences (Δ) > 0°C [%] and (ii) differences (Δ) > 0.5°C or < -0.5°C [%], representing the threshold of exceeding logger resolution of 0.5°C. Differences (Δ) > 0 [%] and > 3.5 % or < -3.5 % [%], represent the threshold exceeding logger resolution for relative air humidity of 3.5 % (Figs. 5 and 6). Data is presented in order of significance of the results, from differences in minimum to mean to maximum temperature and relative air humidity between the treatments.

4.1.1. Differences in daily minimum temperatures inside the canopy

No differences larger than the offset of logger resolution could be detected for minimum temperatures between the treatments, independent of row orientation and wind speed in all periods of spring, summer and autumn (range of P: 7 to 46 %; Fig. 2). Nevertheless, trends in minimum temperature difference (i.e. $\Delta < 0.5^\circ\text{C}$) could be detected for the 2020 vintage. Terraced vineyards of both row orientations, E-W and NW-SE, showed slightly higher minimum temperatures concomitant to higher daily sums of global radiation values during all seasons in 2020. Maximum differences for both row orientations of terraced vineyards in 2020 reached 0.29°C and 0.25°C (P ≈ 75 %) in spring, 0.34°C (P ≈ 80 %) in summer and up to 0.45°C in autumn (P ≈ 80 %). In summer and autumn 2019 minimum temperatures were the same (P = 50–60%).

4.1.2. Differences in daily mean temperatures inside the canopy

While no differences between treatments exceeding logger resolution of 0.5°C were observed, small differences ($\Delta < 0.5^\circ\text{C}$) could be found mainly for vineyards in the comparing of N-S/E-W planting directions (Fig. 3). Probabilities were generally high (86–99 %) at medium to greater amounts of the daily sum of global radiation (7.5–9 kWhm⁻²). At calm wind and for wind speeds between 2 ms⁻² and 4 ms⁻² at a daily sum of global radiation of 4.5–6 kWhm⁻² in spring and summer 2019 as well as in summer 2020 control vineyards planted in N-S orientation showed higher temperatures than terraced vineyards (difference of 0.22–0.43°C, at P of 80–97 %; data not shown). Solid probabilities were obtained for temperature differences in the range of 0.26°C and 0.45°C during spring, 0.36°C to 0.7°C during summer and 0.4°C to 0.65°C in

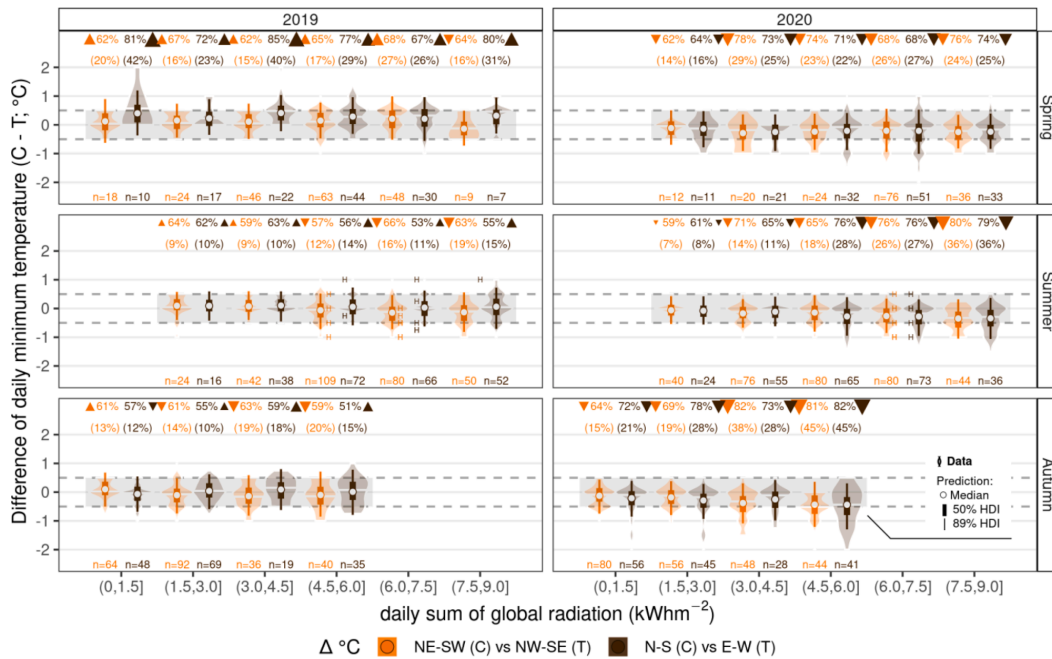


Fig. 2. Posterior predicted differences (median, 50 % and 89 % HDI) of daily minimum temperature between control (C) and terraced (T) vineyards for different daily sum of global radiation values and wind speed $< 2 \text{ ms}^{-1}$, vintage and season from Bayesian generalized linear mixed effects model. Percentages (%) represent the probability of C-T > 0 and percentage in brackets (%) represents the probability of C-T > 0.5. Violin plots show the density distributions of the measurement data including the median (white line). Triangle direction and size highlight the tendency and robustness of treatment differences ($\blacktriangle = \text{C} > \text{T}$; $\blacktriangledown = \text{C} < \text{T}$). Dashed lines represent the $\pm 0.5 \text{ }^\circ\text{C}$ sensor accuracy.

autumn (September and October). Control vineyards in NE-SW orientation only showed solid probabilities in spring of 2019 with maximum differences in daily mean temperature of 0.17°C and tendencies in the same range for being higher in temperature than the terraced treatment during summer and autumn months at medium daily sum of global radiation. With an increase in the daily sum of global radiation in summer differences became less pronounced.

4.1.3. Differences in daily maximum temperatures and temperature amplitude inside the canopy

Little effect of daily minimum temperatures on the vineyard system or row orientation resulted in a higher impact of differences in daily maximum temperatures on daily temperature amplitudes. The pattern of daily temperature amplitudes followed the pattern of daily maximum temperatures (Fig. S2). In general, control vineyards showed higher daily temperature amplitudes. Probabilities of absolute maximum temperature differences greater than 0.5°C between C and T treatments were in the range of 13 and 91 % (Fig. 4). Low probabilities were associated with categories of a low daily sum of global radiation across all seasons and years, while higher probabilities (i.e. $> 80 \%$) were found in summer and autumn. Eventually, the difference was more consistent when comparing N-S and E-W row orientations (south-exposed vineyards), especially in summer of 2019, where NE-SW and NW-SE (SW-exposed vineyards) comparison did not show signs of a difference between the control and terraced vineyards (e.g. 50 % probability of difference greater than 0 for the highest daily sum of global radiation category in summer 2019). While N-S oriented control vineyards were up to 1.73°C higher in temperature compared to terraced vineyards during radiation-intense summer days ($P = 90 \%$), the NW-SE control vineyard showed the same, but a little cooler and less reliable, tendency in the summer of 2020 (maximum difference of 1.08°C , $P \approx 70 \%$). For

spring of 2019 and 2020 probabilities of differences in daily maximum temperature between C and T were generally lower than for the seasons of summer and autumn. Higher daily sums of global radiations indicated higher probabilities of differences in the range $> 0.5^\circ\text{C}$ for the N-S oriented vineyards. The maximum differences for control vineyards in N-S direction were in the range of 0.37°C to 0.69°C in spring of 2019 and 0.46°C to above 1°C in spring of 2020, ascending with an increasing daily sum of global radiation. While for control vineyards planted in NE-SW orientation the range was within 0.36°C and 0.58°C along with high daily sum of global radiation values ($P > 80 \%$). The letter “H” indicates observations during heat waves in the summer of 2019 and 2020 (Fig. 4). Within these periods differences of up to 5°C were measured. These extremes exceed the range of the most probable predicted differences. However, most of the heat wave observations did not show extreme outlying behaviour. High probabilities can be observed for trends in higher maximum temperature of C treatments planted in N-S direction in autumn of 2019 and 2020. In both vintages a maximum difference of about 2°C could be detected at increased daily sum of global radiation values and under calm wind conditions. Contrarily, terraced vineyards of NW-SE orientation tended to become higher in temperature in autumn of 2019 with rising daily sum of global radiation (0.61°C to 0.81°C). However, in autumn 2020 no differences could be observed for vineyard pairs planted in NE-SW and NW-SE orientation (Fig. 4).

4.1.4. Differences in daily minimum relative air humidity inside the canopy

Probabilities of differences in daily minimum relative air humidity values ranged from 1 to 39 %, indicating no differences larger than logger accuracy of $\pm 3.5 \%$ (Fig. 5). Probabilities of minor differences $[-3.5, 3.5 \%]$ were observed within the range of 50 to 94 %. Small differences ($P > 70 \%$) were found for N-S/E-W planted vineyard

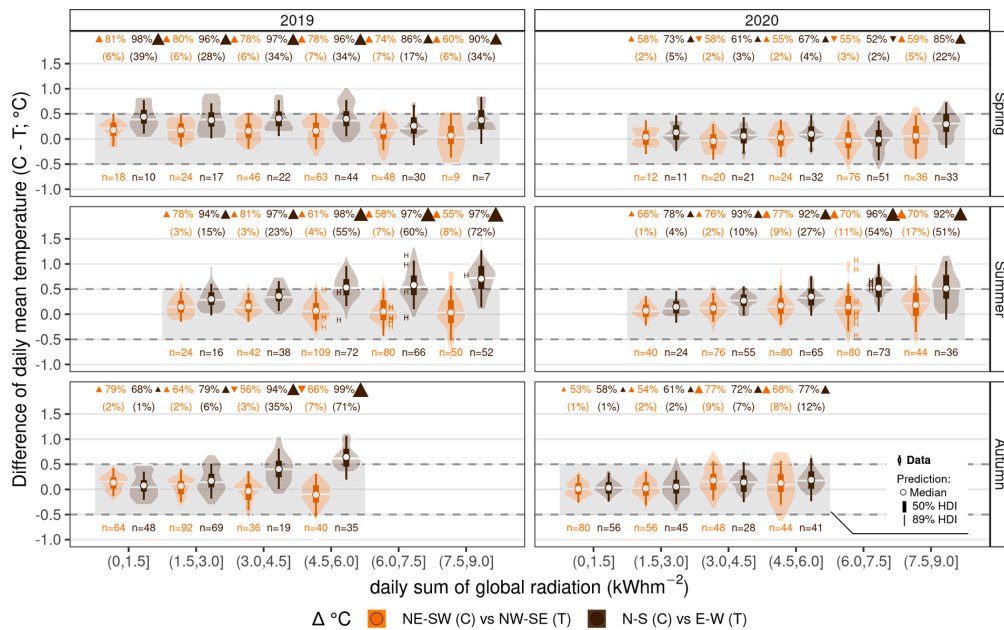


Fig. 3. Posterior predicted differences (median, 50 % and 89 % HDI) of daily mean temperature between control (C) and terraced (T) vineyards for different daily sum of global radiation values and wind speed $< 2 \text{ ms}^{-1}$, vintage and season from Bayesian generalized linear mixed effects model. Percentages (%) represent the probability of C-T > 0 and percentage in brackets ((%)) represents the probability of C-T > 0.5. Violin plots show the density distributions of the measurement data including the median (white line). Triangle direction and size highlight the tendency and robustness of treatment differences (▲ = C>T; ▼ = C<T). Dashed lines represent the $\pm 0.5 \text{ }^\circ\text{C}$ sensor accuracy.

comparison mostly at high daily sum of global radiation values. Terraced vineyards planted in E-W direction tended to have higher values of relative air humidity in summer and autumn of 2019 and 2020 for daily sum of global radiation values of $> 3 \text{ kWhm}^{-2}$, showing probabilities of up to 87 % (Fig. 5). Differences in vineyard comparison of NE-SW/NW-SE row orientation were slightly higher 0 %; but showed high differences in autumn of 2019 (+2 % relative air humidity). Nevertheless, differences were (i) minor and (ii) showed small values of P.

4.1.5. Differences in daily maximum relative air humidity inside the canopy

Relative air humidity probabilities for daily maximum differences were minor within a range of 50 % to 95 %, while differences exceeding $\pm 3.5 \text{ %}$ logger accuracy was between 1 and 26 % (Fig. 6). For small differences [-3.5, 3.5 %] probabilities were more pronounced in the months of autumn (2019 and 2020) and summer of 2019. Relative air humidity values followed the trend of warmer control vineyards in N-S and NE-SW oriented (control) vineyards. Only one value, however, exceeded the logger accuracy threshold of 3.5 % for the high daily sum of global radiation records in autumn of 2020 (3.7 %, Fig. 6). All other data was within the measurement uncertainty.

4.2. Canopy surface radiation measurements

4.2.1. Cumulated relative global radiation measurements

The proportion of radiation interception of the canopy sides did not differ between years at the different experimental sites within different row orientations (Fig. 7). The means of the absolute values of cumulated received solar radiation at bunch zone height are displayed in the supplementary material (Table S2). The radiation energy received at the bunch zone was lowest at canopy sides exposed to north and its 45°-shifted treatments (NE, NW). The share of ambient global radiation for

northward exposed canopy sides was low (9 to 22 %) during all measurement periods. NE-exposed sides showed similarly low values and values of the NW-side of the canopy ranged between 20 and 30 %. E-facing canopies received a share of global radiation of about 30 % (Table S2). Obtained values of SW-exposed sides showed high values of global radiation (values $> 10 \text{ kWhm}^{-2}$), covering the gap between W-ward and S-facing canopy sides. In Fig. 7A vine rows in NE-SW direction are compared to their NW-SE terraced equivalent for both years. The mean intercepted light energy (dashed lines) of the two systems was equal during summer (differences ranged between zero and eleven percent during flowering and onset of ripening), but in autumn at developmental stage of harvest ripeness the terraced vineyards benefited by sunlight due to higher light interception on the southwest side of the canopy, caused by the lower sun level at this time of the year. Differences were more pronounced in 2019 (16 to 20 %; Fig. 7A). East and west sides of the control canopy showed similar values of relative cumulative global radiation (Fig. 7B) during all measurement periods, with mostly slightly higher values for the W side of the canopy. In terraced vineyards, the north side of the canopy received much less light (e.g. approximately -50 % at flowering and about four to five times less during onset of ripening) compared to its opposed sunlit southern side. The biggest differences can be observed at the development stage of full ripeness (harvest), where south exposed canopies received five to eight times more sunlight leading also to a high canopy mean of cumulative global radiation. Canopy sides of the control vineyards in N-S orientation showed no big differences, similar to the previously measured periods (Fig. 7B). Values exceeding 100 % resulted from site specific calibration and external calculation of daily global radiation sums used for normalization (Fig. 7 and Table S2). Nevertheless, the data shows reliable observations of the proportion in energy balance of the distinctive canopy sides.

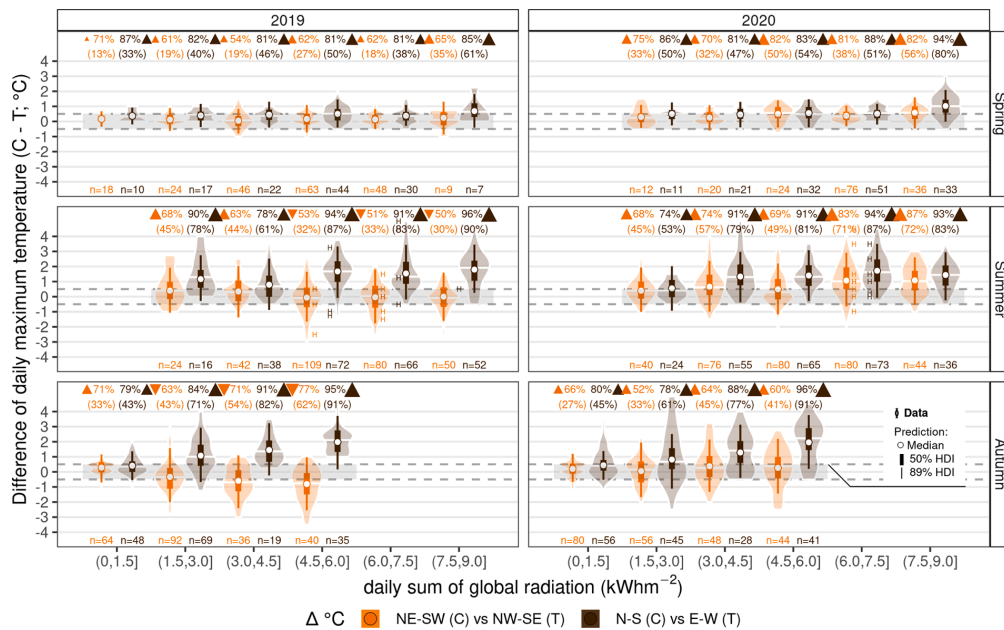


Fig. 4. Posterior predicted differences (median, 50 % and 89 % HDI) of daily maximum temperature between control (C) and terraced (T) vineyards for different daily sum of global radiation values and wind speed $< 2 \text{ ms}^{-1}$, vintage and season from Bayesian generalized linear mixed effects model. Percentages (%) represent the probability of C-T > 0 and percentage in brackets ((%)) represents the probability of C-T > 0.5. Violin plots show the density distributions of the measurement data including the median (white line). Triangle direction and size highlight the tendency and robustness of treatment differences ($\blacktriangle = C > T$; $\blacktriangledown = C < T$). Dashed lines represent the ± 0.5 sensor accuracy.

4.2.2. Canopy surface temperature measurements

The increase in temperature of the respective grapevine canopy surface followed the daily course of the sun. NE-, SE- and E-exposed canopy sides showed an early and fast increase of surface temperature at sunrise (Fig. 8). SE- (control) and NE- (terraced) sides of the canopy became 4°C to 7°C warmer compared to the, at the time shaded canopy equivalent NW and SW, respectively (Fig. 8A–C). While SE-canopy side temperatures reached maximum values (Tmax) at noon and early afternoon during flowering and close to harvest, maximum temperatures of SE at the onset of ripening occurred simultaneously with the NW-facing canopy side in late afternoon. The terraced vineyard of canopy sides NE (hill facing) and SW (valley facing) reached their maximum temperatures at the same time in the afternoon during all measurement periods. Around early afternoon (01:00 pm) canopy warming accelerated at canopies with westward exposition (W, NW, SW). SW-facing canopy sides, being the warmest in every measurement period, reached Tmax about two hours earlier (04:00 pm) than NW-exposed canopy sides and then declined faster. After sunset temperature curves overlapped, but terraced vineyards generally stayed warmer overnight. The comparison of N-S and E-W oriented vineyards showed the same pattern. However, with the sun rising, E and W sides of the control vineyards warmed up faster during summer measurement periods. While both shaded canopy sides of control (E) and terraced vineyards (N) showed similar temperature profiles during the day, S-side of T canopy warmed up faster until reaching a maximum in the early afternoon. W-side of the control reached Tmax in the late afternoon. Temperature decline in the evening was again generally faster for control vineyards compared to the terraced sites (Fig. 8D and E).

The average of daily temperature course of both canopy sides of each treatment resulted in a similar pattern of temperature distribution during the day (Fig. 9A–E). Terraced vineyards showed higher canopy surface temperatures at night time compared to canopies of control

vineyards on sunny days. Days with cloudy weather conditions did not show such a pattern (results not shown). With the sun rising, control vineyards warmed up faster until around noon. Terraced vineyard temperature rose fast creating a maximum difference between treatments of almost 4°C compared to the control. In the late afternoon, control vineyards canopy surface temperature peaked again until a decline close to sunset. During the night, the maximum value of mean canopy surface temperatures was about 1.5°C lower for control vineyards compared to terraced sites (Fig. 9).

4.3. 4.3 Phenology & vegetative growth

4.3.1. Phenological development

In general, all control vineyards showed a small advance in the phenological growth stage of budburst (E-L 4, green tip visible) in both years. In 2019 an earlier bud break in vineyards planted in N-S orientation (GM, RB) was observed compared to terraced vineyards which had an approximate delay of two days. Scoring showed an advanced growth stage for control vineyards planted in NE-SW direction with an earlier bud burst in 2020. For all control treatments bud break was observed three days earlier compared to terraced sites. At two sites (GM, RB) bud break of both treatments happened simultaneously.

Full bloom (E-L 23) occurred a little earlier for control treatments in 2019 and 2020 compared to terraces vineyards which showed a delay of three days (GM, RB, LB) or two days (LE, LS, AS). At site K flowering occurred simultaneously for both treatments. Advanced flowering in 2020 was found at sites GM, RB and K with a lead of four, four and two days, respectively. All other vineyard pairs showed a similar occurrence of 50 % cap fall, with a slight advance of control vineyards.

Technological records of the onset of ripening for both treatments at the five sites tested are shown in Table 3. Determining measurements for the onset of ripening were late in 2019. Data is inconsistent between

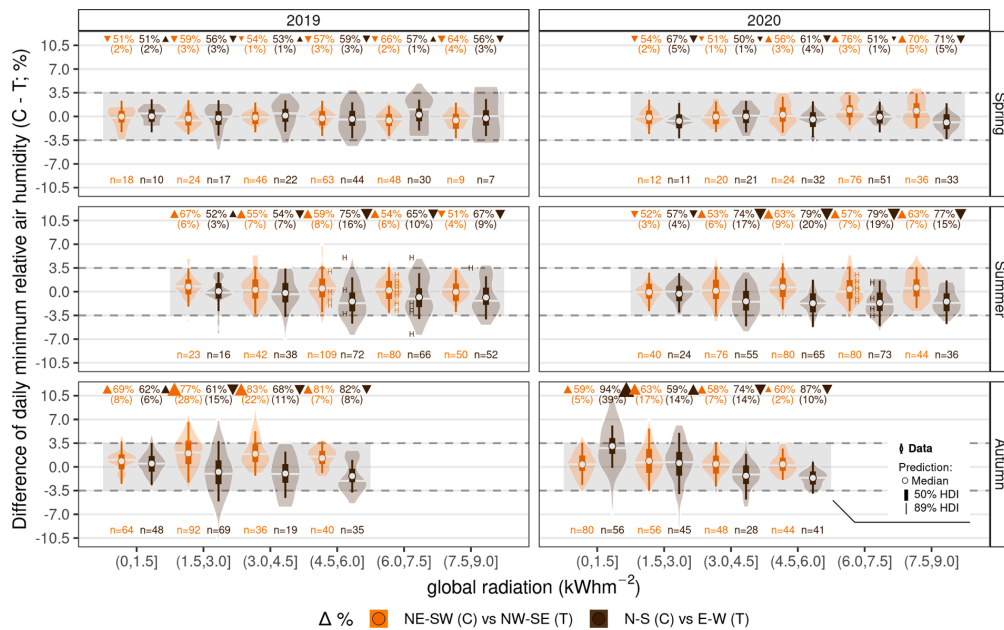


Fig. 5. Posterior predicted differences (median, 50 % and 89 % HDI) of daily minimum relative air humidity between control (C) and terraced (T) vineyards for different daily sum of global radiation values and wind speed $< 2 \text{ ms}^{-1}$, vintage and season from Bayesian generalized linear mixed effects model. Percentages (%) represent the probability of $C-T > 0$ and percentage in brackets ((%)) represents the probability of $C-T > 0.5$. Violin plots show the density distributions of the measurement data including the median (white line). Triangle direction and size highlight the tendency and robustness of treatment differences ($\blacktriangle = C > T$; $\blacktriangledown = C < T$). Dashed lines represent the ± 3.5 % sensor accuracy.

years for most sites. Only at site LE terraced vineyards showed an earlier beginning of ripening during both years, while for control treatment in GM total soluble solids were higher (Table 3).

4.3.2. Shoot growth measurements

In both years it was observed that control vineyards showed an increased shoot growth rate, i.e. cm length per degree day, at all sites and for the first measurement dates (Fig. 10). In 2019 shoot development was consistently faster at sites GM and LE in the control groups compared to shoots of the terraced vineyards. The other two sites showed an early convergence of shoot length, approximately at the mid/end of May (~DOY 135–140). The 2020 vegetation period showed a similar trend pattern of shoot growth for both treatments. Control vineyards started with faster shoot growth until the mid of May for all vineyards observed. By that time shoots of vines planted on terraces exceeded control vines' shoot length until the first trimming.

5. Discussion

Data of the Geisenheim weather station showed that within the last five decades (1970s to 2020) solar radiation increased for each season by 0.9, 1.1. and 0.4 kWhm^{-2} (spring, summer and autumn, respectively; Fig. S3), which is in accordance with the findings of global brightening since the 1990s (Wild et al., 2005). In line with this observation is the increase of summer days, i.e. daily $T_{\text{max}} \geq 25^\circ\text{C}$ (five days in spring, 25 days in summer and three days in autumn), and heat days, i.e. daily $T_{\text{max}} \geq 30^\circ\text{C}$ (one day in spring, twelve days in summer and one days in autumn; Figs. S4 and S5, respectively) for the months within the vegetation period the mid-20th century for the Rheingau wine growing region. The impacts of global climate change on viticulture have already been discussed intensively (Jones et al., 2005; Santos et al., 2020; Schultz, 2000; van Leeuwen et al., 2019). For warm to hot growing

regions exacerbating projections, e.g. an overall warming and drying from the mid to the end of the century (Santillán et al., 2020), a shift of berry ripening phase into warmer summer months (Webb et al., 2007) and earlier and intensified heat wave occurrences (Fraga et al., 2020) have been forecasted. Even though cool climate grape growing regions will face changes too, predictions point to rather beneficial conditions favouring consistency in berry ripening, wine quality and vintage characteristics (Jones et al. 2005). Nevertheless, over the last fifty years the average temperature during vegetation period increased by 0.9°C with average values during the periods of 14.8°C , 15.2°C and 15.7°C for 1971–2000, 1981–2010 and 1991–2020, respectively (data of Geisenheim weather station) causing a shift of the growing region of Rheingau from cool (13°C to 15°C) to intermediate (15°C to 17°C) climate (Hall and Jones, 2009). This may affect berry composition and wine profile (Jones et al., 2012; Molitor and Junk, 2019). Single vintages of previous years showed an immense increase of average temperature during vegetation period (2018: 17.8°C , 2019: 16.4°C , 2020: 16.7°C ; Table S1). Schultz (2016) stated that vegetation period temperature has already exceeded estimated upper limits for traditionally grown grapevines in the Rheingau grape growing region. But also, that these upper limits are not really known, since ecophysiological adaptation, plasticity of grapevine cultivars and changing management practice alter the performance of the vines (Schultz, 2016; van Leeuwen et al., 2013). To reduce impact of a changing climatic environment several mitigation techniques such as adjusting leaf area to fruit weight ratio or changing the trellis system of the vines have been developed and are already being adopted by winegrowers (Gutiérrez-Gamboa et al., 2021; Santos et al., 2020).

Grapevine phenological development is heavily influenced by soil temperature in spring, activating nutrient mobilization and alterations in phytohormone dominance in respective grapevine organs (Liu and Sherif, 2019; Zelleke and Kliewer, 1979). Bud tissue temperature may be

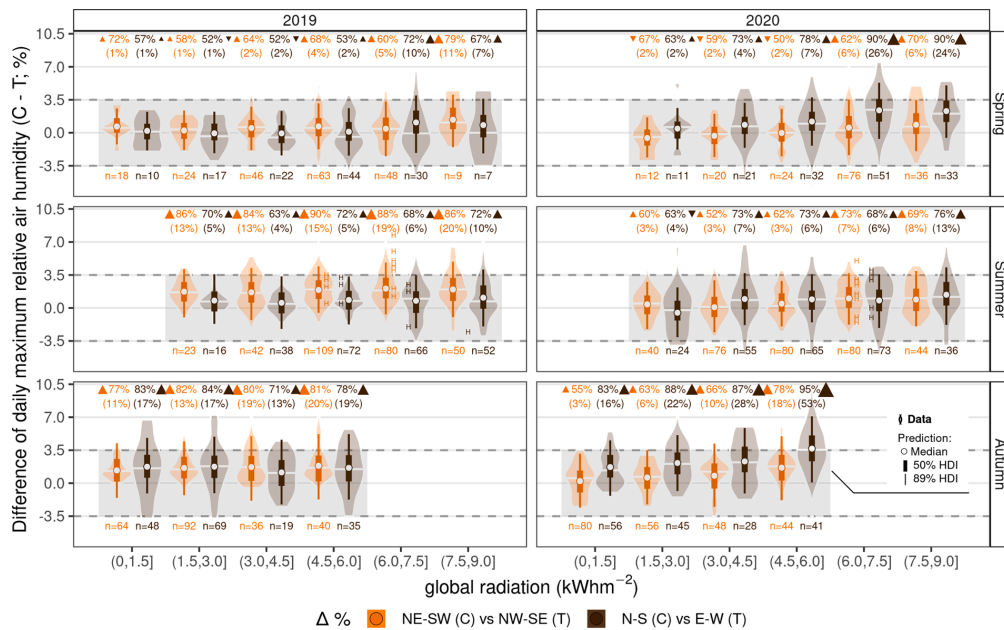


Fig. 6. Posterior predicted differences (median, 50 % and 89 % HDI) of daily maximum relative air humidity between control (C) and terraced (T) vineyards for different daily sum of global radiation values and wind speed $< 2 \text{ ms}^{-1}$, vintage and season from Bayesian generalized linear mixed effects model. Percentages (%) represent the probability of C-T > 0 and percentage in brackets ((%)) represents the probability of C-T > 0.5. Violin plots show the density distributions of the measurement data including the median (white line). Triangle direction and size highlight the tendency and robustness of treatment differences ($\blacktriangle = \text{C} > \text{T}$; $\blacktriangledown = \text{C} < \text{T}$). Dashed lines represent the $\pm 3.5\%$ sensor accuracy.

more important for the bud break date than ambient temperature (Keller and Tarara, 2010), since bud tissue can exceed ambient daytime temperature by 1°C to 2°C in March and April (Peña Quiñones et al., 2019). Neither soil nor bud temperatures were measured during this experiment. However, bud burst recordings generally showed a minor advance for the control vines compared to those planted on terraces. Small ($< 0.5^\circ\text{C}$) but reliably ($P > 80\%$) higher differences in the temperature of the bunch zone were observed for control vineyards in spring, mainly for Tmax in 2019 and 2020 (Fig. 4), but also for Tmean in 2019 (Fig. 3), with a clear favour for N-S planted vines. The bare or at least less covered soil of the control vineyards might have been warmed faster compared to grass-covered embankments of terraced vineyards in early spring (Nazrala, 2007; Penfold and Collins, 2012; Pradel and Pieri, 2000). Tmin data is inconsistent between the years, highlighting a vintage effect on daily minimum temperature observations, tending to favour terraced vineyards with slightly higher temperatures in 2020 (Fig. 2).

Comparable with budburst observations, a tendency of slightly earlier flowering was detected, although there may not be a strong projected relationship between these events (Tomasi et al., 2011). Jones and Davis (2000) mentioned the impact of sunshine hours during budburst on inflorescence differentiation. Radiation measurements did not take place during the stage of budburst. Still, light conditions during bud burst can be assumed to be similar, since no possible canopy shading of neighbouring rows altered sunlight distribution. Nevertheless, maximum temperatures in spring are known to mainly impact on the date of flowering (Fraga et al., 2016; Tomasi et al., 2011) and control vineyards showed slight but consistently higher maximum temperatures in spring, which may favour a slightly advanced flowering. Even though differences shown in this study were small and may not affect practical viticultural decisions prior to veraison, the terracing of vineyards may serve as an addition to this toolbox for viticulturists.

The shoot growth pattern between budburst and flowering was quite similar for all treatments, despite two sites in 2019 (GM and LE; Fig. 10). The more apparent differences may result from a significantly higher pre-flowering nitrogen status (N, measured as leaf chlorophyll; data not shown) of the control vineyards in GM and LE in that year. Starting with a trend for a more rapid shoot development of the control vines, i.e. higher growth in length per degree day, terraced vineyards exceeded them in shoot length from mid of May onward. In addition to differences in N supply, the water availability plays an important role as well. In the early years of the vineyard development the, competition with cover crop on the embankments may strongly affect vegetative and reproductive growth of young vines planted on terraces. However, literature reviewed by Michalsky (1976) showed that root growth was higher in length on terraced compared to non-terraced vineyards and roots of vines on terraces tended to grow towards the centre of the platform, where a higher soil water content exists. Due to the orientation along the contour of the hill terraced vineyards may also improve infiltration and water storage during spring and winter (Ramos and Mulligan, 2005). On the contrary, soil depth at steep slopes is usually shallow at steep slopes and the run-off is by far higher (Emde, 1992). Bordini et al. (2016) found the highest amount of roots at depths of 0.2 m to 0.6 m. While young vines planted on terraces may be competing strongly with embankment weeds, fully adapted grapevines may benefit from higher water availability, depending on evapotranspirative demand of the surrounding vegetation.

Tarara et al. (2005) found that shoots parallel to prevailing wind were longer, while shoot growth of the windward side of a N-S oriented canopy was reduced, inter alia due to possible heat flux. The effect of wind is not only important regarding growth perturbation. Jagoutz (2004) described the prevailing wind directions under different diurnal conditions. The prevailing wind direction at clear sky days during spring and summer in the Rheingau grape growing region is SW, and W

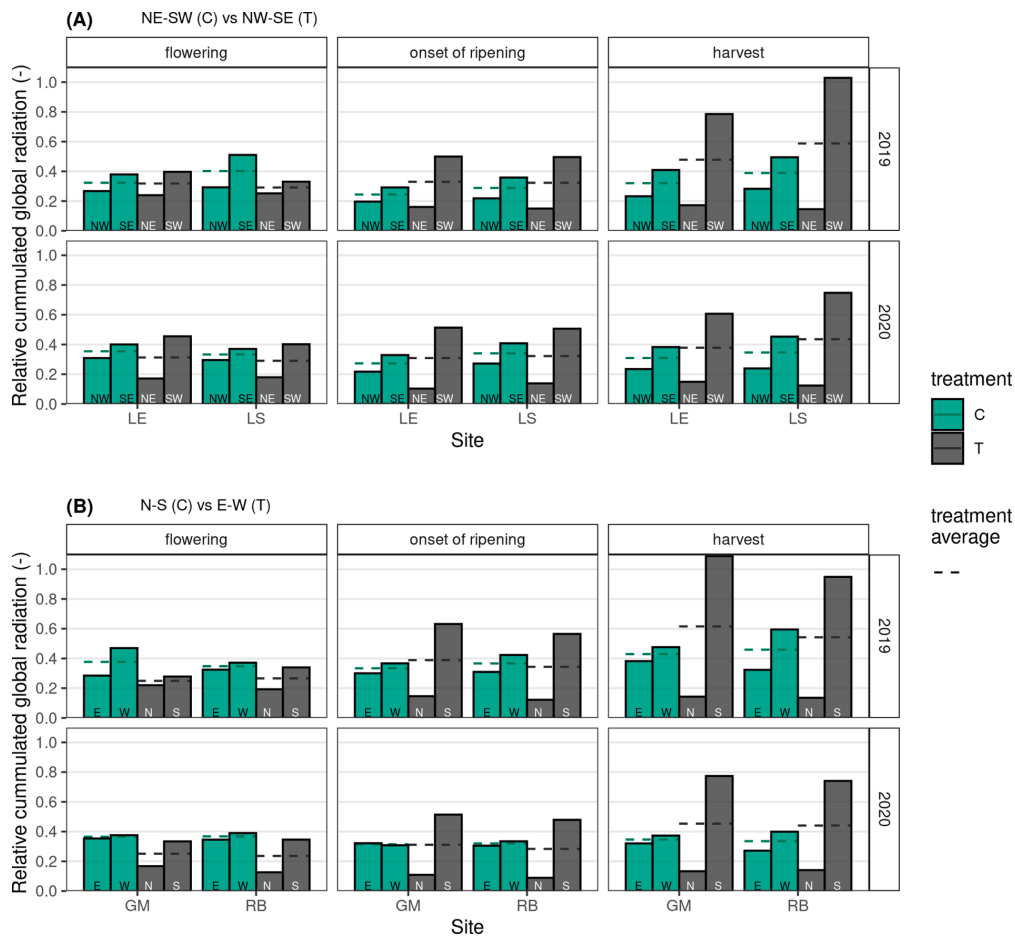


Fig. 7. Cumulative solar radiation measurement normalized by global radiation data of local weather stations (dimensionless; (-)) for (A) NE-SW/NW-SE and (B) for N-S/E-W comparison. Bar colour indicates treatment, canopy (control = C; terraced = T), exposition is annotated at the bottom of each bar. Mean canopy energy interception is represented by dashed line.

between early and late morning (03:00 am to 09:00 am) as well as E from late morning to afternoon (09:00 am to 03:00 pm). Furthermore, warm upslope winds occur during summer months blowing from south. After sunset katabatic wind forms and flows to the valley from NW/NNW, draining cold air to the foot of the hill. In autumn afternoon wind blows from NE and SW (Jagoutz, 2004). This pattern of wind may explain both observations of temperature: (i) differences between control and treatment and (ii) the extent of differences between the different row orientations. Perpendicular to prevailing wind planted vineyard rows sheltered their neighbours, which reduced wind speed at bunch zone height of wide spaced vines ($3\text{ m} \times 1.7\text{ m}$) by 0.8 ms^{-1} as shown by Heilman et al. (1994). More narrow planted rows, like in control treatments, may be even more effective in reducing wind speed.

A distinct microclimate evolves only under sunny conditions with wind speed $<2\text{ ms}^{-1}$ (Horney, 1975). Differences in temperature between treatments became more apparent with an increase in daily global radiation values and at calm wind conditions. The deceleration of wind allows to build and maintain a distinctive microclimate in the vineyard, even more promoted by an increase in leaf area (Figs. 3 and 4). Low wind speed and high relative air humidity enhances the risk of fungal

disease development (Sentelhas et al., 2008; Thomas, 1988). Most pathogens need high humidity values to sporulate (in general RH $>85\%$; Carroll and Wilcox, 2003; Pardo et al., 2005; Thind et al., 2004). Presented differences between treatments of daily relative air humidity values were minor in this study (Figs. 5 and 6). Slightly higher minimum values of relative air humidity were found for terraced vineyards, mainly for E-W orientation in summer and autumn, whereas for maximum values control vineyards in N-S orientations showed higher values of relative air humidity. Climatic conditions in 2019 and 2020 were favourable for vine health and plant protection measures. No fungal infections could be detected during the two years of study. Hunter et al. (2016) also showed minor differences of hourly mean relative air humidity between row orientations for a vineyard planted in the flat in South Africa. An adequate canopy management is essential to lower the risk of fungal diseases, especially prior to veraison (Smart and Robinson, 1991). Therefore, properly scheduled canopy management may affect relative air humidity inside the canopy more than row orientation changes, although other microclimate parameters are notably affected by a change in row alignment.

At the experimental sites wind is free to move in E-W oriented vine

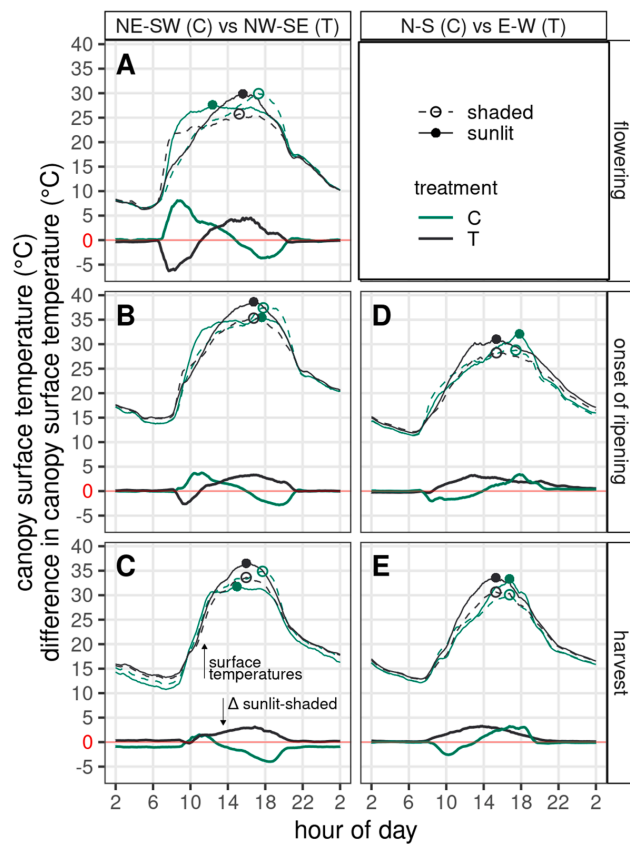


Fig. 8. Daily course of canopy surface temperature separated by canopy side (A, B, C: site LS with control row orientation of NE-SW and terraced row orientation NE-SW, D, E: site RB with N-S orientation for control (C) and E-W orientation for terraced vineyards (T)). Sunlit canopy sides (solid line): SE (LS, C) and SW (LS, T); W (RB, C) and S (RB, T). Shaded canopy sides (dashed lines): NW (LS, C) and NE (LS, T); E (RB, C) and N (RB, T). Red line indicates zero. Thick lines show differences between canopy sides of a treatment (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

rows, thus hindering warm air to accumulate. Planting vines in line of the greatest slope (e.g. N-S) allows warm upslope winds to enhance temperature in the vineyard during day, while cold drainage flow during night increases the temperature amplitude, as observed (Fig. S2). For control vineyards planted in NE-SW direction, the prevailing wind direction of SW in the morning means a parallel wind flow. On the opposite within terraced E-W oriented vineyards, only during early hours of the day microclimate is affected by wind flow. During September and October, when the canopy is fully developed, NE-winds occur, which led to warmer conditions in terraced vineyards, as seen in autumn of 2019 (Fig. 4) and 2020 (Fig. 2). Depending on row orientation, but even more on vineyard geometry and orography, terraces act like semi-natural impediments (Evans, 2000). Thus, cold air flow during the night may not have affected terraced vineyards as much as those planted upslope. This would lead to higher minimum temperatures during night and a compression of the diurnal temperature range, even though katabatic winds from NW/NNW flow parallel to NW-SE oriented terraces from early evening. This was supported by canopy surface temperature measurements recorded in summer and autumn of 2020 (Figs. 8 and 9). During night time the average surface temperature of the canopy showed consistently warmer conditions in terraced vineyards regardless of row orientation (Fig. 9). During a sunny day course there was a high probability ($P > 80\%$; Fig. S2), that terraced vineyard's temperature amplitude was 1.4°C to 2.6°C more damped during summer and autumn compared to control vineyards (N-S/E-W comparison).

The impact of damped diurnal temperature ranges on fruit

parameters has been investigated in previous studies (Cohen et al., 2012; de Ressaiguer et al., 2020; Gaiotti et al., 2018; Kliewer and Torres, 1972). Cool nights are associated with a high potential for colour and aromas, if full maturation is achieved (Tonietto and Carbonneau, 2004), but night temperatures $< 15^{\circ}\text{C}$ reduced assimilation during the consecutive day and export of sugar to sink (Tombsi et al., 2019). While warmer temperatures before onset of ripening increase malat content in grape berries, warmer night temperatures post-veraison are related to higher respiration of malic acid, thus lower total acidity and higher pH (Rienth et al., 2016; Sweetman et al., 2014). The mean of minimum temperatures in September ("cool night index", CI) was "very cool" ($< 12^{\circ}\text{C}$, Tonietto and Carbonneau (2004)) for all vineyards observed, except RB in 2020 ($12 < \text{CI} < 14$, "cool"). Usually, terraced vineyards showed a slightly higher CI (0.05 to 0.55°C) compared to control and temperature amplitudes in this study were not as high as in studies mentioned above. A general global increase in minimum (as well as maximum) temperatures was shown by Vose et al. (2005) and warm days and warm nights are predicted to likely increase in frequency during the next decades (IPCC, 2013). Noteworthy, in the Rheingau region where this study was conducted, Schultz (2016) observed an overall trend of continuously decreasing daily temperature amplitudes over a period of the last hundred years. Small, but consistently elevated minimum temperatures may affect physiological or enzymatic processes in terraced grapevines more than in control vines, due to higher minimum temperatures during night. Berry composition of grapes originating from terraced vineyards in E-W orientation may therefore be

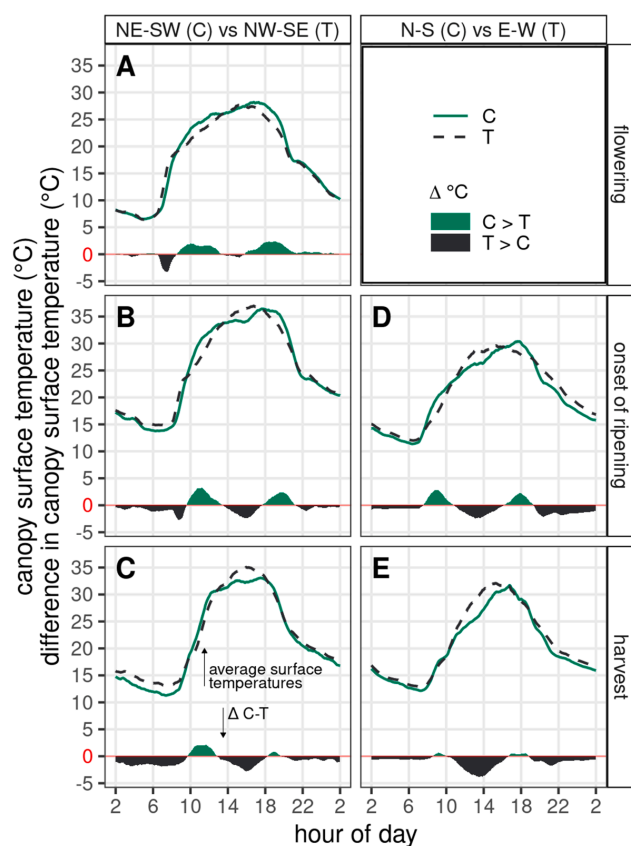


Fig. 9. Daily course of canopy surface temperature averaged (A, B, C: site LS with control row orientation of NE-SW and terraced row orientation NE-SW, D, E: site RB with N-S orientation for control (C) and E-W orientation for terraced vines (T)). Bottom line shows differences between average canopy temperatures of treatments. Red line indicates zero. Area plots indicate difference, colours indicate whether C>T (green) or T>C (black) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

Table 3

Comparison of total soluble solids ($^{\circ}$ Brix, mean \pm standard deviation) at the onset of the ripening phase for control (C) and terraced vineyards (T) in 2019 and 2020 for different sites. DAB indicates days after budburst.

Site	Total soluble solids ($^{\circ}$ Brix)						
	2019			2020			
	C	T	DAB	C	T	DAB	
GM	12.4 \pm 0.1	12 \pm 0.7	125	9.4 \pm 0.4	7.9 \pm 0.2	119	
LE	9.2 \pm 0.3	10.8 \pm 0.2	122	6.5 \pm 0.0	6.8 \pm 0.0	126	
LS	9.9 \pm 0.5	9.6 \pm 0.1	122	6.8 \pm 0.0	7.1 \pm 0.0	126	
K	8.3 \pm 0.2	9.6 \pm 0.1	118	6.8 \pm 0.1	6.5 \pm 0.1	112	
RB	11.7 \pm 0.2	9.7 \pm 0.1	118	6.5 \pm 0.0	6.7 \pm 0.0	112	

more affected in the future compared to control vineyards planted in N-S orientation.

Berry composition is strongly affected by solar radiation due to photosynthetic performance (carbon assimilation), thermal effects as well as phytochromatic and enzymatic activity (Smart, 1987). Maximum differences in canopy surface temperature usually occurred shortly after sunrise (Fig. 9). Differences may be higher between canopy sides in the morning, but maximum temperature is reached in the afternoon, showing a more severe impact on grapevine physiology. Excessive heat and light, often the precursor of drought stress, down-regulates photosynthesis and increases respiration leading to an adverse carbon balance, reduced yield and vegetative growth as well as an altered fruit composition (Palliotti and Poni, 2015). From noon to early evening,

terraced vineyards showed warmer canopy surface temperatures, due to direct exposition of the valley-facing canopy sides of the vines towards the sun, approximating or even exceeding the optimal range of photosynthesis (Schultz, 2000). Indeed, the sun-exposed canopy sides (S and SW) contribute far to the heat balance in terraced vineyards during daytime, especially during the ripening phase (Fig. 8). In control vineyards (N-S and NE-SW oriented), however, the radiation balance was more even among canopy sides. Especially during extreme events, such as heat waves, the effect on canopy sides may differ due to row orientation. Response of treatments to heat waves in summer are indicated in Figs. 2 and 3 (letter "H"). Especially at the crucial development stages of anthesis and during berry ripening, grapevine yield is sensitive to extreme temperatures due to a negative impact on fruit set and inhibition of berry growth (Moriondo and Bindi, 2007). There was no clear effect visible of minimum temperature on treatment ($P < 30\%$), since night temperatures were less increased compared to day temperature. Control vines were more disadvantaged by heat waves, i.e. affected by exposure to higher temperatures, than terraced vineyards, especially in N-S oriented vineyard rows (Fig. 3). An increase in number and higher intensity of heatwaves has been reported, leading to an increase in frequency of sunburn observations in Europe (Gambetta et al., 2020). However, even though S- and SW-exposed canopy sites of vines planted in a terraced vineyard were almost fully exposed all day during midsummer, W- an NW-facing canopy sides (control) showed higher incidences and severity of sun burn damage (data not shown). This might be due to a more constant irradiation (Fig. 7), thus a better

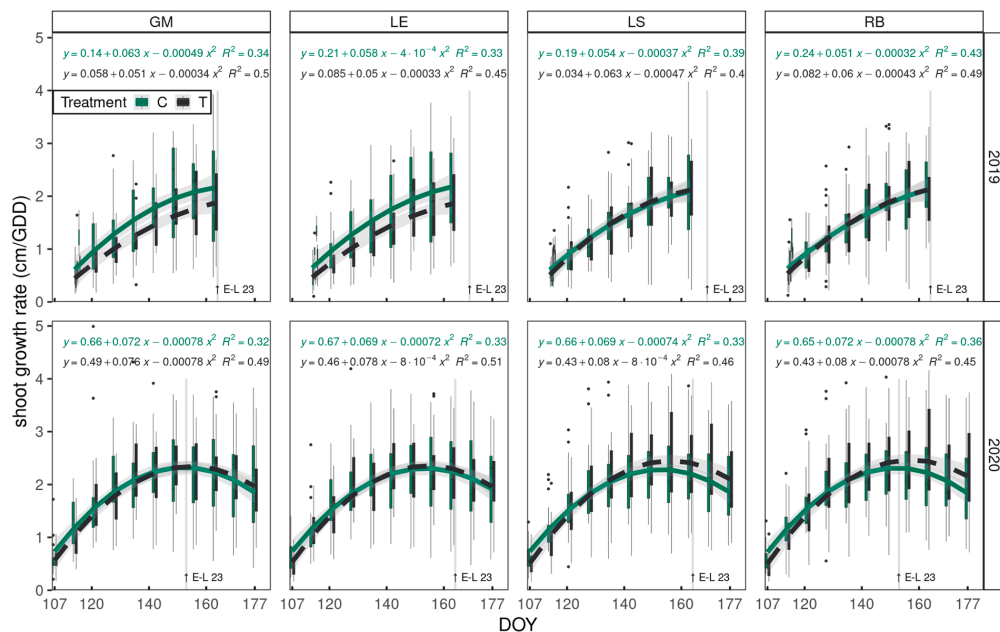


Fig. 10. Shoot growth rate (cm/GDD) per measurement date (DOY) separated by vintage for sites GM, LE, LS and RB. Lines represent fitted polynomial trend for each treatment (solid lines = control (C); dashed lines = terraced vineyards (T)), boxplots indicate data variability. Flowering date of C is highlighted by arrow and annotation (E-L 23).

adaptation of the grapes grown on terraces (Gambetta et al., 2020). West sides of canopies usually face the highest temperatures during the day, both in northern- and southern hemisphere, leading to higher sunburn damage compared to other row orientations (Webb et al., 2010). Depending on row orientation as well as the conditions of steep slopes changed temperature and light regime cause an alteration in berry composition and secondary metabolite profile.

6. Conclusion

The choice of row orientation in steep slope sites has a crucial impact on temperature parameters. Despite small differences in minimum temperatures, the analysis showed reliable results for higher temperatures in terraced vineyards during night. Differences in daily mean and maximum temperature as well as temperature amplitude were higher for vineyards planted in line of the greatest slope, most pronounced for N-S oriented vineyard rows. In general, differences between treatments increased with a rise in daily sum of global radiation at calm wind. Measurements of diurnal solar light distribution and light interception at bunch zone height showed differences between treatments and especially in autumn more favourable light conditions for terraced vineyard sites. In addition to economic considerations, changes of row orientation, through vineyard terracing, should be recognized as a possible tool to mitigate future environmental impacts on steep slope sites.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank the Deutsche Bundesstiftung Umwelt for founding the BioQuiS project (funding number AZ 34025) in which the experiments were carried out. We also thank the partner wineries for providing their vineyards for the investigations. We are grateful for the collegial exchange with Prof. Dr. Ilona Leyer and Prof. Dr. Claudia Kammann (Hochschule Geisenheim University, Department of Applied Ecology) and furthermore Andreas Ehlig for providing weather station data. Additionally thanks to Christian Frings for the technical support and Anthony William Bennett for proofreading the work.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.agrformet.2021.108515](https://doi.org/10.1016/j.agrformet.2021.108515).

References

- Bontempo, A., Smith, J., Brandt, M., Peterlunger, E., Stoll, M., 2018. Evaluation of photosensitive films for light measurements in the fruiting zone of grapevine canopies. *Vitis* 57 (4). <https://doi.org/10.5073/vitis.2018.57.159-165>.
- Bordoni, M., Persichillo, M.G., Meisina, C., 2016. The role of the vineyards on slope stability: a case study from an area susceptible to shallow landslides. *ROL* 39. <https://doi.org/10.3301/ROL.2016.34>.
- Bürkner, P.-C., 2017. Brms: an R package for bayesian multilevel models using stan. *J. Stat. Softw.* 80 (1) <https://doi.org/10.18637/jss.v080.i01>.
- Bürkner, P.-C., 2018. Advanced bayesian multilevel modeling with the R package brms. *R J.* 10 (1) <https://doi.org/10.32614/RJ-2018-017>.
- Campos, I., Neale, C.M.U., Calera, A., 2017. Is row orientation a determinant factor for radiation interception in row vineyards? *Aust. J. Grape. Wine Res.* 23 (1) <https://doi.org/10.1111/ajgw.12246>.
- Carroll, J.E., Wilcox, W.F., 2003. Effects of humidity on the development of grapevine powdery mildew. *Phytopathology* 93 (9). <https://doi.org/10.1094/PHYTO.2003.93.9.1137>.

- Cohen, S.D., Tarara, J.M., Kennedy, J.A., 2012. Diurnal temperature range compression hastens berry development and modifies flavonoid partitioning in grapes. *Am. J. Enol. Vitic.* 63 (1) <https://doi.org/10.5344/ajev.2011.11015>.
- Coombe, B.G., 1995. Growth stages of the grapevine: adoption of a system for identifying grapevine growth stages. *Aust. J. Grape. Wine Res.* 1 (2) <https://doi.org/10.1111/j.1755-0238.1995.tb00086.x>.
- de Rességuier, L., Mary, S., Le Roux, R., Petitjean, T., Quéno, H., van Leeuwen, C., 2020. Temperature variability at local scale in the Bordeaux area: relations with environmental factors and impact on vine phenology. *Front. Plant. Sci.* 11 <https://doi.org/10.3389/fpls.2020.00515>.
- Dowle, M., Srinivasan, A., 2020. Data.Table: Extension of 'Data.Frame'. <https://CRAN.R-project.org/package=data.table>.
- Emde, K., 1992. Experimentelle Untersuchungen zu Oberflächenabfluss und Bodenaustrag in Verbindung mit Starkregen bei verschiedenen Bewirtschaftungssystemen in Weinbergsarealen des oberen Rheingaus. Gesellschaft zur Förderung der Forschungsanstalt Geisenheim (GFGH), Geisenheim.
- Evans, R.G., 2000. The art of protecting grapevines from low temperature injury. In: *Proceedings of the ASEV 50th Anniversary Annual Meeting. Cold Hardiness Workshop*, Seattle, WA, 19th-23rd June.
- Flegal, J.M., Hughes, J., Vats, D., Dai, N., 2020. Mcmcse: monte carlo standard errors for MCMC. Riverside, CA, Denver, CO, Coventry, UK, and Minneapolis, MN.
- Fraga, H., Molitor, D., Leolini, L., Santos, J.A., 2020. What is the impact of heatwaves on european viticulture? A modeling assessment. *Appl. Sci.* 10 (9). doi:10.3390/app10093030.
- Fraga, H., Santos, J.A., Moutinho-Pereira, J., Carlos, C., Silvestre, J., Eiras-Dias, J., Mota, T., Malheiro, A.C., 2016. Statistical modelling of grapevine phenology in portuguese wine regions: observed trends and climate change projections. *J. Agric. Sci.* 154 (5) <https://doi.org/10.1017/S0021859615000933>.
- Friedel, M., 2018. Microclimatic influences on grape quality. Doctoral dissertation, Gießen.
- Gaiotti, F., Pastore, C., Filippetti, J., Lovat, L., Belfiore, N., Tomasi, D., 2018. Low night temperature at veraison enhances the accumulation of anthocyanins in corvina grapes (*Vitis vinifera* L.). *Sci. Rep.* 8 (1). doi:10.1038/s41598-018-26921-4.
- Gambetta, J.M., Holzapfel, B.P., Stoll, M., Friedel, M., 2020. Sunburn in grapes: a Review. *Front. Plant. Sci.* 11 <https://doi.org/10.3389/fpls.2020.604691>.
- Grifoni, D., Carreras, G., Zipoli, G., Sabatini, F., Dalla Marta, A., Orlandini, S., 2008. Row orientation effect on UV-B, UV-A and PAR solar irradiation components in vineyards at Tuscany, Italy. *Int. J. Biometeorol.* <https://doi.org/10.1007/s00484-008-0168-1>.
- Gutiérrez-Gamboá, G., Zheng, W., Martínez de Toda, F., 2021. Current viticultural techniques to mitigate the effects of global warming on grape and wine quality: a comprehensive review. *Food Res. Int.* 139 <https://doi.org/10.1016/j.foodres.2020.109946>.
- Hall, A., Jones, G.V., 2009. Effect of potential atmospheric warming on temperature-based indices describing Australian winegrape growing conditions. *Aust. J. Grape. Wine Res.* 15 (2) <https://doi.org/10.1111/j.1755-0238.2008.00035.x>.
- Heilman, J.L., McInnes, K., Savage, M.J., Gesch, R.W., Lascano, R.J., 1994. Soil and canopy energy balances in a west texas vineyard. *Agric. For. Meteorol.* 71 (1-2) [https://doi.org/10.1016/0168-1923\(94\)90102-3](https://doi.org/10.1016/0168-1923(94)90102-3).
- Hofmann, M., Lux, R., Schultz, H.R., 2014. Constructing a framework for risk analyses of climate change effects on the water budget of differently sloped vineyards with a numeric simulation using the Monte Carlo method coupled to a water balance model. *Front. Plant. Sci.* 5 <https://doi.org/10.3389/fpls.2014.00645>.
- Hofmann, M., Schultz, H.R., 2015. In: *Proceedings of the Modeling the Water Balance of Sloped Vineyards Under Various Climate Change Scenarios*. BIO web of Conferences 5 <https://doi.org/10.1051/bioconf/20150501026>.
- Hoppmann, D., Schaller, K., 1981. Der Einfluß verschiedener Standortfaktoren auf Qualität und Quantität der Reben: 2. Mitteilung: Entwicklung der Qualität in guten und besten Jahrgängen, und im 11jährigen Mittel, in: F. Dr. Fraund (Ed.), *Die Wein-Wissenschaft*. 36. Jahrgang. Fachverlag Dr. Fraund, Wiesbaden.
- Hoppmann, D., Schaller, K., Stoll, M., 2017. *Terroir: Wetter, Klima und Boden im Weinbau*. 2. Ulmer, Stuttgart, Hohenheim aktualisierte Auflage ed.
- Horney, G., 1975. Das häufigkeitsspektrum der windrichtungen in ökologischer Sicht (dargestellt an den besonderen Verhältnissen im Rheingau). *Berichte des deutschen Wetterdienstes* (138).
- Hunter, J.J., Volschenk, C.G., Zorer, R., 2016. Vineyard row orientation of *Vitis vinifera* L. cv. shiraz/101-14 Mgt: climatic profiles and vine physiological status. *Agric. For. Meteorol.* 228-229. <https://doi.org/10.1016/j.agrformet.2016.06.013>.
- Hunter, J.K., Tarricone, L., Volschenk, C., Giacalone, C., Melo, M.S., Zorer, R., 2020. Grapevine physiological response to row orientation-induced spatial radiation and microclimate changes. *OENO One* 54 (2). <https://doi.org/10.20870/oeno-one.2020.54.2.3100>.
- IPCC, 2013. *Climate change 2013: the physical science basis: contribution of working group I to fifth assessment report of the intergovernmental panel on climate change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Jagoutz, H., 2004. Der Einfluss des Windes, in: O. Löhnertz, D. Hoppmann, K. Emde, K. Friedrich, M. Schmanke, T. Zimmer (Eds.), *Die Standortkartierung Der Hessischen Weinbaugebiete*, 2., neu bearb. Aufl. Ed., Hessisches Landesamt für Umwelt und Geologie Wiesbaden.
- Jagoutz, H., 2005. *Bewässerungsbedarf von Reben in der Vergangenheit und in der Zukunft*. In: Schruf, G. (Ed.), *Deutsches Weinbau-Jahrbuch 2006*. Eugen Ulmer KG, Stuttgart.
- Job, H., Murphy, A., 2006. Germany's mosel valley: can tourism help preserve its cultural heritage? *Tour. Rev. Int.* 9 (4) <https://doi.org/10.3727/154427206776330526>.
- Jones, G.V., Davis, R.E., 2000. Climate influences on grapevine phenology, grape composition, and wine production and quality for Bordeaux, France. *Am. J. Enol. Vitic.* 51 (3).
- Jones, G.V., Reid, R., Vilks, A., 2012. In: Dougherty, P.H. (Ed.), *Proceedings of the Climate, Grapes, and Wine: Structure and Suitability in a Variable and Changing Climate*, 15. Springer, Dordrecht. The Geography of WineNetherlands.
- Jones, G.V., White, M.A., Cooper, O.R., Storchmann, K., 2005. Climate change and global wine quality. *Climatic Change* 73 (3). <https://doi.org/10.1007/s10584-005-4704-2>.
- Keller, M., Tarara, J.M., 2010. Warm spring temperatures induce persistent season-long changes in shoot development in grapevines. *Ann. Bot.* 106 (1) <https://doi.org/10.1093/aob/mcq091>.
- Kliewer, W.M., Torres, R.E., 1972. Effect of controlled day and night temperatures on grape coloration. *Am. J. Enol. Vitic.* 23 (2).
- Liu, J., Sherif, S.M., 2019. Hormonal orchestration of bud dormancy cycle in deciduous woody perennials. *Front. Plant. Sci.* 10 <https://doi.org/10.3389/fpls.2019.01136>.
- Maixner, M., Porten, M., Schmitt, T., 2012. Wechselwirkungen zwischen der Bewirtschaftung und der Biodiversität von Weinbau-Stellagen. *Julius-Kühn-Archiv*. https://doi.org/10.5073/jka.2012.436.008_436.
- Michalsky, A., 1976. Die Querterrassierung im Weinbau und ihr Einfluss auf verschiedene kleinklimatische und pedologische Faktoren sowie die Leistung der Rebe. *KTBL-Schriften-Vertrieb im Landwirtschaftsverlag*. Hiltrup, Westfalen.
- Molitor, D., Junk, J., 2019. 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* 53 (3). <https://doi.org/10.20870/oeno-one.2019.53.3.2329>.
- Moriondo, M., Bindi, M., 2007. Impact of climate change on the phenology of typical mediterranean crops. *Ital. J. Agrometeorol.* 3.
- Nazralla, J.J.B., 2007. *Microclima de la Canopia de la vid: Influencia Del Manejo Del Suelo y Coberturas Vegetales*. Revista de la Facultad de Ciencias Agrarias Universidad de Cuyo.
- Pallioti, A., Poni, S., 2015. Grapevine under light and heat stresses. In: Gerós, H., Chaves, M.M., Gil, H.M., Delrot, S. (Eds.), *Grapevine in a Changing Environment*. John Wiley & Sons, Ltd, Chichester, UK vol. 186.
- Pardo, E., Marín, S., Sanchis, V., Ramos, A.J., 2005. Impact of relative humidity and temperature on visible fungal growth and OTA production of ochratoxinigenic aspergillus ochraceus isolates on grapes. *Food Microbiol.* 22 (5) <https://doi.org/10.1016/j.fm.2004.11.004>.
- Peña Quiñones, A.J., Keller, M., Salazar Gutierrez, M.R., Khot, L., Hoogenboom, G., 2019. Comparison between grapevine tissue temperature and air temperature. *Sci. Hortic.* 247 (3) <https://doi.org/10.1016/j.scienta.2018.12.032>.
- Penfold, C., Collins, C., 2012. Cover crops and vineyard floor temperature, Adelaide.
- Petit, C., Konold, W., Höchtel, F., 2012. Historic terraced vineyards: impressive witnesses of vernacular architecture. *Landsch. Hist.* 33 (1) <https://doi.org/10.1080/01433768.2012.671029>.
- Pradel, E., Pieri, P., 2000. Influence of a grass layer on vineyard soil temperature. *Aust. J. Grape. Wine Res.* 6 (1) <https://doi.org/10.1111/j.1755-0238.2000.tb00163.x>.
- Preuschen, G., 1977. *Terrassen am Steilhang? In: Götz, B., Madel, W. (Eds.), Deutsches Weinbau-Jahrbuch 1978*. Waldkircher Verlagsgesellschaft, Waldkirch.
- Ramos, M.C., Mulligan, M., 2005. Spatial modelling of the impact of climate variability on the annual soil moisture regime in a mechanized Mediterranean vineyard. *J. Hydrol.* 306 (1-4) <https://doi.org/10.1016/j.jhydrol.2004.09.013>.
- Rienh, M., Torregrosa, L., Sarah, G., Ardisson, M., Brillouet, J.-M., Romieu, C., 2016. Temperature desynchronizes sugar and organic acid metabolism in ripening grapevine fruits and remodels their transcriptome. *BMC Plant Biol.* 16 (1) <https://doi.org/10.1186/s12870-016-0850-0>.
- Santillán, D., Garrote, L., Iglesias, A., Sotes, V., 2020. Climate change risks and adaptation: new indicators for mediterranean viticulture. *Mitig. Adapt. Strateg. Glob. Change* 25 (5). <https://doi.org/10.1007/s11027-019-09899-w>.
- 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., Kartschall, T., Menz, C., Molitor, D., Junk, J., Beyer, M., Schultz, H.R., 2020. A review of the potential climate change impacts and adaptation options for european viticulture. *Appl. Sci.* 10 (9) <https://doi.org/10.3390/app10093092>.
- Schultz, H.R., 2000. Climate change and viticulture: a European perspective on climatology, carbon dioxide and UV-B effects. *Aust. J. Grape. Wine Res.* 6 (1) <https://doi.org/10.1111/j.1755-0238.2000.tb00156.x>.
- Schultz, H.R., 2016. Global climate change, sustainability, and some challenges for grape and wine production. *J. Wine Econ.* 11 (1) <https://doi.org/10.1017/jwe.2015.31>.
- Sentelhas, P.C., Dalla Marta, A., Orlandini, S., Santos, E.A., Gillespie, T.J., Gleason, M.L., 2008. Suitability of relative humidity as an estimator of leaf wetness duration. *Agric. For. Meteorol.* 148 (3) <https://doi.org/10.1016/j.agrformet.2007.09.011>.
- Smart, R., Robinson, M., 1991. *Sunlight into Wine: A Handbook for Winegrape Canopy Management*. Winetitles, Adelaide.
- Smart, R.E., 1987. Influence of light on composition and quality of grapes. *Acta Hortic.* (206) <https://doi.org/10.17660/ActaHortic.1987.206.2>.
- Stoll, M., Schultz, H.R., 2021. *Statistiken, Tabellen, Verzeichnisse*, 71. Verlag Eugen Ulmer, Stuttgart, pp. 161-165.
- Strub, L., Kurth, A., Mueller Loose, S., 2020. Effects of viticultural mechanization on working time requirements and production costs. *Am. J. Enol. Vitic.* <https://doi.org/10.5344/ajev.2020.20027>.
- Strub, L., Mueller Loose, S., 2021. The cost disadvantage of steep slope viticulture and strategies for its preservation. *OENO One* 55 (1). <https://doi.org/10.20870/oeno-one.2021.55.1.4494>.
- Sweetman, C., Sadras, V.O., Hancock, R.D., Soole, K.L., Ford, C.M., 2014. Metabolic effects of elevated temperature on organic acid degradation in ripening *Vitis vinifera* fruit. *J. Exp. Bot.* 65 (20) <https://doi.org/10.1093/jxb/eru343>.

- Tarara, J.M., Ferguson, J.C., Hoheisel, G.-A., Perez Peña, J.E., 2005. Asymmetrical canopy architecture due to prevailing wind direction and row orientation creates an imbalance in irradiance at the fruiting zone of grapevines. *Agric. For. Meteorol.* 135 (1-4) <https://doi.org/10.1016/j.agrformet.2005.11.011>.
- Thind, T.S., Arora, J.K., Mohan, C., Raj, P., 2004. Epidemiology of powdery mildew, downy mildew and anthracnose diseases of grapevine. In: Naqvi, S.A.M.H. (Ed.), *Diseases of Fruits and Vegetables Volume I*. Kluwer Academic Publishers, Dordrecht vol. 11.
- Thomas, C.S., 1988. The effects of wind speed, temperature, and relative humidity on development of aerial mycelium and conidia of *botrytis cinerea* on grape. *Phytopathology* 78 (3). <https://doi.org/10.1094/Phyto-78-260>.
- Tomasi, D., Jones, G.V., Giust, M., Lovat, L., Gaiotti, F., 2011. Grapevine phenology and climate change: relationships and trends in the veneto region of Italy for 1964-2009. *Am. J. Enol. Vitic.* 62 (3) <https://doi.org/10.5344/ajev.2011.10108>.
- Tombesi, S., Cincera, I., Frioni, T., Ughini, V., Gatti, M., Palliotti, A., Poni, S., 2019. Relationship among night temperature, carbohydrate translocation and inhibition of grapevine leaf photosynthesis. *Environ. Exp. Bot.* 157 (352) <https://doi.org/10.1016/j.envexpbot.2018.10.023>.
- Tonietto, J., Carboneau, A., 2004. A multicriteria climatic classification system for grape-growing regions worldwide. *Agric. For. Meteorol.* 124 (1-2) <https://doi.org/10.1016/j.agrformet.2003.06.001>.
- van Leeuwen, C., Agnès, D.-I., Dubernet, M., Duchène, E., Gowdy, M., Marguerit, E., Pieri, P., Parker, A., de Rességuier, L., Ollat, N., 2019. An update on the impact of climate change in viticulture and potential adaptations. *Agronomy* 9 (9). <https://doi.org/10.3390/agronomy9090514>.
- van Leeuwen, C., Schultz, H.R., Garcia de Cortazar-Atauri, I., Duchène, E., Ollat, N., Pieri, P., Bois, B., Goutouly, J.P., Quénoel, H., Touzard, J.M., Malheiro, A.C., Bavaresco, L., Delrot, S., 2013. Why climate change will not dramatically decrease viticultural suitability in main wine-producing areas by 2050. *Proc. Natl. Acad. Sci.* 110 (33) <https://doi.org/10.1073/pnas.1307927110>. U S A.
- Vats, D., Flegal, J.M., Jones, G.L., 2019. Multivariate output analysis for Markov chain Monte Carlo. *Biometrika* (2), 106. <https://doi.org/10.1093/biomet/asz002>.
- Vehtari, A., Gelman, A., Simpson, D., Carpenter, B., Bürkner, P.-C., 2020. Rank-normalization, folding, and localization: an improved R for assessing convergence of MCMC. *Bayesian Anal.* <https://doi.org/10.1214/20-ba1221>.
- Vose, R.S., Easterling, D.R., Gleason, B., 2005. Maximum and minimum temperature trends for the globe: an update through 2004. *Geophys. Res. Lett.* 32 (23) <https://doi.org/10.1029/2005GL024379>.
- Webb, L., Whetton, P.H., Barlow, E.W.R., 2007. Modeled impact of future climate change on the phenology of winegrapes in Australia. *Aust. J. Grape. Wine Res.* 13 (3) <https://doi.org/10.1111/j.1755-0238.2007.tb00247.x>.
- Webb, L., Whiting, J., Watt, A., Hill, T., Wigg, F., Dunn, G., Needs, S., Barlow, E.W.R., 2010. Managing grapevines through severe heat: a survey of growers after the 2009 summer heatwave in South-Eastern Australia. *J. Wine Res.* 21 (2-3) <https://doi.org/10.1080/09571264.2010.530106>.
- Wickham, H., 2016. *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag, New York.
- Wild, M., Gilgen, H., Roesch, A., Ohmura, A., Long, C.N., Dutton, E.G., Forgan, B., Kallis, A., Russak, V., Tsvetkov, A., 2005. From dimming to brightening: decadal changes in solar radiation at Earth's surface. *Science* 308 (5723). <https://doi.org/10.1126/science.1103215>.
- Zelleke, A., Kliewer, W.M., 1979. Influence of root temperature and rootstock on budbreak, shoot growth, and fruit composition of Cabernet Sauvignon grapevines grown under controlled conditions. *Am. J. Enol. Vitic.* 30 (4).

Chapter III: Implication of Row Orientation Changes on Fruit Parameters of *Vitis vinifera* L. cv. Riesling in Steep Slope Vineyards

This chapter has been published as:

Strack, T.; Stoll, M. (2021). Implication of Row Orientation Changes on Fruit Parameters of *Vitis vinifera* L. cv. Riesling in Steep Slope Vineyards. *Foods*. 2021, 10, 2682. <https://doi.org/10.3390/foods10112682>.

Author Contributions

Conceptualization: T.S.

Data curation: T.S.

Formal analysis: T.S.

Funding acquisition: M.S.

Investigation: T.S.

Methodology: T.S.

Project administration: M.S.

Resources: M.S.

Supervision: M.S.

Validation: M.S.

Visualization: T.S.

Writing – original draft: T.S.

Writing – review & editing: M.S.

All authors have read and agreed to the published version of the manuscript.

Article

Implication of Row Orientation Changes on Fruit Parameters of *Vitis vinifera* L. cv. Riesling in Steep Slope Vineyards

Timo Strack  and Manfred Stoll

Department of General and Organic Viticulture, Hochschule Geisenheim University, Von-Lade-Straße 1, 65366 Geisenheim, Germany; Manfred.Stoll@hs-gm.de

* Correspondence: timo.strack@hs-gm.de; Tel.: +49-6722-502-149

Abstract: Row orientation, among others, is a crucial factor in determining grapevine performance and health status, thus affecting berry components that form the basis of the later wine profile. However, the literature about the impact of changes in row orientation at steep slope sites on grapevine fruit composition as well as the differentiation between canopy sides hardly exists. Thus, the aim of this work was to gain knowledge about the impact of row orientation in steep slope vineyards on selected primary and secondary metabolites in berries of *Vitis vinifera* L. cv. Riesling. Samples were taken from both canopy sides of different row orientations of terraced and downslope vineyards in steep slopes. Free amino acids in the juice and flavonols in the berry skin had a positive correlation to sunlight exposure. Furthermore, grapevines showed adaptations to constantly higher light conditions, e.g., physiologically in reduction in chlorophyll content or protective mechanisms resulting in a lower susceptibility to sunburn damage. Thus, grapevine fruit parameters are affected by row orientation change in steep slopes.

Keywords: terraced vineyard; berry quality; canopy microclimate; cluster exposition; amino acids; polyphenols



Citation: Strack, T.; Stoll, M. Implication of Row Orientation Changes on Fruit Parameters of *Vitis vinifera* L. cv. Riesling in Steep Slope Vineyards. *Foods* **2021**, *10*, 2682. <https://doi.org/10.3390/foods10112682>

Academic Editor: Onofrio Corona

Received: 21 September 2021

Accepted: 26 October 2021

Published: 3 November 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Content and composition of primary and secondary metabolites present in pulp, skin and seeds of grapevine berries significantly determine wine quality. Furthermore, plants primary metabolites (e.g., sugars, organic acids and amino acids) are crucial for vegetative and generative growth, whilst secondary metabolites (e.g., phenolic, pigment and aroma compounds) play an important role in environmental interactions, e.g., adaptation to biotic and abiotic stressors.

The exposure of grapevine berries to solar radiation and high temperature bears the risk of sunburn and crop damage [1], but is also known to alter the amount and composition of antioxidative substances, which are important for palatability and are valuable for consumers' health [2]. The ongoing change in climate may, therefore, not only impact the suitability of grapevine cultivation in some regions and its performance, but also berry quality parameters and thus traditional wine profiles [3].

Lately, research was conducted on *Vitis vinifera* L. cultivar Riesling, the leading cultivar for high quality white wine production in Germany and other countries worldwide [4]. Friedel et al. [5] showed that the expression of monoterpene and flavonol metabolic genes in Riesling berries were up-regulated by bunch exposure to sunlight. Further studies confirmed the effect of cluster exposure on the alteration of phenolic substances of berries of the same variety. Sun-exposed bunches resulted in about 50% higher phenolic concentrations on average [6], while shading reduced total phenolics significantly by 43% and 56%, compared to different defoliation means [7]. An increased exposure to UV-B radiation resulted in a decreased content and an altered composition of amino acids in Riesling [7,8], whereas no differences were detected in other grape varieties [9–11]. The concentration

and composition of certain amino acids is not only associated with the amount of sunlight, daytime and photosynthetic activity of the plant [12], but also depends on grapevine cultivar [13], tissue [14] and origin [15].

Furthermore, the degree of bunch exposure to sunlight is known to affect aroma precursors and compounds of grapes [16]. The impact of natural shading through row orientation on norisoprenoid levels in Riesling was studied in South Africa [17]. Marais et al. [17] found significantly higher norisoprenoid precursors in berries matured under sunlit conditions compared to bunches ripened on the shaded side of the canopy. Since the expression of several aroma compounds in Riesling found to be light dependent [5], it seems that a minimum exposure of above 20% ambient light is necessary for a positive response of monoterpenes [18]. However, the 20% light intensity threshold also applies for the formation of undesired norisoprenoid TDN (1,1,6-trimethyl-1,2-dihydronaphthalene) and its precursor Riesling acetal [19,20].

A change in row orientation, particularly under steep slope conditions, modifies light microclimate in the vineyard [21,22], which affects the diurnal pattern of grapevine canopy temperature, bunch zone light interception [23] and photosynthetically active radiation [24]. Energy input into a vineyard increases with the degree of slope and may result in 30 to 40% higher solar energy intake compared to flat vineyard sites [25,26]. Hence, row orientation changes at steep slopes, i.e., by carving terraces into the slope, affect bunch zone light interception considerably [23].

The aim of this study was to determine the effects of different irradiation conditions on the composition of selected fruit parameters of Riesling grape berries by separating the berry exposition from both canopy sides of different row orientations in two steep slope vineyard systems, i.e., terraced and downsloped vineyards.

2. Materials and Methods

In 2019 and 2020, data were collected in the Rheingau wine-growing region on *V. vinifera* L. cultivar Riesling. Three vineyard pairs, each consisting of a vineyard according to the standard cultivation method of vines planted downslope (control, C) and a terraced vineyard system (T) were selected. The down-sloped vineyard site Geisenheimer Rothenberg (GM) represented the N–S row orientation, while the terraced treatment was aligned from E to W. At the sites Lorcher Eisersgrube (LE) and Lorcher Sesselberg (LS) row orientations adapted to the Rhine river-dependent orography. Hence, control vineyards were NE–SW-oriented while terraced vineyards were planted in NW–SE direction. The vines were trained using vertical shoot positioning (VSP), with a single guyot comprising 6–8 buds per m². Row spacing ranged from 1.4 m to 2 m among the control treatment and 1.8 to 2.3 m on terraces, depending on vineyard age and feasibility to mechanization. Vine space ranged from 1 m to 1.2 m in down sloped vineyards and 0.6 m to 0.7 m on terraces. Detailed weather conditions can be found in Table S1 and are displayed in Figure S1. Further information on the experimental setup was previously described [23].

2.1. Berry Sampling and Processing

At grapevine development stage E-L 38 (berries harvest-ripe [27]), three replicates of one hundred to two hundred healthy berries were randomly collected from each side of the canopy for berry maturity analyses.

For berry skin polyphenol analyses three replicates of twenty berries per sample were cut with the pedicel, flushed with CO₂ and immediately frozen in liquid nitrogen. Samples were stored at −80 °C until further processing.

2.1.1. Berry Juice Analyses

Berries were pressed twice at 0.6 MPa for approximately two minutes (Longarone 85, Eis System GmbH, Norderstedt, Germany), interrupted by a manual crumbling. The obtained juice was centrifuged for five minutes at 7830 rpm and 20 °C (Eppendorf 5430 R, Hamburg, Germany) and filtered coarsely (33/N). After a second centrifugation step

at 14,000 rpm for five minutes, the yeast assimilable α -amino nitrogen content was determined by a spectrophotometer (Specord 50 plus, Analytik Jena, Jena, Germany) using a N-Acetyl-L-Cysteine/ophthalaldehyde (N-OPA) assay [28]. Total soluble solids (TSS), total titratable acidity (TTA), malic acid (MA) and tartaric acid (TA) were analysed by Fourier-transformed infrared spectroscopy (FTIR) via a FT2 Winescan spectrometer (FOSS, Hillerød, Denmark) using an in-house grape must calibration. Amino acid spectrum was obtained using an automatic amino acid analyser S433 (Sykam Chromatographie Vertriebs GmbH, Fürstfeldbruck, Germany) according to the protocol of Krause and Löhnertz [29]. The separation of amino acids from the juice occurred at a cation exchange separation column via the distinctive isoelectric point of each individual amino acid, aided by a lithium citrate buffer (pH 2.2). Amino acids were qualitatively measured by the retention time. During post column derivatisation, the amino acids were labelled with the reagent ninhydrin at a temperature of 130 °C. An UV/VIS-detector measured the primary and secondary amino acids quantitatively at 570 nm and 440 nm, respectively. All data were transformed from content to concentration (i.e., content per gram berry fresh weight).

2.1.2. Berry Skin Polyphenol Analysis

Frozen berries were peeled under CO₂ atmosphere. Berry skins were freeze dried, ground and desiccated until further processing. Phenolic compounds were then extracted by acidified acetonitrile under SO₂ protection prior to vacuum distillation. The polyphenolic extracts were analysed by an UHPLC system (UltiMate 3000, ThermoFischer, Dreieich, Germany) coupled to a UV/VIS diode array detector (Vanquish, ThermoFischer, Dreieich, Germany). Additionally, samples were measured by a LXQ mass spectrometer (ThermoFischer, Dreieich, Germany). Then, 3 μ L sample volume were injected at a flow rate of 250 μ L min⁻¹ into a 150 \times 2 mm (inner diameter) 3 μ m Luna 3u C18 100 A column (Phenomenex, Aschaffenburg, Germany) for chromatographic separation. Flavanols, phenolic acids and flavonols were detected at wavelengths of 280 nm, 320 nm and 360 nm, respectively. The identification of the peaks was based on HPLC retention time, the UV spectra and mass spectral data. External calibration curves were used for quantification.

Elution conditions were: solvent A was 2% acetic acid; solvent B was acetonitrile/water/acetic acid (50:50:0.5; *v/v/v*). Gradient elution was applied: 0–20 min from 96–50% solvent A, 4–50% solvent B, 20–23.1 min to 100% B; washing with 100% B for 2 min before re-equilibrating the column. The following mass spec conditions were used: ESI source voltage –3.00 kV during negative and +5.00 kV during positive ionization mode; capillary temperature 275 °C; collision energy for MSⁿ-experiments 35% (arbitrary units). A table containing all standard sources is presented in the supplementary material (Table S3). Where no standards were available, substances were quantified using the calibration for the closest phenolic relatives (caftaric acid as caffeic acid; fertaric acid as ferulic acid, coumaric acid and p-CGT as coumaric acid) [7].

2.2. Canopy Density Measurements

Point Quadrat Analysis [30] was conducted at flowering, onset of ripening and at harvest to obtain additional information on bunch zone light conditions. Data was collected by inserting a thin metal rod into the canopy along a measuring tape. Distance between insertions was 20 cm. One hundred insertions were made within four replicates. Leaf layer number (LLN), percentage of interior clusters (PIC) and percentage of interior leaves (PIL) were calculated from recordings of contact with leaves and clusters, according to Smart and Robinson [30]. The data is presented in the Supplementary Material (Table S4).

2.3. Cluster Light Interception

Cluster light environment was measured via dyed triacetyl cellulose strips (OptoLeaf R-3D, Taisei-Environmental & Landscape Group, Tokyo, Japan). A grid (1 m \times 0.3 m) equipped with fifteen light sensitive films (LSF) was placed in front of either canopy sides, both sunlit and shaded, at bunch zone height (0.7 m to 1 m) at all experimental sites in 2019

and 2020 during same time intervals at flowering (LSF_f), onset of ripening (LSF_o) and berries harvest-ripe (LSF_h). Film fading values were converted by calibration curves via regression equations obtained from a nearby weather station, maintained by Hochschule Geisenheim University (49°98'4" N; 07°95'44" E) [23]. The data were used as additional quantitative parameter in principal component analysis to incorporate environmental data, which is an important driver of grapevine fruit quality. The data are presented in the supplementary material (Table S5).

2.4. Leaf Nutritional Status

A functioning photosynthesis apparatus is important for plant growth in general and is determining for yield and berry quality in grapevine, since assimilated carbon is a key element in organic structures such as carbohydrates, amino acids or polyphenols. A chlorophyll-meter (Dualex 4 scientific, Force-A, Orsay, France) was used for leaf chlorophyll measurements at two dates (flowering and bunch closure). The optical chlorophyll index (Chl_i) was obtained by measuring the abaxial and adaxial side of three leaves per canopy side on three selected and labelled shoots of six randomly selected vines of each treatment and site. Leaf position and leaf age was considered similar due to measuring at comparable internode lengths. The Chl_i index is recognized to perform well as a proxy for leaf nitrogen content [31].

2.5. Scoring of Sunburn Damage

Subsequent to a row of heat days (i.e., daily maximum temperatures >30 °C), sunburn damage was assessed in both years of 2019 (01.08.) and 2020 (13.08.). Four hundred grape cluster per vintage, site, treatment and canopy side were evaluated following the seven steps assessment scheme of EPPO guideline 1/031(3) [32], in order to evaluate reactions of clusters exposed to different light regimes under extreme environmental conditions.

2.6. Statistical Analyses

Principal component analysis (PCA) was used for exploratory data analysis of berry ingredients to examine the associations between individuals and variables and to detect main components for later analyses. Data were checked for correlations and auto scaled (i.e., $\frac{x_i - \text{mean}(x)}{\text{sd}(x)}$). PCA was performed using R packages *FactoMineR* [33] for conducting and *factoextra* for visualization. All analyses were implemented within the *RStudio* environment (v1.4.1106 (11 February 2021)).

Pairwise multiple comparison via Student–Newmann–Keuls test (significance level of $\alpha = 0.05$) was applied subsequent to one-way analyses of variance (ANOVA) conducted on data of berry juice (harvest parameters and amino acids) and berry skin (polyphenol analyses) as well as Chl_i measurements for the factor exposition. Subsets were divided into single vintages and in case of Chl_i measurements into development stages. All data sets were tested for homoscedasticity of variance via Levene test and checked visually for normal distribution of residuals.

Sunburn data were analysed via a non-parametric Kruskal–Wallis test. Results were compared post hoc via Dunn’s test (Bonferroni-adjusted, significance level of $\alpha = 0.05$).

Statistical analyses were conducted using R packages *agricolae* [34], *car* [35] and *multcomp* [36].

3. Results

Principal component analysis explained approximately 65% of total variance. In total, 72 individual samples and 54 variables (i.e., six technological juice parameters, 28 amino acids and related derivatives as well as twenty polyphenolic compounds) were analysed by principal component analysis. Additionally, thirteen quantitative variables (i.e., cluster light environment data, canopy density parameters and berry weight) were added. The best distinguishing factor for the individual samples was (bunch) exposition. The score plot

(Figure 1A) illustrates the individual samples grouped by exposition. Figure 1B displays the variables with the highest contribution.

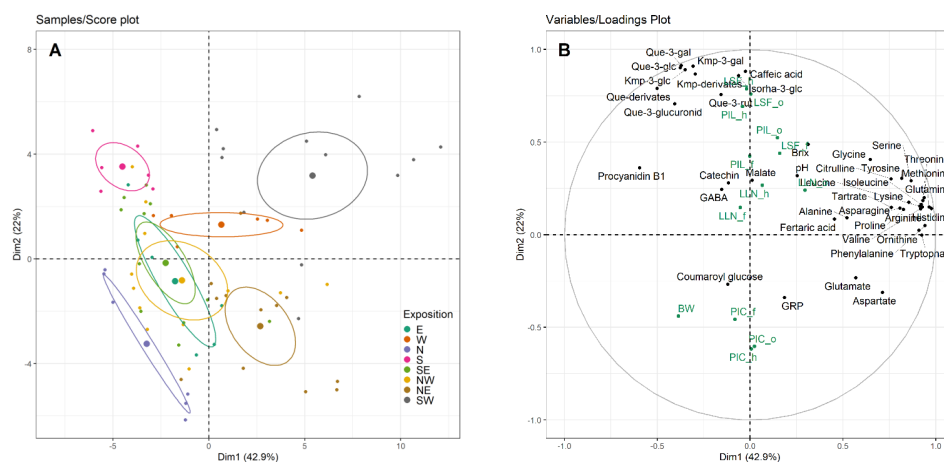


Figure 1. Principal component analysis. (A) Score plot of individuals. Dots represent individual samples and dot colour indicates bunch exposition. Big dots show the mean of sample group, ellipses represent 95% confidence interval. (B) Loadings plot of variables. Black labels show analysed berry parameters (concentrations). Green labels represent supplementary quantitative data. BW = berry weight, LLN = leaf layer number, PIC = percentage of interior clusters, PIL = percentage of interior leaves (_f = flowering, _o = onset of ripening, _h = harvest-ripe), LSF = bunch zone radiation energy interception, GABA = γ -aminobutyric acid, gal = galactoside, glc = glucoside, rut = rutinoid, GRP = grape reaction product, Kmp = kaempferol, Que = quercetin.

SW-exposed canopy sides were characterized by a positive coordinate on the first dimension (Dim1) and the second dimension (Dim2) axes (Figure 1A). SW exposition of terraced vineyards showed high association with amino acid concentrations and low values of berry weight, procyanidin B1 and PIC (Figure 1B). Whereas S-exposed berries showed a strongly negative association with Dim1 (Figure 1A), thus low levels of amino acids. Dimension 2 opposed individuals of S- and SW-exposition (strong positive correlated to the axis) to individuals of N- and NE-exposition (strong negative relationship to the axis). A positive association to Dim2 related to bunch zone sun light interception (LSF) and flavonols.

Distance between sunlit (i.e., S, SW) and shaded (i.e., N, NE) sides of terraced vineyards (Dim2), but also between row orientations, in particular of terraced vineyards (Dim1), and exposition, was apparent. The canopy sides of control vineyards (E, W, NW, SE) scattered around the centre with a small negative association to Dim1. The W- and SE-exposed berries showed a trending positive association to Dim2 (Figure 1A), demonstrating their higher share on daily radiation compared to the E- and NW-facing canopy sides.

3.1. Berry Composition

To evaluate the effect of irradiation, harvest-ripe berries were picked from the different canopy sides and analysed separately.

3.1.1. Berry Juice Composition

Analysed parameters of juice obtained from harvest-ripe berries showed similar trends between the two vintages 2019 and 2020 for sites with the row comparison of NE–SW and NW–SE (sites LE and LS). Control vineyards achieved higher contents of total soluble solids and berry weight compared to the terraced treatment, resulting in a lower concentration of TSS (Table 1). The highly sun-exposed canopy sides W and SE showed the highest Brix values per gram berry weight.

Table 1. Berry maturity parameters (mean \pm standard deviation) of Riesling juice obtained from harvest-ripe berries in 2019 and 2020, separated by canopy sides of each treatment (control = C, terraced vineyard = T). Lower case indicates results of Student–Newmann–Keuls test. Different letters show significant differences ($p < 0.05$) between canopy expositions in respective vintage for every site. GM = Geisenheimer Rothenberg, LE = Lorcher Eisersgrube, LS = Lorcher Sesselberg, TSS = total soluble solids, TTA = total titratable acidity, N-OPA = yeast assimilable nitrogen. Table shows juice parameter content per gram berry fresh weight.

Vintage	Site	Treatment	Exposition	TSS ($^{\circ}$ Brix g^{-1})	TTA ($g L^{-1} g^{-1}$)	Tartaric Acid ($g L^{-1} g^{-1}$)	Malic Acid ($g L^{-1} g^{-1}$)	pH	N-OPA ($g L^{-1} g^{-1}$)	Berry Weight (g)
2019	GM	C	E	22.50 \pm 0.44 a	12.00 \pm 0.67 a	9.46 \pm 0.52 a	3.18 \pm 0.20 a	2.90 \pm 0.00 b	60.06 \pm 3.97 b	0.88 \pm 0.02 c
2019	GM	C	W	22.57 \pm 0.45 a	10.49 \pm 0.20 b	8.63 \pm 0.14 b	2.57 \pm 0.04 b	3.07 \pm 0.06 a	75.51 \pm 7.94 a	0.87 \pm 0.01 c
2019	GM	T	N	18.73 \pm 0.25 c	7.44 \pm 0.27 d	5.28 \pm 0.12 d	2.37 \pm 0.15 b	2.9 \pm 0.00 b	26.71 \pm 1.89 c	1.12 \pm 0.02 a
2019	GM	T	S	20.12 \pm 0.26 b	8.24 \pm 0.12 c	6.20 \pm 0.10 c	2.26 \pm 0.09 b	2.97 \pm 0.06 b	32.92 \pm 0.77 c	1.02 \pm 0.01 b
2019	LE	C	NW	15.94 \pm 0.14 d	5.96 \pm 0.09 c	4.22 \pm 0.07 c	1.82 \pm 0.03 c	2.87 \pm 0.06 c	40.93 \pm 1.29 c	1.20 \pm 0.01 a
2019	LE	C	SE	16.65 \pm 0.30 c	6.24 \pm 0.25 c	4.53 \pm 0.17 c	1.83 \pm 0.10 c	2.90 \pm 0.00 c	42.85 \pm 1.04 c	1.18 \pm 0.02 a
2019	LE	T	NE	24.11 \pm 0.51 b	13.33 \pm 0.30 b	10.28 \pm 0.29 b	4.06 \pm 0.20 b	3.17 \pm 0.06 b	182.57 \pm 19.8 b	0.77 \pm 0.01 b
2019	LE	T	SW	28.22 \pm 0.25 a	17.33 \pm 0.6 a	13.9 \pm 0.61 a	5.08 \pm 0.07 a	3.27 \pm 0.06 a	304.90 \pm 33.19 a	0.67 \pm 0.01 c
2019	LS	C	NW	19.19 \pm 0.04 c	8.03 \pm 0.04 c	5.92 \pm 0.07 c	2.38 \pm 0.01 c	2.93 \pm 0.06 ab	63.32 \pm 2.25 c	1.00 \pm 0.00 b
2019	LS	C	SE	18.76 \pm 0.12 c	7.41 \pm 0.07 c	5.57 \pm 0.06 c	2.19 \pm 0.02 c	3.00 \pm 0.00 a	56.09 \pm 3.99 c	1.06 \pm 0.01 a
2019	LS	T	NE	22.06 \pm 0.67 b	10.39 \pm 0.51 b	8.11 \pm 0.44 b	2.69 \pm 0.14 b	2.90 \pm 0.00 b	113.60 \pm 1.72 b	0.86 \pm 0.02 c
2019	LS	T	SW	25.26 \pm 0.68 a	13.91 \pm 0.86 a	11.15 \pm 0.79 a	3.35 \pm 0.15 a	3.00 \pm 0.00 a	171.79 \pm 10.11 a	0.75 \pm 0.02 d
2020	GM	C	E	17.51 \pm 0.08 c	6.98 \pm 0.11 a	6.95 \pm 0.10 a	0.93 \pm 0.07 b	3.07 \pm 0.06 b	54.58 \pm 2.04 b	1.14 \pm 0.01 b
2020	GM	C	W	18.77 \pm 0.13 a	7.18 \pm 0.26 a	7.09 \pm 0.26 a	0.69 \pm 0.02 c	3.20 \pm 0.00 a	73.13 \pm 2.16 a	1.08 \pm 0.02 c
2020	GM	T	N	17.79 \pm 0.06 c	7.13 \pm 0.00 a	6.42 \pm 0.05 b	1.42 \pm 0.05 a	3.00 \pm 0.00 c	38.11 \pm 0.75 c	1.17 \pm 0.00 a
2020	GM	T	S	18.24 \pm 0.37 b	6.88 \pm 0.15 a	6.78 \pm 0.22 a	0.93 \pm 0.02 b	3.10 \pm 0.00 b	36.37 \pm 2.24 c	1.17 \pm 0.02 a
2020	LE	C	NW	14.53 \pm 0.13 d	4.65 \pm 0.09 d	4.09 \pm 0.05 d	0.98 \pm 0.05 c	2.90 \pm 0.00 b	27.57 \pm 1.1 c	1.42 \pm 0.01 a
2020	LE	C	SE	15.79 \pm 0.27 c	5.57 \pm 0.16 c	4.89 \pm 0.14 c	1.18 \pm 0.05 b	2.90 \pm 0.00 b	30.05 \pm 1.91 c	1.32 \pm 0.02 b
2020	LE	T	NE	17.72 \pm 0.11 b	9.61 \pm 0.22 b	8.34 \pm 0.24 b	2.23 \pm 0.03 a	2.97 \pm 0.06 a	76.95 \pm 2.98 b	1.02 \pm 0.01 c
2020	LE	T	SW	19.19 \pm 0.44 a	11.15 \pm 0.66 a	10.00 \pm 0.59 a	2.37 \pm 0.14 a	3.00 \pm 0.00 a	119.24 \pm 6.2 a	0.95 \pm 0.02 d
2020	LS	C	NW	15.58 \pm 0.21 d	5.21 \pm 0.15 d	4.81 \pm 0.15 d	0.95 \pm 0.03 b	2.90 \pm 0.00 b	45.60 \pm 3.70 c	1.29 \pm 0.02 a
2020	LS	C	SE	16.73 \pm 0.34 c	5.98 \pm 0.23 c	5.60 \pm 0.22 c	1.05 \pm 0.05 b	3.00 \pm 0.00 a	52.65 \pm 2.97 c	1.22 \pm 0.02 b
2020	LS	T	NE	18.77 \pm 0.24 b	10.82 \pm 0.13 b	9.70 \pm 0.11 b	2.16 \pm 0.03 a	2.87 \pm 0.06 b	98.13 \pm 6.48 b	0.96 \pm 0.01 c
2020	LS	T	SW	20.71 \pm 0.43 a	13.05 \pm 0.74 a	12.25 \pm 0.66 a	2.27 \pm 0.12 a	2.90 \pm 0.00 b	136.67 \pm 15.3 a	0.89 \pm 0.02 d

Amounts of tartrate and malate were low for SE-exposed berries, resulting in lowest amounts of total titratable acidity, along with the NW-exposed samples. Terraced vineyards in NW–SE orientation showed the highest levels of acidity, but tended to result in the highest pH (Table 1). The E–W-oriented terraced treatment achieved higher amounts of total soluble solids and berry weight compared to the N–S-oriented control. TTA was highest for control treatments in 2019, but similar between treatments in 2020. In general, the hill-facing canopy side of the terrace (N) and the shaded side of the control vineyard (E) showed the highest amounts of malate within this site. The juice pH mainly increased on the W-exposed canopy side (Table 1).

N-OPA values were the highest in samples of SW- and NE-exposed berries. Here, the more sunlit canopy side (SW) showed higher values than the hill-facing NE-exposed side. Samples from NE–SW oriented control vineyards had lower N-OPA values than the terraced vineyards. In N–S-oriented vineyards, the sunlit W-exposed berries showed higher N-OPA concentrations than E-facing samples, while both canopy sides of the terraced treatment did not differ in their low N-OPA concentrations (Table 1).

Treatments were significantly different in amino acid concentrations (Table S6). Similar trends among different row orientation systems were observed. In both years, the N–S-oriented control vineyard showed higher free and total amino acid concentrations compared to the terraced treatment (Table S6). The E-exposed berries of the control usually showed lower free amino acid concentrations compared to the more sunlit W side of the canopy (Figure 2). The hill- and valley-facing sides of terraced vineyards planted in E–W orientation (N and S) showed no differences in the total concentration of amino acids.

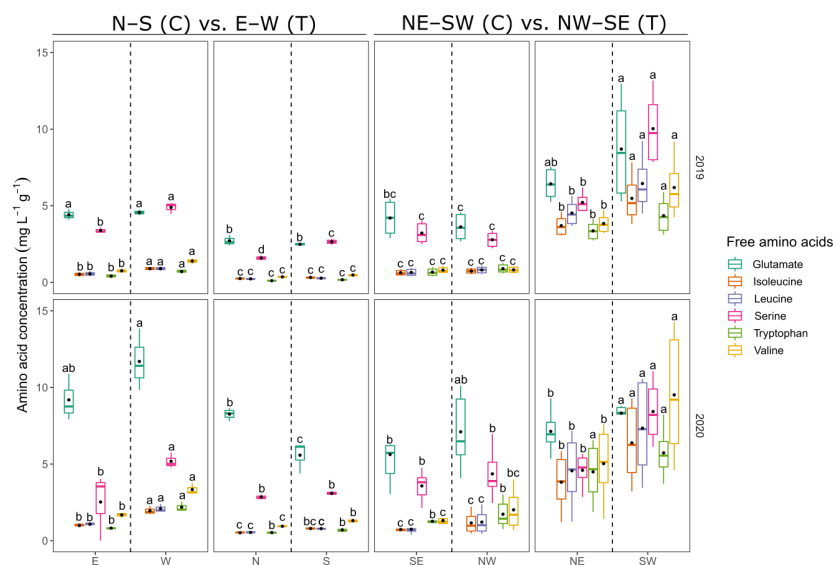


Figure 2. Comparison of selected primary amino acid concentrations ($\text{mg L}^{-1} \text{g}^{-1}$) obtained from juice of harvest-ripe berries. Boxplots show the distribution of the data. Median is indicated by horizontal line in the boxplot, mean values are represented by a black dot in the respective boxplots. Different colors indicate different amino acids. Lower case indicates results of Student–Newman–Keuls post-hoc test (different letters show significant differences ($p < 0.05$)) between canopy exposition (E = east, W = west, N = north, S = south, SE = southeast, NW = northwest, NE = northeast, SE = southeast) within row orientation pairs in respective vintage.

However, terraced vineyards planted in NW–SE direction contained higher amounts of total and single amino acid concentrations compared to NE–SW oriented control vineyards (Figure 2, Table S6). The NE–SW control vineyard often showed similar values of single and

total amino acid concentrations of grape juice obtained from NW- and SE-exposed berries (Figure 2, Table S6). In NW–SE-aligned vineyards (T), SW-exposed berries usually showed higher amounts of single free amino acids compared to NE-exposed samples (Figure 2).

The proportional difference of total amino acids between SE (stronger light exposed) and the, within the course of a day, less sun-exposed NW side of the canopy ranged between -2.63% and 52.14% , resulting in no significant differences (Table S7). Row orientation change to NW–SE alignment increased the differences in total amino acids to 1.8- to 4-fold (NE) and 2.2- to 6-fold (SW), depending on the year and site. W-facing canopy sides showed about 1.5 times higher total amino acid concentrations compared to the E-facing side. N- and S-exposed berries (T) showed approximately half of the total amino acid content compared to the comparative exposition E (C).

Arginine, proline and glutamine were the most abundant free amino acids in terms of proportion (total sample averages: 25%, 19% and 12%, respectively; Table S7). Arginine was found in high concentrations at site LE and LS in both treatments and years. Terraced vineyards at site LE and LS showed higher concentrations for arginine and glutamine compared to control. In turn, control vineyards planted in NE–SW direction showed higher concentrations and share of proline (Tables S6 and S7). Proline was also higher in terraced vineyards of E–W orientation, while arginine and glutamine were more abundant in the N–S-aligned control vineyard. Glutamate, GABA and alanine had a maximum share of 13.5% on total amino acid concentration. Glutamate, GABA and alanine showed higher concentrations in berries from NE–SW oriented terraces compared to control, but had a lower share on total amino acids. Vines planted in N–S direction showed higher values in glutamate, GABA and alanine, but the values represented a lower proportion to total amino acid concentration compared to the E–W-aligned terraced treatment (Tables S6 and S7).

3.1.2. Berry Skin Polyphenol Content

Results of berry skin polyphenols were consistent during both years of the experiment. Only single parameters showed a little variation between vintages. In general, catechin and procyanidin B1 did not differ much among exposition and sites. However, control vineyards showed a tendency of higher values for the sum of flavanols (Figure 3, Table S8).

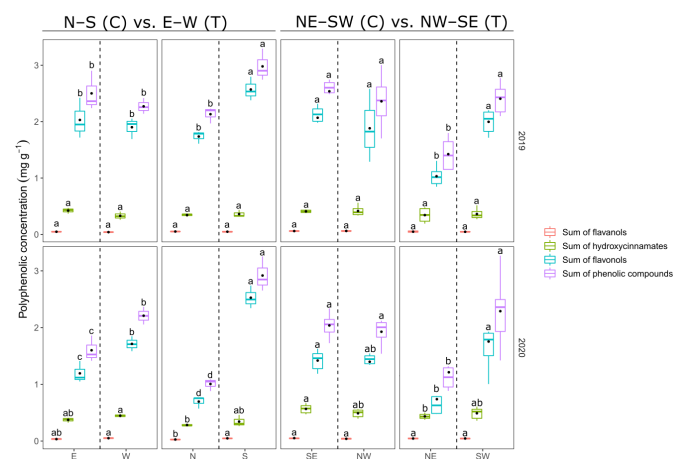


Figure 3. Comparison of sums of polyphenolic concentrations (mg g^{-1}) obtained from skins of harvest-ripe berries. Boxplots show the distribution of the data. Median is indicated by horizontal line in the boxplot, mean values are represented by a black dot in the respective boxplots. Different colors indicate different groups of polyphenolics. Lower case indicate results of Student–Newman–Keuls post-hoc test (different letters show significant differences ($p < 0.05$)) between canopy exposition (E = east, W = west, N = north, S = south, SE = southeast, NW = northwest, NE = northeast, SE = southeast) within row orientation pairs in respective vintage.

At site GM, the W-exposed berries showed highest amount of fertaric acid and caffeic acid in 2020, while N- and NE-exposed berry skin extracts showed the lowest values consistently. Nevertheless, differences in results of total hydroxycinnamates were not consistent between the years (Table S8).

Flavonols were highest for berries harvested from the valley-facing sides of the terraced vineyards (S and SW). SE- and NW-exposed samples from the control vineyards did not differ, while W-exposed berries tended to have higher flavonols and sum of phenolic content compared to those exposed to the east (Figure 3, Table S8). In essence, the more sun-exposed canopy sides showed the highest values in sum of phenolic content of the berry skin (Figure 1A,B and Figure 3).

3.2. Leaf Nitrogen Content

Significant differences ($p < 0.05$) were found for leaf Chl_i measurements between expositions on each measurement date (Figure 4). Single canopy sides did not always reach optimum Chl_i content [31] during the three years tested. Mainly NW- and SW-exposed canopy sides, but also S- and W-facing leaves showed the lowest, and often insufficient, leaf Chl_i values.

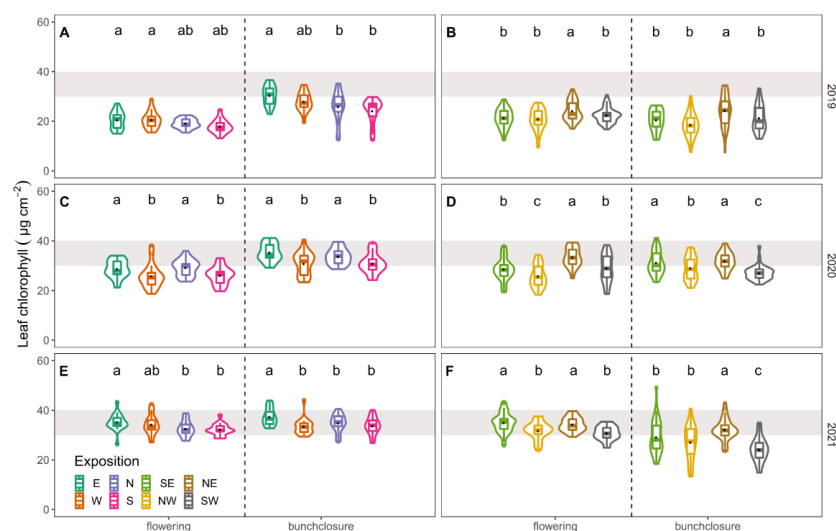


Figure 4. Leaf chlorophyll content ($\mu\text{g cm}^{-2}$) measured at development stages flowering and bunch closure in 2019 (A,B), 2020 (C,D) and 2021 (E,F). Violins show the distribution of the data. Median is indicated by horizontal line in the boxplot, mean values are represented by a black dot in the respective boxplots. Different colours represent different canopy expositions. The grey background shows approximated optimum range [31]. Lower case indicate results of Student–Newman–Keuls post hoc test (different letters show significant differences ($p < 0.05$)) between canopy exposition (E = east, W = west, N = north, S = south, SE = southeast, NW = northwest, NE = northeast, SE = southeast) in respective vintage and development stage for N–S/E–W and NW–SE/NE–SW row orientations.

Results of Chl_i measurements were different for the respective canopy side comparisons between the vintages. Chl_i content increased in N–S (control) and E–W (terraced) oriented rows from flowering to bunch closure in all years. The Chl_i content of the control vineyard was higher compared to the E–W-oriented terraced treatment (Figure 4A, C), while in 2020 there was no difference between treatments. In 2021 Chl_i values were highest for the observed canopy sides. Again, control vineyards tended to show higher leaf chloro-

phyll content compared to the terrace, mainly due to high mean value of E-facing leaves (Figure 4E).

NW–SE oriented terraces showed higher Chl_i values at flowering compared to the control vineyards planted in NE–SW direction (Figure 4B,D). In 2021, data were less clear due to high Chl_i levels in SE-exposed leaves (Figure 4F). At bunch closure, the NE–SW aligned control vineyard tended to have a higher mean leaf Chl_i content. In general, less sun-exposed canopy sides (E, N, NE, but also SE) showed higher Chl_i values compared to their sun-exposed equivalents, which had a higher sun exposition during the afternoon and early evening (S, W and NW and SW).

3.3. Sunburn Damage

The results of sunburn-damaged grapes are shown in Figure 5. In general, sunburn damage was higher in 2019 compared to the vintage of 2020.

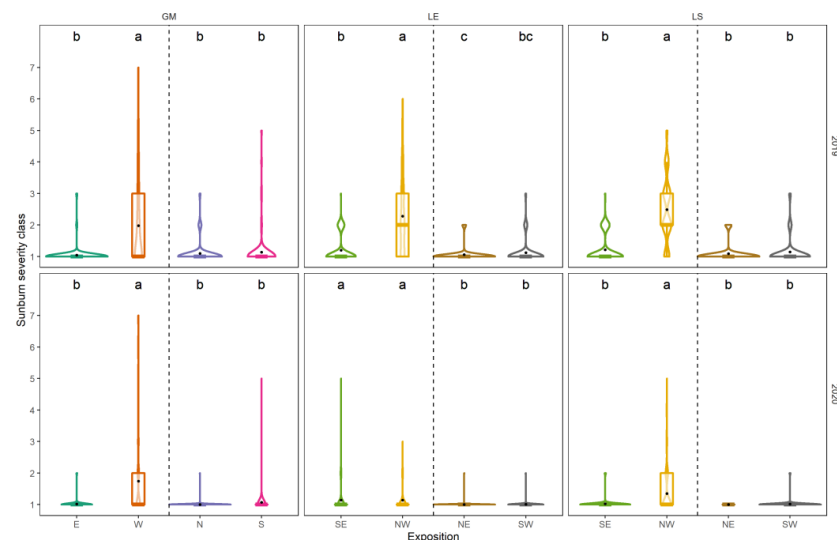


Figure 5. Post-heat wave sunburn damage scoring for vintages 2019 and 2020 for three different sites (Geisenheimer Rothenberg = GM, Lorcher Eisersgrube = LE, Lorcher Sesselberg = LS). Treatments are separated by the vertical dashed line. Violins show the distribution of the data ($n = 400$). Median is indicated by the horizontal line in the boxplot, mean values are represented by black dot in the respective boxplots. Different colours represent different canopy expositions. Lower case indicate results of Dunn's test (different letters show significant differences ($p < 0.05$)) between canopy exposition (E = east, W = west, N = north, S = south, SE = southeast, NW = northwest, NE = northeast, SE = southeast) at the respective site, vintage and development stage for N–S/E–W and NW–SE/NE–SW row orientations. Definition of sunburn severity classes: 1 = no disease; 2 = < 5%; 3 = 5–10%; 4 = 10–25%; 5 = 25–50%; 6 = 50–75%; 7 = > 75% (according to EPPO guideline PP 1/031(3)).

At the site GM, the W-exposed side of the canopy showed a significant higher severity of sunburn damage on the grapes compared to the E-exposed side of the same canopy or any canopy side of the terraced vineyard (Figure 5). However, the during the day constantly irradiated valley facing side of the terrace (S) did not differ from the shaded canopy sides facing N or E.

In both years, control vineyards planted in NE–SW direction showed higher incidences of sunburn-damaged grapes compared to terraced vineyards in NW–SE alignment. The most affected treatment was the control with its NW-exposed canopy side, followed by the sunlit SE-exposed canopy side (Figure 5). Small sunburn incidences were observed

at SW-facing canopy sides of terraced vineyards, in spite of higher energy input. The hill-facing NE-exposed canopy side was not affected by sunburn damage.

4. Discussion

Recent research described the microclimatic conditions of two management systems with different row orientations in steep slopes [23]. It was found that daily temperature parameters were generally higher in steep slope vineyards planted downslope compared to terraced vineyards, especially for N–S row orientations, except for daily minimum temperature. While the valley-facing sides of terraced vineyards showed the highest light interception values at bunch zone height, canopy sides of downslope aligned vineyards were more balanced in sun exposure [23]. Grapevine fruit quality crucially depends on microclimate, mainly described by berry exposition to the sun [37]. Slightly excessive light and temperature leads to metabolic protective mechanisms, e.g., accumulation of phenolics or heat shock proteins, known to alter later wine quality [38–40]. Previous research conducted on flat vineyards focused on differences in microclimate [41,42], physiological behaviour of the grapevine [43,44] and its effects on fruit parameters [45,46] and wine [47–49] in respect to row orientation changes, further considering differences in canopy sides. However, to our knowledge, literature about the impact of row orientation on steep slopes on grapevine fruit composition as well as a differentiation between canopy sides is not available. Thus, data presented in this work will help to understand the role of quality determining factors such as row orientation and its impact on primary and secondary metabolites of *V. vinifera* L. cv. Riesling in steep slope vineyards.

4.1. Berry Parameters

It needs to be considered that vineyards were cultivated by different wineries with individual schedules of vineyard management. Despite the renunciation of fertilizers during the experimental years, an influence of the vineyard management cannot be excluded, i.e., by different timing of, e.g., soil or canopy management. Nonetheless, applied means followed the common practice and is partly owed to the management system itself.

Beyond this, a clear distinction of canopy sides, row orientation and treatments was shown by the principal component analysis (Figure 1A).

4.1.1. Berry Juice Parameters

Related to berry weight, total soluble solid values were always the highest in SW-exposed berries and higher in S- and W-exposed berries compared to N- or E-facing berry samples (Table 1). This is based on a concentration effect, coinciding with smaller berries due to higher light exposure [50]. The concentrations of organic acids were usually highest in terraced vineyards planted in NW–SE direction and were also generally higher for small berries, predominately from well-irradiated canopy sides, e.g., W and SW (Table 1).

The yeast assimilable nitrogen content, expressed as N-OPA, was generally low in both years, due to multiannual drought stress of previous seasons 2017 to 2019. A sufficient provision of yeast assimilable nitrogen, e.g., ammonia and primary amino acids, may not necessarily lead to more aromatic wines [51], but guarantees growth of *Saccharomyces cerevisiae* and a successful fermentation [52]. The concentrations of N-OPA and amino acids varied between treatments of different row orientations. In both years, differences between sunlit and shaded canopy sides existed at each site within the same vineyards and the same row orientations (Table S6). Total amino acid concentrations were always significantly higher in W-exposed berries, compared to those picked from the E-exposed side of the control canopy. Additionally, grape berries harvested from the valley-facing side (SW) of NW–SE oriented terraces showed significantly higher total amino acid concentrations compared to the hill-facing NE-pendant. Beside the fact that no differences were found among total amino acid concentrations in the comparison of N- to S-facing berries on terraces or NW- to SE-exposed control berries (Table S6), juice from sun-exposed berries showed higher amino acid concentrations compared to those derived from shaded berries.

This is in contrast to earlier studies on Riesling relating the inhibition of amino acid synthesis to sunlight UV-B [7,8,11], but is in accordance with the findings in other grapevine cultivars [9,14]. Bunch zone leaf removal decreased amino acid concentration significantly in Sauvignon blanc [53]. The application of leaf removal on the shaded, i.e., less sunlit, side of the canopy is a common practice in viticulture to enhance aroma precursors and to prevent diseases. Bunch zone leaf removal may lower amino acid concentration due to a reduction in source leaves. In 2019 leaf removal was applied moderately at site GM at both treatments (C and T) on the shaded sides of the canopy (E and N, respectively). Whilst the E-facing berries of N-S-oriented rows showed a significant decrease (−28.5%) in total amino acid concentration compared to the more sunlit, non-defoliated, W-side of the canopy, there was no difference between the canopy sides of the E-W-oriented terraced vineyard (Table S6). A higher number of leaf layers (LLN, Table S4) may explain why the highly sun exposed S-facing canopy side of the terrace did not differentiate from the hill-facing N-side. Solar radiation is highly absorbed by single leaf blades, leading to an effective shading of subjacent leaves or clusters [30]. However, during berry ripening, the maximum temperature of both canopy sides of E-W-oriented vineyards coincide in the early afternoon [23], leading to the assumption that the contradictory role of UV-B on amino acids may play a subordinated role to temperature. Another possible explanation might be the compensation capacity of grapevines shown after defoliation treatments, by which photosynthetic activity is regained theoretically [54]. LLN was low at the SE-facing side of the canopy (Table S4). During the day, radiation may have penetrated the porous canopy side and warmed up NW-facing clusters. S-, W- and SW-canopy sides constantly showed warmer temperatures during the day, while SE- sides of control vines are just slightly more favoured by sunlight than the NW-sides [23]. Leaves shading the clusters may reduce excessive heat leading to a more favourable condition for amino acid accumulation in the berries. Nevertheless, Arrizabalaga-Arriazu et al. [55] found a tendency to the reduction in total amino acid concentration at maturity for a temperature difference of 4 °C compared to ambient environment, whereas the relative abundance of aspartates, shikimates, phosphoglycerates and pyruvates was increased. However, results of the study showed high standard errors, reducing the significance. GABA, proline and their precursor glutamate were increased in berries of heated vines [56] and were attributed to warm growing seasons [57]. Same amino acids were also elevated in samples from commonly warmer N-S-oriented control vineyards and terraces in NW-SE orientation in this study, where highly exposed SW-canopy sides reached high maximum temperatures [23]. It was suggested, that GABA plays a role as a protective against UV-B-induced oxidative stress in grape berries [11]. Furthermore, amino acid biosynthesis of several amino acids was up-regulated under drought stress conditions [58,59]. Proline, leucine, isoleucine, and valine as well as serine and tryptophan were elevated for highly exposed S- and SW-facing canopies (Figure 2). Therefore, it can be concluded, that highly sun-exposed berries responded to the stressors of light and high temperatures, possibly accompanied by drought stress, by accumulating some of the defence-related amino acids.

Contrarily to others [38,60], samples derived from elevated temperature and high light influenced SW-sides of the canopy were high in above mentioned amino acids, but also showed high values of malate (Table 1). Commonly, low berry malate content is attributed to high temperature exposure post-véraison [61,62]. However, Sweetman et al. [56] found that berries exposed to higher temperatures post-véraison decreased in malate content, but did not change when minimum temperatures were also elevated. Higher values of malate from berries of the highly sun-exposed SW side of the canopies may be explained by generally higher night temperatures in terraced vineyards [23].

4.1.2. Berry Skin Parameters

Flavonols showed a strong correlation to light exposure (Figure 1B). Pieri et al. [46] defined a positive relationship between incoming solar radiation at berry scale with the total amount of berry skin flavonols. Flavonols were proposed to be an adequate indicator

for differences in light microclimate [40,63]. Martínez-Lüscher et al. highlighted the correlation between Que-3-glc and Kmp-3-glc with the summed amount of UV-B received by Tempranillo clusters [11] and Friedel et al. [7] found no increase in quercetin glucosides in shaded Riesling clusters. In this study, those two flavonols were lowest in sunlight-reduced expositions of the terraced canopies (namely N and NE; Table S8), where the canopy light regimes are only one fifth of global radiation [23]. No clear effect of cluster exposition could be attributed to the sum of flavanols and total hydroxycinnamates (Figure 3), but caffeic acid and ferulic acid tended to be higher in more sunlit samples, approving previous findings [5–7,38]. The opposed behaviour of flavonols and hydroxycinnamates was also shown by Reshef et al., who highlighted the importance of canopy side and berry orientation on grape berry metabolic composition due to light intensity levels [38,60]. While polyphenols play a major role in red wine production, too high concentrations in juice and wine of white grape cultivars may be detrimental to consumers' perception. Therefore, cluster exposure to high light intensities and temperature must be well considered concerning desired wine style. Furthermore, berry health usually benefits from light exposure, but berries are vulnerable to solar heating resulting in loss of berry mass and quality or sunburn damage [1,64].

Sunburn is the physiological disorder which occurs on berries after the exposure of intensive irradiation by sunlight, due to high UV radiation and excessive temperature [1].

Sunburn scoring data clearly showed, that during the afternoon exposed canopy sides (i.e., W and NW) of a grapevine are more prone to damage compared to berries growing in less sunlit locations of the plant, i.e., E, N and NE, (Figure 5). Interestingly, the most sun-exposed canopy sides (S and SW) did not differ from their shaded equivalent (i.e., N and NE). Several authors pointed out the importance of row orientation and, thus, exposition, on grape sunburn damage due to high irradiation of the afternoon sun [1,65,66]. Apart from this, grapevines are able to acquire berry protection due to several mechanisms [1]. Light induces photo-protective mechanisms, including the metabolism of phenolic components [5,67] or heat shock proteins [68,69], both relying on sufficient amino acid resources, e.g., phenylalanine. Phenylalanine was high in exposed S-, W- and SW-berries (Table S6). The role of phenylalanine in secondary metabolite biosynthesis is crucial, due to its key role in the phenylpropanoid pathway [70]. Furthermore, phenylalanine is explicitly rate-limiting for some secondary metabolites in grapevine, e.g., quercetins [71]. Samples high in the amino acid phenylalanine were also high in flavonols, such as several quercetins (Tables S6 and S8). While SW-exposed samples showed the highest concentrations of stress responding amino acids (Table S6), S-facing berries showed the highest values of sun-screening flavonols (Table S8). The increased incidence of sunburn on W- and NW-facing clusters was also promoted by the wave angle of sunbeams. The lower sun position leads to a more directed warming of the clusters, which does not affect S-facing canopy sides during noon, when sun's zenith is reached. Consequently, row orientation changes successfully prevented sunburn damage (Figure 5).

4.2. Leaf Nitrogen

Light stimulates aboveground growth of the grapevine [72]. A higher exposed leaf mass under non-limiting growth conditions benefits carbon assimilation. However, excessive light conditions bare the risk of damaging proteins and the light harvesting pigments of the photosynthetic system [73]. High irradiation of leaf tissue results in significantly lower leaf chlorophyll content compared to shaded leaves [74,75], which was also confirmed for exposed canopies in this study (Figure 4). Suggested optimum values for leaf Chl_i content were seldom reached by the different canopy sites of the examined steep slope management systems [31]. N-, E- and NE-exposed leaves showed the highest Chl_i values (Figure 4). However, under humid conditions of 2021, leaves of the W- and S-side of the canopy showed optimum Chl_i values. This highlights the importance of water availability for leaf morphology and thus photosynthetically performance and can be used as a proxy for the estimation of leaves physiological and nutritional status [76], further esti-

mating grapevine performance [77]. In this study, however, it is not possible to distinguish between performances of single canopy sides using Chl_i content as a proxy. Although, north-, east- and northeast-exposed canopies showed highest chlorophyll levels, shaded canopy sides performed inferior to more sunlit canopy sides (Figure 4, Table 1). While it is possible to influence performance of source organs [78], the partitioning of carbon structures (i.e., sucrose and amino acids) follows physical (sink gradients) or enzymatic regulatory mechanisms in the berry [79].

5. Conclusions

In steep slope vineyards, fruit composition was affected by a change in row orientation mainly due to microclimatic effects of sunlight (i.e., irradiation and temperature). Additionally, water supply may play a major role in nutrition availability and grapevine performance. Whilst terraced vineyards reduce the risk of erosion and improve the infiltration during precipitation, not fully adapted vines suffer from water stress are likely to be hassled further through a higher evapotranspiration demand from a higher exposed surface of the embankments. Hence, further research must evaluate applicable methods to improve soil water retention, grapevine root development and hydraulics in steep slope vineyard systems.

A change in cluster exposition, as a consequence of a change in row alignment, showed to be a viable tool to reduce the risk of sunburn. Furthermore, the differences in fruit composition between canopy sides of terraced vineyards may be useful to achieve different quality goals in view of climate change adaption, i.e., lower TSS or maintaining higher acidity, by selective harvesting.

Supplementary Materials: The following are available online at <https://www.mdpi.com/article/10.3390/foods10112682/s1>, Table S1: Summarized weather conditions for 2019–2021. Figure S1: Mean air temperature (solid line) and daily rainfall (black bars) during vegetation periods (1 April to 1 October) 2019, 2020 and 2021 in Geisenheim (Rheingau, Germany). Table S2: List of standards used for calibration of the UHPLC and determination of grape skin phenolics. Table S3: Canopy density parameters for experimental sites Geisenheimer Rothenberg (= GM), Lorcher Eisersgrube (= LE) and Lorcher Sesselberg (= LS), separated by treatment (control = C, terraced vineyard = T), exposition and different grapevine growth stages in 2019 and 2020. Table S4: Relative cumulative solar radiation measurements (Whm^{-2}) normalized by global radiation data of local weather stations, separated by year for each site, treatment (C = control; T = terraced vineyard), exposition and development stage. Table S5: Amino acid concentration (mean \pm standard deviation; $\text{mg L}^{-1} \text{g}^{-1}$) of Riesling juice obtained from harvest-ripe berries in 2019 and 2020, separated by canopy sides of each treatment. Table S6: Share of single amino acid concentration on total amino acid concentrations (%) of Riesling juice obtained from harvest-ripe berries in 2019 and 2020, separated by canopy sides of each treatment. Table S7: Polyphenolic content (mean \pm standard deviation; $\mu\text{g g}^{-1}$ berry fresh weight) of Riesling berry skins obtained from harvest-ripe berries in 2019 and 2020, separated by canopy sides of each treatment.

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

Funding: This research as part of the BioQuiS project (www.bioquis.de) was funded by Deutsche Bundesstiftung Umwelt (funding number AZ 34025). We acknowledge support by the German Research Foundation (Deutsche Forschungsgemeinschaft DFG)—project number 432888308—and the Open Access Publishing Fund of Geisenheim University.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: We thank the partner wineries (Weingut der Hochschule Geisenheim (Geisenheim), Weingüter Wegeler (Oestrich-Winkel), Weingut Laquai (Lorch) and Weingut Altenkirch (Lorch)) for providing their vineyards for the investigations. We acknowledge the support of Regine

Donecker, Jesus Felipe Ravelo Rodríguez and Annette Rheinberger in laboratory analyses as well as Anja Giehl, Anja Rheinberger and Birgit Krause for conducting polyphenol and amino acid analyses. Additionally, thanks to Anthony William Bennett for proofreading the work.

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

References

- Gambetta, J.M.; Holzapfel, B.P.; Stoll, M.; Friedel, M. Sunburn in Grapes: A Review. *Front. Plant Sci.* **2020**, *11*, 604691. [[CrossRef](#)]
- Yang, J.; Xiao, Y.-Y. Grape phytochemicals and associated health benefits. *Crit. Rev. Food Sci. Nutr.* **2013**, *53*, 1202–1225. [[CrossRef](#)] [[PubMed](#)]
- 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](#)]
- OIV. *Focus OIV 2017: Distribution of the World's Grapevine Varieties*; OIV: Paris, France, 2017.
- Friedel, M.; Frotscher, J.; Nitsch, M.; Hofmann, M.; Bogs, J.; Stoll, M.; Dietrich, H. Light promotes expression of monoterpene and flavonol metabolic genes and enhances flavour of winegrape berries (*Vitis vinifera* L. cv. Riesling). *Aust. J. Grape Wine Res.* **2016**, *22*, 409–421. [[CrossRef](#)]
- Brandt, M.; Scheidweiler, M.; Rauhut, D.; Patz, C.-D.; Will, F.; Zorn, H.; Stoll, M. The influence of temperature and solar radiation on phenols in berry skin and maturity parameters of *Vitis vinifera* L. cv. Riesling. *OENO One* **2019**, *53*, 2. [[CrossRef](#)]
- 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. [[CrossRef](#)]
- Schultz, H.R.; Löhnertz, O.; Bettner, W.; Balo, B.; Linsenmeier, A.; Jähnisch, A.; Müller, M.; Gaubatz, B.; Varadi, G. Is grape composition affected by current levels of UV-B radiation. *Vitis* **1998**, *37*, 191–192.
- Keller, M.; Torres-Martinez, N. Does UV radiation affect winegrape composition? *Acta Hort.* **2004**, 313–319. [[CrossRef](#)]
- Gregan, S.M.; Wargent, J.J.; Liu, L.; Shinkle, J.; Hofmann, R.; Winfield, C.; Trought, M.; Jordan, B. Effects of solar ultraviolet radiation and canopy manipulation on the biochemical composition of Sauvignon Blanc grapes. *Aust. J. Grape Wine Res.* **2012**, *18*, 227–238. [[CrossRef](#)]
- Martínez-Lüscher, J.; Torres, N.; Hilbert, G.; Richard, T.; Sánchez-Díaz, M.; Delrot, S.; Aguirreolea, J.; Pascual, I.; Gomès, E. Ultraviolet-B radiation modifies the quantitative and qualitative profile of flavonoids and amino acids in grape berries. *Phytochemistry* **2014**, *102*, 106–114. [[CrossRef](#)]
- Wang, L.; Harada, J.; Endo, Y.; Hisamoto, M.; Saito, F.; Okuda, T. Diurnal Changes in Amino Acid Concentrations in Riesling and Chardonnay Grape Juices and a Possible Role of Sunlight. *Am. J. Enol. Vitic.* **2014**, *65*, 435–442. [[CrossRef](#)]
- Stines, A.P.; Grubb, J.; Gockowiak, H.; Henschke, P.A.; Høj, P.B.; Heeswijck, R. Proline and arginine accumulation in developing berries of *Vitis vinifera* L. in Australian vineyards: Influence of vine cultivar, berry maturity and tissue type. *Aust. J. Grape Wine Res.* **2000**, *6*, 150–158. [[CrossRef](#)]
- Guan, L.; Wu, B.; Hilbert, G.; Li, S.; Gomès, E.; Delrot, S.; Dai, Z. Cluster shading modifies amino acids in grape (*Vitis vinifera* L.) berries in a genotype- and tissue-dependent manner. *Food Res. Int.* **2017**, *98*, 2–9. [[CrossRef](#)] [[PubMed](#)]
- Spayd, S.E.; Andersen-Bagge, J. Free Amino Acid Composition of Grape Juice from 12 *Vitis vinifera* Cultivars in Washington. *Am. J. Enol. Vitic.* **1996**, *47*, 389.
- Alem, H.; Rigou, P.; Schneider, R.; Ojeda, H.; Torregrosa, L. Impact of agronomic practices on grape aroma composition: A review. *J. Sci. Food Agric.* **2019**, *99*, 975–985. [[CrossRef](#)]
- Marais, J.; van Wyk, C.J.; Rapp, A. Effect of Sunlight and Shade on Norisoprenoid Levels in Maturing Weisser Riesling and Chenin blanc Grapes and Weisser Riesling Wines. *S. Afr. J. Enol. Vitic.* **2017**, *13*, 23–32. [[CrossRef](#)]
- Meyers, J.M.; Sacks, G.L.; Vanden Heuvel, J.E. Glycosylated Aroma Compound Responses in 'Riesling' Wine Grapes to Cluster Exposure and Vine Yield. *HortTechnology* **2013**, *23*, 581–588. [[CrossRef](#)]
- Gerdes, S.M.; Winterhalter, P.; Ebeler, S.E. Effect of Sunlight Exposure on Norisoprenoid Formation in White Riesling Grapes. In *Food Flavor*; Tamura, H., Ebeler, S.E., Kubota, K., Takeoka, G.R., Eds.; American Chemical Society: Washington, DC, USA, 2008; pp. 262–272, ISBN 9780841274112.
- Daniel, M.A.; Capone, D.L.; Sefton, M.A.; Elsey, G.M. Riesling acetal is a precursor to 1,1,6-trimethyl-1,2-dihydronaphthalene (TDN) in wine. *Aust. J. Grape Wine Res.* **2009**, *15*, 93–96. [[CrossRef](#)]
- Smart, R.E. Sunlight Interception by Vineyards. *Am. J. Enol. Vitic.* **1973**, *24*, 141.
- Hunter, J.J.; Volschenk, C.G.; Zorer, R. Vineyard row orientation of *Vitis vinifera* L. cv. Shiraz/101-14 Mgt: Climatic profiles and vine physiological status. *Agric. For. Meteorol.* **2016**, *228–229*, 104–119. [[CrossRef](#)]
- Strack, T.; Schmidt, D.; Stoll, M. Impact of steep slope management system and row orientation on canopy microclimate. Comparing terraces to downslope vineyards. *Agric. For. Meteorol.* **2021**, *307*, 108515. [[CrossRef](#)]
- Grifoni, D.; Carreras, G.; Zipoli, G.; Sabatini, F.; Dalla Marta, A.; Orlandini, S. Row orientation effect on UV-B, UV-A and PAR solar irradiation components in vineyards at Tuscany, Italy. *Int. J. Biometeor.* **2008**, *52*, 755–763. [[CrossRef](#)]
- Hoppmann, D.; Schaller, K.; Stoll, M. *Terroir: Wetter, Klima und Boden im Weinbau*, 2nd ed.; Aktualisierte Auflage; Ulmer: Stuttgart, Germany, 2017; ISBN 978-3800103508.

26. Jagoutz, H. Bewässerungsbedarf von Reben in der Vergangenheit und in der Zukunft. In *Deutsches Weinbau-Jahrbuch 2006*; Schruft, G., Ed.; Eugen Ulmer KG: Stuttgart, Germany, 2005; pp. 43–49, ISBN 978-3-8001-4900-X.
27. 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](#)]
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.
29. Krause, B.; Löhnertz, O. Saccharopin und Pipecolinsäure: Diagnostische Biomarker in der klassischen Aminosäureanalytik. *MTA Dialog.* **2017**, *18*, 316–321. [[CrossRef](#)]
30. Smart, R.E.; Robinson, M. *Sunlight into Wine: A Handbook for Winegrape Canopy Management*; Winetitles Media: Ashford, Australia, 1991; ISBN 1875130101.
31. Cerovic, Z.G.; Ghazlen, N.B.; Milhade, C.; Obert, M.; Debuisson, S.; Le Moigne, M. Nondestructive diagnostic test for nitrogen nutrition of grapevine (*Vitis vinifera* L.) based on dual leaf-clip measurements in the field. *J. Agric. Food Chem.* **2015**, *63*, 3669–3680. [[CrossRef](#)]
32. EPPO. EPPO Database on PP1 Standards. Available online: <https://pp1.eppo.int/standards/PP1-031-3> (accessed on 1 November 2021).
33. Lê, S.; Josse, J.; Husson, F. FactoMineR: An R Package for Multivariate Analysis. *J. Stat. Soft.* **2008**, *25*. [[CrossRef](#)]
34. De Mendiburu, F.; Yaseen, M. Agricolae: Statistical Procedures for Agricultural Research. Available online: <https://cran.r-project.org/package=agricolae> (accessed on 1 November 2021).
35. Fox, J.; Weisberg, S. *An R Companion to Applied Regression*, 3rd ed.; Sage: Thousand Oaks, CA, USA, 2019.
36. Hothorn, T.; Bretz, F.; Westfall, P. Simultaneous inference in general parametric models. *Biom. J.* **2008**, *50*, 346–363. [[CrossRef](#)]
37. Smart, R.E. Principles of Grapevine Canopy Microclimate Manipulation with Implications for Yield and Quality. A Review. *Am. J. Enol. Vitic.* **1985**, *36*, 230.
38. Reshef, N.; Walbaum, N.; Agam, N.; Fait, A. Sunlight Modulates Fruit Metabolic Profile and Shapes the Spatial Pattern of Compound Accumulation within the Grape Cluster. *Front. Plant Sci.* **2017**, *8*, 70. [[CrossRef](#)]
39. Du Plessis, K.; Young, P.R.; Eyéghé-Bickong, H.A.; Vivier, M.A. The Transcriptional Responses and Metabolic Consequences of Acclimation to Elevated Light Exposure in Grapevine Berries. *Front. Plant Sci.* **2017**, *8*, 1261. [[CrossRef](#)] [[PubMed](#)]
40. Pereira, G.E.; Gaudillere, J.-P.; Pieri, P.; Hilbert, G.; Maucourt, M.; Deborde, C.; Moing, A.; Rolin, D. Microclimate influence on mineral and metabolic profiles of grape berries. *J. Agric. Food Chem.* **2006**, *54*, 6765–6775. [[CrossRef](#)]
41. Hunter, J.J.; Volschenk, C.G.; Bonnardot, V. Linking grapevine row orientation to a changing climate in South Africa. In Proceedings of the 60th German Grape and Wine Congress, International IVIF Congress, Stuttgart, Germany, 24–27 March 2010; pp. 60–70.
42. Friedel, M. Microclimatic Influences on Grape Quality. Ph.D. Dissertation, Universitätsbibliothek, Gießen, Germany, 2018.
43. Hunter, J.J.; Volschenk, C.G.; Booysse, M. Vineyard row orientation and grape ripeness level effects on vegetative and reproductive growth characteristics of *Vitis vinifera* L. cv. Shiraz/101-14 Mgt. *Eur. J. Agron.* **2017**, *84*, 47–57. [[CrossRef](#)]
44. Hunter, J.K.; Tarricone, L.; Volschenk, C.; Giacalone, C.; Melo, M.S.; Zorer, R. Grapevine physiological response to row orientation-induced spatial radiation and microclimate changes. *OENO One* **2020**, *54*, 411–433. [[CrossRef](#)]
45. Friedel, M.; Patz, C.-D.; Stoll, M. Impact of row orientation on berry quality parameters White Riesling (*Vitis vinifera* L.). In Proceedings of the 17th International Symposium GiESCO, Asti-Alba, Italy, 29 August–2 September 2011; Novello, V., Bovio, M., Cavalletto, S., Eds.; Le Progès Agricole et Viticole: Asti-Alba, Italy, 2011; pp. 327–330.
46. Pieri, P.; Zott, K.; Gomès, E.; Hilbert, G. Nested effects of berry half, berry and bunch microclimate on biochemical composition in grape. *OENO One* **2016**, *50*, 23. [[CrossRef](#)]
47. Minnaar, P.P.; Jolly, N.P.; Ntushelo, N.S. Effect of Grapevine Canopy Side on Selected Sensory Attributes of Pinotage and Cabernet Sauvignon Wines. *S. Afr. J. Enol. Vitic.* **2020**, *41*. [[CrossRef](#)]
48. Lee, S.-H.; Seo, M.-J.; Riu, M.; Cotta, J.P.; Block, D.E.; Dokoozlian, N.K.; Ebeler, S.E. Vine Microclimate and Norisoprenoid Concentration in Cabernet Sauvignon Grapes and Wines. *Am. J. Enol. Vitic.* **2007**, *58*, 291.
49. Chorti, E.; Theocharis, S.; Bouloukostas, K.; Kallithraka, S.; Kotseridis, Y.; Koundouras, S. Row Orientation and Defoliation Effects on Grape Composition of *Vitis vinifera* L. Agiorgitiko in Nemea (Greece). *E3S Web Conf.* **2018**, *50*, 1039. [[CrossRef](#)]
50. Shellie, K.C. Interactive Effects of Deficit Irrigation and Berry Exposure Aspect on Merlot and Cabernet Sauvignon in an Arid Climate. *Am. J. Enol. Vitic.* **2011**, *62*, 462–470. [[CrossRef](#)]
51. Crépin, L.; Truong, N.M.; Bloem, A.; Sanchez, I.; Dequin, S.; Camarasa, C. Management of Multiple Nitrogen Sources during Wine Fermentation by *Saccharomyces cerevisiae*. *Appl. Environ. Microbiol.* **2017**, *83*, e02617-16. [[CrossRef](#)] [[PubMed](#)]
52. Gobert, A.; Tourdot-Maréchal, R.; Sparrow, C.; Morge, C.; Alexandre, H. Influence of nitrogen status in wine alcoholic fermentation. *Food Microbiol.* **2019**, *83*, 71–85. [[CrossRef](#)]
53. Gegan, S.M.; Winefield, C.; Jordan, B. Amino acid metabolism and accumulation in ‘Sauvignon Blanc’ grapes—Investigating berry composition in response to canopy manipulation. *Acta Hort.* **2017**, *9–14*. [[CrossRef](#)]
54. Bahr, C.; Schmidt, D.; Friedel, M.; Kahlen, K. Leaf removal effects on light absorption in virtual Riesling canopies (*Vitis vinifera* L.). *Silico Plants* **2021**. [[CrossRef](#)]

55. Arrizabalaga-Arriazu, M.; Gomès, E.; Morales, F.; Irigoyen, J.J.; Pascual, I.; Hilbert, G. High Temperature and Elevated Carbon Dioxide Modify Berry Composition of Different Clones of Grapevine (*Vitis vinifera* L.) cv. Tempranillo. *Front. Plant Sci.* **2020**, *11*, 603687. [[CrossRef](#)] [[PubMed](#)]
56. 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](#)] [[PubMed](#)]
57. Pereira, G.E.; Gaudillere, J.-P.; van Leeuwen, C.; Hilbert, G.; Maucourt, M.; Deborde, C.; Moing, A.; Rolin, D. 1H NMR metabolite fingerprints of grape berry: Comparison of vintage and soil effects in Bordeaux grapevine growing areas. *Anal. Chim. Acta* **2006**, *563*, 346–352. [[CrossRef](#)]
58. Gambetta, G.A.; Herrera, J.C.; Dayer, S.; Feng, Q.; Hochberg, U.; Castellarin, S.D. The physiology of drought stress in grapevine: Towards an integrative definition of drought tolerance. *J. Exp. Bot.* **2020**, *71*, 4658–4676. [[CrossRef](#)] [[PubMed](#)]
59. Herrera, J.C.; Hochberg, U.; Degu, A.; Sabbatini, P.; Lazarovitch, N.; Castellarin, S.D.; Fait, A.; Alberti, G.; Peterlunger, E. Grape Metabolic Response to Postveraison Water Deficit Is Affected by Interseason Weather Variability. *J. Agric. Food Chem.* **2017**, *65*, 5868–5878. [[CrossRef](#)] [[PubMed](#)]
60. Reshef, N.; Fait, A.; Agam, N. Grape berry position affects the diurnal dynamics of its metabolic profile. *Plant Cell Environ.* **2019**, *42*, 1897–1912. [[CrossRef](#)]
61. Sweetman, C.; Deluc, L.G.; Cramer, G.R.; Ford, C.M.; Soole, K.L. Regulation of malate metabolism in grape berry and other developing fruits. *Phytochemistry* **2009**, *70*, 1329–1344. [[CrossRef](#)]
62. Rienth, M.; Torregrosa, L.; Sarah, G.; Ardisson, M.; Brillouet, J.-M.; Romieu, C. Temperature desynchronizes sugar and organic acid metabolism in ripening grapevine fruits and remodels their transcriptome. *BMC Plant Biol.* **2016**, *16*, 164. [[CrossRef](#)]
63. Reshef, N.; Agam, N.; Fait, A. Grape Berry Acclimation to Excessive Solar Irradiance Leads to Repartitioning between Major Flavonoid Groups. *J. Agric. Food Chem.* **2018**, *66*, 3624–3636. [[CrossRef](#)]
64. Smart, R.E.; Sinclair, T.R. Solar heating of grape berries and other spherical fruits. *Agric. Meteorol.* **1976**, *17*, 241–259. [[CrossRef](#)]
65. Webb, L.; Whiting, J.; Watt, A.; Hill, T.; Wigg, F.; Dunn, G.; Needs, S.; Barlow, E.W.R. Managing Grapevines through Severe Heat: A Survey of Growers after the 2009 Summer Heatwave in South-eastern Australia. *J. Wine Res.* **2010**, *21*, 147–165. [[CrossRef](#)]
66. Schultz, H.R. Sommer 98: Verbrennungserscheinungen an den Trauben: Einfacher Sonnenbrand oder Umweltschaden? *Der Dtsch. Weinbau* **1999**, *3*, 12–15.
67. Teixeira, A.; Eiras-Dias, J.; Castellarin, S.D.; Gerós, H. Berry phenolics of grapevine under challenging environments. *Int. J. Mol. Sci.* **2013**, *14*, 18711–18739. [[CrossRef](#)] [[PubMed](#)]
68. Banilas, G.; Korkas, E.; Englezos, V.; Nisiotou, A.A.; Hatzopoulos, P. Genome-wide analysis of the heat shock protein 90 gene family in grapevine (*Vitis vinifera* L.). *Aust. J. Grape Wine Res.* **2012**, *18*, 29–38. [[CrossRef](#)]
69. Rocheta, M.; Becker, J.D.; Coito, J.L.; Carvalho, L.; Amâncio, S. Heat and water stress induce unique transcriptional signatures of heat-shock proteins and transcription factors in grapevine. *Funct. Integr. Genom.* **2014**, *14*, 135–148. [[CrossRef](#)]
70. Dixon, R.A.; Paiva, N.L. Stress-Induced Phenylpropanoid Metabolism. *Plant Cell* **1995**, *7*, 1085–1097. [[CrossRef](#)] [[PubMed](#)]
71. Manela, N.; Oliva, M.; Ovadia, R.; Sikron-Persi, N.; Ayenew, B.; Fait, A.; Galili, G.; Perl, A.; Weiss, D.; Oren-Shamir, M. Phenylalanine and tyrosine levels are rate-limiting factors in production of health promoting metabolites in *Vitis vinifera* cv. Gamay Red cell suspension. *Front. Plant Sci.* **2015**, *6*, 538. [[CrossRef](#)]
72. Grechi, I.; Vivin, P.; Hilbert, G.; Milin, S.; Robert, T.; Gaudillere, J.-P. Effect of light and nitrogen supply on internal C:N balance and control of root-to-shoot biomass allocation in grapevine. *Environ. Exp. Bot.* **2007**, *59*, 139–149. [[CrossRef](#)]
73. Flexas, J.; Hendrickson, L.; Chow, W.S. Photoinactivation of photosystem II in high light-acclimated grapevines. *Funct. Plant Biol.* **2001**, *28*, 755. [[CrossRef](#)]
74. Cartechini, A.; Palliotti, A. Effect of Shading on Vine Morphology and Productivity and Leaf Gas Exchange Characteristics in Grapevines in the Field. *Am. J. Enol. Vitic.* **1995**, *46*, 227–234.
75. Luo, Y.Y.; Li, R.X.; Jiang, Q.S.; Bai, R.; Duan, D. Changes in the chlorophyll content of grape leaves could provide a physiological index for responses and adaptation to UV-C radiation. *Nord. J. Bot.* **2019**, *37*, 2101. [[CrossRef](#)]
76. Steele, M.R.; Gitelson, A.A.; Rundquist, D.C. A Comparison of Two Techniques for Nondestructive Measurement of Chlorophyll Content in Grapevine Leaves. *Agron. J.* **2008**, *100*, 779–782. [[CrossRef](#)]
77. Taskos, D.G.; Koundouras, S.; Stamatiadis, S.; Zioziou, E.; Nikolaou, N.; Karakioulakis, K.; Theodorou, N. Using active canopy sensors and chlorophyll meters to estimate grapevine nitrogen status and productivity. *Precis. Agric.* **2015**, *16*, 77–98. [[CrossRef](#)]
78. Chanishvili, S.S.; Badridze, G.S.; Barblishvili, T.F.; Dolidze, M.D. Defoliation, Photosynthetic Rates, and Assimilate Transport in Grapevine Plants. *Russ. J. Plant Physiol.* **2005**, *52*, 448–453. [[CrossRef](#)]
79. Li, Y.-M.; Forney, C.; Bondada, B.; Leng, F.; Xie, Z.-S. The Molecular Regulation of Carbon Sink Strength in Grapevine (*Vitis vinifera* L.). *Front. Plant Sci.* **2020**, *11*, 606918. [[CrossRef](#)]

Chapter IV: Soil water dynamics and drought stress response of *Vitis vinifera* L. in steep slope vineyard systems

This chapter has been published as:

Strack, T.; Stoll, M. (2022). Soil water dynamics and drought stress response of *Vitis vinifera* L. in steep slope vineyard systems. *Agric. Wat. Man.* 2022, 274, 107967. <https://doi.org/10.1016/j.agwat.2022.107967>

Author Contributions

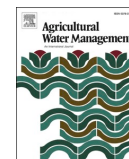
Conceptualization: T.S. & M.S.
Data curation: T.S.
Formal analysis: T.S.
Funding acquisition: M.S.
Investigation: T.S.
Methodology: T.S.
Project administration: M.S.
Resources: M.S.
Supervision: M.S.
Validation: M.S.
Visualization: T.S.
Writing – original draft: T.S.
Writing – review & editing: M.S.

All authors have read and agreed to the published version of the manuscript.



Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwatSoil water dynamics and drought stress response of *Vitis vinifera* L. in steep slope vineyard systemsTimo Strack^{*}, Manfred Stoll

Department of General and Organic Viticulture, Hochschule Geisenheim University, Von-Lade-Strasse 1, Geisenheim 65366, Germany

ARTICLE INFO

Handling Editor - Dr. B.E. Clothier

Keywords:

Soil moisture
Terraced vineyard
Water balance
Water budget
Abiotic stress

ABSTRACT

The accessibility to water is a crucial factor for grapevine performance in vineyards. A sufficient supply of water favors vegetative growth, yield formation and fruit ripening. Under a changing climate, especially steep slope wine-growing regions may face severe problems in soil moisture conservation due to oftentimes lower soil water holding capacity and a larger radiation intake on the, usually South-facing, hill slopes, which causes a higher evaporative demand compared to vineyards in the flat. The impact of two steep slope vineyard management systems on water retention and drought stress response of grapevines was assessed. Soil water dynamics in the inter-vine space of steep slope sites planted downslope (control, C) and of terraces (T) were compared. Terraced vineyards were capable to retain up to a 40 % higher relative percentage of winter precipitation, compared to the control. Vines in the early years of their adaption phase planted on terraced vineyards generally displayed a higher drought stress response, showed lower vigour, lower yield and lower sugar yield. The older the terrace system, the better the performance compared to C became. This suggests a high competition of young grapevines to the cover cropped embankments of terraced vineyards. Therefore, means to improve root development and to reduce water and nutrient competition in the early years of terrace construction are crucial for successful grapevine adaptation, for the increase of resilience to abiotic stress factors and finally for the maintenance of valuable steep slope vineyard sites for grapevine cultivation.

1. Introduction

Grapevine (*Vitis vinifera* L.) cultivars are well-adapted to different climate zones around the globe. Despite its high plasticity to different growing conditions, physiological performance of grapevines may suffer under enhanced abiotic stress situations, e.g. drought, which may be expressed by a reduction or a loss in photosynthetic activity (Flexas et al., 2004; Lovisolo et al., 2010), a cessation in above-ground growth (Vuerich et al., 2021) and, finally, in yield reduction (Gambetta et al., 2020). Nevertheless, best vintages are yielded from vines growing under slightly challenging environmental conditions (Blank et al., 2019; van Leeuwen and Darriet, 2016), benefiting the accumulation of protective metabolites, e.g. anthocyanins (Castellarin et al., 2007) or terpenes (Savoi et al., 2016), which are desirable in wine-making. Deficit irrigation strategies were therefore developed, e.g. partial root zone drying (Romero et al., 2016; Stoll et al., 2000b, 2000a) or regulated deficit irrigation (Acevedo-Opazo et al., 2010; Chaves et al., 2010). While various irrigation concepts are common practice in arid or new world vineyards (Johnson-Bell, 2018), old world vineyards are usually lacking

of infrastructure for irrigation, despite of (inter-)governmental subsidies, e.g. the European Agricultural Fund for Rural Development (EAFRD) of the European Union. Oftentimes, legal rights of an appellation of protected geographical origin or vineyard infrastructure do not allow the irrigation of sites in need, i.e. steep slope vineyards. Additionally, with a shortening of global fresh water resources or the withdrawal of irrigation water from communal bodies (e.g. groundwater wells or surface waters) the legitimacy of irrigation of grapes produced for wine-making purpose has to be questioned. Alternatively, the usage of winery waste water treatment found to be economical and environmental sustainable (Canaj et al., 2021), but may not be feasible for small wineries. Especially at steep slope vineyard sites, the access to water plays an important role, since potential evaporation may be 0.5–0.8 mm day⁻¹ higher during the vegetation period compared to common vineyards in the flat (Hofmann et al., 2014). The water consumption of the grapevine is dynamic throughout the growing season and mainly depends on the grapevine development stage, the weather conditions as well as on vineyard geometry parameters (Hofmann et al., 2022). The evaporative demand of the grapevine under cool climate conditions

^{*} Corresponding author.

E-mail address: timo.strack@hs-gm.de (T. Strack).

<https://doi.org/10.1016/j.agwat.2022.107967>

Received 24 August 2022; Received in revised form 26 September 2022; Accepted 27 September 2022

Available online 21 October 2022

0378-3774/© 2022 Elsevier B.V. All rights reserved.

ranges from 350 mm to 500 mm during the vegetation period (Williams, 2014), but varies further depending on planting material, training and management decisions (Medrano et al., 2015; Picón-Toro et al., 2012). On that account, vineyard management alternatives are required to meet the need of sustainable grape production at steep slope sites. Some actions to conserve precipitation water and to reduce evaporation on vineyard sites are ground cover (e.g. mulch or straw), shallow soil cultivation, cover crop and the increase of soil organic matter (Buesa et al., 2021; Gatti et al., 2022). However, steep slope viticulture is already labour-intensive, since mechanization is limited (Strub et al., 2021). Concepts of keeping steep slope viticulture economically viable include the formation of terraces (Strub and Müller-Loose, 2021). Today, a modern kind of vineyard terraces is being constructed via a 'cut and fill' procedure: a caterpillar levels the first platform along the contour of the hill and compacts the soil in this process. An excavator forms the embankment with the tilting bucket. The caterpillar then uses the excavated soil to build the next terrace. The embankments are stabilized immediately by sowing a grass mixture afterwards. A single row of vines is planted at 0.3 m distance from the edge of the platform. Historically, terraces were built for agricultural purpose inter alia to reduce physical strains and increase water retention (Tarolli et al., 2014). Yet, evaporation of the terrace embankments account for about one-third of the water loss of the terrace (Lü et al., 2009), resulting from a high sun exposed surface, which further requires cover crop for stabilization. Especially young vines prior to full adaptation may suffer from the competition to cover crops. Therefore, the benefits of vineyard terracing on soil moisture conservation and availability have to be tested. Thus, the aim of this study was to investigate soil moisture dynamics in two steep slope vineyard systems, i.e. terraced and downslope planted vineyards, to evaluate the effect of vineyard transformation and its impact on grapevine drought stress response.

2. Materials and methods

Data sampling was conducted in the Rheingau wine-growing region (Germany). Four vineyard pairs, each consisting of a vineyard according to the standard cultivation method of vines planted in downslope (control, C) and a terraced vineyard system (T), were selected (Fig. 1, Fig. 2).

An overview of the vineyard characteristics including the *V. vinifera* L. cultivars is presented in Table 1. The experimental sites comprised vineyards of commercial wineries, which maintained their own

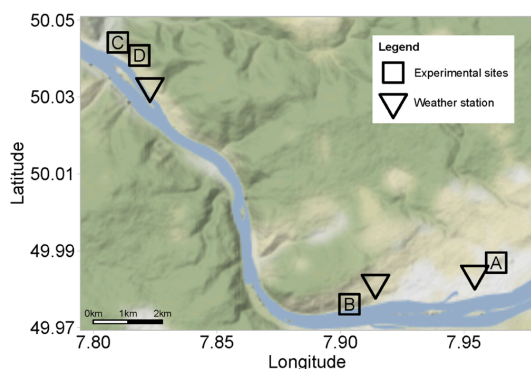


Fig. 1. Locations of experimental sites comprising the control and the terraced treatments (squares) and reference weather stations (triangles) along Rhine River. Lettering of sites: A: GM = Geisenheimer Rothenberg; B: RB = Rüdeshheimer Berg Rottland; C: LE = Lorcher Eisersgrube; D: LS = Lorcher Sesselberg. Source: Map data source: Google Maps Platform.

vineyard management schemes. However, applied means were in accordance to the Code of Good Agricultural Practice. Differences in management are partly owed to the cultivation system itself. All data acquired derived from subplots of the respective vineyards to ensure the temporal feasibility of measurements and to reduce measurement errors by spatial inhomogeneity. The main period of data collection was from spring 2019 to winter 2020. Additional vintages (2018 and 2021) were used to complement the data set.

2.1. Weather conditions during the experimental period

The annual temperatures of 2018–2020 were extraordinary, in comparison to the long-term average of 1981–2010 (LTA, Table S1; data was recorded by a weather station located at and maintained by Hochschule Geisenheim University). The year 2018 was considered one of the hottest years with an annual temperature of 12.3 °C (LTA 10.5 °C) and a vegetation period temperature of 17.8 °C (LTA of 15.2 °C) with 1741 sunshine hours (LTA of 1300 sunshine hours). In 2019, growing season started with hot and dry weather conditions. The mean temperature of the vegetation period (from April to October) was +2.6 °C higher compared to the LTA. Each month showed higher mean temperatures compared to the LTA, except the month of May, both in 2019 and 2020. For 2019 and 2020 there was an annual temperature increase of +1.3 °C and +1.7 °C, respectively. Temperatures in June and July were higher in 2019 compared to 2020 (+2.7 °C and +0.9 °C, respectively), but spring and autumn months showed higher average temperatures in 2020 (April +1.6 °C, May +1.4 °C, September +1.4 °C). Little amount of rain fell since July 2018 (rainfall deficit of –13.5%; sunshine hour surplus of +28 %). In 2019, rainfall was 13.3 % less compared to the LTA and had an increase of 19 % in sunshine hours. When compared to the LTA, precipitation was 23 % less in 2020, while the number of sunshine hours increased by +21 % (Fig. S1, Table S1).

On the contrary, 2021 was different compared to the previous years. Winter months and autumn showed a slight temperature increase of +0.6 °C and +0.2 °C compared to the LTA of 1991–2020 (+1.2 °C and +0.5 °C compared to the three-decade average of 1981–2010), respectively, whereas the temperature during spring 2021 was 2 °C lower compared to the LTA of 1991–2020. The summer temperature of 2021 showed a slight increase of +0.5 °C when compared to the LTA of 1981–2010. Precipitation was 36.3 mm lower in 2021 compared to the LTA of 1981–2020. Rainfall was highest in the winter and summer of 2021. Sunshine hours were increased in 2021 by +4.4 % and +7.8 %, compared to the LTA of 1981–2010 (Fig. S1, Table S1).

Additional information about the weather conditions in the lower Rheingau valley are provided in the supplementary material (Table S1, Fig. S1). Additional details about the microclimatic characteristics of the experimental sites are provided in Strack et al. (2021). For the research conducted under practical conditions, selection criteria were i) that on all sites the two treatments were in the next possible proximity to each other (to grant similar environmental conditions) and ii) that the treatments consisted of similar planting material (i.e. variety and rootstock; to allow comparability in regard to physiological parameters). A difference in the vineyard age or the soil characteristics (e.g. field capacity) was accepted due to the research aim of the evaluation of grapevine performance by a change in the management systems. Due to terracing, planting density changes dramatically, since, additionally to the alley width, the width of the embankment as well as the turning plates and cross-paths have to be considered in regards to vineyard area loss (Table 1).

2.2. Soil water monitoring

To monitor the consumption and the replenishment of soil water in the two management systems, volumetric soil moisture content was measured by a capacitance measurement technique (Diviner 2000, Sentek Pty Ltd, Stepney, SA, Australia). In April 2019, at each site and

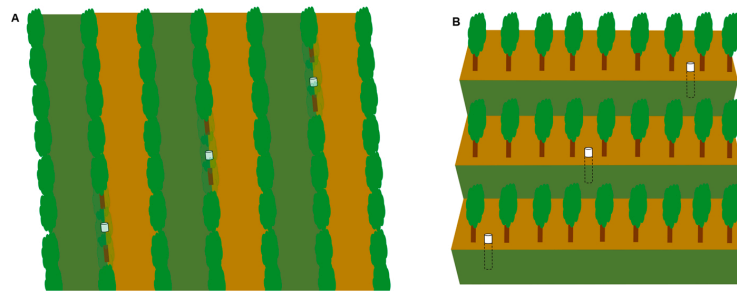


Fig. 2. Schematic representation of the two treatments. A: Control (= C, downslope planted vineyard); B: Terraced vineyard (= T). The location of the access tubes for soil water monitoring in the inter-vine space are illustrated by the white cylinders (dotted lines indicate the embedded tubes).

treatment, three access tubes were installed in the inter-vine space of two vines, at the upper, the middle and the lower slope part of the vineyard (Fig. 2). For this purpose, a metal pipe was driven into the soil to avoid heavy soil disturbance. Access tubes were inserted and the removed soil core from the metal pipe was mixed with water and added around the access tube as filling material to ensure proper contact between tubes and soil. At terraces, access tubes were installed orthogonal to the soil surface, approximately 0.3 m distanced from the edge of the platform in the inter-vine space. At downslope planted vineyards, tubes were installed vertically (i.e. not perpendicular to the hill slope).

Soil moisture measurements were conducted weekly during vegetation period (April to October) and biweekly post-harvest during dormancy (November to March) from April 2019 to November 2021. Data was assessed to a depth of 1 m in 0.1 m measuring intervals.

Data of weather stations in the next possible proximity to the experimental sites was obtained from the Hochschule Geisenheim University weather station network (sensor type 3032 for air temperature recording, rain gauge type 7052 for precipitation measurement and the Combilog 1022 for data logging, Theodor Friedrichs, Schenefeld, Germany) at the sites Lorch (50°0328"N, 7°8229"E), Rüdelsheim (49°9816"N, 7°9142"E) and Geisenheim (49°9840"N, 7°9544"E).

To properly compare changes in soil moisture without an effect of differing soil properties, the relative temporal change in soil water from one measurement day to the following was calculated for every single access tube. The mean of the three measurement points per treatment and site of the consecutive measurement date was divided by the mean of the three measurement points per treatment and site of the previous one, respectively. Subsequently, the calculated values of the terraced vineyards were subtracted from the respective control, i.e. $(\text{Control}_{\text{Date1}}/\text{Control}_{\text{Date0}}) - (\text{Terraced}_{\text{Date1}}/\text{Terraced}_{\text{Date0}})$.

Additionally, the water consumption of the two steep slope vineyard systems was evaluated. The absolute change in soil water was calculated by subtracting the mean absolute value measured at the three access tubes previous to a dry period from the mean absolute value measured at the three access tubes after a dry period from 19/03/2020–29/04/2020 (before grapevine was capable of transpiration) and from 20/05/2020–03/06/2020 (when differences in vineyard water consumption competing to cover crops were assumed to be high between the treatments).

2.3. Plant stress indicators

To evaluate plant stress, carbon isotope discrimination was conducted on grape berry juice from vintages of 2018–2021. In 2019 and 2020, pre-dawn leaf water potential was measured post-anthesis spontaneously at days of the year (DOY), when grapevines were assumed to be affected by drought (i.e. after a period of dry conditions) to ensure highest possible stress response of the grapevine.

2.3.1. Pre-dawn leaf water potential measurements (Ψ_{pd})

On each of the three measurement dates during a vegetation period, pre-dawn leaf water potential was assessed on eight leaves per site and treatment using a pressure chamber (Soilmoisture Corp., Santa Barbara, CA, USA), according to the technique described by Scholander et al. (1965). Sound, non-senescent leaves were wrapped in a plastic bag, detached from the shoot via a single cut and measured directly, by slowly increasing chamber pressure until the endpoint, when xylem sap became visible on the cut surface (Turner, 1988). Measurements were conducted pre-dawn (Ψ_{pd}) in close proximity to the soil moisture monitoring tubes.

2.3.2. Berry sugar carbon isotope discrimination ($\delta^{13}\text{C}$)

Juice samples derived from a sample of one hundred to two hundred ripe berries, randomly picked at harvest date from each side of the grapevine canopy within the whole subplots, respectively. Berries were pressed twice at 0.6 MPa for approximately two minutes (Longarone 85, Eis-System GmbH, Norderstedt, Germany), interrupted by a manual crumbling. The obtained juice was centrifuged for five minutes at 7830 rpm and 20 °C (Eppendorf 5430 R, Hamburg, Germany) and filtered coarsely (16 μ Munktell 33/N 90 g m⁻² folded filter; Ahlstrom, Helsinki, Finland). No further juice preparation was conducted, as suggested by Gaudillère et al. (2002). Two aliquots of 12 μ L juice sample were pipetted in a 5 \times 9 mm tin capsule (IVA Analysetechnik GmbH & Co. KG, Meerbusch, Germany) and oven-dried for 24 h at 60 °C. The capsule was folded, pressed tightly and encased in a second tin capsule, which was also folded and pressed. After combustion at 920 °C, carbon isotopes were measured with the Vario Pyro Cube analyser (Elementar, Langensfeld, Germany) coupled to a stable isotope ratio mass spectrometer (Elementar UK, Stockport, UK). The results are expressed in ‰ VPDB standard (Farquhar et al., 1989) with reference values based on IAEA CH3 (sucrose; Coplen et al., 2006).

2.4. Vegetative and generative response parameters

Grapevine vegetative and generative performance is a viable indicator of plant's drought stress (Gambetta et al., 2020; Pellegrino et al., 2005). All grapevines selected for recordings of crop and growth parameters were chosen by their appearance, i.e. healthy, in regard to fungal diseases, and for the experimental site representative regarding their vigour.

2.4.1. Grapevine lateral leaf area estimation

In 2019 and 2020, leaf area of lateral shoots was estimated according to the non-destructive method of Lopes and Pinto (2005). Six vines per vineyard were labelled in 2019 and used for repeated measurements in close proximity to the soil moisture monitoring tubes. On each vine, one representative shoot (i.e. healthy, fruit-bearing and average-sized) was selected visually. The leaf area per shoot was estimated considering the

Table 1
Geometric parameters and planting information of the vineyard sites (GM = Geisenheimer Rothenberg; RB = Rüdesheimer Rothenberg; LE = Lorcher Eisensgrube; LS = Lorcher Sesselberg) and treatments (C = control, downslope planted vineyard; T = terraced vineyard).

Site	Treatment	Row orientation	Exposition	Slope	Alley width (m)	Vineyard characteristics					Platform			Embankment			Planting information	
						Planting distance (m)	Planting density (vines ha ⁻¹)*	Distance to crown (m)	Soil type	Field capacity (mm)**	Irrigation	Width (m)	Length (m)	Height (m)	Width (m)	Variety (Rootstock)	Year of planting	
GM	C	N-S	S	36 %	1.40	1.00	7143	-	silty loam	66-209	×	-	-	-	-	Riesling (5C, 3309C)	1971	
	T	E-W	S	36 %	2.00	0.70	3968	0.30	silty loam	129-191	×	2.30	1.20	1.50	1.30	Riesling (5C)	1974	
RB	C	N-S	S	40 %	2.00	1.00	5000	-	silty clayey loam	53-129	✓	-	-	-	-	Cabernet Sauvignon (SO4)	2012	
	T	E-W	S	50 %	2.00	0.70	3663	0.30	silty clayey loam	53-66	✓	2.30	2.60	2.00	1.60	Cabernet Sauvignon	2012	
LE	C	NE-SW	SW	40 %	2.00	1.10	4545	-	silty clayey loam	143-173	×	-	-	-	-	Riesling (Börner)	2008	
	T	NW-SE	SW	45 %	2.30	0.60	4762	0.30	silty clayey loam	129-186	×	2.60	2.10	1.60	0.90	Riesling (Börner)	2013	
LS	C	NE-SW	SW	40 %	2.00	1.20	4167	-	silty loam	113-186	×	-	-	-	-	Riesling (Börner)	2001	
	T	NW-SE	SW	40 %	1.80	0.70	3861	0.30	silty loam	117-186	×	2.10	1.90	1.50	1.60	Riesling (Börner)	2008	

* theoretical estimation

** information provided online by the Hessisches Landesamt für Naturschutz, Umwelt und Geologie (data source: <https://weinbaustandort.hessen.de/>).

leaf area of the largest leaf (i.e. the sum of the two lateral veins of the largest leaf) and the calculated mean lateral leaf area (i.e. the average leaf area of the largest and the leaf area of the smallest leaf multiplied by the number of leaves of the shoot). In this regard, a tape measure was used to obtain the lengths of the leaf veins.

2.4.2. Pruning wood

Pruning wood fresh weights were assessed during dormancy in the winters from 2018 to 2020. A total of thirty vines per site and treatment were labelled in 2018 and used for repeated measurements. The fresh weight of the pruning wood was assessed by weighing the pruned cane and annual shoots.

2.4.3. Yield and sugar yield

Yield per vine was calculated by counting and weighing the grape bunches of the six vines per site and treatment labelled for leaf area estimation. To assess further grapevine performance, sugar yield was calculated by multiplying the berry juice sugar content (g L^{-1} ; measured by fourier-transformed infrared spectroscopy (FTIR) via a FT2 Winescan spectrometer (FOSS, Hillerød, Denmark) using an in-house grape must calibration) with the juice yield per vine (L). The calculation was based on a theoretical juice yield of 75 % after pressing.

2.4.4. Statistical analyses

The data was processed and visualised within the *RStudio* environment (v1.4.1717) using the *stats* and *tidyverse* packages. The plant stress indicators (Ψ_{pd} and $\delta^{13}\text{C}$) and vegetative response parameters (leaf area estimation and pruning fresh weights) were evaluated by the non-parametric Mann-Whitney-U test to assess statistical differences between the two treatments at each site.

3. Results

3.1. Soil moisture dynamics in different steep slope management systems

3.1.1. Temporal development of soil moisture changes

In Fig. 3, the differences in the percentage change of soil water content (SWC) to a depth of 1 m between treatments of every two consecutive measurement days, are displayed.

The highest differences in the percentage change between the two treatments could be observed in late winter/early spring, close to the beginning of the vegetation period. At the beginning of March 2020 and the mid of February 2021, a 30–40 % higher water storage could be observed in the terraced treatments, compared to the control at the two experimental sites LE and LS (Fig. 3C, D). All other measuring dates during winter showed only a small difference in percentage change (i.e. $\pm 5\%$) between the two treatments. At site GM, there was only one date which showed a difference in percentage change between the treatments higher than 10 % at the end of the winter: at the beginning of February 2021, after 25 mm rain fell, the terraced treatment at site GM had a higher increase in percentage change of soil water content from one measurement day to the next, compared to the control (Fig. 3A). At site RB, there was only one late winter date in 2020, when the terraced treatment showed a higher increase in percentage change of soil water content compared to the control. The effects of the irrigation at site RB in the two years of 2019 and 2020 are clearly visible in Fig. 3B (dates of irrigation are displayed by down pointing arrows). Irrigation led to high differences in percentage change of soil water content, i.e. a higher percentage increase for the treatment which was artificially watered and a decrease in percentage change in the other treatment led to amplitudes up to 40 % difference (Fig. 3B, Table S2). During dry periods, predominantly in summer when soil water content was generally low, only small differences in percentage change between the treatments were visible. After precipitation events, water retention was higher in the terraced

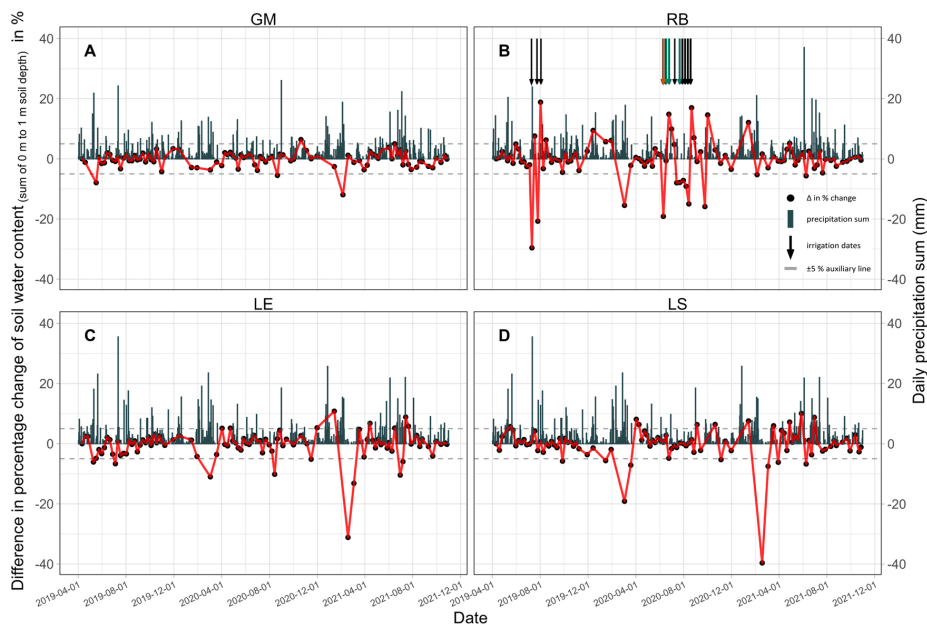


Fig. 3. Dynamic of the difference in percentage change of the soil water content of the control and the terraced treatments (solid red line) at different sites (A: GM = Geisenheimer Rothenberg; B: RB = Rüdeshheimer Berg Rottland; C: LE = Lorcher Eisersgrube; D: LS = Lorcher Sesselberg) over time. Arrows display the irrigation dates at site RB for either both treatments (black arrow), the control (blue arrow) or the terraced treatment (red arrow). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

treatments. The water depletion was similar between the treatments in the days post-precipitation suggesting an actual accumulation of precipitation water in the soil of the terraced treatment (Fig. 3).

3.1.2. Soil moisture depletion under dry conditions

Exemplarily, the percentage change in consumption of soil water content (SWC) in a 10 cm-interval up to 1 m soil depth during dry periods of mid-March to end of April (41 days) and mid of May to beginning of June (14 days) at the four experimental sites (GM, RB, LE and LS) is displayed in Fig. 4A and B.

During the early spring (mid-March to the end April) of 2020, the differences in soil water dynamics (summed for a depth of 1 m) were considerably higher compared to the later development stage of the grapevine (Fig. 4). The dynamic of soil water changes per measurement interval varied between the experimental sites. At site GM and LS, the terraced treatments showed notably higher percentage changes in soil water content for each measurement interval, compared to control. Resulting from a high variability, the treatments at site RB did not differ from each other. At the site LE, the change in soil moisture observed between 50 cm and 70 cm suggests a low water holding capacity at this range, since the percentage changes of C became less than 10 %. Likewise, the terraced treatment at site LE showed low water retention capacity in depth lower 80 cm.

At the end of May 2020, when vines approximately reached the onset of flowering, differences in soil water loss became remarkably lower compared to the former measurement period. In general, single measurement intervals showed low percentage changes (approximately $\leq 10\%$) for the soil layers lower than the first 20 cm (Fig. 4).

3.2. Plant stress indicators

3.2.1. Pre-dawn leaf water potential

Drought stress, identified by pre-dawn leaf water potential measures, increased during the summer of 2019 and 2020 (Fig. 5). In general, control treatments showed a tendency to less negative values. Where treatments were statistically different, vines of the control indicated less drought stress. At site GM, no significant differences in pre-dawn leaf water potential could be detected between the treatments during the entire time of the experiment.

Especially at site RB, both treatments showed low pre-dawn leaf water potential values, despite of various irrigation treatments. In 2019, irrigation was applied rather late (Table S2), so that the vines faced a severe water deficit (< -0.6 MPa) in the terraced treatment close after flowering (DOY 180). Even though irrigation was applied during July, both treatments at site RB suffered from severe water deficits, but showed no statistical differences until mid of August 2019 (DOY 229). In 2020, irrigation means were applied at site RB after cap-fall was completed. The amount of the supplied water per vine provided at the single irrigation dates was rather low (C: 2.86 L vine^{-1} to 7.14 L vine^{-1} and T: 3.32 L vine^{-1} to 6.63 L vine^{-1} ; Table S2), thus it was not possible to prevent vines from high drought stress levels. At the sites LE and LS, vines planted on terraced vineyards suffered from higher water deficits compared to C, except at DOY 187 in 2019, where at site LS the control showed lower Ψ_{pd} values. At site LS, differences between treatments were not as clear as at site LE.

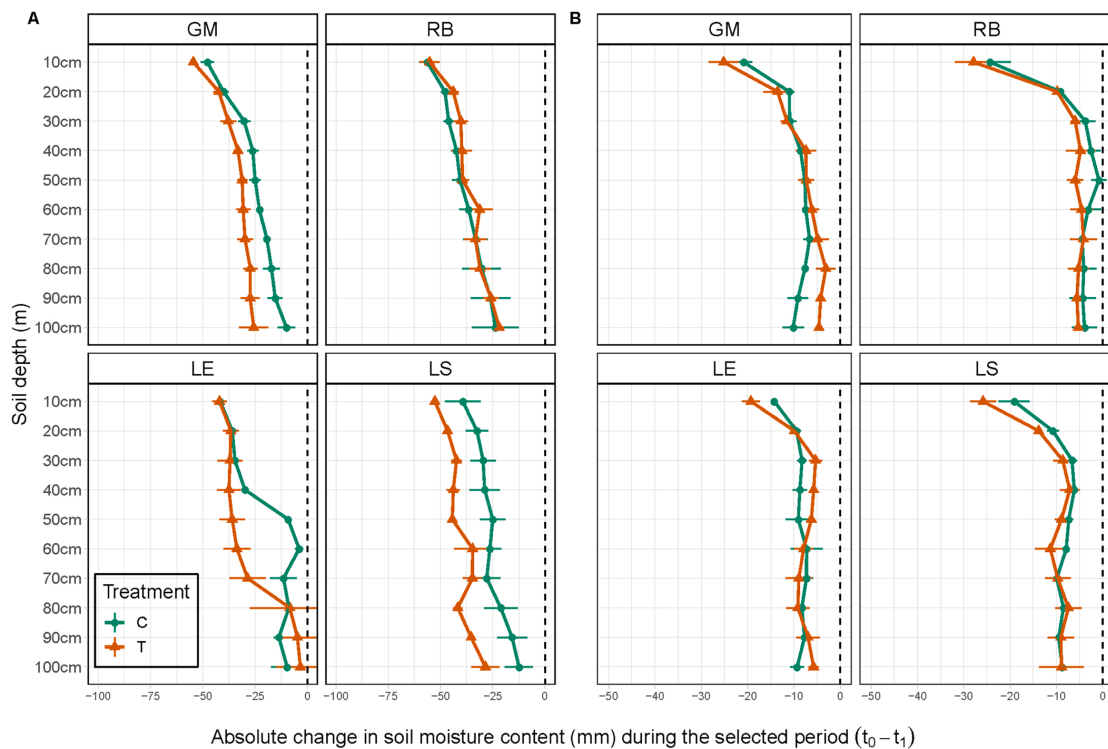


Fig. 4. Percentage change in soil moisture content (%) in a 10 cm-interval up to 1 m soil depth before and after a period of dry conditions in early spring ($t_0 = 19/03/2020$ to $t_1 = 29/04/2020$; A) and close after spring frost ($t_0 = 20/05/2020$ to $t_1 = 03/06/2020$; B) at different sites (GM = Geisenheimer Rothenberg; RB = Rüdesheimer Berg Rottland; LE = Lorcher Eisersgrube; LS = Lorcher Sesselberg) and treatments (C = control; filled circle and T = terraced; filled triangle). Symbols and vertical axis display mean value of three sampling tubes, standard deviation is indicated by horizontal lines.

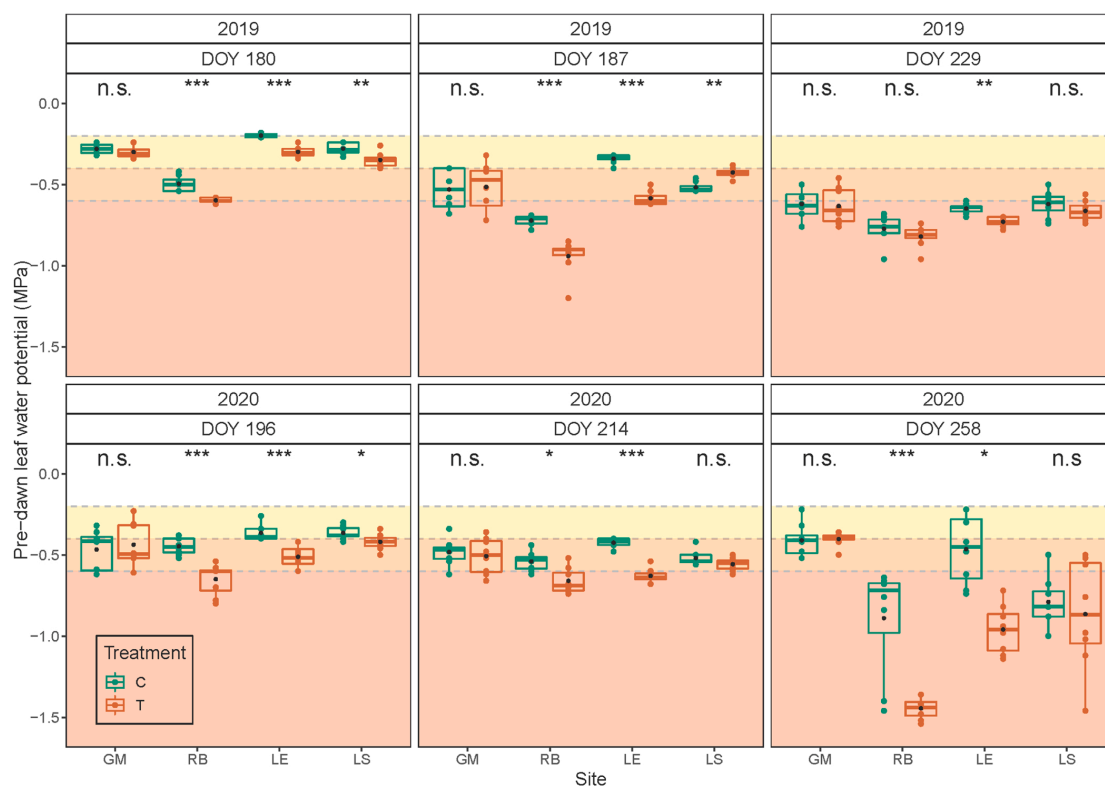


Fig. 5. Pre-dawn leaf water potential measured on grapevines of different treatments (C = control, downslope planted vineyard; T = terraced vineyard; n = 8) and sites (GM = Geisenheimer Rothenberg; RB = Rüdesheimer Berg Rottland; LE = Lorcher Eisersgrube; LS = Lorcher Sesselberg) at different days of the year (DOY) in 2019 and 2020. Points show single measurements, boxplots show distribution of data. Median is indicated by the horizontal line in the boxplot, mean values are represented by a black dot in the respective boxplots. Asterisks denote significant differences (* = p < 0.05; ** = p < 0.01; *** = p < 0.001; n.s. = not significant) of non-parametric Mann-Whitney-U test between treatments at one site and measurement date. Background colors indicate ranges of drought stress (white = 0 MPa to -0.19 MPa = no water deficit; yellow = -0.2 MPa to -0.39 MPa = mild water deficit; orange = -0.4 MPa to -0.59 MPa = moderate water deficit; red = <-0.6 MPa = severe water deficit). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2.2. Carbon isotope discrimination ($\delta^{13}C$)

Vines planted on terraces generally showed a higher risk of drought stress during berry maturation, compared to the control vines (Table 2). An exceptional case was found for the site GM during all four years, where downslope planted vines (control) displayed a higher, i.e. more positive, carbon isotope ratio in the sugars of mature berries compared to terraced vines. No statistical differences were found between

treatments at site LS in 2020, due to high variance in data and at site RB in 2018 and in 2020, probably due to the irrigation management of both treatments (Table S2).

Table 2

Carbon isotope discrimination values (mean \pm standard deviation; n = 6) measured on grape berry sugar obtained from juice of harvest-ripe berries of four vintages from different treatments (C = control, downslope planted vineyard; T = terraced vineyard) and sites (GM = Geisenheimer Rothenberg; RB = Rüdesheimer Berg Rottland; LE = Lorcher Eisersgrube; LS = Lorcher Sesselberg). Asterisks denote significant differences (** = p < 0.01; n.s. = not significant) of non-parametric Mann-Whitney-U test between treatments at one site.

	2018			2019			2020			2021		
	C	T	sign.	C	T	sign.	C	T	sign.	C	T	sign.
GM	-24.08 \pm 0.04	-24.50 \pm 0.06	**	-22.65 \pm 0.05	-24.40 \pm 0.06	**	-18.07 \pm 0.28	-19.49 \pm 0.10	**	-23.23 \pm 0.05	-23.53 \pm 0.05	**
RB	-22.12 \pm 0.13	-22.12 \pm 0.23	n.s.	-22.12 \pm 0.04	-21.63 \pm 0.10	**	-18.49 \pm 0.15	-18.50 \pm 0.31	n.s.	-20.75 \pm 0.14	-20.12 \pm 0.13	**
LE	-25.73 \pm 0.08	-23.28 \pm 0.08	**	-24.40 \pm 0.06	-22.08 \pm 0.04	**	-19.71 \pm 0.12	-17.85 \pm 0.24	**	-24.15 \pm 0.05	-21.88 \pm 0.04	**
LS	-24.37 \pm 0.05	-23.52 \pm 0.08	**	-23.05 \pm 0.10	-22.10 \pm 0.06	**	-18.33 \pm 0.37	-17.97 \pm 0.48	n.s.	-22.97 \pm 0.05	-22.45 \pm 0.05	**

3.3. Vegetative and generative plant response parameters

3.3.1. Grapevine lateral leaf area estimation

Except the treatments of site RB, which were both irrigated in 2020 (Table S2), terraced vineyards usually showed lower vigour at the onset of ripening (véraison) and at the development stage of harvest-ripe berries (Fig. 6).

No statistical differences were found between the treatments at site GM at véraison in both years and at site RB at véraison and harvest in 2020. In 2019, no significant differences were detected between treatments at site LS (Table S3). In general, the number of field replicates was rather low, which reduces the significance of the results. But the data showed that secondary leaf area tended to be higher in downslope planted vines of all the non-irrigated vineyards tested (Fig. 6).

3.3.2. Pruning wood

The fresh weights of winter pruning mass were always significantly different between treatments, except in 2018 at site GM, where only a trend was visible (Table 3). Each year tested, pruning weights per hectare in downsloped vineyards were higher compared to terraced vineyards.

3.3.3. Yield and sugar yield

Grapevines of terraced vineyards showed continuously lower yields and sugar yields per vine and hectare compared to control vineyards (Table 4). Only in 2019 at site GM, the T treatment had 8 % higher grape yield and a 13 % higher sugar yield per vine compared to control.

In 2019, at site LS, yield and sugar yield per vine were equal between the treatments (Table 4). But in the consecutive years, terraced vineyards showed approximately 20–33 % lower yield per vine. At site LE, the yield per vine of T was about a half to two third lower compared to

control vines. In 2019, the terraced vineyard of site RB suffered from an intense drought stress at anthesis. This led to a reduction of yield per vine of 92 % compared to control. But also in the following years, C showed about twice as much grape yield per vine compared to T.

4. Discussion

The relevance of this work has to be linked to the current, but also to the changing growing conditions grapevines will experience in the near future as well as to the special role of viticulture practices at steep slope sites. Global climate projections show that different regions will experience various changes in the amount of annual precipitation, the rainfall distribution and evapotranspiration (IPCC, 2021). In cool (13–15 °C) to intermediate (15–17 °C) wine-growing regions (Hall and Jones, 2009), like the Rheingau wine-growing region (Germany), annual mean precipitation patterns, but also evapotranspiration, are predicted to increase (IPCC, 2021; Schultz and Hofmann, 2015); especially the latter with a continuous rise in vegetation period temperatures. Schultz and Hofmann (2015) prognosticated, that the gap between the amount of precipitation and potential evaporation during the vegetation period is going to increase in future. Schultz (2017) further highlighted, that the risk of developing a water deficit in cool climate wine-growing regions, like the Rheingau, is driven by the increase in evapotranspiration rather than by a decrease in precipitation. Using a high-resolution, site-specific assessment of drought stress risk, Hofmann et al. (2022) showed that drought stress varies substantially between vineyard sites and will increase further in steep slope-regions in future, compared to rain-fed vineyards in the flat. This will be further enhanced, since the incoming solar radiation is higher on steep hill sites and considerably increases the evapotranspiration on often stony and shallow soils, comprising a low water holding capacity (Hofmann et al., 2014).

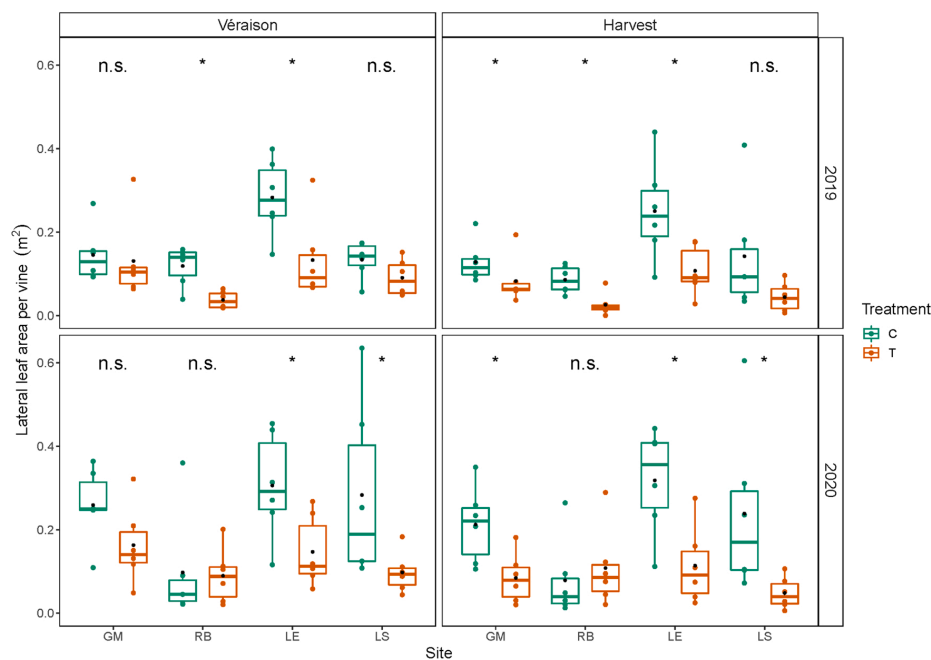


Fig. 6. Comparison of lateral leaf area estimation per vine (m^2) measured on grapevines of different treatments (C = control, downslope planted vineyard; T = terraced vineyard; $n = 6$), development stages and sites (GM = Geisenheimer Rothenberg; RB = Rüdeshheimer Berg Rottland; LE = Lorcher Eisersgrube; LS = Lorcher Sesselberg) in 2019 and 2020. Median is indicated by the horizontal line in the boxplot, mean values are represented by a black dot in the respective boxplots. Asterisks denote significant differences ($* = p < 0.05$; n.s. = not significant) of non-parametric Mann-Whitney-U test between treatments at one site and measurement date.

Table 3

Pruning wood fresh weights (mean \pm standard deviation in kg vine⁻¹ and kg ha⁻¹; n = 30) of different treatments (C = control, downslope planted vineyard; T = terraced vineyard) and sites (GM = Geisenheimer Rothenberg; RB = Rüdeshheimer Berg Rotland; LE = Lorcher Eisersgrube; LS = Lorcher Sesselberg) of three vintages. Asterisks denote significant differences (* = p < 0.05; ** = p < 0.01; *** = p < 0.001; n.s. = not significant) of non-parametric Mann-Whitney-U test between treatments at one site. ND = no data.

		2018			2019			2020		
		C	T	sign.	C	T	sign.	C	T	sign.
GM	kg vine ⁻¹	0.41 \pm 0.18	0.33 \pm 0.13	n.s.	0.35 \pm 0.15	0.20 \pm 0.07	***	0.28 \pm 0.16	0.19 \pm 0.13	***
	kg ha ⁻¹	2895.30 \pm 1251.59	1296.21 \pm 514.87	***	2485.76 \pm 1040.10	788.31 \pm 285.71	***	1985.75 \pm 1176.77	734.08 \pm 514.60	***
RB	kg vine ⁻¹	ND	ND		0.26 \pm 0.11	0.14 \pm 0.03	***	0.27 \pm 0.08	0.21 \pm 0.13	*
	kg ha ⁻¹	ND	ND		1290.00 \pm 546.05	525.03 \pm 101.95	***	1373.33 \pm 414.96	786.32 \pm 493.77	***
LE	kg vine ⁻¹	0.58 \pm 0.27	0.26 \pm 0.12	***	0.35 \pm 0.10	0.15 \pm 0.08	***	0.38 \pm 0.13	0.18 \pm 0.09	***
	kg ha ⁻¹	2655.80 \pm 1234.97	1228.60 \pm 569.99	***	1581.66 \pm 443.14	733.35 \pm 376.13	***	1728.62 \pm 579.90	877.80 \pm 416.21	***
LS	kg vine ⁻¹	0.44 \pm 0.15	0.27 \pm 0.13	***	0.17 \pm 0.06	0.14 \pm 0.06	*	0.20 \pm 0.06	0.19 \pm 0.08	n.s.
	kg ha ⁻¹	1827.92 \pm 616.68	1032.17 \pm 499.00	***	691.72 \pm 231.78	530.24 \pm 230.09	**	834.79 \pm 261.14	745.17 \pm 314.18	n.s.

Table 4

Average fruit and sugar yield per vine and hectare (absolute values (kg) and percentage difference (Δ) to control) of different treatments (C = control, downslope planted vineyard; T = terraced vineyard) and sites (GM = Geisenheimer Rothenberg; RB = Rüdeshheimer Berg Rotland; LE = Lorcher Eisersgrube; LS = Lorcher Sesselberg) of three vintages. N.D. = no data.

			2019			2020			2021		
			C	T	Δ	C	T	Δ	C	T	Δ
GM	Yield	kg vine ⁻¹	1.60	1.73	8 %	2.05	1.52	-26 %	2.62	1.24	-53 %
		kg ha ⁻¹	11,433.75	6873.30	-40 %	14637.76	6048.47	-59 %	18,741.59	4915.79	-74 %
	Sugar yield	kg vine ⁻¹	0.23	0.26	13 %	0.30	0.24	-20 %	0.36	0.16	-56 %
RB	Yield	kg ha ⁻¹	1642.89	1031.68	-37 %	2142.90	952.32	-56 %	2537.61	627.01	-75 %
		kg vine ⁻¹	1.67	0.14	-92 %	1.37	0.68	-51 %	2.34	1.43	-39 %
	Sugar yield	kg ha ⁻¹	8333.83	515.73	-94 %	6847.10	2481.04	-64 %	11,705.68	5238.85	-55 %
LE	Yield	kg vine ⁻¹	0.30	0.03	-90 %	0.22	0.12	-45 %	N.D.	N.D.	N.D.
		kg ha ⁻¹	1500.00	109.89	-93 %	1100.00	439.56	-60 %	N.D.	N.D.	N.D.
	Sugar yield	kg vine ⁻¹	2.66	1.13	-57 %	2.87	1.56	-45 %	3.45	1.13	-67 %
LS	Yield	kg ha ⁻¹	12,068.82	5375.09	-55 %	13,042.07	7452.15	-43 %	15,667.84	5388.67	-66 %
		kg vine ⁻¹	0.37	0.15	-59 %	0.44	0.20	-55 %	0.50	0.14	-73 %
	Sugar yield	kg ha ⁻¹	1681.65	714.30	-58 %	1999.80	952.40	-52 %	2285.15	643.14	-72 %
LS	Yield	kg vine ⁻¹	1.22	1.23	1 %	1.90	1.28	-32 %	2.18	1.74	-20 %
		kg ha ⁻¹	5073.29	4753.89	-6 %	7913.46	4953.36	-37 %	9084.06	6735.68	-26 %
	Sugar yield	kg vine ⁻¹	0.17	0.17	0 %	0.28	0.17	-39 %	0.31	0.22	-29 %
		kg ha ⁻¹	708.39	656.37	-7 %	1166.76	656.37	-44 %	1295.61	848.36	-35 %

Additionally, steep slope vineyards are prone to soil and nutrient loss through erosion (Pijl et al., 2020), which increases with slope gradient and length of the hillside (Emde, 1992; Rodrigo-Comino, 2018). A recent work by Pijl et al. (2022) highlighted the benefits of modern terraces regarding the conservation of soil water and the reduction of soil erosion and sediment fluxes.

In the years of 2018–2020, annual rainfall was lower in the Rheingau wine-growing region compared to the long-term average of 1981–2010 (–13 %, –13 % and –23 %, respectively; Table S1) and the experimental sites experienced a dry period over three years. In 2021, the annual precipitation was a little higher compared to the previous years, but was still dryer than the long-term average (–4 % compared to the long-term average 1991–2020 and –7 % compared to the long-term average 1981–2010; Table S1). While the actual grapevine transpiration may vary considerably, the potential evapotranspiration of flat vineyards in Geisenheim (Rheingau, Germany) is approximately 500 mm during the vegetation period (Hoppmann et al., 2017) or 800 mm per year, increasing with slope (Hofmann et al., 2014). Those values exceed the annual amount of precipitation clearly (Table S1), but this does not necessarily result in grapevine drought stress, since transpiration shows plasticity and the water use efficiency of grapevines under drought may improve during the season due to stomatal regulation induced by ABA signalling and the incorporation of osmotically active solutes, which interacts with the stomatal apparatus (Gambetta et al., 2020; Herrera et al., 2022), due to ‘priming’ (Zamorano et al., 2021) or due to long-term adaptation by assumed epigenetically changes (Pagay et al., 2022).

The impact of drought stress on grapevine depends on the severity

and the timing of the event. The evapotranspirative demand of the atmosphere affects the vine and intensifies concomitantly to the development of foliage. Furthermore, different growth stages are diversely susceptible. In general, low water availability affects cell division and cell expansion, independent of the organ tissue. While drought stress is able to inhibit vegetative growth from the time of when leaves are capable to perform photosynthesis throughout the whole vegetation period, the generative development is highly vulnerable from pre-bloom to fruit-set, since pollen fertility is particularly sensitive to drought (Keller, 2020). A poor anthesis results in lower yields due to shoots with less fruitful clusters, meaning a reduced berry number which can further be reduced in size. Drought during bloom may also affect yield in the consecutive vintage (Keller, 2020). The Rheingau is one of the German wine-growing regions, which is at highest risk of future potential yield losses due to pre-véraison water shortage (Yang et al., 2022). In 2019 at site RB, yield loss in the terraced treatment was severe due to a pre-anthesis drought event. Inflorescences were shed, which led to a 90 %-reduction of yield in the terraced vineyard compared to the control treatment (Table 4). With minor exceptions, e.g. site GM in 2019, terraced vineyards yielded a lower fruit mass per vine during the years (Table 4).

Under drought conditions, berry growth may be supported by storage reserves from perennial sources (woody grapevine parts and roots), which may be at the expense of lower frost hardiness and a reduction in shoot development in the next year (Junquera et al., 2012). The pruning weight data displayed in Table 3, suggests a lower carbohydrate storage in the woody parts of vines planted on terraces, either by an allocation of reserves to support fruit ripening or a general reduction of

photosynthetic performance, i.e. carbon assimilation, due to stomatal closure as a reaction of drought experience. This is supported by the $\delta^{13}\text{C}$ analyses, which showed a higher drought stress response, in terms of an altered carbon assimilation, in terraced vineyards compared to control during the whole period of fruit development, except at site GM (Table 2).

In general, the grapevine adaptation to local conditions and the achievement of full economic performance (i.e. yield stability and vine balance) is delayed and usually lower at steep slopes comprising shallow and stony soils compared to flat, rain-fed vineyards. Certainly, at site LE and LS, years of planting were different between the treatments (terraced vineyards were planted +5 and +7 years later compared the control; Table 1), which may affect results due to possibly less developed or adapted root system in T over time (Zhang et al., 2018). However, at site RB, vines were planted in the same year and at site GM the three-year difference between treatments would not influence the established vines in their physiological behavior, since young vines, planted in a flat vineyard, showed similar yield and pruning weights compared to fully-adapted vines in the fifth year after planting (Bou Nader et al., 2019). In the present study, the vines of the oldest vineyard terrace (site GM) showed either less stress response (Table 2) or did not distinguish from control in their pre-dawn leaf water potential measurements (Fig. 5). The fifty-year-old grapevines might have been able to root in deeper soil layers or to exploit higher soil moisture from the platform centre. In addition, differences between treatments might have also been reduced due to a high water holding capacity of the soils on that site (Table 1). Studies on the impact of grapevine age on the tolerance to water deficit showed, that due to a shallower root system young vines were more vulnerable to soil drying conditions compared to older and more adapted vines (Bou Nader et al., 2019; Grigg et al., 2018). Furthermore, in our study, soil moisture dynamics were recorded at the platform edge of the terrace, but literature cited in Michalsky (1976) indicates that root growth was higher in length on terraces compared to vines planted downslope, and that roots of vines planted on terraces tended to grow towards the centre of the platform, where a higher soil water content would exist (Michalsky, 1976). Hence, once the vines start to adapt, irrigation water should be applied on the foot of the embankments through subsurface drip lines, forcing the roots to grow towards the hill side.

Modern, driveable, vineyard terraces have to be constructed and maintained properly. Poorly managed and insufficient stabilized embankments (i.e. by the renunciation of vegetation cover or dry stones) may lead to collapses of the terrace and an increase in soil erosion (Pijl et al., 2020; Rodrigo-Comino et al., 2019). The positive contribution of weeds and other crops covering bare embankment soil of vineyard terraces are ecosystem services like the prevention of erosion, the providing of food and shelter for beneficial insects or the improvement of soil physical and chemical characteristics. However, while young vines planted on terraces may be competing strongly with embankment vegetation used for soil stability, fully adapted grapevines may benefit from higher water availability in the middle of the terrace platform, depending on the water consumption of the surrounding vegetation. Row orientation affects the radiation energy partitioning of the grapevine and the vineyard soil (Zorer et al., 2017), thus influencing the water balance of the vineyard (Kool et al., 2021). Depending on intercropping, the evapotranspiration of the soil may be little (0.5 mm d^{-1}) to almost as high as the grapevine transpiration (3 mm d^{-1}) itself (Celette et al., 2010). Cover cropped embankments in E-W, but also in NW-SE aligned terraces, are irradiated almost the whole day, whereas the tractor alley may be shaded by the grapevine canopy. To evaluate the soil water budget in terraced vineyards an already existing model for radiation partitioning and water balance for steep slope vineyards would have to be adapted for the vineyard system planted along the contour line of the hill (Hofmann et al., 2014). Lopes et al. (2015) quantified the water use of several weeds and cover crops in a rain-fed steep slope vineyard in the Rheingau wine-growing region and showed, that depending on their

dispersion, transpiration values per square meter soil cover per day were on average 2.7 to five times higher compared to grapevine. The difference in vineyard soil plant cover between the control and the terraced treatments was highest during the early part of the vegetation period (mid of May, when mulching is conducted in control vineyards to reduce the risk of late-frost damage, but embankment vegetation is maintained). However, only small difference in the percentage change of soil water content could be found between the treatments at all experimental sites close after the period of late-frost risk (Fig. 4B). The small differences may be due to a rather dry and sunny spring (Table S1). Soils with a fewer amount of soil water content also showed smaller percentage changes in soil water content. Earlier in the season, the management systems displayed considerable differences in soil water loss rates from mid-March to the end of April (Fig. 4A), which may also lead to a delay in shoot growth in the terraced treatment (Strack et al., 2021).

Even though vineyard terraces are able to conserve water during precipitation events due to an increased water infiltration (Fig. 3) and a reduction of run-off (Armáez et al., 2015; Pijl et al., 2022), they show a large potential evaporation resulting from a larger surface exposed to solar irradiation and wind compared to down-sloped vineyards (Lü et al., 2009). The solar energy intake of the two systems may be the same during the day, but terraced vineyards showed lower daytime temperatures compared to down-slope planted vineyards, which may indicate a cooling effect of a higher transpiration activity of embankment weeds and cover crop (Strack et al., 2021). Additionally, a lower planting density resulting from a bigger distance between vineyard rows in the terrace system may increase the wind flux, which further increases water consumption by accompanying vineyard plants (Heilman et al., 1994). Projections of the near future show, that under a dryer climate low density vineyards in the plane (i.e. $2'500 \text{ vines ha}^{-1}$ instead of $5'000 \text{ vines ha}^{-1}$) may benefit from a higher amount of free transpirable soil water (FTSW; van Leeuwen et al., 2019). However, under less favorable soil conditions (FTSW = 100 mm ; as it can be often found at steep slope sites, see also Table 1) a lower planting density barely improved FTSW (van Leeuwen et al., 2019).

The differences in drought stress response were mainly pronounced during fruit development before the beginning of ripening (Fig. 5). After véraison, berry development is less sensitive to drought stress and may profit from a reduced vegetative growth, due to better solar irradiation and a lower risks of noble rot infection (Smart and Robinson, 1991). The small changes in weekly water content measurements post-véraison (Fig. 3) implied a low plasticity of water supply from soils with low water holding capacity during summer in years of reduced precipitation. On the one hand, grapevine water consumption is closely linked to its leaf area, more precisely the transpiration surface of the plant (Ohan-Levi et al., 2020). On the other hand, secondary leaf area is strongly affected by water deficit (Lebon et al., 2001; Pellegrino et al., 2005). Grapevine vegetative performance of the terraced vineyards was lower at harvest time at all sites (Fig. 6, Table 4). A clear tendency was shown, that control vineyards display higher vigour compared to terraced treatments (Fig. 6, Table 3). In 2020, when both types of grapevine management, i.e. vines planted on terraces or downslope, at site RB were irrigated regularly (Table S2), treatments showed no statistical differences in lateral leaf area, but a slight tendency of higher lateral leaf area in T compared to C (Fig. 6). This suggests that a vine planted on the edge of a terrace platform is able to outperform disadvantages related to water availability, if supported by means of irrigation. However, since the irrigation of luxury goods, like wine, bears the high risk of social injustice, alternatives to an improved water supply or availability have to be found. Possible solutions may be the relocation of the drip lines to the foot of the embankment or the incorporation of an optimized drainage system during the vineyard transformation process to slowly supply excessive precipitation water from the pathways or turning plates of the terrace to the vineyard soil (Pijl et al., 2020; Tarolli et al., 2015). Special attention should be paid to viticultural management decisions and breeding. The selection of a suitable rootstock showing better root

architecture and being less vulnerable to drought stress and the scion (Ollat et al., 2017), the trellising, as well as the controlling of vine balance (ratio of vegetative to generative growth) has to be considered. Further measures are the increase of soil organic matter to improve water storage capacity, ground cover management to reduce evapotranspiration, a shallow soil cultivation to increase water availability during droughts or the application of soil amendments (i.e. biochar; Schmidt et al., 2021) and/or the inoculation of beneficial root symbionts (i.e. rhizosphere engineering; Dries et al., 2021) to improve water storage and water uptake by grapevine roots.

In conclusion, the collected data related to drought stress parameters, highlighted a better overall performance of control vines compared to the terraced treatment. However, the fifty-year-old vineyards at site GM, showed less drought stress during the seasons (Fig. 5). This is of particular importance since the years were the study was performed will most likely become common scenarios in the near future under changing climate conditions. All other terraces in this study were constructed and planted not later than ten years ago. Thus, it may be inferred that young vines need longer to adapt to the specific conditions of a high-competitive environment like the terraced situation of a larger exposed soil surface area. Nevertheless, the transformation of steep hill sites to terraces may allow the retention of winter precipitation water and the reduction of soil and nutrient loss induced by rainfall events. Additionally, terrace embankments have the potential to diversify the monocultural vineyard landscape and to cross-link biotopes if an adequate cover cropping, i.e. regionally adapted flower seed mixture, is used for biological stabilization (Wersebeckmann et al., 2022). A fast adaptation of grapevines to the vineyard site is desired by viticulturists for reasons of lowering costs of grapevine nursing and increasing yield. In this context, site-specific solutions have to be developed on how to improve the adaptation and resilience of young vines on terraced vineyard sites. The aim is to support a fast development of grapevine roots to overcome competition with highly drought-adapted spontaneous, or for stabilization reasons, inevitable co-vegetation, to further allow successful grapevine cultivation at drought risk threatened steep slope sites.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors would like to thank the Deutsche Bundesstiftung Umwelt for founding the BioQuiS project (funding number AZ 34025) in which the experiments were carried out. We appreciate the assistance of Dr. Christian Borsch (JLU Gießen) who conducted the carbon isotope discrimination analyses. Special thanks to Christian Frings for the technical support and maintenance of the measuring devices and Marco Hofmann for his competent support and knowledge sharing. We also thank the partner wineries for providing their vineyards for the investigations (Weingut der Hochschule Geisenheim (Geisenheim), Weingüter Wegeler (Oestrich-Winkel), Weingut Laquai (Lorch), Weingut Altenkirch (Lorch), Weingut Breuer (Rüdesheim am Rhein) and Hessische Staatsweingüter Kloster Eberbach (Eltville)).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2022.107967.

References

- Acevedo-Opazo, C., Ortega-Farías, S., Fuentes, S., 2010. Effects of grapevine (*Vitis vinifera* L.) water status on water consumption, vegetative growth and grape quality: an irrigation scheduling application to achieve regulated deficit irrigation. *Agric. Water Manag.* 97, 956–964. <https://doi.org/10.1016/j.agwat.2010.01.025>.
- Arnaez, J., Lana-Renault, N., Lasanta, T., Ruiz-Flaño, P., Castroviejo, J., 2015. Effects of farming terraces on hydrological and geomorphological processes. A review. *Catena* 128, 122–134. <https://doi.org/10.1016/j.catena.2015.01.021>.
- Blank, M., Hofmann, M., Stoll, M., 2019. Seasonal differences in *Vitis vinifera* L. cv. Pinot noir fruit and wine quality in relation to climate. *OENO One* 53. <https://doi.org/10.20870/oeno-one.2019.53.2.2427>.
- Bou Nader, K., Stoll, M., Rauhut, D., Patz, C.-D., Jung, R., Loehner, O., Schultz, H.R., Hilbert, G., Renaud, C., Roby, J.-P., Delrot, S., Gomes, E., 2019. Impact of grapevine age on water status and productivity of *Vitis vinifera* L. cv. Riesling. *Eur. J. Agron.* 104, 1–12. <https://doi.org/10.1016/j.eja.2018.12.009>.
- Buesa, I., Mirás-Avalos, J.M., Paz, J.M., de Visconti, F., Sanz, F., Yeves, A., Guerra, D., Intrigliolo, D.S., 2021. Soil management in semi-arid vineyards: combined effects of organic mulching and no-tillage under different water regimes. *Eur. J. Agron.* 123, 126198. <https://doi.org/10.1016/j.eja.2020.126198>.
- Canaj, K., Morrone, D., Roma, R., Boari, F., Cantore, V., Todorovic, M., 2021. Reclaimed water for vineyard irrigation in a mediterranean context: life cycle environmental impacts, life cycle costs, and eco-efficiency. *Water* 13, 2242. <https://doi.org/10.3390/w13162242>.
- Castellarin, S.D., Pfeiffer, A., Sivilotti, P., Degan, M., Peterlunger, E., Di Gasparo, G., 2007. Transcriptional regulation of anthocyanin biosynthesis in ripening fruits of grapevine under seasonal water deficit. *Plant Cell Environ.* 30, 1381–1399. <https://doi.org/10.1111/j.1365-3040.2007.01716.x>.
- Celette, F., Ripoche, A., Gary, C., 2010. WaLIS—A simple model to simulate water partitioning in a crop association: the example of an intercropped vineyard. *Agric. Water Manag.* 97, 1749–1759. <https://doi.org/10.1016/j.agwat.2010.06.008>.
- Chaves, M.M., Zarrouk, O., Francisco, R., Costa, J.M., Santos, T., Regalado, A.P., Rodrigues, M.L., Lopes, C.M., 2010. Grapevine under deficit irrigation: hints from physiological and molecular data. *Ann. Bot.* 105, 661–676. <https://doi.org/10.1093/aob/mcq030>.
- Coplen, T.B., Brand, W.A., Gehre, M., Gröning, M., Meijer, H.A.J., Toman, B., Verkooren, R.M., 2006. New guidelines for $\delta^{13}\text{C}$ measurements. *Anal. Chem.* 78, 2439–2441. <https://doi.org/10.1021/ac052027c>.
- Dries, L., Hendgen, M., Schnell, S., Löhner, O., Vortkamp, A., 2021. Rhizosphere engineering: leading towards a sustainable viticulture. *OENO One* 55, 353–363. <https://doi.org/10.20870/oeno-one.2021.55.2.4534>.
- Emde, K., 1992. Experimentelle Untersuchungen zu Oberflächenabfluss und Bodenaustrag in Verbindung mit Starkregen bei verschiedenen Bewirtschaftungssystemen in Weinbergsarealen des oberen Rheingaus. *Gesellschaft zur Förderung der Forschungsanstalt Geisenheim. Geisenheim* 248.
- Farquhar, G.D., Ehleringer, J.R., Hubick, K.T., 1989. Carbon isotope discrimination and photosynthesis. *Annu. Rev. Plant Physiol. Plant Mol. Biol.* 40, 503–537. <https://doi.org/10.1146/annurev.pp.40.060189.002443>.
- Flexas, J., Bota, J., Cifre, J., Escalano, J.M., Galmes, J., Gulias, J., Lefi, E.-K., Martínez-Cañellas, S.F., Moreno, M.T., Ribas-Carbo, M., Riera, D., Sampo, B., Medrano, H., 2004. Understanding down-regulation of photosynthesis under water stress: future prospects and searching for physiological tools for irrigation management. *Ann. Appl. Biol.* 144, 273–283. <https://doi.org/10.1111/j.1744-7348.2004.tb00343.x>.
- Gambetta, G.A., Herrera, J.C., Dayer, S., Feng, Q., Hochberg, U., Castellarin, S.D., 2020. The physiology of drought stress in grapevine: towards an integrative definition of drought tolerance. *J. Exp. Bot.* 71, 4658–4676. <https://doi.org/10.1093/jxb/eraa245>.
- Gatti, M., Garavani, A., Squeri, C., Capri, C., Diti, I., D'Ambrosio, R., Frioni, T., Scotti, C., Poni, S., 2022. Inter-row floor management is a powerful factor for optimising vine balance in a non-irrigated organic Barbera vineyard in northern Italy. *Eur. J. Agron.* 136, 126490. <https://doi.org/10.1016/j.eja.2022.126490>.
- Gaudillère, J.-P., van Leeuwen, C., Ollat, N., 2002. Carbon isotope composition of sugars in grapevine, an integrated indicator of vineyard water status. *J. Exp. Bot.* 53, 757–763. <https://doi.org/10.1093/jxb/53.369.757>.
- Grigg, D., Methven, D., Bei, R., de Rodríguez López, C.M., Dry, P., Collins, C., 2018. Effect of vine age on vine performance of Shiraz in the Barossa Valley, Australia. *Aust. J. Grape Wine Res.* 24, 75–87. <https://doi.org/10.1111/ajgw.12312>.
- Hall, A., Jones, G.V., 2009. Effect of potential atmospheric warming on temperature-based indices describing Australian winegrape growing conditions. *Aust. J. Grape Wine Res.* 15, 97–119. <https://doi.org/10.1111/j.1755-0238.2008.00035.x>.
- Heilmann, J., McInnes, K., Savage, M., Gesch, R., Lascano, R., 1994. Soil and canopy energy balances in a west Texas vineyard. *Agric. For. Meteorol.* 71, 99–114. [https://doi.org/10.1016/0168-1923\(94\)90102-3](https://doi.org/10.1016/0168-1923(94)90102-3).
- Herrera, J.C., Calderan, A., Gambetta, G.A., Peterlunger, E., Forneke, A., Sivilotti, P., Cochard, H., Hochberg, U., 2022. Stomatal responses in grapevine become increasingly more tolerant to low water potentials throughout the growing season. *Plant J. Cell Mol. Biol.* 109, 804–815. <https://doi.org/10.1111/tpj.15591>.
- Hofmann, M., Lux, R., Schultz, H.R., 2014. Constructing a framework for risk analyses of climate change effects on the water budget of differently sloped vineyards with a numeric simulation using the Monte Carlo method coupled to a water balance model. *Front. Plant Sci.* 5, 645. <https://doi.org/10.3389/fpls.2014.00645>.
- Hofmann, M., Volosciuk, C., Dubrovský, M., Maraun, D., Schultz, H.R., 2022. Downscaling of climate change scenarios for a high-resolution, site-specific assessment of drought stress risk for two viticultural regions with heterogeneous landscapes. *Earth Syst. Dyn.* 13, 911–934. <https://doi.org/10.5194/esd-13-911-2022>.

- Hoppmann, D., Schaller, K., Stoll, M., 2017. Terroir: Wetter, Klima und Boden im Weinbau, second ed., Ulmer, Stuttgart, Hohenheim, 372.
- IPCC, 2021. Climate Change 2021: The Physical Science Basis: Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press.
- Johnson-Bell, L., 2018. Climate change and water management: non-viability of freshwater irrigation in viticulture. In: Leal Filho, W., Wall, T., Azeiteiro, U., Azul, A. M., Brandli, L., Ozuyar, P.G. (Eds.), Good Health and Well-Being, 24. Springer International Publishing, Cham, pp. 1–11.
- Junquera, P., Lissarrague, J.R., Jiménez, L., Linares, R., Baeza, P., 2012. Long-term effects of different irrigation strategies on yield components, vine vigour, and grape composition in cv. Cabernet-Sauvignon (*Vitis vinifera* L.). *Irrig. Sci.* 30, 351–361. <https://doi.org/10.1007/s00271-012-0348-y>.
- Keller, M., 2020. The Science of Grapevines. Academic Press, Amsterdam, p. 541 (An imprint of Elsevier).
- Kool, D., Kustas, W.P., Ben-Gal, A., Agam, N., 2021. Energy partitioning between plant canopy and soil, performance of the two-source energy balance model in a vineyard. *Agric. For. Meteorol.* 300, 108328 <https://doi.org/10.1016/j.agrformet.2021.108328>.
- Lebon, E., Pellegrino, A., Lecour, J., Tardieu, F., 2001. Shoot architectural responses induced by controlled soil water deficit in vine (*Vitis vinifera* L. cv. Grenache noir). In: AGRO Montpellier (Ed.), Proceedings Twelfth GESCO Conference: Compte rendu vol. 1. Montpellier, France, 229–235.
- van Leeuwen, C., Darriet, P., 2016. The impact of climate change on viticulture and wine quality. *J. Wine Econ.* 11, 150–167. <https://doi.org/10.1017/jwe.2015.21>.
- van Leeuwen, C., Pieri, P., Gowdy, M., Ollat, N., Roby, J.-P., 2019. Reduced density is an environmental friendly and cost effective solution to increase resilience to drought in vineyards in a context of climate change. *OENO One* 53, 129–146. <https://doi.org/10.20870/oeno-one.2019.53.2.2420>.
- Lopes, C.M., Monteiro, A., Rückert, F.E., Gruber, B., Steinberg, B., Schultz, H.R., 2015. Transpiration of grapevines and co-habiting cover crop and weed species in a vineyard. A “snapshot” at diurnal trends. *Vitis* 43, 111–117. <https://doi.org/10.5073/vitis.2004.43.111-117>.
- Lovisololo, C., Perrone, I., Carra, A., Ferrandino, A., Flexas, J., Medrano, H., Schubert, A., 2010. Drought-induced changes in development and function of grapevine (*Vitis spp.*) organs and in their hydraulic and non-hydraulic interactions at the whole-plant level: a physiological and molecular update. *Funct. Plant Biol.* 37, 98. <https://doi.org/10.1071/FP09191>.
- Lopes, C.M., Pinto, P.A., 2005. Easy and accurate estimation of grapevine leaf area with simple mathematical models. *Vitis* 44, 55–61.
- Lü, H., Zhu, Y., Skaggs, T.H., Yu, Z., 2009. Comparison of measured and simulated water storage in dryland terraces of the Loess Plateau, China. *Agric. Water Manag.* 96, 299–306. <https://doi.org/10.1016/j.agwat.2008.08.010>.
- Medrano, H., Tomás, M., Martorell, S., Escalona, J.-M., Pou, A., Fuentes, S., Flexas, J., Bota, J., 2015. Improving water use efficiency of vineyards in semi-arid regions. A review. *Agron. Sustain. Dev.* 35, 499–517. <https://doi.org/10.1007/s13593-014-0280-z>.
- Michalsky, A., 1976. Die Querterrassierung im Weinbau und ihr Einfluss auf verschiedene klein-klimatische und pedologische Faktoren sowie die Leistung der Rebe. KTBL-Schriften-Vertrieb in Landwirtschaftsverl., Hiltrup (Westf.), 159.
- Ohana-Levi, N., Munitz, S., Ben-Gal, A., Netzer, Y., 2020. Evaluation of within-season grapevine evapotranspiration patterns and drivers using generalized additive models. *Agric. Water Manag.* 228, 105808 <https://doi.org/10.1016/j.agwat.2019.105808>.
- Ollat, N., Cookson, S.J., Lauvegeat, V., Marguerit, E., Barrieu, F., Gambetta, G., Goutouly, J.-P., Tandonnet, J.-P., Vivin, P., Delrot, S., 2017. Grapevine roots: the dark side. *Acta Hort.* 213–226. <https://doi.org/10.17660/ActaHortic.2017.1188.28>.
- Pagay, V., Furlan, T.S., Kidman, C.M., Nagahatenna, D., 2022. Long-term drought adaptation of unirrigated grapevines (*Vitis vinifera* L.). *Theor. Exp. Plant Physiol.* 259, 660. <https://doi.org/10.1007/s40626-022-00243-3>.
- Pellegrino, A., Lebon, E., Simmoneau, T., Wery, J., 2005. Towards a simple indicator of water stress in grapevine (*Vitis vinifera* L.) based on the differential sensitivities of vegetative growth components. *Aust. J. Grape Wine Res.* 11, 306–315. <https://doi.org/10.1111/j.1755-0238.2005.tb00030.x>.
- Picón-Toro, J., González-Dugo, V., Uriarte, D., Mancha, L.A., Testi, L., 2012. Effects of canopy size and water stress over the crop coefficient of a “Tempranillo” vineyard in south-western Spain. *Irrig. Sci.* 30, 419–432. <https://doi.org/10.1007/s00271-012-0351-3>.
- Pijl, A., Reuter, L.E., Quarella, E., Vogel, T.A., Tarolli, P., 2020. GIS-based soil erosion modelling under various steep-slope vineyard practices. *Catena* 193, 104604. <https://doi.org/10.1016/j.catena.2020.104604>.
- Pijl, A., Wang, W., Straffellini, E., Tarolli, P., 2022. Soil and water conservation in terraced and non-terraced cultivations: an extensive comparison of 50 vineyards. *Land Degrad. Dev.* 33, 596–610. <https://doi.org/10.1002/ldr.4170>.
- Rodrigo-Comino, J., 2018. Five decades of soil erosion research in “terroir”. *The State-of-the-Art. Earth Sci. Rev.* 179, 436–447. <https://doi.org/10.1016/j.earscirev.2018.02.014>.
- Rodrigo-Comino, J., Seeger, M., Iserloh, T., Senciales González, J.M., Ruiz-Sinoga, J.D., Ries, J.B., 2019. Rainfall-simulated quantification of initial soil erosion processes in sloping and poorly maintained terraced vineyards - key issues for sustainable management systems. *Sci. Total Environ.* 660, 1047–1057. <https://doi.org/10.1016/j.scitotenv.2018.12.451>.
- Romero, P., García García, J., Fernández-Fernández, J.I., Muñoz, R.G., del Amor Saavedra, F., Martínez-Cutillas, A., 2016. Improving berry and wine quality attributes and vineyard economic efficiency by long-term deficit irrigation practices under semiarid conditions. *Sci. Hortic.* 203, 69–85. <https://doi.org/10.1016/j.scienta.2016.03.013>.
- Savoi, S., Wong, D.C.J., Arapitsas, P., Miculan, M., Buchetti, B., Peterlunger, E., Fait, A., Mattivi, F., Castellari, S.D., 2016. Transcriptome and metabolite profiling reveals that prolonged drought modulates the phenylpropanoid and terpenoid pathway in white grapes (*Vitis vinifera* L.). *BMC Plant Biol.* 16, 67. <https://doi.org/10.1186/s12870-016-0760-1>.
- Schmidt, H.-P., Kammann, C., Hagemann, N., Leifeld, J., Bucheli, T.D., Sánchez Monedero, M.A., Cayuela, M.L., 2021. Biochar in agriculture – a systematic review of 26 global meta-analyses. *GCB Bioenergy* 13, 1708–1730. <https://doi.org/10.1111/gcb.12889>.
- Scholander, P.F., Bradstreet, E.D., Hemmingsen, E.A., Hammel, H.T., 1965. Sap pressure in vascular plants: negative hydrostatic pressure can be measured in plants. *Science* 148, 339–346. <https://doi.org/10.1126/science.148.3668.339>.
- Schultz, H.R., 2017. Issues to be considered for strategic adaptation to climate evolution – is atmospheric evaporative demand changing. *OENO One* 51, 107–114. <https://doi.org/10.20870/oeno-one.2017.51.2.1619>.
- Schultz, H.R., Hofmann, M., 2015. The ups and downs of environmental impact on grapevines. In: Gerós, H., Chaves, M.M., Gil, H.M., Delrot, S. (Eds.), Grapevine in a Changing Environment, 97. John Wiley & Sons, Ltd, Chichester, UK, pp. 18–37.
- Smart, R., Robinson, M., 1991. Sunlight Into Wine: a Handbook for Winegrape Canopy Management. Winetitles, Adelaide, p. 88.
- Stoll, M., Dry, P., Loveys, B., Stewart, D., McCarthy, M., 2000a. Partial rootzone drying: effects on root distribution and commercial application of a new irrigation technique. *Wine Vitic. J.* 74–77.
- Stoll, M., Loveys, B., Dry, P., 2000b. Hormonal changes induced by partial rootzone drying of irrigated grapevine. *J. Exp. Bot.* 51, 1627–1634. <https://doi.org/10.1093/jxb/51.350.1627>.
- Strack, T., Schmidt, D., Stoll, M., 2021. Impact of steep slope management system and row orientation on canopy microclimate. Comparing terraces to downslope vineyards. *Agric. For. Meteorol.* 307, 108515 <https://doi.org/10.1016/j.agrformet.2021.108515>.
- Strub, L., Kurth, A., Loose, S.M., 2021. Effects of viticultural mechanization on working time requirements and production costs. *Am. J. Enol. Vitic.* 72, 46–55. <https://doi.org/10.5344/ajev.2020.20027>.
- Strub, L., Müller-Loose, S., 2021. The cost disadvantage of steep slope viticulture and strategies for its preservation. *OENO One* 55, 49–68. <https://doi.org/10.20870/oeno-one.2021.55.1.4494>.
- Tarolli, P., Preti, F., Romano, N., 2014. Terraced landscapes: from an old best practice to a potential hazard for soil degradation due to land abandonment. *Anthropocene* 6, 10–25. <https://doi.org/10.1016/j.ancene.2014.03.002>.
- Tarolli, P., Sofia, G., Calligaro, S., Prosdociimi, M., Preti, F., Dalla Fontana, G., 2015. Vineyards in terraced landscapes: new opportunities from lidar data. *Land Degrad. Dev.* 26, 92–102. <https://doi.org/10.1002/ldr.2311>.
- Turner, N.C., 1988. Measurement of plant water status by the pressure chamber technique. *Irrig. Sci.* 9, 289–308. <https://doi.org/10.1007/BF00296704>.
- Vuerich, M., Braidotti, R., Sivilotti, P., Alberti, G., Casolo, V., Braidotti, E., Boscutti, F., Calderan, A., Petrusa, E., 2021. Response of Merlot grapevine to drought is associated to adjustments of growth and nonstructural carbohydrates allocation in above and underground organs. *Water* 13, 2336. <https://doi.org/10.3390/w13172336>.
- Wersebeckmann, V., Entling, M.H., Leyer, I., 2022. Revegetation of vineyard terrace embankments: a matter of seed mixture and seeding technique. *J. Environ. Manag.* 317, 115409 <https://doi.org/10.1016/j.jenvman.2022.115409>.
- Williams, L.E., 2014. Determination of evapotranspiration and crop coefficients for a chardonnay vineyard located in a cool climate. *Am. J. Enol. Vitic.* 65, 159–169. <https://doi.org/10.5344/ajev.2014.12104>.
- Yang, C., Menz, C., Fraga, H., Costafreda-Aumedes, S., Leolini, L., Ramos, M.C., Molitor, D., van Leeuwen, C., Santos, J.A., 2022. Assessing the grapevine crop water stress indicator over the flowering-veraison phase and the potential yield loss rate in important European wine regions. *Agric. Water Manag.* 261, 107349 <https://doi.org/10.1016/j.agwat.2021.107349>.
- Zamorano, D., Franck, N., Pastenes, C., Wallberg, B., Garrido, M., Silva, H., 2021. Improved physiological performance in grapevine (*Vitis vinifera* L.) cv. Cabernet Sauvignon facing recurrent drought stress. *Aust. J. Grape Wine Res.* 27, 258–268. <https://doi.org/10.1111/ajgw.12482>.
- Zhang, Y., Wu, X., Wang, S., Niu, H., 2018. The simulation of the vine biomass at different planting ages in Ningxia vineyards using DNDC model. *Acta Ecol. Sin.* 38, 281–287. <https://doi.org/10.1016/j.chnaes.2018.01.012>.
- Zorer, R., Volschenk, C.G., Hunter, J.J., 2017. Integrating geographic information systems and hemispherical photography in the assessment of canopy light profiles in a vineyard. *Agric. For. Meteorol.* 232, 672–681. <https://doi.org/10.1016/j.agrformet.2016.09.011>.

Chapter V: General Discussion

This doctoral thesis aimed to investigate the effects of a management system transformation from steep slope vineyards planted down the slope (control, C) to terraced vineyard systems (T). How the changes in geometry and in row orientation affect the microclimate, the soil water dynamics and the performance of the grapevine has been displayed in the previous Chapters II to IV.

The hypotheses and research questions raised shall be discussed in a coherent approach to link the single papers, add further information and consequently provide conclusions.

5.1 Vineyard terracing is a useful tool to mitigate weather extremes

The hypothesis **H_I**, that *vineyard terracing affects the canopy microclimate and leads to lower temperature parameters and a more favourable canopy irradiation* was tested in Chapter II (Strack et al., 2021).

The data evaluation showed, that vineyard terracing does affect canopy microclimate, but does not overall lead to lower temperature parameters, e.g. minimum temperatures.

Additionally, a generally more favourable canopy irradiation and temperature must be discussed in a more differentiated manner.

In Chapter II, the application of an advanced computational method, i.e. a Bayesian linear mixed effect model approach, was used to properly account for the complexity of the conducted experiment. The data recorded comprises two vegetation periods. A longer time series would have increased the significance of the results. However, given the level of the factors involved in the analysis (i.e. daily weather parameters from each treatment and site, different row orientations, different seasons and years as well as their interactions), robust results were found, which showed both a treatment and a row orientation effect on the microclimate of grapevines grown at steep slopes (Strack et al., 2021).

As already highlighted in Chapter I, the development of a *stable* microclimate in the vineyard depends on the atmospheric conditions and is particularly pronounced at sunny summer days under calm wind conditions (i.e. a wind speed less than 2 m s^{-1} ; Horney, 1975). Furthermore, the developmental stage of the grapevine is a relevant factor regarding the bunch zone microclimate, since it affects the porosity of the canopy and, thus the penetration intensity of the solar radiation into the canopy (i.e. the warming of the grapevine clusters in case of direct exposition or its protection by leaf shading; Smart, 1985). Additionally, the vineyard geometry and the row orientation either support or hamper the wind flux, e.g. by the area of direct sun-exposure and the

heat accumulation due to wind protection. Furthermore, the canopy density and the row spacing may influence the degree of the intra-vineyard turbulences (Weiss and Allen, 1976; Chahine et al., 2014).

Small, but constantly robust increases in temperature ($<0.5\text{ }^{\circ}\text{C}$) were found in the C treatments in the N-S orientation for the daily mean and the daily maximum temperatures. In the C treatments in NE-SW orientation, the temperature increase was either less pronounced or less robust. Especially during days with a high amount of solar irradiation, C treatments showed higher air temperature recordings and a higher number in heat days (i.e. a daily maximum temperature $>30\text{ }^{\circ}\text{C}$), compared to the T treatments (Strack et al., 2021). The exceptionally hot and dry years of 2018 to 2020 and 2022 gave a foretaste on future climate scenarios, when certain temperature parameters, the frequency of extreme weather conditions and their persistence are likely to increase (Pfleiderer et al., 2019; IPCC, 2021).

Canopy surface temperatures of terraces were higher compared to C treatments during the night, as it was also observed for the bunch zone temperature recordings (Strack et al., 2021). Gaps remain in the knowledge on the effect of night temperatures on the carbon metabolism of the grapevine (Tombesi et al., 2019), however, it was shown, that lower minimum temperatures increased the expression of genes related to the secondary metabolism of the grapevine, which are linked to a higher amount of quality-determining berry components, like pigments and aroma compounds (Kliewer and Torres, 1972; Mori et al., 2005; Rienth et al., 2014). Unlike the recordings of higher daily mean and daily maximum temperatures in C vineyards, both row orientations of the terraced vineyard systems (E-W and NW-SE) showed the highest values in leaf surface temperatures, measured at the valley-facing side of the canopy (S and SW) during different major growth stages of the grapevine (Strack et al., 2021). This may be explained by less transpiration activity, induced by a higher drought stress response of the terraced treatment (Strack and Stoll, 2022) and, thus the closing of stomata (Gambetta et al., 2020a).

The absolute difference in the minimum temperatures recorded in the bunch zone between the T and the C treatments were rather small (Strack et al., 2021). It still has to be investigated, if a small, but constant increase of night temperatures ($<0.5\text{ }^{\circ}\text{C}$) affect berry quality parameters (Trought et al., 2015). A rise in night temperatures was already observed in the Rheingau wine-growing region (Schultz, 2000) and is predicted to increase (IPCC, 2013), which may lead to a higher impact on grape berry composition in T vineyards in the Rheingau wine-growing region in the future, compared to vineyards planted downslope. Nevertheless, by vineyard terracing temperature extremes and their impact on grapevine can be lowered, as shown by the reduced

effect of heat waves due to the lowered number of heat days (Strack et al., 2021) and reduced sunburn incidences (Strack and Stoll, 2021).

Climate conditions at the 50°N latitude are likely to become more demanding in future, i.e. a general increase in temperature and a rising number of heat events, which are, in part, leading to a higher atmospheric demand in evapotranspiration, in addition to a shift in precipitation patterns (Schultz and Hofmann, 2015; IPCC, 2021). Extreme weather events, both cold and heat spells, hail and heavy precipitation, among others, influence the vegetative and generative development of the grapevine and have an impact on the viticultural success parameters of quality and yield. The ability to adapt to the upcoming harshening conditions may determine the ecological and economical sustainability of (steep slope) viticulture (van Leeuwen and Darriet, 2016).

The benefits of a warmer growing condition in cool climate regions are highlighted by different authors, e.g. an improved aroma-ripening in – especially under cool climate late-ripening – grape cultivars like White Riesling, the introduction of *new* grapevine varieties into the wine-growing region's portfolio (e.g. for red wine production or white varieties originating from Mediterranean climates) and the suitability of more northerly grape-growing (Jones et al., 2005b; Sgubin et al., 2022). Thus, the varietal range is likely to change under future climate conditions (Jones et al., 2012). However, not only the direct challenges by a changing climate affects grapevine cultivation. Further issues will be the migration of biotic stressors (fungi and plant-feeding insects, which may function as a virus-carrying vector) in new habitats. To address the issues of the different abiotic and biotic stressors and to achieve the aspired halving of pesticide use in the European Union by 2030, the breeding of new grape varieties and rootstocks is one key component of adapting to future threats.

Traditional wine profiles may experience an alteration under changing environmental conditions (Trought et al., 2015) and certain wine-growing regions may exceed the range of their theoretical optimum growing season temperatures for the grapevine (Jones et al., 2005b). This may be more significantly pronounced at steep slope vineyard sites. Grapevines, however, show a high plasticity in the response to a variety of growing conditions. But to obtain the grape quality which is desired by wine-makers, actions to mitigate extreme weather conditions may have to be applied. It is of importance to viticulturists to be capable to respond to uncertain, but likely, negative climate change outcomes with economically viable tools.

The fast development of low-cost monitoring devices allows a high resolution recording of microclimate data (Spachos, 2020; Valente et al., 2022). Establishing a high-performing wireless sensor network in single vineyards or whole wine-growing regions will support viticulturists and

consultants in their decision-making process regarding future climate issues, i.e. drought risks, to apply site-specific mitigation strategies (Hofmann et al., 2022).

Short-term adaption strategies to mitigate climate change impacts on the vineyard are applied during and may not last longer than the current vegetation period of the grapevine. Usually, the overall aim is a delay of phenological major stages, e.g. bud break, flowering, as well as véraison, to postpone the berry ripening and the harvest into less hot months of the year. Santos et al. (2020) and Previtali et al. (2022) list measures to achieve a reduction in carbon assimilation of the grapevine canopy to obtain both, lower sugar and higher acidity levels at harvest, i.e. a delay in ripening (Stoll et al., 2013). However, many short-term actions require manual labour and/or investments which may lead to higher costs, especially for steep slope-viticulturists, as stated in Chapter I, or include risks in regard to yield or quality losses due to unpredictable weather events in the forthcoming growing season.

On the other hand, long-term adaption strategies affect several years of cultivation and may include further, more intensive efforts to implement. Said efforts may encompass changes in the training and trellising of the grapevines, changes in the planting density, changes in the selection of the planting material or a change in the vineyard location to cooler climate regions, i.e. a shift to higher latitudes, higher elevations, side valleys or north-exposed slopes (Santos et al., 2020). The translocation of vineyards from the flat to higher located hill-sides may require the establishing of terraces. The restoration of abandoned vineyard sites may be beneficial regarding the provision of ecosystem services, the support of biodiversity and an increase in tourist attraction. However, a potential conflict of different interests may result from the rededication of (semi-) natural sites to agricultural land, due to the massive interference in the terrain structure and the possible negative impacts on the environment. However, vineyard terraces have the potential to promote biodiversity and to increase soil organic carbon (Chen et al., 2020; Wersebeckmann et al., 2021; Wersebeckmann et al., 2022). To what extent vineyard terracing may contribute to a *carbon neutral wine production* would have to be assessed by a budgeting (Chiriaco et al., 2019; Da Pinto Silva and Da Esteves Silva, 2022). However, the observed benefits in the prevention of soil erosion and the potential reduction in pesticides due to the distinctive geometry of the terrace favour this kind of vineyard management system (Jörger et al., 2008b).

The vineyard transformation to a terrace is a long-term decision and may contribute as a tool to mitigate forthcoming challenges which are caused by a vastly changing climate.

Grapevine phenology is already affected by an increase in vegetation period temperature at the 50°N latitude and is likely to be constantly advanced in future, compared to past decades

(Duchêne and Schneider, 2005; Jones et al., 2005a; Droulia and Charalampopoulos, 2022; Ramos and Martínez de Toda, 2022). The trends in global warming already show an advanced grapevine phenology and an impact on berry maturation (Hofmann et al., 2021).

The phenological observations during the experimental period were somewhat inconsistent, but generally showed a budburst, which was a few days earlier in C treatments and a delay in flowering of T treatments over the years. Contrarily to previous vintages, bud break was approximately delayed by seven days in all of the terraced treatments in 2021, compared to the control (unpublished data; Strack et al., 2021). In all control treatments in 2021, flowering generally was two days in advance compared to the terraced treatments. This observation highlights both, the possibility to delay major phenological stages by a change in the management system, i.e. terracing; but also, the ability of the grapevine to catch up in the vegetative development compared to C. However, to mitigate the impact of such a strong biological and physical driver like temperature a set of different measures should be applied to cumulate the effects of the single actions conducted (van Leeuwen et al., 2019).

The advance in budburst in the control treatments also resulted in an advance in the shoot growth of the grapevines in C treatments (Figure 3).

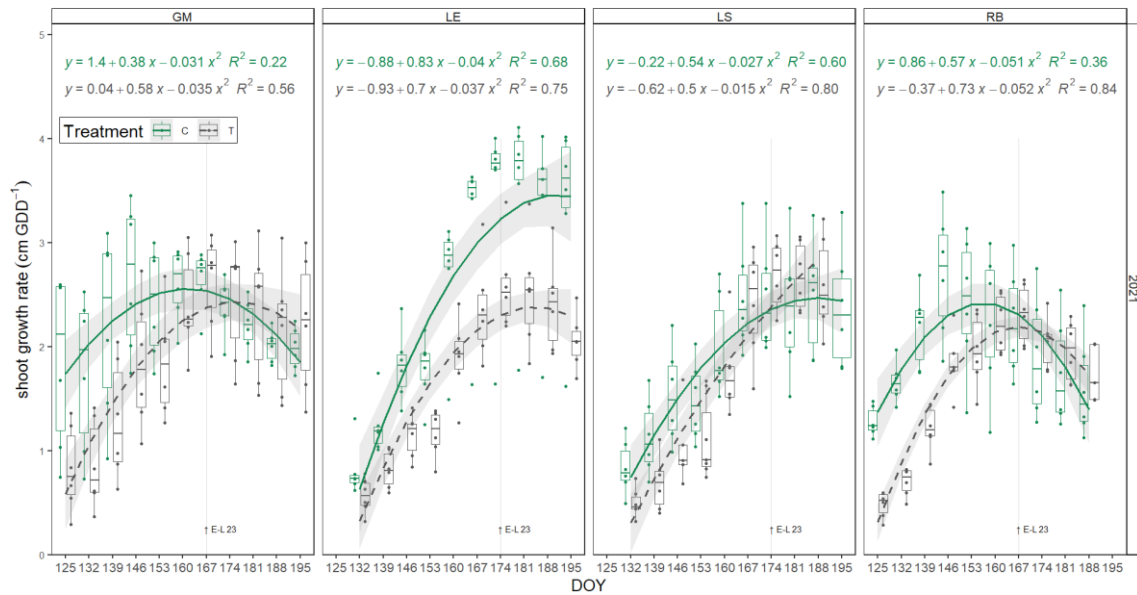


Figure 3. Shoot growth rate (cm GDD⁻¹) per measurement date (DOY) of the year 2021 for the sites GM, LE, LS and RB. Lines represent the fitted polynomial trend for each treatment (solid lines = control (C); dashed lines =terraced vineyards (T)), the boxplots indicate data variability. The flowering date of C is highlighted by an arrow and an annotation (E-L 23). Unpublished data.

The results in Figure 3 display the data of six vines, which comprise the mean of three measured shoots. It is apparent, that all of the treatments measured showed a high variability between the

grapevines in all treatments and at all sites over all measurement periods (Figure 3; Strack et al., 2021). In 2021, however, the variation in the shoot growth rate of the measured vines was lower (expressed by the data variability and the coefficient of determination in Figure 3), compared to the previous years (Strack et al., 2021). This may indicate, that less intense weather conditions in spring and early summer, i.e. less dry and less warm, may result in a more homogenous shoot growth in a vineyard. Additionally, in future years, grapevine shoot growth may be more uneven within a vineyard between bud break and berry development. This may lead further to difficulties in canopy management, since a varying shoot length of the vines require additional labour for shoot positioning and trimming or an adapted training system. Overall, the shoot growth rate showed less variability in T treatments during all observed measurement periods (Figure 3; Strack et al., 2021). However, a homogenous vine growth also depends on uniform soil conditions and an even water availability within the vineyard plot.

A fast shoot growth during the stage of early grapevine development is desired to avoid damages of pests feeding on the young shoots. On the other hand, well-developed shoots earlier in the year, i.e. an advance in phenology, is adverse, due to a potential risk increase in late-frost damage (Kartschall et al., 2015), provided that the date of the last late-frost event may not be shifted to earlier in the year (Molitor et al., 2014). Either way, no general statement about a higher rate in shoot growth of either of the two systems, based on the slope of the polynomial function, can be made.

Conspicuously, in the control vineyard of site LE, shoot growth rate reached a growth speed of about 3.5 cm GDD^{-1} (Figure 3), while the maximum growth increase at all other vineyard sites during all three measurement years from 2019 to 2021 was approximately 2.5 cm GDD^{-1} (Figure 3, Strack et al., 2021). It is possible, that an intensive removal of young shoots at the C of site LE during the mid of May 2021, led to an unbalance between the treatments and favoured the growth of the remaining shoots of the C grapevines at site LE. In fact, the leaf layer number (LLN) recorded for the SE-exposed canopy side in C at site LE in 2021 showed continuously low values over the whole vegetation period in 2021 (flowering: 0.14; véraison: 0.17; harvest-ripe: 0.12; Figure 4), which may explain the deviation in shoot growth rate compared to the previous years and the other treatments at all sites. Additionally, due to a possible higher solar exposure of the temperature sensors inside the possibly less dense bunch zone, thus higher temperature recordings, a bias in the calculated index may be possible as well.

This highlights the importance of a clear communication with the partner wineries and the sound monitoring of the experimental sites to avoid interferences in the experimental design or to be

able to detect and to explain observed variance in the data. In Strack et al. (2021), the experimental setup comprised fourteen vineyards managed by seven different wineries. Differences in management practices and production aims were tried to be excluded by a lively exchange with the partner wineries. However, a certain influence of individual management decisions cannot always be excluded, especially in research conducted under practical conditions (Henke, 2000).

But not only the manipulation of the canopy, e.g. by the means of shoot removal or defoliation, may alter the growth behaviour of a grapevine, its yield or the composition of grapevine berries by the alteration of the carbon assimilation capacity. A further limitation of this research work is the age difference of the grapevines. Especially for the vineyards planted at the sites LE and LS, the age gap (+5 and +7 years) between the grapevines may have impacted the growth parameters, due to differences in the root development and therefore the plant's accessible soil volume. However, since the number of modern terraces in the Rheingau wine-growing region is limited and, furthermore, the criteria for the selection (i.e. a close proximity and comparable planting material; Table 2) were quite narrow, some compromises had to be accepted and need to be discussed in the respective context. It can be assumed, that over time, a sufficiently established root system will eliminate the impact of a difference in age between the treatments.

Nonetheless, to what extent the grapevine age affected the data recorded for the purpose of microclimate comparison of C and T is uncertain. Older grapevines show the tendency of a higher transpiration activity compared to younger vines (Bou Nader et al., 2019) displaying higher transpiration rates (Montoro et al., 2016). Transpiration activity results in a cooling of the grapevine canopy. Under cool climate conditions (i.e. a monthly average maximum temperature range of 20 °C to 27 °C during summer months) the average cooling power of 3 m to 6 m high and sunlit grapevine canopies may be 60 W m⁻² month⁻¹ to 130 W m⁻² month⁻¹ (Yazdanseta, 2017). However, grapevine canopies in Germany may show maximum canopy heights of approximately 1.5 m only. Furthermore, transpiration varies during the day and throughout the growing season, due to the stomatal response to rising temperature and the limitation in water availability (Cuevas et al., 2006; Herrera et al., 2022).

Both treatments, regardless of row orientation, showed a leaf surface temperature increase, lasting for approximately four hours, during the time of full sun exposure of the canopy side, respectively, where a limited grapevine transpiration can be assumed (Strack et al., 2021). Based on the data provided in Strack and Stoll (2022), it can be further assumed, that stomatal conductance was limited during the summer month in all treatments at all sites, due to mild to moderate water deficits.

5.2 Vineyard terracing alters the composition of grapevine berries

The investigation of how *the change in row orientation by vineyard terracing affects the bunch zone light environment and further impacts on the cluster composition of Vitis vinifera L. cv. White Riesling*, was subject of the testing of the second hypothesis **H_{II}**, described in Chapter II (Strack and Stoll, 2021) of this work.

Three of the seven vineyard pairs were chosen to investigate the influence of a change in row orientation by vineyard terracing. Each of the three vineyard pairs share the same planting material regarding the rootstock, respectively, but the varietal clones differ. The two clones of White Riesling (198 Gm and 239 Gm) used at the site GM, are quite comparable in their viticultural and enological characteristics. Both show moderate yields, high sugar and acidity levels and the same degree of susceptibility to grey rot infection. At site LE and LS, however, the White Riesling clones of both control treatments are unknown. While in the terraced treatment of LS the White Riesling clone 198 Gm was used, the White Riesling clone chosen for the site LE was 64 Gm, which differs to the *standard* clones (198 Gm and 239 Gm) in a slightly increased yield and a higher expression in terpenes (Schmid et al., 2011).

To reduce this bias, not only the treatments (C and T), but also the row orientation and the respective canopy sides of the particular treatment × row orientation combination was covered within the evaluation of an effect on quality-determining berry parameters (Strack and Stoll, 2021).

Grapevine berry quality is highly linked to light conditions (Friedel et al., 2015; Friedel et al., 2016). Pieri et al. (2016) described a positive linear relationship with solar radiation on the composition of Merlot berries in regard to flavonol concentrations in the berry skin. The more a grapevine berry is exposed to light, the higher the accumulation of photoprotective substances, e.g. pigments, volatiles and polyphenols becomes (Martínez-Lüscher et al., 2014; Joubert et al., 2016). Depending on the grape variety, the desired wine style and matrix, a formerly desired berry protection may be detrimental to the later wine quality, if the concentrations of the named substances are too high and may result in off-flavours due the increased formation of TDN or the change in colour as observed in Riesling wines (Grebneva et al., 2022).

The effect of sunlight is difficult to separate from thermal radiation. While, for example, light favours the formation of anthocyanins in Pinot noir berries, an increase in temperature negatively impacts the anthocyanin biosynthesis (Mori et al., 2007).

The response of the grapevine regarding the composition of the berry (juice and skin), but also the leaf, showed a clear connection to solar radiation of the respective canopy side (Strack and Stoll, 2021). In 2021, when the number of sunshine hours and the temperature were generally lower during summer, compared to the previous years of 2019 and 2020, it became apparent, that the difference in the expression of the irradiation-related juice parameters was less pronounced between the respective canopy sides. The single sub-treatments (expositions) converged and were less distinct (Figure 4).

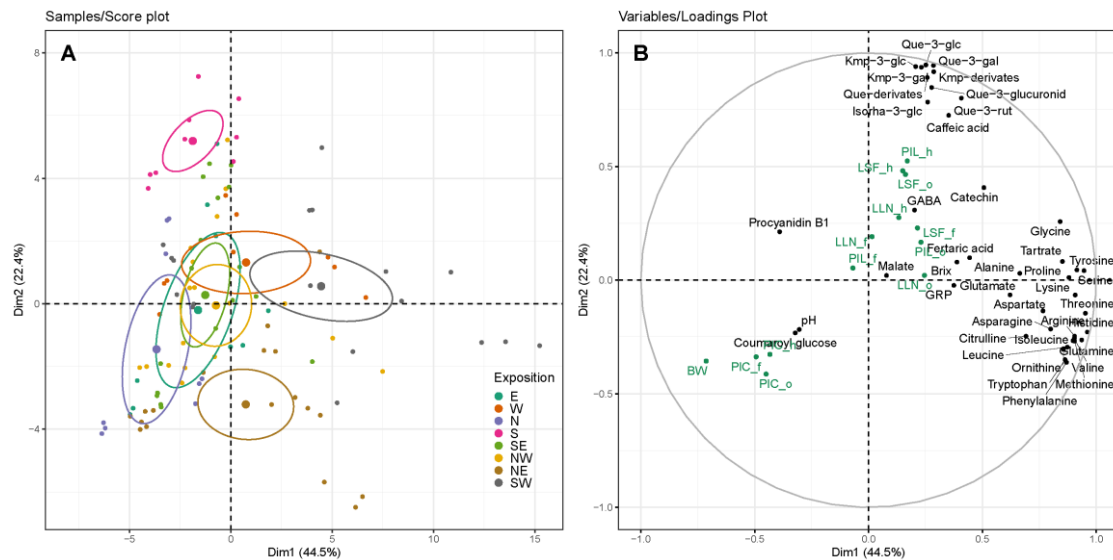


Figure 4. Principal component analysis of the years 2019 to 2021. (A) Score plot of individuals. Dots represent individual samples and dot colour indicates bunch exposition. Big dots show the mean of sample group, ellipses represent 95% confidence interval. (B) Loadings plot of variables. Black labels show analysed berry parameters (concentrations). Green labels represent supplementary quantitative data. BW = berry weight, LLN = leaf layer number, PIC = percentage of interior clusters, PIL = percentage of interior leaves (_f = flowering, _o = onset of ripening, _h = harvest-ripe), LSF = bunch zone radiation energy interception, GABA = γ -aminobutyric acid, gal = galactoside, glc = glucoside, rut = rutinoid, GRP = grape reaction product, Kmp = kaempferol, Que = quercetin.

Especially the canopy sides of the C treatments (SE, NW, E and to a less extend W) showed similar juice and berry parameters (Figure 4). However, the canopy sides of the terraced vineyards were still distinguishable from each other.

This confirms that the microclimate, more precisely the conditions for the development of a distinctive microclimate, determines the composition of the grapevine berry. In Strack et al. (2021) the difference in bunch zone irradiation for different row orientations and canopy sides was described. In general, ‘Exposition’ and ‘Vintage’ were the factors which mostly determined the analysed berry parameters (Figure 4, Table 3).

Table 3. Results of the multifactorial analysis of variance (ANOVA) for the difference in the response of different quality-determining berry parameters per gram berry weight to the factors ‘Exposition’, ‘Vintage’, ‘Site’ and the interaction between ‘Site’ and ‘Treatment’.

Variable:	Total soluble solids	Total acidity	Total amino acids	Total phenolics
Factor:	(°Brix g ⁻¹)	(g L ⁻¹ g ⁻¹)	(mg L ⁻¹ g ⁻¹)	(mg g ⁻¹)
Exposition	***	***	***	***
Vintage	***	***	***	***
Site	n.s.	n.s.	n.s.	n.s.
Treatment:Site	n.s.	n.s.	n.s.	n.s.

While during anthesis (mid-June) a higher cumulated amount of solar energy was received by the bunch zone of the control treatments, the incidence of sunlight increased more and more with the progressing season in the terraced treatments of both row orientations (E-W and NW-SE), but remained rather static in the control treatments (N-S and NE-SW). The valley-facing canopy sides of the terraced treatments contributed to the total light energy interception the highest, while the hill-facing side of the canopy received constantly low sunlight into the bunch zone (Strack et al., 2021).

A homogenous, high quality grape yield is desired by viticulturists. However, due to spatial heterogeneity in the vineyard soil and the influence of topography, the potential of an overall high juice quality is usually diminished by the high variability in the level of ripening of the crop (Kontoudakis et al., 2011; Santesteban, 2019).

Selective harvesting may increase the net benefit of a winery by separating different berry quality levels (Bramley et al., 2011). However, a targeted blend of clusters showing different grape ripening levels may also be beneficial to preserve juice acidity and to lower alcohol content (Guerrini et al., 2018), which may be desirable due to rising climate risk factors (Droulia and Charalampopoulos, 2021). Attention should be paid to a potential increase in bitterness, if the ripening levels differ too much (Guerrini et al., 2018).

In Chapter II (Strack and Stoll, 2021), differences in grape quality were discussed and the relation to solar exposure was highlighted. Regarding a potential risk in an increase of bitterness-enhancing substances, the concentrations of flavanols and hydroxycinnamates did not differ between the respective canopy sides in 2019 and 2020, under high sun irradiation and high temperatures. High sun-exposed canopy sides of the T treatments (S and SW) were significantly higher in flavonols (Strack and Stoll, 2021). In 2021, no significant differences were found in the total phenolic concentrations of C vineyards (E compared to W and SE compared to NW), whereas highly significant results were found between the canopy sides of the terraced treatments.

Consequently, vineyard terracing affects quality-determining berry parameters by the amount of light separation. The wall-like shielding of the grapevine canopy leads to a clear distinction between the two canopy sides of a treatment and results in a heterogenous crop quality. However, the potential overall quality of a terraced vineyard showed to be capable to reach high quality standards of the fruit composition. Ganter and Männle (2008) mentioned the benefits of vineyard terracing on the colour of red wines, but also report about a shift in the aroma profile of Riesling wines from fruity to green, in some cases. Therefore, site-specific means should be applied to achieve the desired fruit quality of the cultivar and the aspired quality and aroma profile of the wine.

By using selective harvesting, terraced vineyards may provide further levers to enologists to improve the wine-making process, especially under consideration of climate change impacts on the fruit quality. Row orientation changes by vineyard terracing showed to be a useful tool to prevent grapes from sunburn, thus to reduce quality and yield losses to the wine grower. Terraced vineyards are further capable of providing high-quality grape yields for premium wine production.

5.3 Vineyard terracing comprises the chance of precipitation retention, but bares the risk of drought stress in the early years of grapevine establishment

The third hypothesis H_{III} raised in this work, that *vineyard terracing improves the retention of precipitation, results in a higher water availability for the grapevine, thus leads to a lower drought stress response* had to be partially rejected.

Vineyard terracing was able to increase water retention (Strack and Stoll, 2022), due to a presumably reduced infiltration speed, less surface runoff of precipitation and a possible higher storage of the water due to a higher soil volume (Tarolli et al., 2014). However, it can be assumed, that the competition to the embankment cover crop and its potential evaporation was high (Lü et al., 2009), which led to an enhanced drought stress response of the – not finally adapted – grapevines planted at the platform edge of the terraced vineyards (Strack and Stoll, 2022).

Celette et al. (2008) pointed out the benefit of an improved replenishment of soil water by the use of cover cropping, due to better infiltration and less runoff of winter precipitation. However, accompanying vegetation emerges earlier than the grapevine, thus it is likely, that a large share of the retained water is consumed by the shrubs and grasses before the vegetative development of the grapevine has even started. Depending on the soil conditions, e.g. the soil depth, this may result in a high competition to water once the grapevine develops in growth, leading to a drought stress impact (Celette et al., 2005; Celette et al., 2008).

A general definition of drought stress tolerance in grapevines may be: the ability to maintain a sufficient performance under water deficient conditions without the detrimental effects on grapevine health as well as fruit quality and a satisfactory yield. Gambetta et al. (2020a) reviewed the grapevine's physiological mechanisms in response to drought and a range of methodological approaches to determine a specific variety's drought tolerance.

Severity classes of pre-dawn leaf water potential and its impact on grapevine physiology are described by Carbonneau (2006) and Deloire et al. (2016), respectively, and range from no water deficit (0 MPa to -0.2 MPa), mild water deficit (-0.2 to -0.4), moderate water deficit (-0.4 MPa to -0.6 MPa) to severe water deficit (<-0.6 MPa). A mild to moderate drought stress impact (-0.3 to -0.5 MPa) on the grapevine is seen as positive for the later wine, since it enhances the contents of valuable secondary metabolites (Savoi et al., 2020). Mild stress symptoms in grapevine arise from values of the fraction of transpirable soil water (FTSW) of approximately <40 % (Lebon et al., 2003) and do affect stomatal behaviour by lowering the relative transpiration (Hofmann et al., 2014) and stomatal conductance (Lebon et al., 2003) of the grapevine. This segues into the reduction or cessation of vegetative growth parameters (FTSW approximately <20 %), e.g. lateral leaf area (Lebon et al., 2001; Pellegrino et al., 2005).

The actual ability of the grapevine to thrive under a high-competitive environment depends on the adaptation ability of a genotype to the existing soil and microclimate conditions.

Rooting depth and thereby the potential increase in water availability plays an important role in the plant's resilience towards dry periods (Alsina et al., 2011). The site-specific selection of suitable rootstocks is therefore an important tool to improve the grapevine's performance in a high-competitive environment, like cover-cropped vineyard terraces. In general, grapevines planted at steep slope vineyards with shallow soils and low field capacity need more time to fully develop their yield and quality potential, compared to vineyards in the flat.

Ganter and Männle (2008) described the experience of wine-growers cultivating grapevines on modern terraces, which suggests a better establishment of the grapevines eight to ten years after planting, compared to grapevines planted downslope. Additionally, they indicate that young vines planted on terraces tend to show an increased drought stress, which was induced or enhanced by the competition to permanent cover crop (Ganter and Männle, 2008). This observation coincides with the results of Strack and Stoll (2022), presented in Chapter IV. All vineyards showed mild to moderate or even severe responses to water deficit during the dry summer of 2019 and 2020. In Strack and Stoll (2022), the observed vineyards showed a rather low field capacity, typical for steep slope sites.

The success of grapevine cultivation on steep slopes under future climate scenarios was subject of recent research. Hofmann et al. (2022) identified already challenged steep slope vineyards in regard to water deficit and projected an increase in drought risk of such until the end of the current century. This is in accordance to the predicted increase in an atmospheric water demand under harshening climate conditions (Clarke et al., 2022). Considering these findings, viable solutions have to be found to maintain viticulture threatened by climate change.

Technical solutions to increase water supply to the grapevine are discussed in Strack and Stoll (2022). However, since fresh water resources will be limited further in future and oftentimes irrigation infrastructure is not available, the main goal should be the improvement of the vineyard system itself – not only in regard to water deficiency.

Despite the risk of enhancing drought stress due to an additional water consumption, vineyard terraces proved to promote biodiversity (Wersebeckmann et al., 2021; Wersebeckmann et al., 2022) and are capable to provide further eco-system services, e.g. erosion prevention (Wei et al., 2016).

Several erosion events could be observed during heavy precipitation events in almost every recent year, especially during those which displayed particular dry summers (e.g. 2018, 2019, 2020 and 2022). While no quantitative records were collected at the Geisenheimer Rothenberg, the visual documentation of the two different management systems of C and T at the experimental site showed significant differences in their capability of erosion prevention, in particular, the conservation of valuable vineyard soil, its structure and nutrients (Figure 5).



Figure 5. Impact of a heavy precipitation event (25 mm in one hour) on the vineyard soil after a hot and dry period on the 24th of June 2022 at the Geisenheimer Rothenberg. The downslope planted vineyard showed an enormous loss of soil (left), while no surface soil erosion could be observed in the terraced treatment (right).

However, an improved soil management (e.g. a reduction in tillage or the maintenance of cover

crop) in the control plot would have significantly reduced the amount of soil particle movement (Biddoccu et al., 2020; Pijl et al., 2020). On the one hand, the choice of cover crop management options is limited under low annual rainfall, since drought stress risk increases (Novara et al., 2021). On the other hand, an cover crop management which is applied in accordance with the soil field capacity and the prevailing weather conditions, e.g. a partial permanent grass cover may result in the benefit of soil conservation without the risk of an increased yield loss (Delpuech and Metay, 2018).

Modern vineyard terracing requires a biological stabilization of the embankment, since the reinforcement by dry-stone walls is not sustainable in economical terms. Moreover, bare soil or sporadically grown ground cover by natural vegetation may lead to soil loss.

In Strack and Stoll (2022) the soil water dynamics of terraced vineyards was investigated by measuring the soil water content in the inter-vine space at the edge of the terrace platform. Due to the necessity of tractor traffic it was not possible to apply the used measuring technique in the middle or the back end of the platform. Therefore, no statement about the total water storage capacity of the modern terrace system could be made.

Michalsky (1976) mentioned the benefits of vineyard terracing regarding a reduction in surface runoff and the increased infiltration of precipitation. However, the disadvantage of an increased evapotranspiration by a higher exposure of the embankment soil and the cover crops was also contrasted. The review of mainly Romanian literature by Michalsky (1976) suggests a higher retention of soil moisture in older terraces with an increased platform size. This highlights the importance in lowering embankment heights to reduce water loss by an improved ratio of platform width to embankment height (Lü et al., 2009). However, this may result in a loss of cultivation area for the grapevines (Koblet and Faust, 1992).

According to the reviewed literature, a zoning of soil water content on terraces is possible (Michalsky, 1976). The highest content of soil water can be found in the middle of the terrace platform, probably due to the highest soil depth and the shading by the grapevine canopy. Suggested measures to improve soil water conservation are, together with the characteristics of the terrace (slope and width of the platform and the embankment, the distance of the vines to the edge of the platform and the age of the terrace), a site-adapted soil cultivation, the application of organic fertilizers or compost and the adequate selection of the training system (Michalsky, 1976).

Ultimately, this highlights the importance of an individual, site-specific cultivation strategy of the vineyard terrace to achieve the aspired yield and grape quality for wine-making purpose.

5.4 Concluding remarks

The use of terraces for the purpose of land cultivation has been proved over centuries on different soil types, climate conditions and crops. However, in our modern times the production aims, demographic structures, chances but also challenges completely differ from those of past times. Especially steep slope viticulture is threatened by the highly competitive wine market, due to the increased production costs and a comparatively low yield as well as the projected intensification of climate conditions, which may be detrimental for grape quality.

Vineyard terracing demonstrated to be a capable method of reducing production costs in steep slope viticulture, to be a viable tool to mitigate weather extremes and to produce healthy grapes suitable for high-quality wine production.

The inherent row orientation changes in vineyard terracing alter the light climate conditions and favour berry ripening processes, in particular, during the late summer and early autumn months. Concomitantly, grape clusters are better protected against sunburn damage due to the constant radiation, thus the acclimatization of the highly exposed, valley-facing berries. This results in an altered profile of secondary metabolites, e.g. amino acids and polyphenols, and further provides an enological tool of yield diversification by the mean of a selective harvest.

The results obtained from the hot and dry years present during the experimental period indicate, that terraced vineyards are able to improve canopy microclimate by lowering inner-canopy temperature parameters. However, night temperatures tended to be slightly increased in terraced vineyards compared to the control sites. The number of hot and dry periods are likely to increase in the future. These observations imply, that vineyard terracing may be a strategy to alter the vineyard microclimate in order to reduce the detrimental impact of rising day temperatures.

Establishing grapevines at steep slopes is challenging, since soil conditions are usually less favourable due to shallow soils with low water holding capacity. Terraced vineyards showed a high drought stress response during summer, but were able to retain a higher amount of precipitation during winter. Older, better established grapevines, however, showed less susceptibility to drought compared to younger vines. Regardless of the management system, solutions must be developed to sufficiently provide the grapevine with water.

In short, the construction of vineyard terraces is an economical and an ecological viable method to maintain highly valuable steep slope vineyard sites. The system offers interesting possibilities to integrate the landscape's multifunctionality by applying ecosystem services, producing high-quality grapes and to match the challenges of future growing conditions.

References

- Alsina, M.M., Smart, D.R., Bauerle, T., Herralde, F. de, Biel, C., Stockert, C., Negron, C., Save, R., 2011. Seasonal changes of whole root system conductance by a drought-tolerant grape root system. *Journal of experimental botany* 62, 99–109. <https://doi.org/10.1093/jxb/erq247>.
- Alston, J.M., Sambucci, O., 2019. Grapes in the World Economy, in: Cantu, D., Walker, M.A. (Eds.), *The Grape Genome*, vol. 38. Springer International Publishing, Cham, pp. 1–24.
- Arnáez, J., Lana-Renault, N., Lasanta, T., Ruiz-Flaño, P., Castroviejo, J., 2015. Effects of farming terraces on hydrological and geomorphological processes. A review. *CATENA* 128, 122–134. <https://doi.org/10.1016/j.catena.2015.01.021>.
- Assandri, G., Bogliani, G., Pedrini, P., Brambilla, M., 2016. Diversity in the monotony? Habitat traits and management practices shape avian communities in intensive vineyards. *Agriculture, Ecosystems & Environment* 223, 250–260. <https://doi.org/10.1016/j.agee.2016.03.014>.
- Bagagiolo, G., Biddoccu, M., Rabino, D., Cavallo, E., 2018. Effects of rows arrangement, soil management, and rainfall characteristics on water and soil losses in Italian sloping vineyards. *Environmental research* 166, 690–704. <https://doi.org/10.1016/j.envres.2018.06.048>.
- Becker, A., Dietrich, J., Fröba, N., Huber, G., Kohl, E., Kranich, H., Krolla, A., Michelfelder, U., Plewe, W., Reinhold, C., Sauer, E., Sauer, N., Schroers, J.-O., Schwingenschlögl, P., Walg, O., Wechsler, B., Zänglein, M., 2017. *Weinbau und Kellerwirtschaft: Daten für die Betriebsplanung*, 16th ed. KTBL, Darmstadt.
- Benz, F., 2022. *Erfahrungen zu Nachpflanzungen in Querterrassenweinbergen*. Personal communication. Telephone and e-Mail. Bottenau and Geisenheim.
- Biddoccu, M., Guzmán, G., Capello, G., Thielke, T., Strauss, P., Winter, S., Zaller, J.G., Nicolai, A., Cluzeau, D., Popescu, D., Bunea, C., Hoble, A., Cavallo, E., Gómez, J.A., 2020. Evaluation of soil erosion risk and identification of soil cover and management factor (C) for RUSLE in European vineyards with different soil management. *International Soil and Water Conservation Research* 8, 337–353. <https://doi.org/10.1016/j.iswcr.2020.07.003>.
- Böhme, A., 2003. *Umweltgerechte Technik für den Steillagenweinbau*. Dissertation. KTBL-Schriften-Vertrieb im Landwirtschaftsverlag, Darmstadt.
- Bou Nader, K., Stoll, M., Rauhut, D., Patz, C.-D., Jung, R., Loehnertz, O., Schultz, H.R., Hilbert, G., Renaud, C., Roby, J.-P., Delrot, S., Gomès, E., 2019. Impact of grapevine age on water status and productivity of *Vitis vinifera* L. cv. Riesling. *European Journal of Agronomy* 104, 1–12. <https://doi.org/10.1016/j.eja.2018.12.009>.
- Bramley, R.G.V., Ouzman, J., Thornton, C., 2011. Selective harvesting is a feasible and profitable strategy even when grape and wine production is geared towards large fermentation volumes. *Australian Journal of Grape and Wine Research* 17, 298–305. <https://doi.org/10.1111/j.1755-0238.2011.00151.x>.
- Buesa, I., Caccavello, G., Merli, M.C., Poni, S., Intrigliolo, D.S., 2017. East-west vineyard trellis system orientation improves water use efficiency and productivity of potted grapevines. *Acta Hort.* 6, 35–42. <https://doi.org/10.17660/ActaHortic.2017.1188.5>.
- Camera, C., Djuma, H., Bruggeman, A., Zoumides, C., Eliades, M., Charalambous, K., Abate,

- D., Faka, M., 2018. Quantifying the effectiveness of mountain terraces on soil erosion protection with sediment traps and dry-stone wall laser scans. *CATENA* 171, 251–264. <https://doi.org/10.1016/j.catena.2018.07.017>.
- Campos, I., Neale, C., Calera, A., 2017. Is row orientation a determinant factor for radiation interception in row vineyards? *Australian Journal of Grape and Wine Research* 23, 77–86. <https://doi.org/10.1111/ajgw.12246>.
- Carbonneau, A., 2006. Aspects qualitatifs, in: *Traité d'irrigation*, 2nd ed. Lavoisier, Cachan, pp. 297–320.
- Celette, F., Gaudin, R., Gary, C., 2008. Spatial and temporal changes to the water regime of a Mediterranean vineyard due to the adoption of cover cropping. *European Journal of Agronomy* 29, 153–162. <https://doi.org/10.1016/j.eja.2008.04.007>.
- Celette, F., Wery, J., Chantelot, E., Celette, J., Gary, C., 2005. Belowground Interactions in a Vine (*Vitis vinifera* L.)-tall Fescue (*Festuca arundinacea* Shreb.) Intercropping System: Water Relations and Growth. *Plant and Soil* 276, 205–217. <https://doi.org/10.1007/s11104-005-4415-5>.
- Chahine, A., Dupont, S., Sinfort, C., Brunet, Y., 2014. Wind-Flow Dynamics Over a Vineyard. *Boundary-Layer Meteorol* 151, 557–577. <https://doi.org/10.1007/s10546-013-9900-4>.
- Chen, D., Wei, W., Daryanto, S., Tarolli, P., 2020. Does terracing enhance soil organic carbon sequestration? A national-scale data analysis in China. *The Science of the total environment* 721, 137751. <https://doi.org/10.1016/j.scitotenv.2020.137751>.
- Chiriaco, M.V., Belli, C., Chiti, T., Trotta, C., Sabbatini, S., 2019. The potential carbon neutrality of sustainable viticulture showed through a comprehensive assessment of the greenhouse gas (GHG) budget of wine production. *Journal of Cleaner Production* 225, 435–450. <https://doi.org/10.1016/j.jclepro.2019.03.192>.
- Clarke, H., Nolan, R.H., Dios, V.R. de, Bradstock, R., Griebel, A., Khanal, S., Boer, M.M., 2022. Forest fire threatens global carbon sinks and population centres under rising atmospheric water demand. *Nature communications* 13, 7161. <https://doi.org/10.1038/s41467-022-34966-3>.
- Cots-Folch, R., Martínez-Casasnovas, J.A., Ramos, M.C., 2006. Land terracing for new vineyard plantations in the north-eastern Spanish Mediterranean region: Landscape effects of the EU Council Regulation policy for vineyards' restructuring. *Agriculture, Ecosystems & Environment* 115, 88–96. <https://doi.org/10.1016/j.agee.2005.11.030>.
- Crosta, G.B., Dal Negro, P., Frattini, P., 2003. Soil slips and debris flows on terraced slopes. *Nat. Hazards Earth Syst. Sci.* 3, 31–42. <https://doi.org/10.5194/nhess-3-31-2003>.
- Cucchiario, S., Paliaga, G., Fallu, D.J., Pears, B.R., Walsh, K., Zhao, P., van Oost, K., Snape, L., Lang, A., Brown, A.G., Tarolli, P., 2021. Volume estimation of soil stored in agricultural terrace systems: A geomorphometric approach. *CATENA* 207, 105687. <https://doi.org/10.1016/j.catena.2021.105687>.
- Cuevas, E., Baeza, P., Lissarrague, J.R., 2006. Variation in stomatal behaviour and gas exchange between mid-morning and mid-afternoon of north–south oriented grapevines (*Vitis vinifera* L. cv. Tempranillo) at different levels of soil water availability. *Scientia Horticulturae* 108,

- 173–180. <https://doi.org/10.1016/j.scienta.2006.01.027>.
- Da Pinto Silva, L., Da Esteves Silva, J.C., 2022. Evaluation of the carbon footprint of the life cycle of wine production: A review. *Cleaner and Circular Bioeconomy* 2, 100021. <https://doi.org/10.1016/j.clcb.2022.100021>.
- Deloire, A., Vaudour, E., Carey, V.A., Bonnardot, V., van Leeuwen, C., 2016. Grapevine responses to terroir: a global approach. *OENO One* 39, 149. <https://doi.org/10.20870/oeno-one.2005.39.4.888>.
- Delpuech, X., Metay, A., 2018. Adapting cover crop soil coverage to soil depth to limit competition for water in a Mediterranean vineyard. *European Journal of Agronomy* 97, 60–69. <https://doi.org/10.1016/j.eja.2018.04.013>.
- Droulia, F., Charalampopoulos, I., 2021. Future Climate Change Impacts on European Viticulture: A Review on Recent Scientific Advances. *Atmosphere* 12, 495. <https://doi.org/10.3390/atmos12040495>.
- Droulia, F., Charalampopoulos, I., 2022. A Review on the Observed Climate Change in Europe and Its Impacts on Viticulture. *Atmosphere* 13, 837. <https://doi.org/10.3390/atmos13050837>.
- Dry, P., 2009. Bunch exposure management, Adelaide. <https://www.mvwi.com.au/factsheets/others/bunch-exposure-management/> (accessed 5 December 2022).
- Duchêne, E., Schneider, C., 2005. Grapevine and climatic changes: a glance at the situation in Alsace. *Agron. Sustain. Dev.* 25, 93–99. <https://doi.org/10.1051/agro:2004057>.
- Evans, R.G., 2000. The art of protecting grapevines low temperature injury, in: Proceedings of the ASEV 50th Anniversary Annual Meeting: Cold Hardiness Workshop, Seattle, WA. June, 19th-23rd 2000, pp. 60–72.
- Friedel, M., 2018. Microclimatic influences on grape quality. Doctoral dissertation. Gießen.
- Friedel, M., Frotscher, J., Nitsch, M., Hofmann, M., Bogs, J., Stoll, M., Dietrich, H., 2016. Light promotes expression of monoterpene and flavonol metabolic genes and enhances flavour of winegrape berries (*Vitis vinifera* L. cv. Riesling). *Australian Journal of Grape and Wine Research* 22, 409–421. <https://doi.org/10.1111/ajgw.12229>.
- Friedel, M., Stoll, M., Patz, C.D., Will, F., Dietrich, H., 2015. Impact of light exposure on fruit composition of white 'Riesling' grape berries (*Vitis vinifera* L.). 107-116 Pages / VITIS - Journal of Grapevine Research, Vol. 54 No. 3 (2015): Vitis. <https://doi.org/10.5073/vitis.2015.54.107-116>.
- Friedel, M., Weber, M., Zacharias, J., Patz, C.-D., Stoll, M., 2012. Impact of microclimate on berry quality parameters of white Riesling (*Vitis vinifera* L.), in: Proceedings of the IXE Congrès International des Terroirs vitivinicoles. IXE International Terroirs Congress 2012, Dijon and Reims (France). 25.-29.06.2012, pp. 8–11.
- Galleguillos, M., Jacob, F., Prévot, L., French, A., Lagacherie, P., 2011. Comparison of two temperature differencing methods to estimate daily evapotranspiration over a Mediterranean vineyard watershed from ASTER data. *Remote Sensing of Environment* 115, 1326–1340. <https://doi.org/10.1016/j.rse.2011.01.013>.

- Gambetta, G.A., Herrera, J.C., Dayer, S., Feng, Q., Hochberg, U., Castellarin, S.D., 2020a. The physiology of drought stress in grapevine: towards an integrative definition of drought tolerance. *Journal of experimental botany* 71, 4658–4676. <https://doi.org/10.1093/jxb/eraa245>.
- Gambetta, J.M., Holzapfel, B.P., Stoll, M., Friedel, M., 2020b. Sunburn in Grapes: A Review. *Frontiers in plant science* 11, 604691. <https://doi.org/10.3389/fpls.2020.604691>.
- Ganter, B., Männle, F., 2008. Kulturführung in der Kleinterrassenbewirtschaftung, in: Staatliches Weinbauinstitut Freiburg (Ed.), *Mechanisierung im Querterrassen-Weinbau: FDW-Berichterstattung 2006/2007*. KTBL-Titel: I/09. Freiburg, pp. 43–49.
- Grebneva, Y., Bilogrevic, E., Rauhut, D., Herderich, M.J., Hixson, J.L., 2022. Impacts of photosensitive bunch zone shading on the volatile composition and sensory attributes for *Vitis vinifera* L. cv. Riesling. *OENO One* 56, 297–311. <https://doi.org/10.20870/oenone.2022.56.3.5364>.
- Grifoni, D., Carreras, G., Zipoli, G., Sabatini, F., Dalla Marta, A., Orlandini, S., 2008. Row orientation effect on UV-B, UV-A and PAR solar irradiation components in vineyards at Tuscany, Italy. *International journal of biometeorology* 52, 755–763. <https://doi.org/10.1007/s00484-008-0168-1>.
- Guerrini, L., Masella, P., Angeloni, G., Calamai, L., Spinelli, S., Di Blasi, S., Parenti, A., 2018. Harvest of Sangiovese grapes: the influence of material other than grape and unripe berries on wine quality. *Eur Food Res Technol* 244, 1487–1496. <https://doi.org/10.1007/s00217-018-3063-y>.
- Hafner, P., Sinn, F., 2015. *Neuanlagen im Steillagenweinbau: Anleitung zur maschinengerechten Erstellung von Neuanlagen im Weinbau*, Auer (Bozen, IT).
- Heilman, J.L., McInnes, K., Savage, M.J., Gesch, R.W., Lascano, R.J., 1994. Soil and canopy energy balances in a west Texas vineyard. *Agricultural and Forest Meteorology* 71, 99–114. [https://doi.org/10.1016/0168-1923\(94\)90102-3](https://doi.org/10.1016/0168-1923(94)90102-3).
- Hellman, E.W., 2003. *Grapevine structure and function*. Oregon Viticulture. Hellman, EW (Ed.). Oregon State University Press, Corvallis, 5–19.
- Henke, C.R., 2000. Making a Place for Science. *Soc Stud Sci* 30, 483–511. <https://doi.org/10.1177/030631200030004001>.
- Herrera, J.C., Calderan, A., Gambetta, G.A., Peterlunger, E., Forneck, A., Sivilotti, P., Cochard, H., Hochberg, U., 2022. Stomatal responses in grapevine become increasingly more tolerant to low water potentials throughout the growing season. *The Plant journal for cell and molecular biology* 109, 804–815. <https://doi.org/10.1111/tpj.15591>.
- Hofmann, M., Hübener Heike, Stoll, M., 2021. Was macht der Klimawandel mit unserem Wetter? Eine weinbauliche Auslese, in: Stoll, M., Schultz, H.-R. (Eds.), *Deutsches Weinbaujahrbuch 2022*. Verlag Eugen Ulmer, Stuttgart, pp. 64–77.
- Hofmann, M., Lux, R., Schultz, H.R., 2014. Constructing a framework for risk analyses of climate change effects on the water budget of differently sloped vineyards with a numeric simulation using the Monte Carlo method coupled to a water balance model. *Frontiers in plant science* 5, 645. <https://doi.org/10.3389/fpls.2014.00645>.

- Hofmann, M., Volosciuk, C., Dubrovský, M., Maraun, D., Schultz, H.R., 2022. Downscaling of climate change scenarios for a high-resolution, site-specific assessment of drought stress risk for two viticultural regions with heterogeneous landscapes. *Earth Syst. Dynam.* 13, 911–934. <https://doi.org/10.5194/esd-13-911-2022>.
- Hoppmann, D., Schaller, K., Stoll, M., 2017. *Terroir: Wetter, Klima und Boden im Weinbau*, 2nd ed. Ulmer Verlag, Stuttgart (Hohenheim), 372 pp.
- Horney, G., 1975. Das Häufigkeitsspektrum der Windrichtungen in ökologischer Sicht (dargestellt an den besonderen Verhältnissen im Rheingau). *Berichte des deutschen Wetterdienstes*.
- Hunter, J., Volschenk, C.G., Zorer, R., 2016. Vineyard row orientation of *Vitis vinifera* L. cv. Shiraz/101-14 Mgt: Climatic profiles and vine physiological status. *Agricultural and Forest Meteorology* 228-229, 104–119. <https://doi.org/10.1016/j.agrformet.2016.06.013>.
- Hunter, J.J., Volschenk, C.G., 2017. Chemical composition and sensory properties of non-wooded and wooded Shiraz (*Vitis vinifera* L.) wine as affected by vineyard row orientation and grape ripeness level. *Journal of the science of food and agriculture* 98, 2689–2704. <https://doi.org/10.1002/jsfa.8763>.
- Hunter, J.J., Volschenk, C.G., Booyse, M., 2017. Vineyard row orientation and grape ripeness level effects on vegetative and reproductive growth characteristics of *Vitis vinifera* L. cv. Shiraz/101-14 Mgt. *European Journal of Agronomy* 84, 47–57. <https://doi.org/10.1016/j.eja.2016.12.004>.
- Hunter, J.J., Volschenk, C.G., Mania, E., Castro, A.V., Booyse, M., Guidoni, S., Pisciotto, A., Di Lorenzo, R., Novello, V., Zorer, R., 2021. Grapevine row orientation mediated temporal and cumulative microclimatic effects on grape berry temperature and composition. *Agricultural and Forest Meteorology* 310, 108660. <https://doi.org/10.1016/j.agrformet.2021.108660>.
- Hunter, J.K., Tarricone, L., Volschenk, C., Giacalone, C., Melo, M.S., Zorer, R., 2020. Grapevine physiological response to row orientation-induced spatial radiation and microclimate changes. *OENO One* 54, 411–433. <https://doi.org/10.20870/oeno-one.2020.54.2.3100>.
- Intrieri, C., Poni, S., Rebucci, B., Magnanini, E., 1998. Row orientation effects on whole-canopy gas exchange of potted and field-grown grapevines. *VITIS* 4, 147–154. <https://doi.org/10.5073/vitis.1998.37.147-154>.
- Intrieri, C., Silvestroni, O., Rebucci, B., Poni, S., Filippetti, I., 1999. The effects of row orientation on growth, yield and dry matter partitioning in "Sangiovese" vines trained to free cordon and spur-pruned cordon, in: *Proceedings of the 11th Meeting: Study group for vine training systems*. GESCO - 11th Meeting, Marsala, Italy. 06.-12.06.1999, pp. 254–262.
- IPCC (Ed.), 2013. *Climate change 2013: The physical science basis: part of the Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge (UK) and New York (NY, USA), 203 pp.
- IPCC, 2021. *Climate Change 2021: The Physical Science Basis: Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, In press.
- Jagoutz, H., 2004. Der Einfluss des Windes, in: Löhnertz, O., Hoppmann, D., Emde, K., Friedrich,

- K., Schmanke, M., Zimmer, T. (Eds.), Die Standortkartierung der hessischen Weinbaugebiete, 2nd ed. Wiesbaden, pp. 45–57.
- Job, H., Murphy, A., 2006. Germany's Mosel Valley: Can Tourism Help Preserve Its Cultural Heritage? *Tourism Review International* 9, 333–347. <https://doi.org/10.3727/154427206776330526>.
- Jones, G.V., Duchêne, E., Tomasi, D., Yuste, J., Braslavska, O., Schultz, H., Martinez, C., Boso, S., Langellier, F., Perruchot, C., Guimberteau, G., 2005a. Changes in European winegrape phenology and relationships with climate, in: *Proceedings GESCO 2005: Vol. I. XIV International GESCO Viticulture Congress, Geisenheim. 23.-27.08.2005. Geisenheim*, pp. 54–61.
- Jones, G.V., Reid, R., Vilks, A., 2012. Climate, Grapes, and Wine: Structure and Suitability in a Variable and Changing Climate, in: Dougherty, P.H. (Ed.), *The Geography of Wine*, vol. 15. Springer Netherlands, Dordrecht, pp. 109–133.
- Jones, G.V., White, M.A., Cooper, O.R., Storchmann, K., 2005b. Climate Change and Global Wine Quality. *Climatic Change* 73, 319–343. <https://doi.org/10.1007/s10584-005-4704-2>.
- Jörger, V., Schrieck, P., Huber, G., Littek, T., 2008a. Arbeitstechniken der Kleinterrassenbewirtschaftung mit arbeits-, betriebswirtschaftlichen und pflanzenbaulichen Daten, in: Achilles, A. (Ed.), *Anlage und Bewirtschaftung von Weinbergterrassen. KTBL, Darmstadt*, pp. 51–105.
- Jörger, V., Schrieck, P., Huber, G., Littek, T., 2008b. Mechanisierung im Querterrassen-Weinbau: FDW-Berichterstattung 2006/2007. KTBL-Titel: I/09 ATW-Nr.: 149, Freiburg.
- Joubert, C., Young, P.R., Eyéghé-Bickong, H.A., Vivier, M.A., 2016. Field-Grown Grapevine Berries Use Carotenoids and the Associated Xanthophyll Cycles to Acclimate to UV Exposure Differentially in High and Low Light (Shade) Conditions. *Frontiers in plant science* 7, 786. <https://doi.org/10.3389/fpls.2016.00786>.
- Kartschall, T., Wodinski, M., Bloh, W. von, Oesterle, H., Rachimow, C., Hoppmann, D., 2015. Changes in phenology and frost risks of *Vitis vinifera* (cv Riesling). *metz* 24, 189–200. <https://doi.org/10.1127/metz/2015/0534>.
- Keller, M., 2020. *The science of grapevines*. Academic Press, an imprint of Elsevier, Amsterdam, 541 pp.
- Kliewer, W.M., Torres, R.E., 1972. Effect of Controlled Day and Night Temperatures on Grape Coloration. *Am J Enol Vitic.* 23, 71.
- Koblet, W., Faust, H., 1992. *Bau und Bewirtschaftung von Kleinterrassen Flugschrift Nr. 85. Eidgenössische Forschungsanstalt für Obst-, Wein- und Gartenbau Wädenswil, Wädenswil (CH)*.
- Königer, W., 1988. Erfahrungen mit der Kleinterrassierung in der Ortenau/Baden, in: Götz, B., Madel, W. (Eds.), *Deutsches Weinbau-Jahrbuch 1989*. Waldkircher Verlagsgesellschaft, Waldkirch im Breisgau, pp. 19–26.
- Kontoudakis, N., Esteruelas, M., Fort, F., Canals, J.M., Freitas, V. de, Zamora, F., 2011. Influence of the heterogeneity of grape phenolic maturity on wine composition and quality. *Food*

- chemistry 124, 767–774. <https://doi.org/10.1016/j.foodchem.2010.06.093>.
- Lebon, E., Dumas, V., Pieri, P., Schultz, H.R., 2003. Modelling the seasonal dynamics of the soil water balance of vineyards. *Functional plant biology: FPB* 30, 699–710. <https://doi.org/10.1071/FP02222>.
- Lebon, E., Pellegrino, A., Lecour, J., Tardieu, F., 2001. Shoot architectural responses induced by controlled soil water deficit in vine (*Vitis vinifera* L. cv. Grenache noir), in: AGRO Montpellier (Ed.), Proceedings 12th GESCO Conference: Compte rendu vol. 1. Montpellier (France), pp. 229–235.
- Löhnertz, O., 1988. Untersuchungen zum zeitlichen Verlauf der Nährstoffaufnahme bei *Vitis-vinifera* c.v. Riesling unter besonderer Berücksichtigung der Makroelemente und des Bewirtschaftungssystems. Gießen, 228 pp.
- Loose, S.M., Szolnoki, G., Fischer, A., 2017. Das Image der Steillage. *Der deutsche Weinbau* 72, 18–22.
- Lu, H.-C., Gao, X.-T., Duan, C.-Q., Li, S.-D., Chen, W., Wang, J., 2021. The Effect of Cluster Position Determined by Vineyard Row Orientation on Grape Flavonoids and Aroma Profiles of *Vitis vinifera* L. cv. Cabernet Sauvignon and Italian Riesling in the North Foot of Tianshan Mountains. *SAJEV* 42. <https://doi.org/10.21548/42-1-4308>.
- Lü, H., Zhu, Y., Skaggs, T.H., Yu, Z., 2009. Comparison of measured and simulated water storage in dryland terraces of the Loess Plateau, China. *Agricultural Water Management* 96, 299–306. <https://doi.org/10.1016/j.agwat.2008.08.010>.
- Martínez-Lüscher, J., Torres, N., Hilbert, G., Richard, T., Sánchez-Díaz, M., Delrot, S., Aguirreolea, J., Pascual, I., Gomès, E., 2014. Ultraviolet-B radiation modifies the quantitative and qualitative profile of flavonoids and amino acids in grape berries. *Phytochemistry* 102, 106–114. <https://doi.org/10.1016/j.phytochem.2014.03.014>.
- McGovern, P.E., Fleming, S.J., Katz, S. (Eds.), 1996. The origins and history of ancient wine. Gordon and Breach publ; Routledge, London, New York (N.Y), 409 pp.
- Michalsky, A., 1976. Die Querterrassierung im Weinbau und ihr Einfluss auf verschiedene kleinklimatische und pedologische Faktoren sowie die Leistung der Rebe. KTBL-Schriften-Vertrieb im Landwirtschaftsverl., Hilstrup (Westf.), 159 pp.
- Minnaar, P., van der Rijst, M., Hunter, K., 2021. Grapevine row orientation, vintage and grape ripeness effect on anthocyanins, flavan-3-ols, flavonols and phenolic acids: I. *Vitis vinifera* L. cv. Syrah grapes. *OENO One* 56, 275–293. <https://doi.org/10.20870/oenone.2022.56.1.4857>.
- Mohr, H.D., 2012. Farbatlas Krankheiten: Schädlinge und Nützlinge an der Weinrebe, 2nd ed. E. Ulmer, Stuttgart, 335 pp.
- Molitor, D., Caffarra, A., Sinigoj, P., Pertot, I., Hoffmann, L., Junk, J., 2014. Late frost damage risk for viticulture under future climate conditions: a case study for the Luxembourgish winegrowing region. *Australian Journal of Grape and Wine Research* 20, 160–168. <https://doi.org/10.1111/ajgw.12059>.
- Montoro, A., Mañas, F., López-Urrea, R., 2016. Transpiration and evaporation of grapevine, two

- components related to irrigation strategy. *Agricultural Water Management* 177, 193–200. <https://doi.org/10.1016/j.agwat.2016.07.005>.
- Mori, K., Goto-Yamamoto, N., Kitayama, M., Hashizume, K., 2007. Effect of high temperature on anthocyanin composition and transcription of flavonoid hydroxylase genes in ‘Pinot noir’ grapes (*Vitis vinifera*). *The Journal of Horticultural Science and Biotechnology* 82, 199–206. <https://doi.org/10.1080/14620316.2007.11512220>.
- Mori, K., Sugaya, S., Gemma, H., 2005. Decreased anthocyanin biosynthesis in grape berries grown under elevated night temperature condition. *Scientia Horticulturae* 105, 319–330. <https://doi.org/10.1016/j.scienta.2005.01.032>.
- Moutinho-Pereira, J.M., Magalhaes, N., Correia, C.M., Torres-Pereira, J.M., 2003. Effects of NW-SE row orientation on grapevine physiology under Mediterranean field conditions. *Agricoltura Mediterranea*, 218–225.
- Novara, A., Cerda, A., Barone, E., Gristina, L., 2021. Cover crop management and water conservation in vineyard and olive orchards. *Soil and Tillage Research* 208, 104896. <https://doi.org/10.1016/j.still.2020.104896>.
- OIV, 2022. Statistics data base: Total vineyard surface area. International Organisation of Vine and Wine. <https://www.oiv.int/en/statistiques/recherche> (accessed 5 July 2022).
- Oliveira, M.T., 2001. Modeling water content of a vineyard soil in the Douro Region, Portugal. *Plant and Soil* 233, 213–221. <https://doi.org/10.1023/A:1010361420899>.
- Pellegrino, A., Lebon, E., Simmoneau, T., Wery, J., 2005. Towards a simple indicator of water stress in grapevine (*Vitis vinifera* L.) based on the differential sensitivities of vegetative growth components. *Aust J Grape Wine Res* 11, 306–315. <https://doi.org/10.1111/j.1755-0238.2005.tb00030.x>.
- Petit, C., Konold, W., Höchtl, F., 2012. Historic terraced vineyards: impressive witnesses of vernacular architecture. *Landscape History* 33, 5–28. <https://doi.org/10.1080/01433768.2012.671029>.
- Pfleiderer, P., Schleussner, C.-F., Kornhuber, K., Coumou, D., 2019. Summer weather becomes more persistent in a 2 °C world. *Nat. Clim. Chang.* 9, 666–671. <https://doi.org/10.1038/s41558-019-0555-0>.
- Pieri, P., Zott, K., Gomès, E., Hilbert, G., 2016. Nested effects of berry half, berry and bunch microclimate on biochemical composition in grape. *OENO One* 50, 23. <https://doi.org/10.20870/oeno-one.2016.50.3.52>.
- Pijl, A., Barneveld, P., Mauri, L., Borsato, E., Grigolato, S., Tarolli, P., 2019. Impact of mechanisation on soil loss in terraced vineyard landscapes. *CIG* 45, 287–308. <https://doi.org/10.18172/cig.3774>.
- Pijl, A., Quarella, E., Vogel, T.A., D’Agostino, V., Tarolli, P., 2021. Remote sensing vs. field-based monitoring of agricultural terrace degradation. *International Soil and Water Conservation Research* 9, 1–10. <https://doi.org/10.1016/j.iswcr.2020.09.001>.
- Pijl, A., Reuter, L.E., Quarella, E., Vogel, T.A., Tarolli, P., 2020. GIS-based soil erosion modelling under various steep-slope vineyard practices. *CATENA* 193, 104604.

<https://doi.org/10.1016/j.catena.2020.104604>.

- Pijl, A., Wang, W., Straffelini, E., Tarolli, P., 2022. Soil and water conservation in terraced and non-terraced cultivations: an extensive comparison of 50 vineyards. *Land Degrad. Develop.* 33, 596–610. <https://doi.org/10.1002/ldr.4170>.
- Porten, M., Hermen, S., 2022. Rechnet sich Terrassenweinbau? *Das deutsche Weinmagazin*, 38–42.
- Porten, M., Treis, F.J., 2008. Querterrassierung mit Fahrterrassen - mehrjährige Erfahrungen auf Schiefer geprägten Böden, in: Schultz, H.R., Stoll, M. (Eds.), *Deutsches Weinbaujahrbuch 2009*. Verlag Eugen Ulmer, Stuttgart.
- Previtali, P., Giorgini, F., Mullen, R.S., Dookozlian, N.K., Wilkinson, K.L., Ford, C.M., 2022. A systematic review and meta-analysis of vineyard techniques used to delay ripening. *Horticulture research* 9, uhac118. <https://doi.org/10.1093/hr/uhac118>.
- Ramos, M.C., Cots-Folch, R., Martínez-Casasnovas, J.A., 2007a. Effects of land terracing on soil properties in the Priorat region in Northeastern Spain: A multivariate analysis. *Geoderma* 142, 251–261. <https://doi.org/10.1016/j.geoderma.2007.08.005>.
- Ramos, M.C., Cots-Folch, R., Martínez-Casasnovas, J.A., 2007b. Sustainability of modern land terracing for vineyard plantation in a Mediterranean mountain environment – The case of the Priorat region (NE Spain). *Geomorphology* 86, 1–11. <https://doi.org/10.1016/j.geomorph.2006.08.004>.
- Ramos, M.C., Martínez de Toda, F., 2022. Influence of weather conditions and projected climate change scenarios on the suitability of *Vitis vinifera* cv. Carignan in Rioja DOCa, Spain. *International journal of biometeorology* 66, 1067–1078. <https://doi.org/10.1007/s00484-022-02258-6>.
- Ramos, M.C., Porta, J., 1997. Analysis of design criteria for vineyard terraces in the mediterranean area of North East Spain. *Soil Technology* 10, 155–166. [https://doi.org/10.1016/S0933-3630\(96\)00006-2](https://doi.org/10.1016/S0933-3630(96)00006-2).
- Reshef, N., Agam, N., Fait, A., 2018. Grape Berry Acclimation to Excessive Solar Irradiance Leads to Repartitioning between Major Flavonoid Groups. *Journal of agricultural and food chemistry* 66, 3624–3636. <https://doi.org/10.1021/acs.jafc.7b04881>.
- Reshef, N., Fait, A., Agam, N., 2019. Grape berry position affects the diurnal dynamics of its metabolic profile. *Plant, cell & environment* 42, 1897–1912. <https://doi.org/10.1111/pce.13522>.
- Reshef, N., Walbaum, N., Agam, N., Fait, A., 2017. Sunlight Modulates Fruit Metabolic Profile and Shapes the Spatial Pattern of Compound Accumulation within the Grape Cluster. *Frontiers in plant science* 8, 70. <https://doi.org/10.3389/fpls.2017.00070>.
- Rienth, M., Torregrosa, L., Kelly, M.T., Luchaire, N., Pellegrino, A., Grimplet, J., Romieu, C., 2014. Is transcriptomic regulation of berry development more important at night than during the day? *PloS one* 9, e88844. <https://doi.org/10.1371/journal.pone.0088844>.
- Rodrigo-Comino, J., Seeger, M., Iserloh, T., Senciales González, J.M., Ruiz-Sinoga, J.D., Ries, J.B., 2019. Rainfall-simulated quantification of initial soil erosion processes in sloping and

- poorly maintained terraced vineyards - Key issues for sustainable management systems. *The Science of the total environment* 660, 1047–1057. <https://doi.org/10.1016/j.scitotenv.2018.12.451>.
- Santesteban, L.G., 2019. Precision viticulture and advanced analytics. A short review. *Food chemistry* 279, 58–62. <https://doi.org/10.1016/j.foodchem.2018.11.140>.
- 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., Kartschall, T., Menz, C., Molitor, D., Junk, J., Beyer, M., Schultz, H.R., 2020. A Review of the Potential Climate Change Impacts and Adaptation Options for European Viticulture. *Applied Sciences* 10, 3092. <https://doi.org/10.3390/app10093092>.
- Savoi, S., Herrera, J.C., Carlin, S., Lotti, C., Bucchetti, B., Peterlunger, E., Castellarin, S.D., Mattivi, F., 2020. From grape berries to wines: drought impacts on key secondary metabolites. *OENO One* 54, 569–582. <https://doi.org/10.20870/oenone.2020.54.3.3093>.
- Schmid, J., Manty, F., Lindner, B., 2011. *Geisenheimer Rebsorten und Klone*, 2nd ed. Forschungsanst, Geisenheim, 156 pp.
- Schreieck, P., 2016. Weinbau in terrassierten Steillagen. *Landinfo*, 11–15.
- Schultz, H.R., 2000. Climate change and viticulture: A European perspective on climatology, carbon dioxide and UV-B effects. *Australian Journal of Grape and Wine Research* 6, 2–12. <https://doi.org/10.1111/j.1755-0238.2000.tb00156.x>.
- Schultz, H.R., Hofmann, M., 2015. The ups and downs of environmental impact on grapevines, in: Gerós, H., Chaves, M.M., Gil, H.M., Delrot, S. (Eds.), *Grapevine in a Changing Environment*, vol. 97. John Wiley & Sons, Ltd, Chichester, UK, pp. 18–37.
- Sechrist, R., 2012. The Origin, Diffusion, and Globalization of Riesling, in: Dougherty, P.H. (Ed.), *The Geography of Wine*. Springer Netherlands, Dordrecht, pp. 195–206.
- Sgubin, G., Swingedouw, D., Mignot, J., Gambetta, G.A., Bois, B., Loukos, H., Noël, T., Pieri, P., García de Cortázar-Atauri, I., Ollat, N., van Leeuwen, C., 2022. Non-linear loss of suitable wine regions over Europe in response to increasing global warming. *Global change biology*. <https://doi.org/10.1111/gcb.16493>.
- Siegfried, W., Schilling, K., Wins, T., 2011. Bau von Rebterrassen. *Schweizer Zeitschrift für Obst- und Weinbau* 147, 6–9.
- Smart, D.R., Schwass, E., Lakso, A., morano, L., 2006. Grapevine Rooting Patterns: A Comprehensive Analysis and a Review. *Am J Enol Vitic.* 57, 89–104.
- Smart, R.E., 1973. Sunlight Interception by Vineyards. *Am J Enol Vitic.* 24, 141.
- Smart, R.E., 1985. Principles of Grapevine Canopy Microclimate Manipulation with Implications for Yield and Quality. A Review. *Am J Enol Vitic.* 36, 230–239.
- Smart, R.E., Robinson, J.B., Due, G.R., Brien, C.J., 1985. Canopy microclimate modification for the cultivar Shiraz I. Definition of canopy microclimate. *VITIS* 24, 17–31. <https://doi.org/10.5073/vitis.1985.24.17-31>.

- Souza, C.R.d., Mota, R.V.d., Silva, C.P.C., Raimundo, R.H.P., Fernandes, F.d.P., Peregrino, I., 2019. Row orientation effects on Syrah grapevine performance during winter growing season. *Rev. Ceres* 66, 184–190. <https://doi.org/10.1590/0034-737X201966030004>.
- Spachos, P., 2020. Towards a Low-Cost Precision Viticulture System Using Internet of Things Devices. *IoT 1*, 5–20. <https://doi.org/10.3390/iot1010002>.
- Stoll, M., Bischoff-Schaefer, M., Lafontaine, M., Tittmann, S., Henschke, J., 2013. Impact of various leaf area modifications on berry maturation in *Vitis vinifera* L. 'Riesling'. *International Society for Horticultural Science*, 293 pp.
- Strack, T., Schmidt, D., Stoll, M., 2021. Impact of steep slope management system and row orientation on canopy microclimate. Comparing terraces to downslope vineyards. *Agricultural and Forest Meteorology* 307, 108515. <https://doi.org/10.1016/j.agrformet.2021.108515>.
- Strack, T., Stoll, M., 2021. Implication of Row Orientation Changes on Fruit Parameters of *Vitis vinifera* L. cv. Riesling in Steep Slope Vineyards. *Foods (Basel, Switzerland)* 10. <https://doi.org/10.3390/foods10112682>.
- Strack, T., Stoll, M., 2022. Soil water dynamics and drought stress response of *Vitis vinifera* L. in steep slope vineyard systems. *Agricultural Water Management* 274, 107967. <https://doi.org/10.1016/j.agwat.2022.107967>.
- Strub, L., Loose, S.M., 2016. Steillagenweinbau: Eine Bestandsaufnahme der bestockten Steillagenrebfläche in Deutschland. *Der deutsche Weinbau* 71, 14–18.
- Strub, L., Mueller Loose, S., 2021. The cost disadvantage of steep slope viticulture and strategies for its preservation. *OENO One* 55, 49–68. <https://doi.org/10.20870/oenone.2021.55.1.4494>.
- Stumm, G., 1985. Steillagenweinbau mit Zukunftsperspektiven?, in: Götz, B., Madel, W. (Eds.), *Deutsches Weinbau-Jahrbuch*. Waldkircher Verlagsgesellschaft, Waldkirch im Breisgau, pp. 7–18.
- Tarara, J.M., Ferguson, J.C., Hoheisel, G.-A., Perez Peña, J.E., 2005. Asymmetrical canopy architecture due to prevailing wind direction and row orientation creates an imbalance in irradiance at the fruiting zone of grapevines. *Agricultural and Forest Meteorology* 135, 144–155. <https://doi.org/10.1016/j.agrformet.2005.11.011>.
- Tarolli, P., Preti, F., Romano, N., 2014. Terraced landscapes: From an old best practice to a potential hazard for soil degradation due to land abandonment. *Anthropocene* 6, 10–25. <https://doi.org/10.1016/j.ancene.2014.03.002>.
- Tarolli, P., Sofia, G., Calligaro, S., Prodocimi, M., Preti, F., Dalla Fontana, G., 2015. Vineyards in Terraced Landscapes: New Opportunities from Lidar Data. *Land Degrad. Develop.* 26, 92–102. <https://doi.org/10.1002/ldr.2311>.
- Tombesi, S., Cincera, I., Frioni, T., Ughini, V., Gatti, M., Palliotti, A., Poni, S., 2019. Relationship among night temperature, carbohydrate translocation and inhibition of grapevine leaf photosynthesis. *Environmental and Experimental Botany* 157, 293–298. <https://doi.org/10.1016/j.envexpbot.2018.10.023>.

- Trought, M., Parker, A.K., van Leeuwen, C., 2015. Can a Change in Vineyard Practice Mitigate Warming due to Climate Change? *Acta Hortic.*, 397–402. <https://doi.org/10.17660/ActaHortic.2015.1082.55>.
- UNESCO, 2000. Wachau Cultural Landscape. UNESCO. <https://whc.unesco.org/en/list/970/>.
- Valente, A., Costa, C., Pereira, L., Soares, B., Lima, J., Soares, S., 2022. A LoRaWAN IoT System for Smart Agriculture for Vine Water Status Determination. *Agriculture* 12, 1695. <https://doi.org/10.3390/agriculture12101695>.
- van Leeuwen, Destrac-Irvine, Dubernet, Duchêne, Gowdy, Marguerit, Pieri, Parker, de Rességuier, Ollat, 2019. An Update on the Impact of Climate Change in Viticulture and Potential Adaptations. *Agronomy* 9, 514. <https://doi.org/10.3390/agronomy9090514>.
- van Leeuwen, C., 2009. Soils and Terroir Expression in Wines, in: Landa, E.R., Feller, C. (Eds.), *Soil and Culture*. Springer Netherlands, Dordrecht, pp. 453–465.
- van Leeuwen, C., Darriet, P., 2016. The Impact of Climate Change on Viticulture and Wine Quality. *J Wine Econ* 11, 150–167. <https://doi.org/10.1017/jwe.2015.21>.
- van Leeuwen, C., Seguin, G., 2006. The concept of terroir in viticulture. *Journal of Wine Research* 17, 1–10. <https://doi.org/10.1080/09571260600633135>.
- Wang, Z., Yin, H., Yang, N., Cao, J., Wang, J., Wang, X., Xi, Z., 2022. Effect of vineyard row orientation on microclimate, phenolic compounds, individual anthocyanins, and free volatile compounds of Cabernet Sauvignon (*Vitis vinifera* L.) in a high-altitude arid valley. *Eur Food Res Technol* 248, 1365–1378. <https://doi.org/10.1007/s00217-022-03961-9>.
- Wehinger, A., Spies, E.-D., 2008. Geotechnische und bodenkundliche Anforderungen bei Querterrassierungen, in: Achilles, A. (Ed.), *Anlage und Bewirtschaftung von Weinbergterrassen*. KTBL, Darmstadt, pp. 13–24.
- Wei, W., Chen, D., Wang, L., Daryanto, S., Chen, L., Yu, Y., Lu, Y., Sun, G., Feng, T., 2016. Global synthesis of the classifications, distributions, benefits and issues of terracing. *Earth-Science Reviews* 159, 388–403. <https://doi.org/10.1016/j.earscirev.2016.06.010>.
- Weiss, A., Allen, L.H., 1976. Vertical and horizontal air flow above rows of a vineyard. *Agricultural Meteorology* 17, 433–452. [https://doi.org/10.1016/0002-1571\(76\)90021-2](https://doi.org/10.1016/0002-1571(76)90021-2).
- Wersebeckmann, V., Entling, M.H., Leyer, I., 2022. Revegetation of vineyard terrace embankments: A matter of seed mixture and seeding technique. *Journal of environmental management* 317, 115409. <https://doi.org/10.1016/j.jenvman.2022.115409>.
- Wersebeckmann, V., Kolb, S., Entling, M.H., Leyer, I., 2021. Maintaining steep slope viticulture for spider diversity. *Global Ecology and Conservation* 29, e01727. <https://doi.org/10.1016/j.gecco.2021.e01727>.
- Yazdanseta, A., 2017. Estimating the Cooling Power through Transpiration of Vining Green Walls in Various Climates, in: *Proceedings of the 2017 Symposium on Simulation for Architecture and Urban Design (SimAUD 2017)*. 2017 Symposium on Simulation for Architecture and Urban Design, Toronto, Canada. 2017-05-22 - 2017-05-24. Society for Modeling and Simulation International (SCS), pp. 235–242.

Zhao, P., Fallu, D.J., Cucchiaro, S., Tarolli, P., Waddington, C., Cockcroft, D., Snape, L., Lang, A., Doetterl, S., Brown, A.G., van Oost, K., 2021. Soil organic carbon stabilization mechanisms and temperature sensitivity in old terraced soils. *Biogeosciences* 18, 6301–6312. <https://doi.org/10.5194/bg-18-6301-2021>.

Zorer, R., Volschenk, C.G., Hunter, J.J., 2017. Integrating Geographic Information Systems and hemispherical photography in the assessment of canopy light profiles in a vineyard. *Agricultural and Forest Meteorology* 232, 672–681. <https://doi.org/10.1016/j.agrformet.2016.09.011>.