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Crop Diversification in Viticulture with Aromatic Plants: Effects of Intercropping on Grapevine Productivity in a Steep-Slope Vineyard in the Mosel Area, Germany

Felix Dittrich [1], Thomas Iserloh [2], Cord-Henrich Treseler [3], Roman Hüppi [4], Sophie Ogan [5], Manuel Seeger [2] and Sören Thiele-Bruhn [1,*]

[1] Department of Soil Science, Trier University, 54296 Trier, Germany; dittrich@uni-trier.de
[2] Department of Physical Geography, Trier University, 54296 Trier, Germany; iserloh@uni-trier.de (T.I.); seeger@uni-trier.de (M.S.)
[3] Winery Dr. Frey, 54441 Kanzem, Germany; flaschenpost@weingutdrfrey.de
[4] Department of Environmental Systems Science, ETH Zürich, 8092 Zürich, Switzerland; roman.hueppi@usys.ethz.ch
[5] Department of Biogeography, Trier University, 54296 Trier, Germany; ogan@uni-trier.de
* Correspondence: thiele@uni-trier.de

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Abstract: The effects of intercropping grapevine with aromatic plants are investigated using a multi-disciplinary approach. Selected results are presented that address the extent to which crop diversification by intercropping impacts grapevine yield and must quality, as well as soil water and mineral nutrients (NO_3-N, NH_4-N, plant-available K and P). The experimental field was a commercial steep-slope vineyard with shallow soils characterized by a high presence of coarse rock fragments in the Mosel area of Germany. The field experiment was set up as randomized block design. Rows were either cultivated with Riesling (*Vitis vinifera* L.) as a monocrop or intercropped with *Origanum vulgare* or *Thymus vulgaris*. Regarding soil moisture and nutrient levels, the topsoil (0–0.1 m) was more affected by intercropping than the subsoil (0.1–0.3 m). Gravimetric moisture was consistently lower in the intercropped topsoil. While NO_3-N was almost unaffected by crop diversification, NH_4-N, K, and P were uniformly reduced in topsoil. Significant differences in grapevine yield and must quality were dominantly attributable to climate variables, rather than to the treatments. Yield stabilization due to intercropping with thyme and oregano seems possible with sufficient rainfall or by irrigation. The long-term effects of intercropping on grapevine growth need further monitoring.

Keywords: perennial cropping systems; grape production; medicinal and aromatic plants; grapevine yield; must quality; experimental design

1. Introduction

Grapevine (*Vitis vinifera* L.) cultivation covers 7.4 million hectares worldwide and has reached a high degree of agronomic specialization [1]. Producers that exclusively cultivate grapevine face increasing economic risks, as climate change may impact vineyard productivity [2]. In addition, many producers strive for a reduction of adverse environmental impacts such as soil degradation, biodiversity decline, and contamination of groundwater and surface water caused by intensive and eventually non-sustainable management practices (i.e., frequent tillage, and intensive fertilizer and pesticide use) [3–8]. Agricultural diversification has been proposed to combine both economic and environmental sustainability, and can be realized by an increase of the crop species diversity (e.g., by intercropping or crop rotation) or noncrop (e.g., by cover-cropping or hedgerows) [9–11]. In viticulture, an increase in plant species diversity, abundance, and soil cover is implemented by the use of cover crops, and this has been frequently reported to mitigate environmental impacts [5,12–15]. Cover crops provide several services for the vineyard ecosystem: protection from soil erosion, water purification, nutrient retention, and improved soil structure, and thus, enhanced water infiltration, increased soil quality, above- and below-ground biological diversity, and a significant contribution to weed, pest, and disease control [6,16–19].

Some authors have also considered regulative effects on grapevine growth as service [12,13], since competition between grapevines and cover crops for soil resources may have beneficial effects on grape yield and quality indices. For example, competition has been shown to limit vigor and vegetative growth, resulting in reduced canopy density, pest incidence, and berry size with increased must quality [12,18]. On the other hand, cover cropping can exert undesired disservices through severe competition or the provision of habitats for pests and pathogens, with significant reductions of grape yield and quality [14,20]. A proper choice and management of cover crops is therefore critical to facilitate services while preventing disservices. Beside the technical and pedoclimatic context, economic concerns (i.e., the risk of lower yields, missing short-term returns, and extra costs for managing cover crops) are most decisive, and limit a systematic adoption to variable spatiotemporal extents (i.e., from alternating row to complete respectively temporary to permanent cover) [15,21,22].

In vineyards, predominantly inter-rows are cover-cropped with purposely seeded or resident species, whereas the grapevine row (i.e., the space underneath and close to the grapevine plants) is still most commonly kept free of vegetation by mechanical or chemical means in order to prevent severe competition and diseases [8,23]. As a result, 20 to 25% of the total vineyard surface (assuming a 2 m row distance and a 0.4–0.5 m row width) remains uncovered, and constitute linear structures that are especially prone to soil erosion. On the other hand, this vacant space bears excellent options for the cultivation of other crops.

Aromatic plants have not yet been considered as viable intercropping option for vineyards, though characteristic traits (e.g., perennial, flat-growing, shade-tolerant and adopted to dry and warm pedoclimatic conditions) and increasing economic demands for products derived from aromatic plants make them suitable to combine short-term returns with environmental benefits [24]. Agronomic cultivation handbooks for aromatic plants describe a low to moderate need for soil resources, plant heights of 0.3 up to 1.0 m (during blossom), and profitable cultivation periods of five to 10 years with up to two harvest cuts per year under favorable climatic conditions [25,26]. Like grapevines, aromatic plants synthesize considerable amounts of secondary metabolites (in response to abiotic and biotic stress), and harvested plant materials, either raw or processed, provide various application possibilities in food, pharmaceutical, and cosmetics industries [24,27], and may act as novel agents for plant protection [28]. Aromatic plants are successfully grown as lower-strata species in multistrata agroforestry systems (e.g., orchards) [29], and can substantially contribute to ecosystem services such as biodiversity and habitat quality, pest and disease control, aesthetical land valorization, soil erosion control, and enhanced resource-use efficiency [27,30,31]. Some aromatic plant species are also capable of tolerating adverse environmental conditions, and have been suggested to be cultivated on marginal (i.e., contaminated, eroded, and moisture-deficient) soils [32–34]. These attributes are applicable to a wide range of vineyards, as they are frequently located on medium to steep slopes where intensive management has led to severe soil erosion and contamination (e.g., with Cu-based fungicides) [3,4,35].

This work has been initiated because, to the best of our knowledge, no specific study has investigated the effects of intercropping grapevine and aromatic plants under field conditions. We define the grapevine row as a valuable production area, where a permanent cultivation of additional, marketable crops (i.e., intercropping) and the concomitant omission of tillage may have profound effects on the overall vineyard productivity, the provision of ecosystem services, and above- and below-ground biodiversity. In this article, we present our experimental design and the development of grapevine yields and must quality, as well as soil water and plant-available nutrient levels over three years after implementing aromatic plants in a steep-slope vineyard. With respect to grapevine productivity, we aim to evaluate impacts of intercropping to assess its potential as appropriate diversification measure in vineyards. To this end, the effects of intercropping underneath grapevines using two aromatic plants (oregano and thyme) on the selected properties of grapevine yield and soil were investigated. Diversified cropping was compared to regular cultivation as a control that goes along with bare soil underneath grapevines.

2. Materials and Methods

2.1. Study Site

The experimental field is a commercial vineyard ('Wawerner Jesuitenberg') in the Mosel area of Germany (Figure 1) that is managed according to organic principles. Standard cultural practices encompass mulching, harrowing of grapevine rows, organic fertilization, and plant protection with Cu-based compounds. According to the Köppen classification, the climate is temperate oceanic, and the mean annual temperature, precipitation, and potential evapotranspiration are 9.1 °C, 722 mm, and 687 mm, respectively (www.am.rlp.de; meteorological station 'Kanzem'). Grapevines (*Vitis vinifera* L. cv. 'Riesling') were grafted on SO4 rootstocks and established in 2008 using wire-framed rows oriented along the slope. The spacing is 2 m between rows and 1 m within rows. The south-exposed vineyard plot has a size of 0.3 ha and a steep inclination (~45%), and has developed from Devonian argillaceous schist (Hunsrück Devonian strata [36]), as well as Pleistocene terrace sediments. Prior to grapevine planting, soil melioration by deep cultivation and amendments of organic and mineral origin modified the initial soil properties. The shallow (<0.5 m) and highly permeable (mean K_f-values in 2019: 2.5×10^{-5} ms^{-1}) soil profile is characterized by a high presence of coarse rock fragments (>50%), mainly ranging from 2 to 20 mm. The fine soil (<2 mm) shows a slightly acidic reaction (6.6 in $CaCl_2$, 1:2.5) and has a sandy loamy texture, and is composed of 60% sand, 25% silt, and 15% clay. A continuous supply of organic matter, via organic fertilization and mulching (pruning residues, cover crops), established a distinct topsoil horizon (0–0.1 m) that is enriched in soil organic carbon (SOC = 3.1%) and shows an effective cation exchange capacity (ECEC) of 12.1 cmol/kg^{-1}. SOC and ECEC in the subsoil horizon (0.1–0.3 m) are 2.2% and 9.0 cmol/kg^{-1}, respectively. According to the world reference base for soil resources, the soil is classified as Eutric Skeletic Regosol (Aric, Humic) [37].

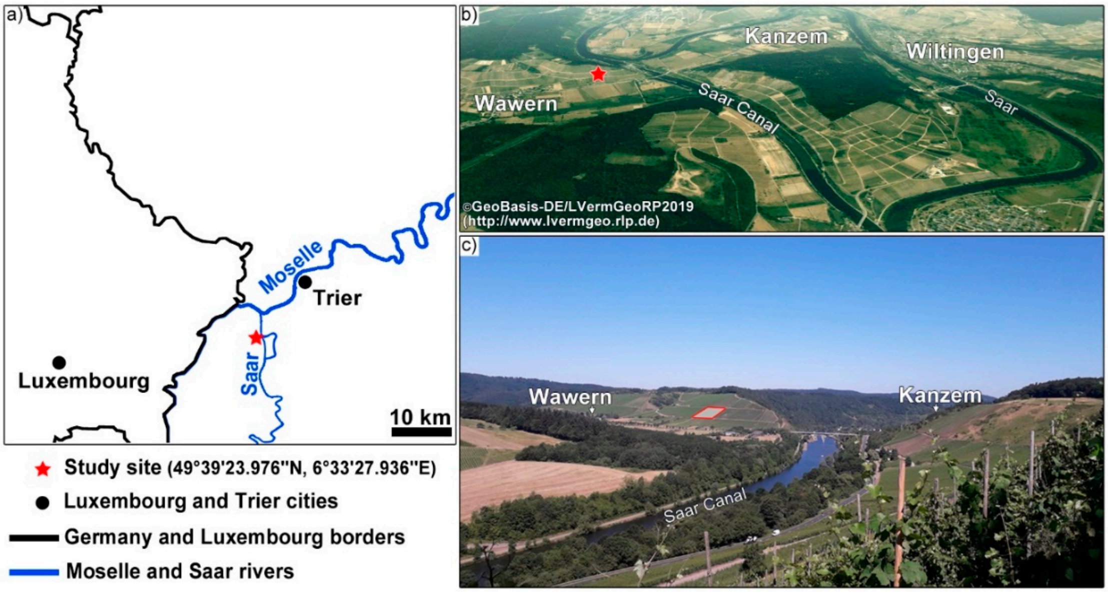

Figure 1. Map indicating the location of the study site (**a**), as well as an aerial view (**b**), and a photo of the study area close to the Saar Canal (**c**).

2.2. Experimental Design

The field experiment was set up as randomized block design (Figure 2) with three blocks, each consisting of two grapevine rows per treatment:

- Control (*Vitis vinifera* L. cv. 'Riesling' monocrop with regular mechanical tillage),
- Oregano (*Vitis vinifera* L. cv. 'Riesling' intercropped with *Origanum vulgare*),
- Thyme (*Vitis vinifera* L. cv. 'Riesling' intercropped with *Thymus vulgaris*).

In May 2018, aromatic plants were manually planted in one row per block as seedlings. The plant material was obtained from Pharma Saat GmbH (www.pharmasaat.de), and the soil was prepared using hand-held tools. A plant density of four (oregano) and five (thyme) seedlings between two grapevines was chosen to achieve proper soil cover for weed suppression and soil erosion control. In April 2019, a further implementation of aromatic plants in the second row per treatment was conducted. The intercropped rows were occasionally irrigated with ~2.6 L/m of grapevine row in 2018 and 2019, in order to prevent withering of seedlings. The total amount of supplied water was 2340 L for each intercropping treatment in 2018 (five applications starting from the planting date until the end of August) and 1400 L in 2019 (three applications in July/August). An evaluation of the performance of aromatic plants without associated grapevines was carried out in a nearby field that was well prepared prior to planting.

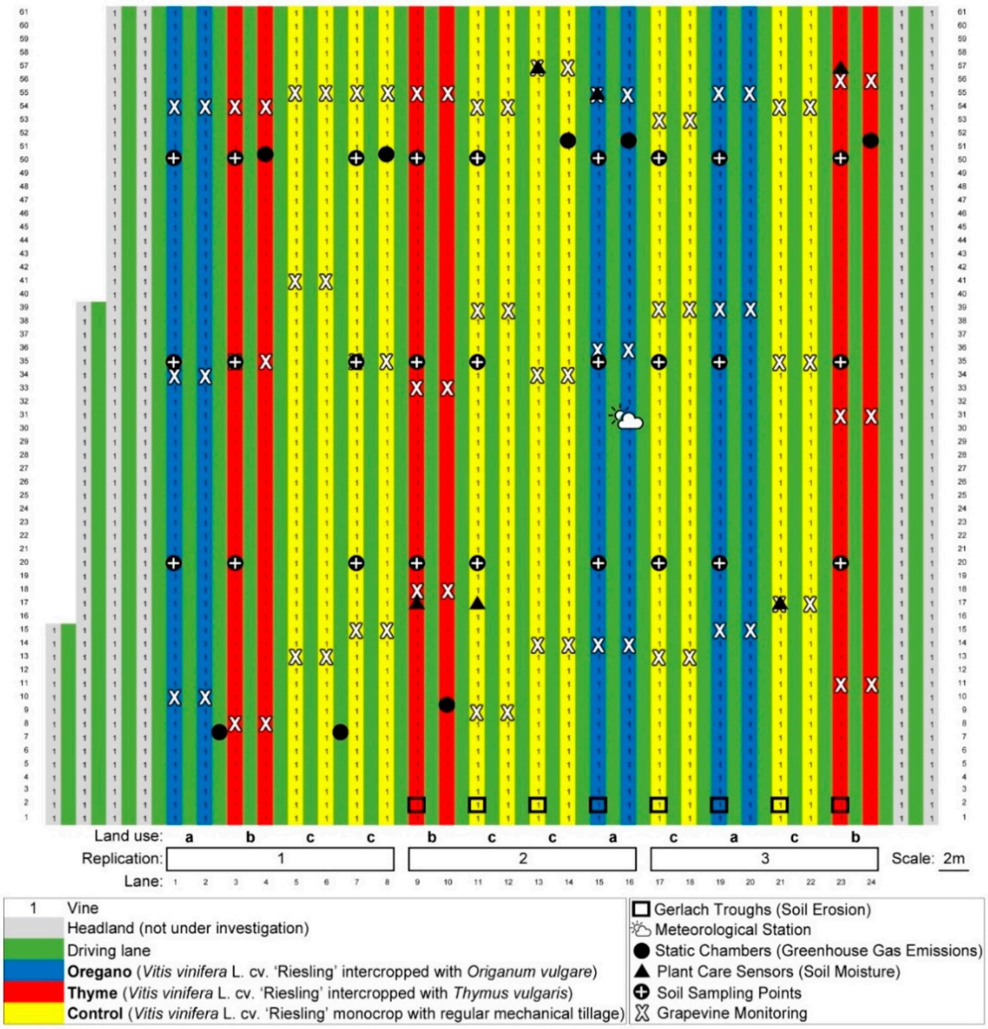

Figure 2. Experimental set-up showing grapevine rows colored according to treatments, and the positioning of monitoring equipment.

2.3. Crop Monitoring

Six grapevines per block and treatment were selected to monitor grapevine performance, yield, and must quality (Figure 2). For each grapevine, the total weight of grapes, the weight of selected berry clusters, and the number of produced clusters were quantified shortly prior to harvest. In addition, the total grape yields per row were determined and expressed per hectare. Must quality was evaluated using pH value (with a digital pH-meter, GPRT 1400 AN, Greisinger, Regenstauf, Germany) titratable acidity (in g/L with Neustädter titration cylinder; Wagner, Merkel, Sulfacor), and the concentration of total soluble solids, an indirect measure of sugar content (measured optically with a refractometer and expressed as °Brix). The incidence of fungal diseases on grape leaves and berries were visually assessed. The vegetative development of aromatic plants was assessed close to monitored grapevines by measuring plant height, length, and width. The aromatic plant root biomass was determined at the end of the experiment in 2020 on a total number of nine individuals per species that were planted in 2018 to estimate their below-ground impact.

2.4. Vineyard Soil Sampling and Analytical Protocols

A comprehensive monitoring of vineyard soil quality in both topsoil and subsoil (0–0.1 and 0.1–0.3 m, respectively) began in October 2018. Sampling was confined to rows diversified in May 2018. A minimum of two samples per block and treatment was continuously taken close (<0.1 m) to the grapevine row, at the beginning and the end of the crop cycle until October 2020 (see Figure 2). Coarse rock fragments were removed from the surface prior to sampling. Gravimetric soil moisture was determined by weighing before and after drying at 105 °C for 24 h. Plant-available forms of potassium (K) and phosphorus (P) were extracted using the calcium-acetate-lactate (CAL) method [38] and expressed as K and P. Briefly, 5 g of air-dried and sieved (<2 mm) soil was agitated for 2 h with 100 mL of CAL solution and subsequently filtered. Filtrates were quantified for K using a flame AAS (SpectrAA-10 Varian, USA) and P using a photospectrometric approach (λ = 710 nm; Shimadzu UV-1650 PC, Shimadzu, Japan) with ammonium molybdate as staining reagent. Ammonium (NH_4-N) and nitrate (NO_3-N) were simultaneously quantified using a continuous segmented flow analyzer (Bran+Luebbe GmbH, Norderstedt, Germany). Briefly, 5 g of frozen, field moist aliquots of aforementioned samples was agitated with 40 mL of 2 m KCl for 1 h and filtrated prior to analysis.

2.5. Soil Erosion Measurements

Continuous soil erosion measurements were conducted at the bottom of each treatment [39]. Gerlach troughs were built, installed, and utilized as sediment collectors [40]. These open soil-erosion plots give information about soil losses, but the contributing area is not defined and may be variable. Consequently, soil-erosion results are shown in kg m^{-1} of slope width. The sediment output of a definable field section was measured under real agricultural conditions. The collected material provided basic data on the transported grain sizes and nutrients of the particular field [41].

2.6. Statistical Analysis

Data analyses were conducted using the R statistical package version 3.3.2. [42]. Yield and must quality differences over time were assessed using one-way analysis of variance (ANOVA), applying a repeated measures design, followed by a Tukeys HSD post-hoc test. One-way ANOVA was used to differentiate between experimental treatments of individual years. In addition, the separation of grapevine yield and quality indices was tested using principal component analysis. Soil moisture and nutrient levels were evaluated using two-way ANOVA with time and depth as focal variables. For given sampling dates and depths, treatment effects were determined using one-way ANOVA. Values were considered significantly different at p-values < 0.05. Prior to analysis, normality and homoscedasticity were assessed using Shapiro-Wilk and Levene's test.

3. Results

3.1. Climatic Phenomena and Effects on Intercrop Growth

Generally, the experimental period was drier than long-term average values, and precipitation sums from calendar quarter (Q) I to III were lowest in 2019 (Table 1). However, considering QI to III, a distinct seasonal variability of precipitation was observed between years: the highest precipitation sums were recorded in QII of 2018, in QIII of 2019, and QI of 2020.

Table 1. Precipitation patterns and vegetation days (TØ > = 5 °C) over the experimental period (2018–2020) obtained from the Kanzem meteorological station (www.am.rlp.de). Long-term precipitation sums (1990–2020 from Trier-Petrisberg, and 2005–2020 from Kanzem) and the precipitation in 2017 were included as supplementary information.

		Precipitation Sum						**Vegetation Days**		
		1990–2020	**2005–2020**	**2017**	**2018**	**2019**	**2020**	**2018**	**2019**	**2020**
Quarter	Months	(mm)						(days)		
I	Jan-Mar	166	153	113	207	149	265	40	51	68
II	Apr-Jun	176	189	113	243	149	128	91	89	91
III	Jul-Sep	193	187	251	124	164	100	92	92	92
IV	Oct-Dec	205	193	250	185	267	234	71	69	66
∑ I-III		535	529	477	574	462	493	223	232	251
∑ I-IV		740	722	727	759	729	727	294	301	317

On 1 June, 2018, a heavy rain event substantially raised the recorded precipitation sums in QII and resulted in a translocation of soil and recently planted intercrop seedlings. A rain peak of 55.6 mm was recorded from 00:00 h–00:59 h, and had its highest intensity of 117.6 mm h^{-1} from 00:05 h–00:10 h. Total soil losses were highest in grapevine rows diversified with thyme (13.7 kg m^{-1}). Substantially lower amounts of soil were collected from Gerlach troughs at the bottom of rows diversified with oregano (0.4 kg m^{-1}) and control rows (0.1 kg m^{-1}). This event and the rather dry conditions in QIII in 2018 caused a poor intercrop establishment. Re-planting of translocated and withered seedlings and manual irrigation were necessary, and increased the management intensity for the diversification treatments. However, the aromatic plant stands recovered and grew even in periods of grapevine dormancy. A steady increase in aromatic plant width and height is shown in Figure 3. The harvest was conducted at blossom, occurring approximately four weeks earlier in case of thyme, and hence restricted their vegetative growth in summer periods when air temperatures and soil water limitation peaked. Overall, oregano plants grew wider and higher in 2019 and 2020, indicating a stronger impact on soil resources. This was confirmed by a notably higher below-ground root biomass of oregano (27 ± 8 g/plant) as compared to thyme (17 ± 11 g/plant) determined at the end of the experiment in 2020.

3.2. Soil Resource Availability and Development

Gravimetric soil moisture and nutrient levels as a function of time, soil depth, and intercrop and monocrop management at given sampling dates are presented in Table 2. Overall, the topsoil (0–0.1 m) was more affected by intercropping than the subsoil (0.1–0.3 m). Soil moisture was consistently lower in the topsoil due to intercropping, and was statistically significant at the end of each crop cycle. Subsoil samples showed inconsistent effects of intercropping on gravimetric water contents: from October 2018 until October 2019; slight increases were present for oregano and thyme, followed by slight decreases.

Table 2. Mean values (± standard deviation in brackets) of soil moisture and nutrient levels as affected by time and treatments. The row total considers all observations on the respective sampling date. Numbers followed by capital letters indicate significant differences between years and depths, whereas numbers followed by lowercase letters indicate significant differences within one year between the experimental treatments. Significance was given at p-level < 0.05.

		Soil Moisture (wt.%)		**NO_3-N (mg/kg)**		**NH_4-N (mg/kg)**		**Available K (mg/kg)**		**Available P (mg/kg)**	
	Depth [m]	**0–0.1**	**0.1–0.3**	**0–0.1**	**0.1–0.3**	**0–0.1**	**0.1–0.3**	**0–0.1**	**0.1–0.3**	**0–0.1**	**0.1–0.3**
October 2018	Total	9.0 (±1.4) F	9.2 (±1.1) F	6.9 (±4.0) A	na	4.5 (±1.9) B	na	689 (±120) A	458 (±82) B	195 (±25) A	165 (±17) BC
	Control	10.0 (±1.1) a	9.0 (±1.1) a	9.6 (±3.7) a	na	5.0 (±1.8) a	na	689 (±57) a	508 (±63) a	212 (±23) a	177 (±15) a
	Oregano	8.6 (±1.4) b	9.1 (±0.9) a	4.7 (±2.3) b	na	4.0 (±1.7) a	na	710 (±160) a	412 (±53) b	179 (±25) b	156 (±15) b
	Thyme	8.5 (±1.2) b	9.3 (±1.3) a	6.3 (±2.9) ab	na	4.6 (±2.2) a	na	669 (±129) a	453 (±100) ab	194 (±16) ab	162 (±15) ab
April 2019	Total	17.3 (±1.9) CD	15.4 (±1.4) D	nd0	2.8 (±0.9) BC	1.3 (±0.8) DE	6.0 (±1.8) A	236 (±55) CD	240 (±45) CD	184 (±38) AB	186 (±25) AB
	Control	18.8 (±1.3) a	14.9 (±1.7) a	nd0	2.8 (±1.0) a	2.0 (±0.9) a	5.9 (±2.7) a	275 (±19) a	247 (±62) a	200 (±13) a	181 (±15) a
	Oregano	16.4 (±2.1) a	15.6 (±1.2) a	nd0	3.1 (±1.1) a	0.8 (±0.3) b	5.8 (±1.3) a	222 (±66) a	239 (±29) a	180 (±41) a	194 (±33) a
	Thyme	16.8 (±1.5) a	15.7 (±1.2) a	nd0	2.6 (±0.6) a	1.0 (±0.4) b	6.2 (±1.6) a	212 (±54) a	233 (±46) a	173 (±50) a	182 (±27) a
October 2019	Total	20.3 (±1.5) B	17.9 (±1.3) C	1.7 (±1.0) BC	3.5 (±3.4) B	0.6 (±0.6) E	0.6 (±1.3) E	244 (±41) CD	283 (±90) C	142 (±9) C	158 (±11) BC
	Control	21.5 (±1.4) a	17.8 (±1.6) a	1.1 (±0.4) a	3.6 (±3.8) a	0.8 (±0.8) a	0.1 (±0.2) a	293 (±26) a	288 (±30) a	147 (±7) a	162 (±6) a
	Oregano	20.2 (±1.1) ab	18.0 (±1.3) a	2.3 (±1.3) a	2.5 (±3.1) a	0.3 (±0.3) a	0.1 (±0.2) a	225 (±21) b	289 (±115) a	135 (±7) a	155 (±7) a
	Thyme	19.2 (±1.0) b	17.9 (±1.1) a	1.7 (±0.7) a	4.3 (±3.6) a	0.7 (±0.5) a	1.4 (±2.0) a	215 (±19) b	272 (±114) a	142 (±10) a	157 (±17) a
April 2020	Total	11.9 (±1.6) E	11.7 (±1.2) E	0.5 (±0.6) BC	0.1 (±0.3) C	1.9 (±0.6) CD	2.3 (±0.8) C	200 (±28) D	211 (±38) D	151 (±15) C	157 (±42) C
	Control	12.8 (±1.8) a	12.3 (±1.4) a	0.4 (±0.5) a	0.3 (±0.3) a	2.0 (±0.4) a	2.6 (±0.9) a	225 (±28) a	232 (±47) a	156 (±16) a	168 (±62) a
	Oregano	11.4 (±1.5) a	11.3 (±1.0) a	0.7 (±0.8) a	0.3 (±0.3) a	1.9 (±0.9) a	2.1 (±0.7) a	186 (±9) b	197 (±16) a	149 (±17) a	144 (±25) a
	Thyme	11.4 (±1.1) a	11.6 (±0.9) a	0.3 (±0.2) a	0.4 (±0.2) a	1.8 (±0.3) a	2.4 (±0.6) a	189 (±23) b	204 (±36) a	148 (±13) a	159 (±31) a
October 2020	Total	26.1 (±3.1) A	20.2 (±2.5) B	6.9 (±3.6) A	7.9 (±5.2) A	2.3 (±0.8) CD	1.7 (±0.9) CD	278 (±35) C	276 (±47) C	143 (±19) C	181 (±42) AB
	Control	28.8 (±1.7) a	20.7 (±2.3) a	7.1 (±4.0) a	8.6 (±6.2) a	2.9 (±0.8) a	1.9 (±0.8) a	298 (±27) a	276 (±31) a	152 (±12) a	167 (±33) a
	Oregano	25.4 (±3.1) b	19.7 (±2.5) a	8.3 (±3.9) a	6.9 (±3.4) a	1.8 (±0.6) b	1.5 (±1.0) a	287 (±33) a	266 (±41) a	140 (±26) a	182 (±35) a
	Thyme	24.0 (±2.1) b	20.1 (±2.8) a	5.4 (±2.6) a	8.1 (±6.1) a	2.2 (±0.6) ab	1.7 (±0.9) a	249 (±26) b	286 (±66) a	137 (±16) a	194 (±53) a

Note: na = data not available; nd = soil content not detectable.

Soil nitrate (NO_3-N) was highest at extreme soil moisture status (i.e., extremely dry) in October 2018, and moist in October 2020. In topsoil samples taken in October 2018, the cultivation of aromatic plants caused a consistent reduction of NO_3-N. In contrast, a slight increase of NO_3-N across both intercropping treatments was detected in October 2019. Soil ammonium (NH_4-N) was uniformly reduced in topsoil due to intercropping, whereas statistical significance was given only in April 2019 and October 2020. Plant-available potassium (K) in both topsoil and subsoil was highest in October 2018, and dropped afterwards. Intercropping consistently reduced available K in topsoil samples from April 2019 onward, and was uniformly significant in October 2019 and April 2020. Plant-available phosphorus (P) was consistently lower in topsoil samples due to intercropping throughout the experiment. Despite a significant decrease in October 2018, K and P in the subsoil were largely unaffected by intercropping.

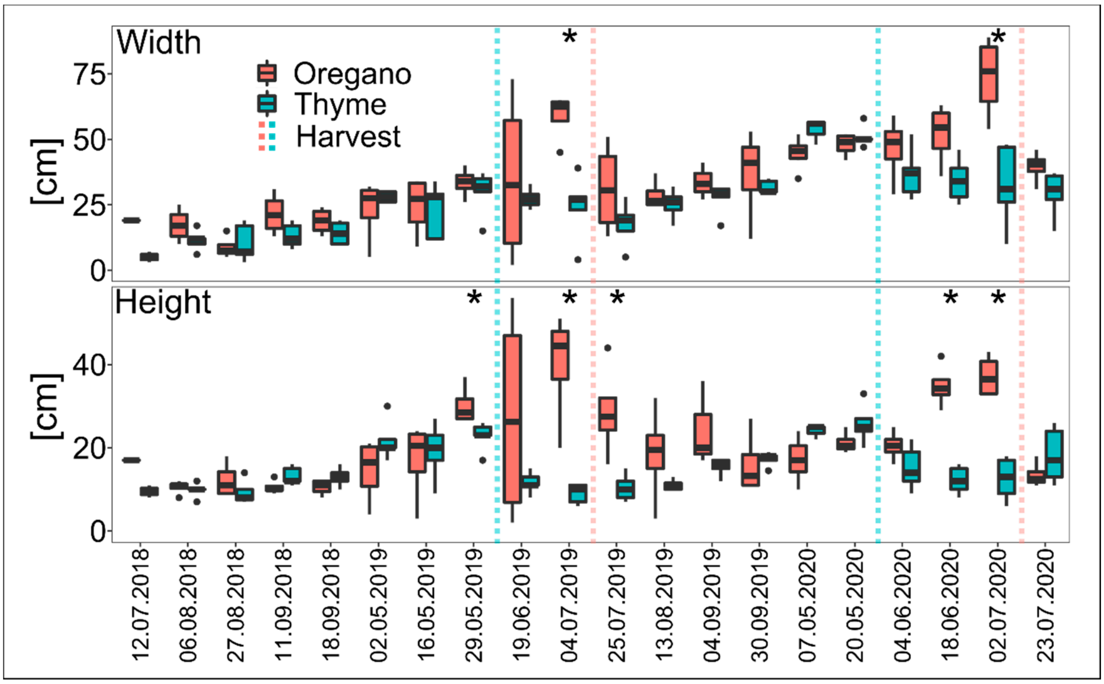

Figure 3. Vegetative development of oregano (red) and thyme (blue) intercrops over two years after planting as indicated by plant width (upper panel) and height (lower panel). Plant width was measured orthogonal to the grapevine row direction. The vertical dashed lines represent harvest dates of aromatic plants. Asterisks (*) indicate significant differences between aromatic plants at p-levels < 0.05.

3.3. Grapevine Performance and Harvest Properties

Grapevine yield and must quality indices as affected by time and treatment are shown in Table 3. Generally, significant differences were dominantly attributable to the different years, rather than to the treatments. Overall crop yields per plant and hectare did not significantly differ between 2018 and 2020. However, in 2019, a clear tendency toward reduced productivity was observed, indicating significantly lower (~20%) yields per hectare. Although more cluster numbers were produced, their lower weight negatively affected yields as compared to the other years. The principal component analysis revealed a clear separation according the three experimental years (Figure 4), whereas no clear separation could be detected by grouping according to the experimental treatments. Furthermore, yields per hectare were closely associated with cluster weights, and opposed the quality indices juice pH and concentrations of total soluble solids (TSS), which were highest in 2019. Concomitantly, must pressed in 2019 showed the lowest amounts of titratable acidity (TA) (Table 3).

Table 3. Mean values (± standard deviation in brackets) of the grapevine yield and must quality indices as affected by time and treatment. The row total considers all observations from the respective year. Numbers followed by capital letters indicate significant differences between years, whereas numbers followed by lowercase letters indicate significant differences within one year between the experimental treatments. Significance was given at p-level < 0.05.

Indices	Treatment	2018	2019	2020
Crop yield (kg/plant)	Total	1.6 (±0.5) A	1.3 (±0.5) A	1.6 (±0.8) A
	Control	1.6 (±0.3) a	1.2 (±0.3) a	1.8 (±0.9) a
	Oregano	1.8 (±0.4) a	1.3 (±0.4) a	1.3 (±0.6) a
	Thyme	1.4 (±0.6) a	1.4 (±0.7) a	1.6 (±1.0) a
Crop yield (kg/ha)	Total	6749 (±536) A	5393 (±698) B	6901 (±1118) A
	Control	6632 (±327) a	5059 (±1108) a	7249 (±1105) a
	Oregano	7113 (±802) a	5329 (±244) a	5952 (±1236) a
	Thyme	6501 (±297) a	5791 (±498) a	7501 (±426) a

Table 3. *Cont.*

Indices	Treatment	2018	2019	2020
Produced clusters (number/plant)	Total	20.9 (±4.8) AB	24.5 (±5.8) A	18.2 (±7.8) B
	Control	22.2 (±5.3) a	23.7 (±5.2) a	20.0 (±5.2) a
	Oregano	22.4 (±3.7) a	25.1 (±7.0) a	13.5 (±6.7) a
	Thyme	18.1 (±4.2) a	24.7 (±5.9) a	19.6 (±9.9) a
Cluster weight (g)	Total	94B (±20) B	75 (±21) C	111 (±32) A
	Control	89 (±22) a	77 (±22) a	107 (±36) a
	Oregano	96 (±23) a	72 (±21) a	114 (±18) a
	Thyme	96 (±15) a	75 (±21) a	112 (±41) a
Juice pH	Total	2.9 (±0.05) C	3.3 (±0.12) A	3.2 (±0.10) B
	Control	2.8 (±0.06) a	3.3 (±0.20) a	3.1 (±0.10) a
	Oregano	2.9 (±0.05) a	3.2 (±0.05) a	3.1 (±0.09) a
	Thyme	2.9 (±0.04) a	3.2 (±0.04) a	3.2 (±0.11) a
Titratable acidity (g/L)	Total	9.0 (±0.7) A	7.8 (±0.5) B	9.2 (±1.4) A
	Control	9.3 (±0.7) a	7.3 (±0.2) b	9.5 (±1.9) a
	Oregano	9.0 (±0.6) a	8.0 (±0.4) a	8.7 (±0.7) a
	Thyme	8.6 (±0.5) a	8.0 (±0.4) a	9.4 (±1.3) a
Total soluble solids (°Brix)	Total	21.4 (±1.3) A	22.1 (±1.5) A	19.3 (±1.6) B
	Control	20.9 (±1.7) a	22.2 (±1.2) a	18.7 (±1.2) a
	Oregano	21.7 (±1.1) a	22.3 (±2.2) a	20.1 (±2.2) a
	Thyme	21.5 (±1.2) a	21.9 (±0.9) a	19.2 (±1.0) a

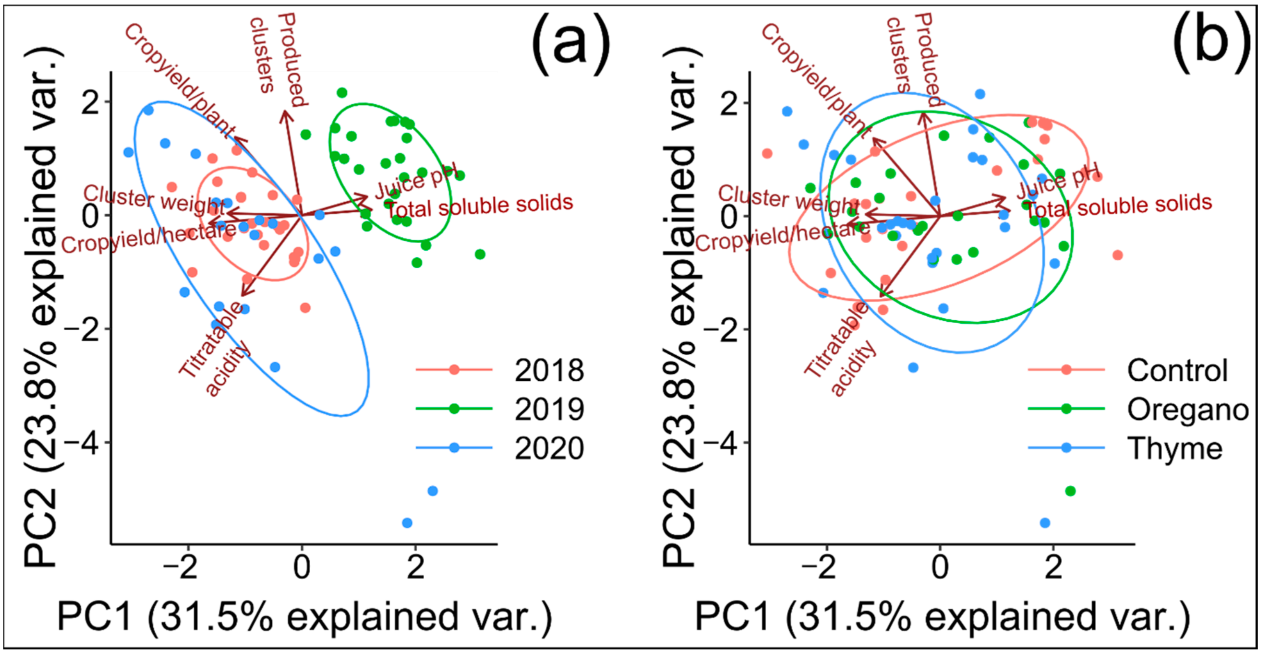

Figure 4. The principal component analysis of the grapevine yield and must quality indices grouped according to the three experimental years (**a**) and the experimental treatments (**b**) considering monocropped and intercropped grapevines.

In 2018, grapevines intercropped with thyme tended to produce a lower number of clusters, corresponding to lower overall yields, whereas the opposite was true for grapevines intercropped with oregano. The trend to depressed yields of grapevines intercropped with thyme was more pronounced in terms of yield per plant (−17%) than for yields per hectare (−5%). Apparently, the average cluster weight did not respond accordingly, and intercropped grapevines tendentially produced heavier clusters when compared to control rows. This consistent response of intercropped grapevines is in line with a trend to higher juice pH values, lower amounts of TA, and increased concentrations of TSS.

In 2019, the productivity of intercropped grapevines showed a uniform trend toward more produced clusters and slightly increased (~10%) overall crop yields per plant and hectare. With regard to this, grapevines intercropped with thyme tended to be slightly more productive as compared to oregano. In contrast, control grapevines tendentially produced heavier clusters. In accordance with the previous year, intercropping mixed cultivation similarly affected must quality in 2019: slightly lower juice pH values corresponded to significantly higher (8.0 vs. 7.3 g/L) amounts of TA.

In 2020, grapevines intercropped with oregano showed a clear trend to reduced (−20%) yields per plant and hectare, following the trends of least numbers, but heaviest weights of clusters. Suitably, juice quality of grapevines intercropped with oregano tended to show lower amounts of TA and higher concentrations of TSS.

4. Discussion

4.1. Effects of Weather Conditions and Crop Plant Diversification

The presented results approve the vital importance of water as a key driver for both biotic and abiotic processes relevant to vineyard productivity. Generally, grapevine yield is composed of several components (e.g., the number of clusters and their weight), and is shaped by the temporal expression of interacting climatic (amount and distribution of precipitation, evaporation), pedological (ability to store and supply water and nutrients), and viticultural (choice of cultivar and rootstock, training system, pruning level, and irrigation) factors [43–45].

Overall, grapevine yields in our study were comparable to those reported from other vineyards [3]. The total amount and distribution of precipitation varied markedly and shaped the general conditions for plant growth. As yield formation was determined over two crop cycles [46,47], the yields seemed to largely depend on the water availability in QIII and QIV of the previous year, when grapevines usually replenish resources, supporting early-phase development in the following year [48]. Additionally, the distinct differences in precipitation recorded during QI restored soil water resources, which were subsequently supplied to grapevines in QII and enabled vigorous growth and a lush canopy development. Consequently, high precipitation sums in QIII and QIV in 2017 and 2019 pre-determined high yield levels in 2018 and 2020, which were realized by comparably high precipitation sums during QI in 2018 and 2020. In addition, significantly more days with an average temperature above 5 °C were recorded in QI of 2020. This threshold temperature is considered as the lower baseline at which grapevine vegetative growth is induced [49,50]. Hence, considerably more vegetation days in QI of 2020 enabled early vegetative grapevine development, and were finally contributing to the highest yields in 2020 measured during the experimental period. Expression of yield components was inversely related in 2019 and 2020, i.e., most numbers, but lightest weights of clusters in 2019, and vice versa in 2020. This response confirmed the yield component compensation principle [51], which states that grapevines compensate modifications of one yield component by changing levels of another yield component, and may offset the loss of yield potential. Must quality responded accordingly and revealed a measurable vintage effect [44], with highest pH values and lowest amounts of titratable acidity found in must from berries harvested in 2019. Apparently, the intense precipitation in QIII of 2019 raised soil moisture levels and favored high nutrient-uptake rates, resulting in a prominent depletion of all measured nutrients in the topsoil. Particularly, the K uptake, due to its neutralizing effect on organic acids [52,53], directly affected must quality. In addition, lower cluster weights and presumably lighter and smaller berries containing relatively higher concentrations of total soluble solids also suggested an indirect impact on must quality [3].

Intercropping and associated cultural practices showed both beneficial and detrimental effects (mostly insignificant) on grapevine yields. Generally, a reducing effect on grapevine growth and yield can be expected due to resource competition, particularly in case of complete and permanent vineyard soil cover, and was also reported from cover-cropping studies conducted in vineyards all over the world [12,54,55]. Clear tendencies toward decreased yields were observed for intercropping with thyme in 2018 and oregano in 2020. In both cases, lower yields were associated with a clear trend toward the production of smallest numbers of clusters. However, clusters tended to be even heavier compared to those from monocropped grapevines. These contrasting effects on yield parameters might be attributable to the compensation principle stated above, but yield losses were not compensated in the case of intercropping with thyme (2018) and oregano (2020), respectively. It must be noted that soil moisture and nutrient levels, determined shortly after harvest, were slightly lower in rows diversified with oregano and thyme compared to control rows. However, they were largely similar between both intercropping treatments so that additional, presumably dynamic factors contributed to the diverse response of yield indices. In this context, water deficits and other stresses during early stages of grapevine development (i.e., around blossom) may induce embryo abortion, poor fruit set, and reduced cluster numbers [48,51]. It must be assumed that stress events of intercropped grapevine rows occurred during QII and/or QIII in 2018 and 2020.

The extreme erosion event in June 2018 resulted in soil losses that were manifoldly higher in rows intercropped with thyme. With respect to the remarkable difference in soil loss between rows intercropped with thyme and oregano, it is likely that minor pedological and topographical variabilities between the recently prepared and planted rows induced a concentrated flow of surface water during the heavy rain event. It is assumed that this event, just at the time of grapevine blossom, induced short-term physiological stress, because a typical consequence of soil erosion is root exposure [56]. Thus, it appears reasonable that the soil-erosion event exposed near-surface secondary site roots of the grapevines and affected the soil-root-shoot-fruit pathway, with negative implications for cluster numbers and yields, as well as for the amount of titratable acidity. In a comprehensive study on the effects of soil erosion on vineyard production across Europe [3], reduced productivity (in terms of overall yields, cluster numbers, and weights) and higher levels of maturity (as indicated by lower amounts of titratable acidity and excessive concentrations of sugar) have been reported for grapevines grown on degraded vineyard plots. However, there is good reason to assume that once diversification crop plants are established, they will substantially contribute to a reduction in soil erosion [57].

Furthermore, the fact that grapevines intercropped with thyme in 2018 were finally capable of producing cluster weights and concentrations of total soluble solids comparable to those of grapevines intercropped with oregano suggests that stress in the early stage of development was of minor importance during berry ripening (veraison). Sugar accumulation and berry growth (due to water import) rapidly increased with the beginning of veraison, and water supply during this developmental phase is even more critical for cluster weights and must quality [51]. In this context, intercropped grapevines apparently profited from manual irrigation applied from the beginning of veraison to prevent withering of intercrop seedlings. On one hand, this measure increased intercrop management intensity and inputs, but in turn, was effective in partially redeeming the developmental drawbacks of grapevines intercropped with thyme, and even increased yields of grapevines intercropped with oregano in comparison to monocropped grapevines managed without additional irrigation.

4.2. Competition between Grapevine and Diversification Crops

Increased yields were also observed for both intercropping treatments in 2019. Because consistent reductions of mineral nutrients (i.e., NH_4-N, K (significantly in October), and P) were observed in topsoil samples of both intercropping treatments throughout 2019, availability of water, rather than nutrients, seemed to be the driving factor for overall vineyard productivity. This finding is in line with several studies that considered soil water availability as the most influential soil component in vineyards (rather than nutrient availability or composition) [43,45]. Another indicator that nutrient competition between grapevines and intercrops was of minor importance was the differentiated response of NO_3-N and NH_4-N to intercropping. NO_3-N is considered the primary nitrogen source for grapevines [51,53,58]. Our results rejected the concern of competition for NO_3-N among grapevines and aromatic plants, which is explained by the strong overall regulation of NO_3-N availability by soil moisture levels. In contrast, NH_4-N with lower mobility in soil was consistently reduced by both species of aromatic plants, indicating their higher affinity and demand toward NH_4-N. Additionally, differences in nutrient status between control (monocropping) and the diversified cropping systems (oregano, thyme) further declined with soil depth (soil layer from 0.1–0.3 m; Table 2). Generally, the rooting depth of grapevine is substantially deeper than that of aromatic plants [59–61]. Hence, we concluded that differences in the nutrient status of the top layer (0–0.1 m) were mostly related to the impact of the diversification plants, while nutrient uptake in the deeper soil was dominated by grapevine and largely unaffected by monocropping and diversified cropping.

Following the necessity of irrigation measures to prevent intercrop withering in 2018 and 2019, the intercropped rows did not receive additional water in 2020. Hence, the substantially lower yields per hectare of grapevines intercropped with oregano suggest severe water limitation by competition. Considering that the oregano was harvested about six weeks later than the thyme in 2020, increased/longer water consumption during periods of rare precipitation appears to be the critical driver for lower yields of grapevines intercropped with oregano. In a comparative study on oregano and thyme performance under open-field and shade-enclosure conditions [62], oregano showed a higher leaf area and increased transpiration, and produced significantly more below- and above-ground biomass. Although the aforementioned study did not report effects on soil resources, we assumed that the higher primary production was associated with a higher consumption of soil resources. However, on both sampling dates in 2020, no significant or distinct differences regarding nutrient concentrations were found among the intercropping treatments. Consequently, oregano seems to be more competitive than thyme, due to an assumed higher consumption of soil water. This assumption was furthermore underlined by a higher root biomass of oregano found at the end of the experiment in 2020.

Interestingly, the amounts of titratable acidity of must obtained from both intercropping treatments were significantly higher in 2019 than for must obtained from control grapevines. Again, the slightly lower cluster weights of intercropped grapevines may have had indirect effects on must quality. However, as the cultivation of aromatic plants also significantly lowered K levels in topsoil samples determined soon after harvest, a direct effect on must quality was most likely attributable to competition for K between intercrops and grapevines. In a review on cover-cropping impacts on grapevine growth and must quality [12], mostly decreased amounts of titratable acidity were found in must from cover-cropped vineyards. However, given the desired wine style in the area, aiming for a well-balanced ratio of sugar and acidity, the higher acidity level maintained in musts from intercropped grapevines is considered positive, when comparing the low level of acidity with musts from the other experimental years.

5. Conclusions

The results of the experimental field study showed that crop-plant diversification using aromatic plants in vineyards can be successfully established. This comports with impacts of intercropping grapevines with aromatic plants on grapevine yield and must quality, as well as soil water and nutrient levels. Our study revealed the potential, but also the possible vulnerabilities, of crop diversification in vineyards. We conclude that climatic variability between the years was the most important factor determining yields, and extreme weather events can induce a significant reduction in productivity. Additionally, we also observed some insignificant yield losses due to intercropping, particularly induced by water competition. With respect to this, thyme appears to be less competitive due to an earlier harvest date and a lower respectively shorter consumption of soil water during the crop cycle. Generally, water competition will be less pronounced in soils with a higher water-storage capacity. Management measures such as irrigation are an option to alleviate competition between grapevines and aromatic plants to ensure long-term vineyard productivity. As irrigation is already widely applied in many viticultural areas around the world, and its further implementation in vineyards, especially in the Mosel region, may become a necessary management tool in the near future due to global climate change, intercrop marketing can be a viable cross-financing option for irrigation investment. However, we found that competition is not necessarily detrimental, and beneficial effects on must quality due to intercropping were found. Especially under high moisture regimes during veraison, additional competition and nutrient uptake by intercrops may enhance final must and wine quality. On sites that are prone to soil erosion, the timing of intercrop establishment needs to be carefully considered (preferably in periods of moist soil, for better infiltration and rapid juvenile development of seedlings). Soil preparation prior to diversified crop establishment may increase soil vulnerability for erosion compared to non-tilled rows, thus counteracting the expected erosion-reducing effect of diversified cropping in the long term. Furthermore, the long-term effects of intercropping on grapevine growth need to be monitored. An overarching evaluation of crop diversification by intercropping in steep-slope vineyards requires the ongoing assessments of viticultural inputs, economic revenues, soil erosion, infiltration capacity, chemical and biological soil quality, greenhouse gas emissions, and pollinator occurrence.

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