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Yield of Müller-Thurgau and Riesling grapevines is altered by meteorological conditions in the current and previous growing seasons

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Abstract

Methods and results: Window pane analysis showed that pre-bloom and bloom minimum temperatures and precipitation sums in the preceding year, winter temperatures, spring temperatures, and post-veraison minimum temperatures in the current year were positively correlated with annual yield; early spring and post-harvest temperatures in the preceding year, and, for Riesling, pre-bloom precipitation sums and post-bloom maximum temperatures in the current year were negatively correlated with annual yield. Models developed from these data simulated annual yield with high accuracy (R^2_{adj} = 0.88 for Riesling, and R^2_{adj} = 0.92 for Müller-Thurgau).

Conclusions: Meteorological conditions during distinct periods of yield formation are correlated with annual yield. Yield models can be used in practical viticulture as well as in climate change impact studies.

Significance and impact of the study: Enhanced understanding of the effects of meteorological conditions during specific periods of yield formation supports growers' efforts to optimize viticultural measures aimed at achieving adequate yield levels.

Key words: Environmental conditions, meteorological conditions, viticulture, *Vitis vinifera*, window pane analysis, yield formation

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Introduction

Grape yields typically show strong year-to-year variation even if the number of buds retained during winter pruning remains constant. This is because yield formation depends on several internal and external factors and their interactions (Keller, 2015). Briefly, annual yield is determined by (i) the number of inflorescences per bud (defined mostly by the number of inflorescence primordia initiated in the year preceding the harvest year); (ii) the number of buds retained in winter pruning; (iii) the degree of budbreak; (iv) the number of grape berries per cluster (defined by the number of flowers per inflorescence and the degree of fruit set); and (v) the size of the berries. Except for the number of buds (which are limited by the grape grower), the factors that determine yield are highly influenced by environmental conditions. Because inflorescence primordia are initiated in the year preceding the year of harvest, yield formation in grapevine is considered a two-year process (Guilpart *et al.*, 2014). Consequently, grapevine reproductive behaviour is affected by the environmental conditions in both the present as well as the preceding year (De la Fuente *et al.*, 2015).

The grapegrowing region "AOP Moselle Luxembourgoise" is located along the southern, south-eastern or eastern exposed slopes of the Moselle River in Luxembourg. Generally, the following factors are involved in yield formation: (i) the genotype, (ii) the vineyard site, (iii) the training system, (iv) cultural practices, (v) legal aspects and, last but not least, (vi) the seasonal meteorological patterns (Keller, 2015). Since the genotypes (cultivars and rootstocks), vineyard sites, training system (predominantly vertical shoot positioning), cultural practices, and legal aspects (maximum yield limits for wine of certified origin and quality) were relatively constant in Luxembourg over the last quarter-century, regional records of annual grape yields are amenable to statistical analysis investigating the impact of variations in meteorological conditions.

In plant pathology, a statistical approach proposed by Coakley and Line already in 1982 (Kriss *et al.*, 2010), which is now commonly referred to as "window pane analysis", is frequently used to detect critical time windows during which variation in environmental variables leads to variation in disease level. In window pane analysis the mean values of environmental variables (summary environmental variables) with overlapping time frames of different lengths are calculated. Thereafter, correlation coefficients between each summary environmental variable and an observed "target variable" (such as the disease level at the end of a season) are computed (Gouache *et al.*, 2015). The methodology of window pane analysis has been extended to several fungal diseases on numerous crops (Kriss *et al.*, 2010). Recently, Molitor *et al.* (2016) used window pane analysis to investigate the influence of environmental conditions on the thermal-temporal development of bunch rot (causal agent: *Botrytis cinerea*) epidemics on grape (*Vitis vinifera*) clusters.

So far, window pane analysis has been used primarily in plant pathology to enhance understanding of patho-systems, improve disease management, and develop forecast models (Gouache *et al.*, 2015). The general methodological construction of window pane analysis, however, should facilitate its application in other fields.

The objective of the present study was to use this statistical approach to detect critical time windows for the formation of annual crop yields in wine grapes. The statistical analysis leveraged a 22-year data set of average annual yields of two of the most widely grown cultivars in Luxembourg (Müller-Thurgau: 323.6 ha; Riesling: 160.2 ha; total: 1294.6 ha (2014; data source: IVV, Remich)). Specific goals were to (i) quantify the impact on harvest yield of meteorological variables during specific periods of yield formation; (ii) identify meteorological variables with predictive value; and (iii) develop models to simulate the annual yield based on meteorological data.

Materials and methods

1. Annual yield records

Total harvested yields (hectolitre (hl); 10 hl of must ≈ 1.3-1.4 t of grapes) for the years 1993 to 2015 of all vineyards of a specific grape cultivar in the Luxembourgish grapegrowing region were recorded by the Institut Viti-vinicole (IVV) in Remich, Luxembourg. Based on these records and the documented vineyard surface area of each cultivar, average cultivar-specific yields (hectolitre per hectare) were calculated for *Vitis vinifera* L. cv. Riesling and Müller-Thurgau (Table 1).

Vineyards in Luxembourg are predominantly cane pruned and trained to vertical shoot-positioning systems. Vine spacing varies from 1.6 to 2 m between rows and from 1.0 to 1.3 m within rows (3800-6200 vines/ha). The major rootstock is SO4. Vineyards are generally not irrigated. During the period of observation, legal maximum limits (yield per hectare)

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for wine of certified origin and quality were constant (Riesling : 120 hl/ha ; Müller-Thurgau : 140 hl/ha). Despite these maximum limits, yield reduction (e.g., by cluster thinning) is not a common practice in the region. Growers have the option to (i) compensate high yields (above the legal limit) in one cultivar by lower yields in another cultivar or (ii) market their wines without certified origin and quality. Consequently, legal limits were occasionally exceeded (Table 1) and did not present a limitation to our analysis.

2. Meteorological and phenological data

Meteorological data were recorded from 1992 through 2015 by a weather station of the national agricultural administration ASTA (Administration des services techniques de l'agriculture) located in the centre of the Luxembourgish grapegrowing region in Remich/Luxembourg (49.54° N, 6.35° E ; 207 m a.s.l.). Vineyards of the region AOP Moselle Luxembourgoise are located in a radius of maximal 20 km around this weather station ; altitudes of vineyards range between 130 and 300 m a.s.l. Air temperatures were measured at 2 m and precipitation at 1 m above the ground. Daily mean temperatures were calculated from daily minimum and maximum temperatures. To test for significant trends during the period of observation (1993-2015), linear correlations between the year (independent variable) and crop as well as meteorological parameters (dependent variables) were calculated. Trends were considered significant if $p \leq 0.05$.

For further statistical analysis, the meteorological data sets were arranged for both cultivars in one of two ways : (i) relative to 1 January (01/01 : day of year (DOY)); or (ii) relative to the date of bloom (D_{68} for BBCH 68 : 80 % of flower caps fallen). The BBCH (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie) scale according to Lorenz *et al.* (1995) describes the phenological growth

Table 1 - Average annual yield (hl/ha) in Luxembourg for the wine grape cultivars Müller-Thurgau and Riesling, as well as key annual and growing season (April – October) meteorological variables (meteorological data from Remich).
Correlations between years and yield as well as the meteorological parameters were calculated.
Trends were considered significant if $p \leq 0.05$.

Year	Yield Müller-Thurgau (hl/ha)	Yield Riesling (hl/ha)	Mean annual temperature (°C)	Mean growing season temperature (°C)	Annual precipitation sum (mm)	Growing season precipitation sum (mm)
1993	137	96	9.9	14.4	737	437
1994	147	94	11.1	14.9	741	451
1995	130	77	10.6	15.3	816	387
1996	118	78	9.0	13.9	534	280
1997*	49	64	10.4	14.7	785	461
1998	142	102	10.2	14.6	790	560
1999	162	110	11.3	15.3	732	409
2000	109	95	11.3	15.3	948	596
2001	122	72	10.7	15.3	994	562
2002	140	98	11.1	15.0	776	414
2003	123	92	11.8	16.7	618	377
2004	153	97	10.9	15.7	638	432
2005	119	89	11.1	16.1	523	324
2006	126	80	11.6	16.7	714	459
2007	129	104	11.6	15.9	837	503
2008	116	86	11.1	15.3	759	435
2009	135	94	11.1	15.9	749	381
2010	105	65	10.0	15.0	695	388
2011	135	88	11.4	15.5	533	287
2012	82	76	10.3	14.4	700	449
2013	101	60	9.9	14.7	813	576
2014	120	86	11.8	15.9	722	444
2015	107	69	11.5	15.6	540	347
Average	125.4	86.7	10.9	15.3	726	433
Trend ($p \leq 0.05$)	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

* Due to severe late frost damage, the yield of the 1997 vintage was not considered in the statistical analyses.

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Table 2 - Average dates of BBCH 09 (budbreak), 63 (early bloom : 30 % of caps fallen), 68 (80 % of caps fallen) and 81 (beginning of ripening) in Luxembourg for the wine grape cultivars Müller-Thurgau and Riesling.

Data were arranged relative to 1 January (DOY) or relative to the date of BBCH 68 (D_{68}). No data for BBCH 81 in Riesling were available. Correlations between years and dates of phenological stages were calculated. Trends were considered significant if $p \leq 0.05$. Data source : Institut Viti-vinicole, Remich.

	Müller-Thurgau								Riesling					
	BBCH 09		BBCH 63		BBCH 68		BBCH 81		BBCH 09		BBCH 63		BBCH 68	
	DOY	D_{68}	DOY	D_{68}	DOY	D_{68}	DOY	D_{68}	DOY	D_{68}	DOY	D_{68}	DOY	D_{68}
1993	116	-48	158	-6	164	0	224	60	116	-49	159	-6	165	0
1994	118	-58	172	-4	176	0	227	51	119	-59	173	-5	178	0
1995	120	-61	177	-4	181	0	230	49	120	-61	177	-4	181	0
1996	119	-61	172	-8	180	0	236	56	119	-62	171	-10	181	0
1997*	115	-63	166	-12	178	0	230	52	115	-63	166	-12	178	0
1998	120	-54	169	-5	174	0	232	58	120	-52	166	-6	172	0
1999	117	-56	167	-6	173	0	230	57	119	-54	167	-6	173	0
2000	117	-49	162	-4	166	0	228	62	115	-51	162	-4	166	0
2001	126	-50	172	-4	176	0	229	53	126	-50	172	-4	176	0
2002	113	-58	167	-4	171	0	227	56	113	-58	167	-4	171	0
2003	111	-51	158	-4	162	0	217	55	111	-51	159	-3	162	0
2004	116	-61	169	-8	177	0	235	58	114	-64	171	-7	178	0
2005	113	-60	169	-4	173	0	225	52	115	-59	169	-5	174	0
2006	122	-51	168	-5	173	0	226	53	125	-51	171	-5	176	0
2007	104	-50	145	-9	154	0	214	60	106	-51	148	-9	157	0
2008	122	-46	160	-8	168	0	224	56	125	-46	162	-9	171	0
2009	108	-61	161	-8	169	0	220	51	110	-62	165	-7	172	0
2010	117	-60	171	-6	177	0	226	49	119	-60	173	-6	179	0
2011	105	-50	148	-7	155	0	210	55	105	-50	148	-7	155	0
2012	117	-57	166	-8	174	0	228	54	119	-57	168	-8	176	0
2013	123	-62	179	-6	185	0	233	48	126	-62	182	-6	188	0
2014	102	-61	158	-5	163	0	219	56	104	-62	161	-5	166	0
2015	119	-50	166	-3	169	0	218	49	118	-51	166	-3	169	0
Av.	116	-56	165	-6	171	0	226	54	116	-56	166	-6	172	0
Trend ($p \leq 0.05$)	n.s.		n.s.		n.s.		r=-0.422 p=0.045		n.s.		n.s.		n.s.	

stages of grapevine. Compared with calendar-based arrangements, arranging meteorological data sets relative to the date of a key phenological event allows time series analyses that are less biased regarding differences in plant development in different growing seasons (Molitor *et al.*, 2016). The date at which BBCH 68 occurred was recorded each year for both cultivars by trained and experienced local observers in all major viticultural areas of Luxembourg. Dates used in the present analysis are average dates, by cultivar, for the whole region. Additional phenological events were similarly recorded annually for the two cultivars (Table 2).

3. Window pane analysis

The impact of the following environmental variables on the average annual crop yields (hl/ha) of the cultivars Müller-Thurgau and Riesling was investigated :

- (i) daily maximum temperatures ;
- (ii) daily minimum temperatures ;
- (iii) daily mean temperatures ;
- (iv) daily precipitation.

Window pane analysis was conducted, to determine critical periods during the preceding year (year -1) or the present crop year (year 0). These critical periods were defined as time windows during which environmental variables may impact yield. Time windows of 10, 20, 30 or 50 days were tested. Windows were moved along the time frame between (i) DOY 1 and DOY 365, or (ii) 150 days prior to D_{68} (= -150 days after D_{68}) and 125 days thereafter in daily steps. Mean values of the environmental variables during each specific window (= summary environmental variables (Kriss *et al.*, 2010)) were calculated separately for each data set. Correlation analysis was conducted for each cultivar, each window width and each starting date to determine

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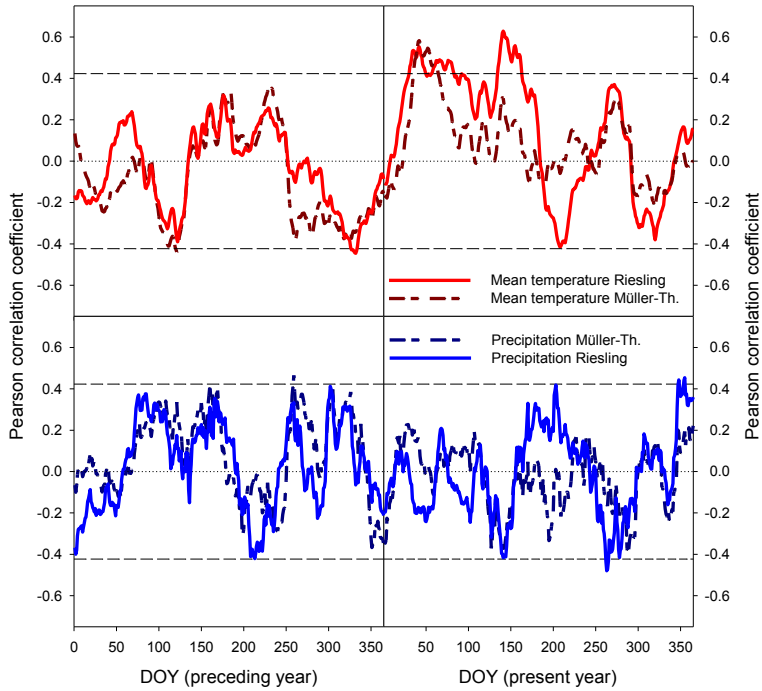


Figure 1 - Pearson correlation coefficients (r) for the association between summary environmental variables (summary daily mean temperature, red/red-brown ; summary daily precipitation, blue/dark blue) and average annual yields of the wine grape cultivars Müller-Thurgau (dashed line) and Riesling (solid line) in Luxembourg.

Pearson r values were calculated for different time windows depending on the starting date of a window, using 30-day windows according to window pane analysis, and shown on the last day of each window. Data were arranged relative to 1 January (day of year, DOY). Results are shown for the year preceding harvest (left panel) and the year of harvest (right panel). Dotted horizontal lines indicate r = 0 ; dashed horizontal lines indicate the critical (positive and negative) r (at p = 0.05).

associations between each summary environmental variable and the average annual yields. Pearson correlation coefficients (r) and significance levels (p) were determined for each summary environmental variable (n = 22 years). Window pane analysis was run for both types of data arrangements as defined above under Meteorological and phenological data. In the DOY-based approach, calculations were not interrupted at the turn of the year when the window width extended outside the year. Due to severe spring frost damage, the 1997 yields were excluded from the statistical analysis.

4 - Development of yield models

Yield models were developed and tested in IBM SPSS Statistics 19 (IBM, Armonk, NY, USA). The Automatic Linear Modelling approach with forward stepwise input parameter elimination was used to simulate yields for Müller-Thurgau and Riesling. Summary environmental variables in the present or the preceding year that were significantly correlated with yield were used as potential input parameters for both types of data arrangement. To minimize redundancy, those potential input parameters were restricted to summary environmental variables representing a local maximum of the absolute values in a series of significant Pearson correlation coefficients. Furthermore, because daily maximum, minimum, and mean temperatures are not independent, only the summary temperature variable with the highest absolute r value was considered when more than one of the three temperature variables showed a significant correlation with yield in any specific period. The decision regarding entry or removal of input parameters into the model was based on the Akaike information criterion. This approach balances the number of input parameters and the complexity of the model ; i. e., the benefit of adding an additional input parameter to the model has to outweigh the increase in model complexity it causes. Model robustness was tested by leave-one-out cross validation. Model accuracy (adjusted R^2), mean bias errors (MBE), and mean absolute errors (MAE) were calculated.

Results

1. Observation data

During the study period, budbreak (BBCH 09) on average occurred on DOY 116 (Müller-Thurgau and

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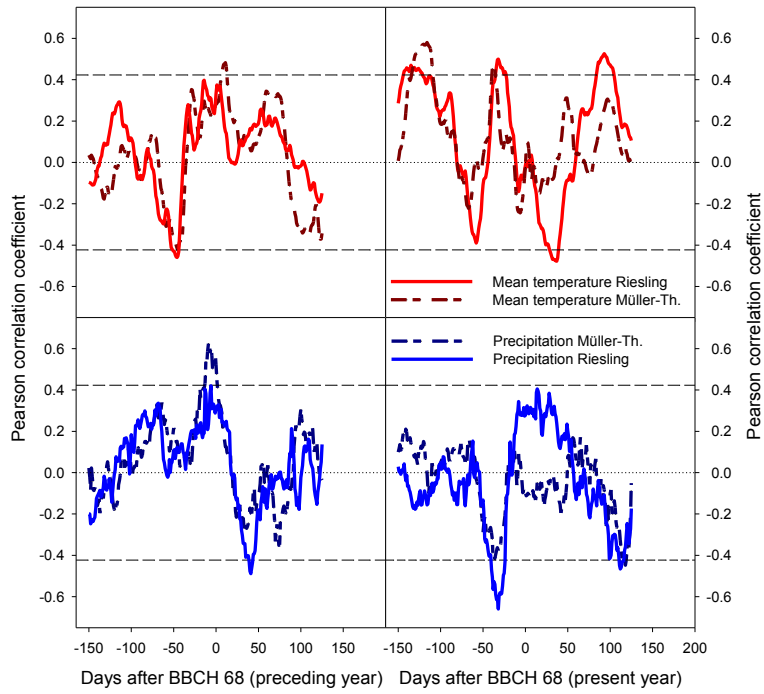


Figure 2 - Pearson correlation coefficients (r) for the association between summary environmental variables (summary daily mean temperature, red/red-brown; summary daily precipitation, blue/dark blue) and average annual yields of the wine grape cultivars Müller-Thurgau (dashed line) and Riesling (solid line) in Luxembourg.

Pearson r values were calculated for different time windows depending on the starting date of a window, using 30-day windows according to window pane analysis, and shown on the last day of each window. Data were arranged relative to the date of BBCH 68. Results are shown for the preceding (left) and the present (right) year. Dotted horizontal lines indicate r = 0; dashed horizontal lines indicate the critical (positive and negative) r (at p = 0.05).

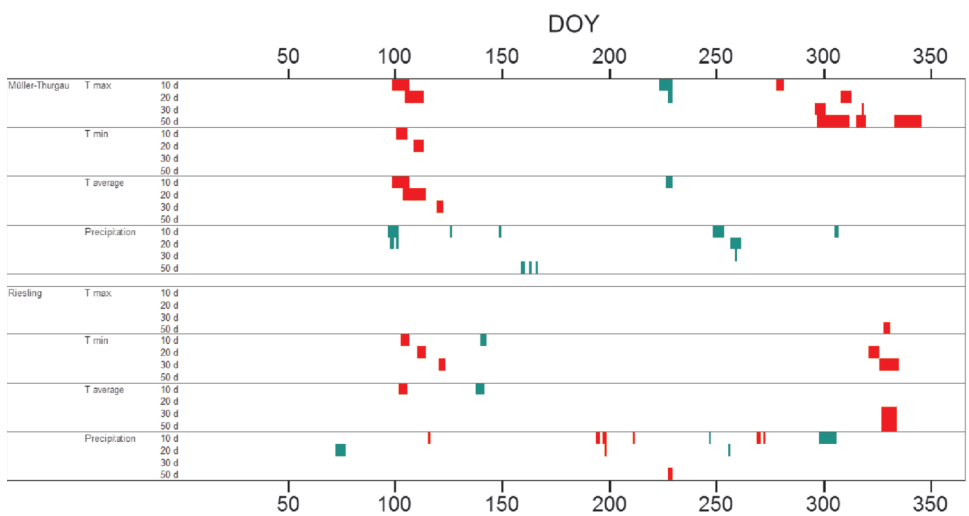


Figure 3 - Significant positive (green) or negative (red) correlations (significance level: $p \leq 0.05$) between the summary daily minimum temperatures, summary daily maximum temperatures, summary daily mean temperatures and summary daily precipitations in different temporal windows (10 days, 20 days, 30 days, 50 days) and the average annual grape yields (hl/ha) in Luxembourg for the wine grape cultivars Müller-Thurgau (upper panel) and Riesling (lower panel) depending on (i) the starting date of a window (DOY) and (ii) the window width according to window pane analysis.

Data were arranged relative to 01/01 for the year preceding the year of harvest (year -1). Correlation coefficients are depicted on the last day of each temporal window.

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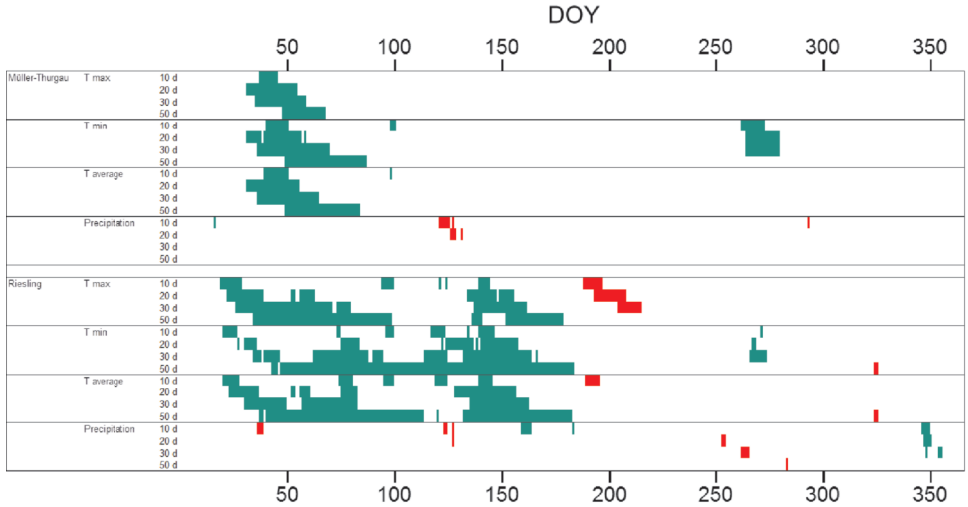


Figure 4 - Significant positive (green) or negative (red) correlations (significance level : $p \leq 0.05$) between the summary daily minimum temperatures, summary daily maximum temperatures, summary daily mean temperatures and summary daily precipitations in different temporal windows (10 days, 20 days, 30 days, 50 days) and the average annual grape yields (hl/ha) in Luxembourg for the wine grape cultivars Müller-Thurgau (upper panel) and Riesling (lower panel) depending on (i) the starting date of a window (DOY) and (ii) the window width according to window pane analysis.

Data were arranged relative to 01/01 for the year of harvest (year 0).

Correlation coefficients are depicted on the last day of each temporal window.

Riesling), with the earliest budbreak occurring on DOY 102 (Müller-Thurgau) and DOY 104 (Riesling). Bloom (BBCH 68) was observed on average on DOY 171 (Müller-Thurgau) or DOY 172 (Riesling). The date of veraison (BBCH 81) was recorded for Müller-Thurgau on average on DOY 226; no records for Riesling were available. There were no significant trends in the dates of the major phenological stages during the study period except for the date of veraison of Müller-Thurgau, which occurred earlier in recent years ($r = -0.42$; $p = 0.045$) (Table 2). Müller-Thurgau yields were on average 45 % higher than Riesling yields ($p < 0.001$). While the yields in years -1 and 0 were not correlated, there was a significant correlation ($r = 0.74$; $p < 0.0001$) between the yields of the two cultivars in year 0. Correlation analysis revealed no significant temporal trends in yield of either cultivar or in meteorological parameters between 1993 and 2015 (Table 1). No significant correlations were observed between yield and mean meteorological conditions (annual mean temperature, mean growing season temperature, annual precipitation sum, growing season precipitation sum) in either the year preceding harvest (year -1) or the year of harvest (year 0).

The mean annual temperature and the mean growing season temperature in year 0 were positively correlated ($r = 0.84$; $p < 0.0001$) as were the mean annual precipitation and the mean growing season precipitation ($r = 0.85$; $p < 0.0001$).

2. Impact of environmental conditions on grape yields

Figure 1 and Figure 2 show examples of window pane analyses, using 30-day windows for the summary daily mean temperature and summary daily precipitation, for both cultivars and both types of data arrangement. As a general concept of window pane analysis, the correlation coefficient depicted on day x represents the correlation between a mean summary environmental variable for the period between day x-29 and day x and the average Müller-Thurgau or Riesling yields in Luxembourg. Significant correlations of yields with temperatures were more common early in the year than later on, and significant correlations with precipitation were rare in both cultivars. All significant positive (green) and negative (red) correlations between the tested summary environmental variables and the average yields for Müller-Thurgau (upper panel) and Riesling (lower panel), according to (i) starting date of a window and (ii) window width (10 days, 20 days, 30 days, or 50 days), are shown in Figure 3 to Figure 6.

Correlations are presented for both year -1 and year 0, and for both types of data arrangement : relative to

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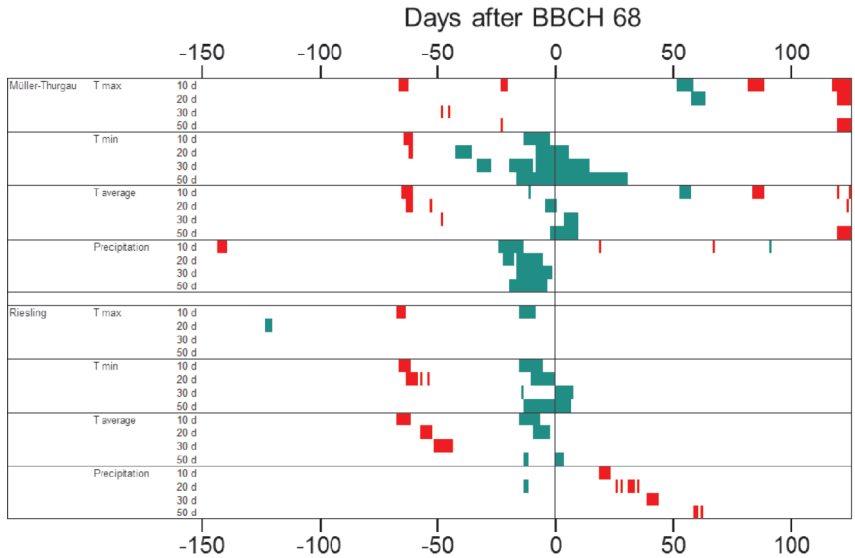


Figure 5 - Significant positive (green) or negative (red) correlations (significance level: $p \leq 0.05$) between the summary daily minimum temperatures, summary daily maximum temperatures, summary daily mean temperatures and summary daily precipitations in different temporal windows (10 days, 20 days, 30 days, 50 days) and the average annual grape yields (hl/ha) in Luxembourg for the wine grape cultivars Müller-Thurgau (upper panel) and Riesling (lower panel) depending on (i) the starting date of a window (relative to the date of BBCH 68) and (ii) the window width according to window pane analysis.

Data were arranged relative to the date of BBCH 68 for the year preceding the year of harvest (year -1).
Correlation coefficients are depicted on the last day of each temporal window.

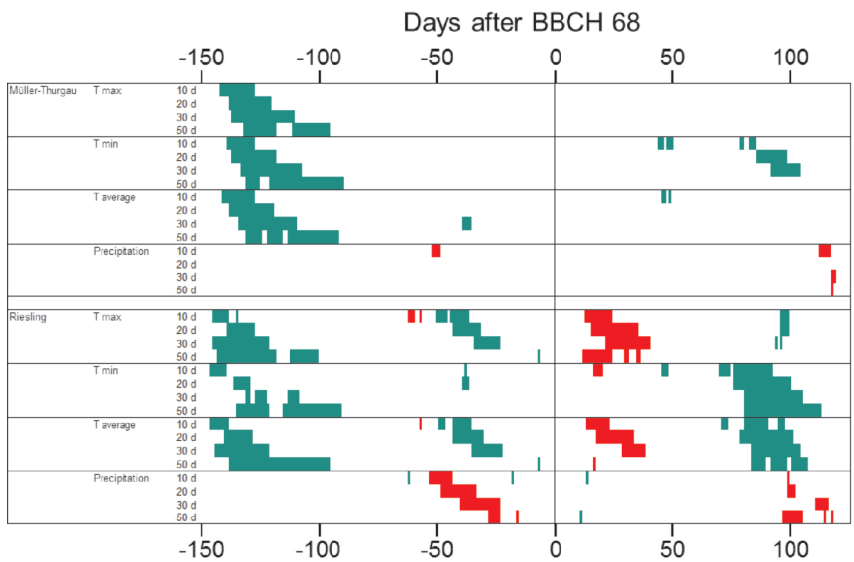


Figure 6 - Significant positive (green) or negative (red) correlations (significance level: $p \leq 0.05$) between the summary daily minimum temperatures, summary daily maximum temperatures, summary daily mean temperatures and summary daily precipitations in different temporal windows (10 days, 20 days, 30 days, 50 days) and the average annual grape yields (hl/ha) in Luxembourg for the wine grape cultivars Müller-Thurgau (upper panel) and Riesling (lower panel) depending on (i) the starting date of a window (relative to the date of BBCH 68) and (ii) the window width according to window pane analysis.

Data were arranged relative to the date of BBCH 68 for the year of harvest (year 0).
Correlation coefficients are depicted on the last day of each temporal window.

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1 January (Figure 3; Figure 4) or relative to the date of BBCH 68 (Figure 5; Figure 6).

Window pane analysis showed that yield formation in the two cultivars responded rather similarly to meteorological conditions in year -1 (Figure 3; Figure 5) but differed markedly in year 0 (Figure 4; Figure 6).

Positive correlations were clustered around BBCH 68 (bloom) in **year -1** for both cultivars, whereas negative correlations occurred for brief periods around, or just before, the time of budbreak (Figure 5). Higher temperatures near budbreak and after harvest in year -1 were often associated with lower yields in year 0, whereas temperature had the opposite effect around bloom.

In the year of harvest, **year 0**, positive correlations, especially between yield and temperature, occurred in late winter and early spring, and again in the period after veraison (Figure 6). Riesling also displayed positive correlations between yield and temperature, and negative correlations between yield and precipitation, during the time leading up to bloom. The post-bloom period, by contrast, was characterized by negative correlations between Riesling yield and temperature. These correlations were much less pronounced or absent in Müller-Thurgau (Figure 6).

The highest correlation coefficients (positive correlations) for **Müller-Thurgau** yields were observed for the summary daily minimum temperature using the 50-day window ending on D_{68} + 2 in year -1 (r = 0.73) and for the summary daily maximum temperature using the 30-day window ending on DOY 41 in year 0 (r = 0.59). The lowest correlation coefficients (negative correlations) were found for the summary daily mean temperature using the 10-day window ending on DOY 103 in the year -1 (r = -0.64) and for the summary daily precipitation using the 10-day window ending on D_{68} - 50 in the year 0 (r = -0.56). The highest correlation coefficients (positive correlations) for **Riesling** yields were observed for the summary daily minimum temperature using the 10-day window ending on DOY 119 in the year 0 (r = 0.66) and for the summary daily minimum temperature using the 30-day window ending on D_{68} + 91 in year 0 (r = 0.65). The lowest correlation coefficients (negative correlations) were found for the summary daily maximum temperature using the 10-day window ending on DOY 192 in the year 0 (r = -0.55) and for the summary daily precipitation using the 30-day window ending on D_{68} - 32 in the year 0 (r = -0.66).

Models to predict yield based on meteorological data

The Automatic Linear Modelling approach identified seven input parameters that best simulated Müller-Thurgau yield based on the adjusted R^2 and the Akaike information criterion (Table 3). These were:

- Summary minimum temperature during pre-bloom in year -1 (positive effect; +);
- Summary mean temperature during ripening in year -1 (negative effect; -);
- Summary maximum temperature around veraison in year -1 (+);
- Summary mean temperature during and after budbreak in year 0 (+);
- Summary precipitation sum during budbreak in year 0 (-);
- Summary precipitation sum during harvest in year 0 (-);
- Summary minimum temperature during ripening in year 0 (+).

For Riesling, five input parameters were identified that best simulated the annual yield (Table 3). These were:

- Summary precipitation sum in late winter in year 0 (-);
- Summary minimum temperature during pre-bloom in year -1 (+);
- Summary minimum temperature during budbreak in year 0 (+);
- Summary precipitation sum during pre-bloom in year -1 (+);
- Summary minimum temperature in late winter and early spring in year 0 (+).

Predicted yields were estimated as the sum of the selected summary environmental variables, used as input parameters, multiplied by the respective coefficients listed in Table 3. For instance, $Yield_{Riesling}$ = 34.609 - 3.553 x input parameter 1 + 2.833 x input parameter 2 + 3.447 x input parameter 3 + 3.107 x input parameter 4 + 2.869 x input parameter 5. The leave-one-out cross validation resulted in coefficients of determination (R^2_{cv}) of 0.851 for Müller-Thurgau and 0.824 for Riesling (Figure 7).

The mean bias errors were 0.2 hl/ha for Müller-Thurgau and 0.0 hl/ha for Riesling, and the mean absolute errors were 5.9 hl/ha for Müller-Thurgau and 4.6 hl/ha for Riesling.

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Table 3 - Input parameters (summary environmental variables) to model the average annual grape yields for the wine grape cultivars Müller-Thurgau and Riesling in Luxembourg.
Data were arranged relative to 1 January (DOY) or relative to the date of BBCH 68 (D_{68}).

Cultivar	Summary environmental variable	Data arrangement	Year	Window width (days)	Window start (DOY / D_{68})	Window end (DOY / D_{68})	Coefficient	Significance (p)
Müller-Th.	Intercept						-45.070	0.091
	T min	D_{68}	-1	50	-47	2	8.981	0.001
	T mean	D_{68}	-1	10	78	87	-2.603	0.004
	T max	D_{68}	-1	10	47	56	1.428	0.013
	T mean	D_{68}	0	30	-67	-38	5.487	0.017
	Precipit.	D_{68}	0	10	-59	-50	-2.480	0.033
	Precipit.	D_{68}	0	10	107	116	-1.913	0.052
	T min	DOY	0	20	248	267	2.132	0.072
	Information criterion	91.226						
	Adjusted R^2	0.915						
Riesling	Intercept						34.609	0.000
	Precipit.	DOY	0	10	28	37	-3.553	0.000
	T min	DOY	-1	10	132	141	2.833	0.000
	T min	DOY	0	10	110	119	3.447	0.000
	Precipit.	D_{68}	-1	20	-32	-13	3.107	0.004
	T min	D_{68}	0	50	-150	-101	2.869	0.010
	Information criterion	77.027						
	Adjusted R^2	0.882						

Discussion

This study confirmed the general notion that annual fluctuations in grape yields are strongly influenced by environmental conditions in both the year preceding the harvest year (year -1) and the harvest year itself (year 0). In the relatively cool and humid climate of Luxembourg, where water deficits during the growing season are rather uncommon, the impact of temperature was clearly dominant over that of precipitation. This indicates that in this region temperature is more often a limiting factor in yield formation than is water supply. With few exceptions, the effect of temperature was mostly positive (i. e., higher temperatures were associated with higher yields), whereas the effect of precipitation was generally negative (i. e., higher precipitation was associated with lower yields). The two types of data arrangement (either relative to 1 January or to the date of BBCH 68) used for window pane analysis generally yielded similar results. However, the phenology-based approach identified more positive correlations between yield and meteorological variables in the vicinity of BBCH 68 for year -1, whereas the calendar-based approach identified more positive correlations during the pre-bloom period for year 0. Hence, both approaches were used in parallel to detect temporal windows of predictive value for yield modelling.

The yield models developed here are based on meteorological conditions that occur within time windows identified by window pane analysis and that are significantly correlated with annual yields. These yield models found that annual grape yields may be predicted with fairly high accuracy using only a handful of summary environmental variables that can be easily computed from data obtained from local weather stations. Correlations between meteorological conditions and yields were often similar for the two cultivars investigated. Nevertheless, Riesling yield seemed to respond more strongly to meteorological conditions than did that of Müller-Thurgau. Considering that Luxembourg is close to the climatic limits for sustainable grape production (average Huglin index of 1714 for the period 1993-2015), one plausible explanation for this difference between cultivars is that Riesling has a greater seasonal heat requirement (1700, according to Huglin, 1978) than Müller-Thurgau (1500).

The good agreement between actual (i. e., observed) and modelled (i. e., predicted) yields in the present study is remarkable, considering that (i) meteorological conditions are not the only factors determining yield, and (ii) extreme weather events may impact yield but are not detected by the present methodology. Extreme weather events that can severely reduce yield include hail storms, severe

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wind, or late spring frosts. Furthermore, yield can be reduced by nutritional deficiencies, as well as diseases or pests (Keller, 2015 ; Stumm, 1985). Additionally, changes in cultural practices due to changing wine styles or consumer preferences may influence yield. Nevertheless, in the period of investigation no significant trends towards higher or lower yields were observed in either cultivar in this study.

Higher spring temperatures in **the period before budbreak in year -1** were associated with lower yields in year 0. Although it occurred in both cultivars, it is presently unknown whether this correlation implies the existence of any underlying physiological causes. Bud development (for year 0) in basal nodes of the year -1 shoots begins several weeks before budbreak (Morrison, 1991) but it is not clear how temperature at this time should impact year 0 yield in cane-pruned vines in which most buds develop after budbreak in year -1.

In both cultivars higher temperatures during the **pre-bloom and bloom period of year -1** led to higher yields in year 0. This early-season temperature effect, and especially the summary mean daily minimum temperature, also emerged as one of the dominant driving variables in the yield model. In accordance with the present results, a model that simulates annual (year 0) Sauvignon blanc yield is partly based on the temperature conditions during this period in year -1 (Trought, 2005). Bud fruitfulness (i. e., inflorescences per shoot) was not assessed as part of the current data set. However, inflorescence primordia initiation starts around budbreak, and inflorescence differentiation

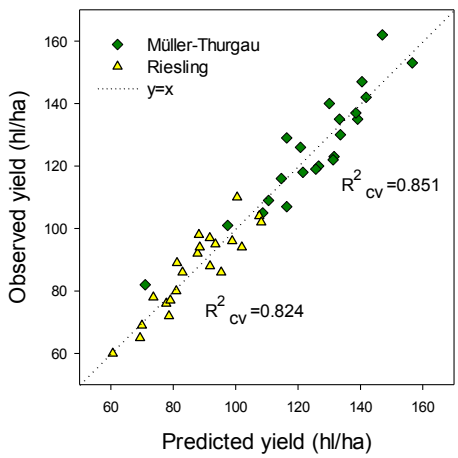


Figure 7 - Leave-one-out cross validations of the models to predict the annual yield of the wine grape cultivars Müller-Thurgau and Riesling. Observed annual yields are plotted against the predicted annual yields for 22 years.

R^2_{cv} is the coefficient of determination for each cultivar.

starts around bloom of year -1 (Alleweldt & Ilter, 1969 ; Morrison, 1991). By favouring assimilate supply to the developing buds, warm and sunny conditions promote the formation of inflorescence primordia, whereas cool and cloudy weather promotes the formation of tendrils (Buttrose, 1970 ; Keller, 2015). Even though the present analysis also revealed a negative effect of dry conditions at the time of inflorescence primordia formation in year -1 on yield in year 0, the impact of early-season rainfall in year -1 seems to be less pronounced under the relatively humid conditions of Luxembourg than in southern France, where water and nitrogen stress during this period was found to determine 65-70 % of grapevine yield in year 0 (Guilpart *et al.*, 2014).

Higher **post-harvest temperatures in year -1** were associated with lower yields in year 0, especially in Müller-Thurgau. Considering that the buds are dormant at this stage (Buttrose, 1970), the reasons, if any, for this inverse correlation remain unknown. Higher temperatures during this period tend to diminish cold acclimation of grapevine buds (Ferguson *et al.*, 2014). Although cold damage is not perceived as a major threat for yield in Luxembourg, cold damage in late autumn, when grapevines have not yet fully cold-acclimated, is not uncommon in other wine regions at similar latitudes and elevations (Bowen *et al.*, 2016 ; Ferguson *et al.*, 2014 ; Keller and Mills, 2007).

In contrast to the negative correlation between yield and year -1 autumn/early-winter temperatures, higher rather than lower temperatures **after mid-winter of year 0** were correlated with higher yields. One might speculate that this is a result of excessively low temperatures occasionally having resulted in cold damage to the buds. However, this explanation seems unlikely, since the absolute minimum temperature recorded during the study period was -15.2°C on 1 January 1997 and on 1 March 2005. Minimum temperatures below -12°C were recorded on only 17 days during the 23-year study period (8 years with absolute annual minimum temperature below -12°C). These temperatures are considerably higher than the typical mid-winter lethal bud temperatures for most *V. vinifera* cultivars (Ferguson *et al.*, 2014). Additional data on inflorescence number and size (i. e., flower number) would be required to ascertain any potential causation underlying the correlations between yield and winter temperatures.

Higher temperatures **during budbreak** and higher temperatures and lower rainfall in the first month **after budbreak** were associated with higher yields, especially in Riesling. The observed temperature

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effect is consistent with earlier research that found that warm conditions during the initial shoot development and flower formation period in spring promoted yield formation in grapevines by increasing leaf area, flower size, and fruit set (Keller *et al.*, 2010). It seems plausible that the inverse correlation between yield and early-season rainfall might be related to the general association of rain with low solar irradiance (i. e., cool temperatures and low light intensity).

Surprisingly, the present analysis did not uncover any significant correlations between yield and the meteorological conditions **around bloom**, even though the process of fruit set is known to be highly sensitive to environmental conditions (Alleweldt and Hofäcker, 1975; Keller, 2015). For instance, both low (<15 °C) and high (>35 °C) temperatures reduce fruit set (Currle *et al.*, 1983; Kliewer, 1977; Mosedale *et al.*, 2015; Nesbitt *et al.*, 2016). Trought (2005) developed a model to predict annual yield of Sauvignon blanc partly based on the temperature at bloom. The most likely reason for the absence of such relationships in the present data set may be that temperatures were rarely below or above the critical thresholds for adequate fruit set (Staudt, 1982). Previous studies (Molitor *et al.*, 2013) showed that mean temperatures during the bloom period in Luxembourg over the years 1993 to 2011 varied between 13.6 and 23.4 °C. Average bloom temperatures below 15 °C were observed only in one (1996) out of 19 seasons.

In Riesling there was a negative correlation between yield and temperatures, especially maximum temperatures, over the first three weeks **after bloom**. The reason for this effect might be that cell division and cell expansion are reduced under heat conditions; e.g., temperatures above 32.5 °C during the period between bloom and 12 to 18 days thereafter have been demonstrated to reduce berry size compared to 25 °C (Kliewer, 1977). The absence of such a correlation in Müller-Thurgau suggests that berry growth in this cultivar might be less heat-sensitive than in Riesling.

Window pane analysis also revealed a positive correlation between yield and temperature, especially minimum temperature, in the period between approximately 60 and 100 days after bloom (i. e., during the **ripening period**). Although this relationship was observed in both cultivars, it was stronger in Riesling. Warmer night-time temperatures are generally associated with more rapid catabolism of malic acid in grape berries, which implies a greater respiratory demand under warm conditions (Keller, 2015). If this metabolic energy demand were coupled with greater sugar accumulation, the higher sink demand could drive more rapid berry expansion due to phloem influx (Keller *et al.*, 2015). However, we are not aware of any data demonstrating a link between malate catabolism and berry growth.

The correlations and models developed in this study may be used to (i) estimate the annual yield potential of Riesling and Müller-Thurgau, and (ii) simulate yield in climate change impact studies. The information on the expected annual yield might be used for harvest and processing logistics. Besides environmental conditions, grape yield can also be modified by cultural practices. At every step of yield formation there are management tools available to optimize final yield according to the specific production target (Keller, 2015). Grape growers may adjust their viticultural practices according to the environmental conditions in the present and the preceding growing season. For instance, the number of buds retained during winter pruning may be reduced if warm conditions during the bloom period of the preceding season give reason to expect a high number of inflorescences per shoot. Moreover, canopy management practices have been shown to be efficient tools to manipulate the degree of fruit set, cluster compactness, and yield. Consequently, if past and present environmental conditions lead to the expectation of an excessively high yield potential (i. e., over-cropping) in the present season, yield-reducing viticultural practices such as early cluster-zone leaf removal (Molitor *et al.*, 2011; Poni *et al.*, 2006; Tardaguila *et al.*, 2008) or late first shoot topping (Hügelschäffer *et al.*, 1994; Molitor *et al.*, 2015) might be employed.

The analyses and models presented here are based on the historic yield records under the specific environmental conditions and viticultural practices in Luxembourg. Nonetheless, the observed correlations between meteorological conditions and yields are generally in accordance with underlying principles described in the literature. Hence, these models may be applicable in other viticultural regions with similar meteorological conditions and viticultural practices. For different conditions or for other cultivars, the models could be parameterized based on regional yield data and meteorological records. Coupling the models with simulations of grape phenology (Molitor *et al.*, 2014b) and with future climate projections for Luxembourg (Molitor *et al.*, 2014a) could support long-term strategic planning in the selection of cultivars for future plantings. However, when using the models in climate change impact studies to predict grape yield in the future,

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some precautions need to be taken : (i) models should not be used outside their calibration frame (e.g., higher temperatures) ; and (ii) legal and market conditions, plant material (e.g., new clones, rootstocks), or viticultural practices might be adapted to the new conditions.

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