DOI: https://doi.org/10.20870/oeno-one.2023.57.4.7719

OPEN ACCESS

ORIGINAL RESEARCH ARTICLE

Impact of cluster thinning and harvest date on berry volatile composition and sensory profile of *Vitis* sp. Seyval blanc and Vandal-Cliche

Paméla Nicolle[1], Catherine Barthe[2,3], Martine Dorais[2], Gaëlle Dubé[4], Paul Angers[2,5] and Karine Pedneault[1,3*]

[1] Département des sciences naturelles, Université du Québec en Outaouais, Gatineau, QC, Canada, J0V 1V0

[2] Centre de Recherche et d'Innovation en Horticulture, Université Laval, Québec, QC, Canada, G1K 7P4

[3] Centre de Développement Bioalimentaire du Québec, La Pocatière, QC, Canada, G0R 1Z0

[4] Freelance Agronomist and Viticulture Consultant, Québec, QC, Canada

[5] Département de Sciences des aliments, Université Laval, Québec, QC, Canada, G1K 7P4

*correspondence:
karine.pedneault@uqo.ca

Associate editor:
Stamatina Kallithraka

Received:
17 August 2023

Accepted:
11 October 2023

Published:
7 November 2023

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ABSTRACT

Northern conditions are challenging for grape and wine producers. To cope with these challenges, the use of early ripening interspecific hybrid *Vitis* sp., such as Seyval blanc and Vandal-Cliche, is often preferred to traditional *V. vinifera*. However, knowledge about cultural practices suitable for interspecific hybrid varieties are still scarce, especially regarding their impact on profiles of volatile compounds and the sensory perception of berries. In this study, the impact of cluster thinning and harvest date on grapevine physiology, must chemical composition and berry sensory attributes of Seyval blanc and Vandal-Cliche was investigated. Three crop loads (100 %, 70 % and 40 % crop) and three harvest dates corresponding to pre-maturity, maturity, and post-maturity were assessed in 2012 and 2013. Cluster thinning significantly decreased the yield of Vandal-Cliche, but not of Seyval blanc, for which it instead improved fruit set without affecting yield. The impact of cluster thinning on must chemical composition was limited for both cultivars, although some significant changes were observed, especially in the cool season of 2013.

Clear variations during ripening, in terms of technological parameters and aroma characteristics, were observed depending on the cultivars and the seasons. In Seyval blanc, C_6-alcohols and C_{13}-norisoprenoids decreased during ripening, while C_6-aldehydes and linalool increased. In Vandal-Cliche, berries from the first and the last sampling dates of the warm season of 2012 showed the highest levels of C_{13}-norisoprenoids, whereas berries from the last sampling date in the cold season of 2013 showed the highest levels of terpenes, C_{13}-norisoprenoids and ethyl esters.

Despite its limited impact on fruit chemical composition, cluster thinning significantly impacted the sensory perception of Vandal-Cliche berries in both years. Cluster-thinned berries had softer skin, sweeter and less acidic pulp, and fruitier skin and pulp aroma. Skin softness allowed excellent discrimination of the maturity of both cultivars during the two study years, suggesting that this descriptor could be a suitable maturity marker for these interspecific hybrid varieties. In summary, cluster thinning proves beneficial for enhancing fruit set in Seyval Blanc in a northern climate; however, its influence on fruit quality is minimal for both cultivars.

KEYWORDS: Berry sensory analysis, cold climate viticulture, crop load, disease resistant grape varieties, fruit ripening, vine balance, volatile compound

INTRODUCTION

The development of cold climate wine production has increased tremendously over the past 10-20 years in Eastern Canada and the Midwestern and Northeastern United States. The expansion of cold climate viticulture relies primarily on interspecific hybrid grape (IHG) varieties that can tolerate harsh winters and whose berries can ripen during short growing seasons (Pedneault *et al.*, 2013; Watrelot *et al.*, 2023). IHG are selected from crosses between the European species *Vitis vinifera* and hardy species from North America, such as *V. riparia*, *V. rupestris* and *V. labrusca*. Very hardy grape varieties, such as *V. riparia*, have high tolerance to frost and fungal diseases and early fruit ripening, while the *V. vinifera* parents provide desirable oenological traits for wine production (Pedneault and Provost, 2016).

IHG varieties are generally more vigorous and tend to produce more fruit and foliage than *V. vinifera* varieties (Pedneault and Provost, 2016). As with other perennial fruit crops, yield largely depends on the variety, plant canopy management (training system, pruning, etc.) and planting density. For instance, in Eastern and Midwestern USA densities of 2.4 m x 3 m are common (1345 vine/ha); when planted in such high densities, the productivity of the IHG variety Frontenac can average 16 T/ha (about 10.9 kg/plant) (Wallis *et al.*, 2017). In Québec, planting densities range from 1,800 to 3,600 vine/ha and white IHG, such as Seyval blanc and Vandal-Cliche, can produce 8 to 12 T/ha (Dubé and Turcotte, 2011; Reynolds *et al.*, 1986b); however, when winter temperatures reach below −27 to −30 °C, which is frequent in Quebec, winter frost can significantly reduce yields in the following season (Atucha *et al.*, 2018).

Vine balance is defined as the ratio between leaf area and fruit yield per vine, and is achieved by altering the relative proportion of vegetative and reproductive growth in grapevine (Howell, 2001; Kliewer and Dokoozlian, 2005). Optimising vine balance involves optimising photosynthate distribution and inducing early (or, in warm areas, later) ripening, thus improving grape quality (Howell, 2001; Morris *et al*., 2004; Reynolds and Heuvel, 2009). According to Howell (2001), leaf to fruit balance is obtained when the optimal yield required for obtaining high quality fruit is achieved without adverse consequences for the vegetative growth. Appropriate grapevine management, including variety-adapted training and trellising, and appropriate viticultural practices, such as cluster thinning and shoot thinning, can help reach this balance (Chapman *et al.*, 2004; Jackson and Lombard, 1993; Morris *et al.*, 2004). In Eastern Canada, attaining a harmonious balance in IHG varieties is a challenge. This is attributed to their inherent moderate to high vigour, as well as the annual variability of the climate in the region. The local growing conditions comprise substantial fluctuations in climate, minimal water stress throughout the season and nutrient-rich soils, which further contribute to the complexity of achieving this equilibrium.

Cluster thinning involves the selective removal of excessive clusters to reduce crop load, increase the leaf to fruit ratio and, ultimately, improve grape and wine quality (Reynolds and Vanden Heuvel, 2009; Morris *et al.*, 2004; Howell, 2001). Studies on cluster thinning in IHG show that this practice may have positive effects on basic berry metrics that are often challenging in a northern climate, such as sugar accumulation and acidity (Morris *et al.*, 2004; Dami *et al.*, 2006). The extent of these effects can, however, vary from one variety to the other, and cluster thinning does not always result in improved berry ripening (Miller *et al.*, 1996; Morris *et al.*, 2004): contrasting results are often obtained due to climate fluctuation (temperature, global irradiance) and depending on vine physiology (rootstock and training) and additional viticultural practices (pruning, shoot thinning) (Ames *et al.*, 2002; Dami *et al.*, 2013; Frioni *et al.*, 2017; Gatti *et al.*, 2012; Ivanišević *et al.*, 2020; Reeve *et al.*, 2016). Furthermore, little is known about the impacts of cluster thinning on other useful metabolites for wine production, such as volatile and phenolic compounds.

Achieving full ripening is a yearly challenge in northern grape producing areas, where cold weather conditions and/or frost can delay phenology, and the prompt decline of the photoperiod and daily temperatures in autumn can slow down berry metabolism in the later ripening stages. While extensive studies on the relationships between the ripening and grape quality of *V. vinifera* varieties have been conducted in multiple wine growing regions of the world (Conde *et al.*, 2007; Fenoll *et al.*, 2009; Kontoudakis *et al.*, 2010; Moigne *et al.*, 2008; Palomo *et al.*, 2007), studies on IHG are still very scarce (Haggerty, 2013; Pedneault *et al.*, 2013; Sun *et al.*, 2011). In Eastern Canada, while summers are short, they can be very warm; such conditions can be detrimental to the quality of certain IHG, such as St.Croix, Sabrevois, Vandal-Cliche and L'Acadie blanc. Indeed, overripe IHG varieties can contain high levels of certain volatile compounds, such as 2-phenylethanol and furaneol, both as free or as glycosylated precursors, which could be detrimental to wine aroma (Campos-Arguedas *et al.*, 2022; Pedneault *et al.*, 2013; Slegers *et al.*, 2015). Therefore, more data is needed on the ripening metabolism of IHG, especially as, with evolving global changes, cold-hardy and disease-resistant cultivars are of increasing interest due to their resilience to challenging environmental conditions and disease pressure levels (Pedneault and Provost, 2016).

We conducted a 2-year study on the impact of cluster thinning and harvest date on vine physiology and grape quality of Seyval blanc and Vandal-Cliche. Seyval blanc is a French variety grown in southern Quebec and Nova Scotia, while Vandal-Cliche is a Canadian variety characteristic of Orleans Island, a colder wine producing area in Québec. We hypothesised that reducing crop load using cluster thinning improves the quality of berries in both varieties as a result of earlier ripening and the improvement of their chemical composition, especially their aroma profile. Three crop load levels (100 %, 70 % and 40 % crop load) and three maturity levels were investigated. Vine physiological parameters (leaf:fruit ratio, yield, clusters per plant, cluster and berry weight), must basic metrics (total soluble solids,

titratable acidity, pH and yeast assimilable nitrogen) and grape phenolic and aroma content were measured. We also assessed the potential of berry sensory analysis for evaluating berry ripening using a trained sensory panel with the aim of providing a usable berry ripening assessment tool for growers.

MATERIALS AND METHODS

1. Chemicals

Absolute ethanol was purchased from Commercial Alcohols (Brampton, ON, Canada) and L-tartaric acid and sodium chloride (NaCl) from Fisher Scientific (Fair Lawn, NJ, USA). Deuterated standards (ethyl acetate-d_8, ethyl butanoate-4,4,4-d_3, benzyl-2,3,4,5,6-d_5 alcohol, 2-phenyl-d_5-ethanol, hexanoic-d_{11} acid, ethyl octanoate-d_{15}, hexanol-d_{13}, acetic acid-d_4, furfural-d_3, linalool-d_3, d_3-methylisoborneol, 3-methyl-1-butyl alcohol-d_4) were purchased from C/D/N Isotopes Inc. (Pointe-Claire, Québec, Canada). β-myrcene was purchased from MP Biomedicals (Santa Ana, CA, USA). Ethyl hexanoate and ethyl propanoate were purchased from Nu-Chek-Prep (Elysian, MN, USA). Ethyl vanillate and nonanal were purchased from Alfa Æsar (Heysam, U.K.). Cafeic acid, citral, citronellol, *cis*-3-hexenal, *cis*-3-hexenol, ethyl acetate, ethyl butyrate, ethyl crotonate, ethyl isovalerate, ethyl 2-methylbutanoate, β-damascenone, decanal, hexanal, hexanol, α-ionol, α-ionone, β-ionone, D-(+)-gluconic acid δ-lactone, linalool, (R)-(+)-limonene, 2-methoxy-4-vinylphenol, nerol, 2-octanone, 1-octen-3-ol, rose oxide, phenylacetaldehyde, quercetine, α-terpineol,-*trans*-2-*cis*-4-heptadienal, *trans*-2-*cis*-6-nonadienal, sorbaldehyde, *trans*-*2*-heptenal, *trans*-2-hexenal, *trans*-2-hexenol, *trans*-2-*trans*-4- heptadienal and 2-undecanone were bought from Sigma-Aldrich (St. Louis, MO, USA). O-phthaldialdehyde assay (NOPA) was purchased from Unitech Scientific (Hawaiian Gardens, CA, USA); ammonia enzymatic detection assay was bought from Sigma-Aldrich (St. Louis, MO, USA).

2. Grape varieties

The white *Vitis*. *sp*. varieties c.v. 'Seyval blanc' (Seibel 5656 x Rayon d'Or (S. 4986)) and 'Vandal-Cliche' (Vandal 63 X Vandal 163) were used for this study. These cultivars were selected because they are widely grown in Quebec, Canada, and are known to be highly productive (Dubé and Turcotte, 2011).

3. Experimental design

Seyval blanc and Vandal-Cliche were treated in separate experiments. Each experiment was set up in a split-split-plot design comprising three parcels (V1, V2, V3, corresponding to three different sites), three crop load levels (C1, C2, C3, corresponding to 100 %, 70 % and 40 % crop load respectively) and three sampling dates (Date 1, Date 2, Date 3, corresponding to pre-maturity, maturity and post-maturity respectively). Six sites located in the area of Montérégie (M) and Quebec (Q) were selected, they contained Seyval blanc (V1M, V2M, V3M) and Vandal-Cliche (V1Q, V2Q, V3Q) respectively. Average meteorological data (temperature, rainfall, relative humidity and solar radiation) from the beginning to the end of the season, and soil composition data (phosphorus, potassium, calcium, magnesium, aluminium and organic matter content) for each site are available in Tables S1 and S2 respectively. Site planting configuration are provided in Table S3.

Each site contained 105 plants distributed over 3 rows (35 plants per row). Crop load treatments (3 treatments) were applied on three subplots randomly distributed over the row and repeated over three rows. Each subplot comprised nine plants that were separated by two guard plants. The nine plants were separated into three sub-subplots of three plants each, that constituted the three sampling dates (Date 1, Date 2, Date 3). Dates attached to each of these sub-subplots were attributed randomly (See Supplementary Material for a diagram of the experimental design). The experiment was conducted over two seasons (2012 and 2013); however, because spring frost caused significant damages to the sites located in Montérégie and one plot located in Quebec (V3Q) in 2013, these sites were removed from the experiment in the second year.

3.1 Treatments

On each experimental plot, Vandal-Cliche vines were trained in Cordon de Royat and Seyval blanc vines in Goblet, but in both training systems the shoots were vertically positioned. Level of crop load was established at initial pruning and harmonised in all the plots to constitute the control load (100 % crop load) as follows: 1) first pruning was carried out in spring (mid-April, before bud break) to 8 stems and 4 buds per stem, 2) after the last spring frost (mid-May), pruning was adjusted to 24 buds on 8 stems and 20 buds on 8 stems of Vandal-Cliche and Seyval banc respectively, and 3) in June, inflorescences were counted on 50 plants at flowering, and the average number constituted the 100 % crop load level. The 70 % and 40 % crop load levels were adjusted accordingly (Table S4). In mid-July, inflorescences were recounted on all plants and their number adjusted as necessary. Due to the high vigour of IHG varieties, pruning was carried out as needed to maintain similar exposed leaf area in each experimental plot during the season until harvest.

3.2 Sampling

Sampling was performed on three different dates (Date 1, Date 2, Date 3), which corresponded to three growing degree-day levels (base temperature of 10°C) (Table S5). Each sample consisted of forty berries randomly picked from each plant in the sub-subplots of each experimental site. The samples were maintained at ~4°C during the journey from the vineyard to the laboratory, where they were then divided into three sub-samples for 1) must basic metrics and must aroma analysis, 2) berry sensory analysis, and 3) must phenolic analysis.

3.3 Grapevine physiology measurements

Leaf area was measured at harvest using an LAI-2000 canopy analyser (LI-COR Biosciences, Lincoln, Nebraska,

USA) with the 180° restriction cap. For each treatment (Crop load*Sampling date) and each experimental site, one measurement between the rows and three measurements at the base of each plant of the experimental unit were taken. The yield and number of clusters were measured for each plant and the leaf area to fruit ratio was calculated. The cluster average weight was measured on three plants per crop load subplot, and berry weight was averaged from 200 berries for each combination of treatment. Finally, the water content of berries was determined by the difference between fresh and dry weight of a 100-berry sample that was dried in an oven for 72 to 90 hours at 65 °C until weight was stable.

4. Chemical analyses

4.1 Grape basic metrics analysis

Grape juice from 200 randomly selected berries was manually extracted using food-grade bags and each sample was centrifuged at 10,000 rpm (4°C, 15 min). The analyses were conducted on fresh musts. Total soluble solids (TSS, °Brix), titratable acidity (TA, g/L tartaric acid equivalent) and pH were measured according to standard protocols (Slegers *et al.*, 2015). The concentration of primary amino nitrogen was determined by NOPA, an ophthaldialdehyde/N-acetyl-L-cysteine spectrophotometric assay using an HP UV-Vis 8453 spectrophotometer (Agilent technologies, Santa Clara, California). Ammonia concentration was analysed using an enzymatic test kit. Both values were combined to provide yeast assimilable nitrogen (YAN). The analyses were performed in duplicate.

4.2 Grape phenolic content

Grape juice from 200 randomly selected berries was manually extracted using food-grade bags and each sample was centrifuged at 10 000 rpm (4°C, 15 min). The analyses were conducted on frozen musts in 2012 and on fresh musts in 2013. Total hydroxycinnamic ester and total flavonoid content were obtained by UV-visible spectrophotometry using an HP UV-Vis 8453 spectrophotometer (Agilent technologies, Santa Clara, California), taking absorbance measurements at 320 nm and 360 nm respectively. Total hydroxycinnamic esters and total flavonoids were quantified according to a previously established calibration from Girard *et al.* (2002); results were expressed in mg/L caffeic acid and quercetin equivalents respectively.

4.3 Volatile compounds analysis

Grape juice samples were prepared and analysed as described by Slegers *et al.* (2015) using an Agilent 6890 Series gas chromatograph-mass spectrophotometer equipped with a time-of-flight (Pegasus HT TOFMS; Leco, Saint Joseph, MI, USA) and a Gerstel Solid-Phase microextraction system (Linthicum, MD, USA) connected to a computer with the Leco ChromaTOF software (Leco, Saint Joseph, MI, USA). Briefly, grape must from 200 randomly selected berries was manually extracted using food-grade bags and each sample was centrifuged at 10,000 rpm (4 °C, 15 min). The analyses were conducted on fresh must. Grape must samples (5 mL) were placed in a 20-mL vial containing sodium chloride (3 g) and a solution of deuterated standards (50 µL) including ethyl acetate-d_8, ethyl butanoate-4,4,4-d_3, benzyl-2,3,4,5,6-d_5 alcohol, 2-phenyl-d_5-ethanol, hexanoic-d_{11} acid, ethyl octanoate-d_{15}, hexanol-d_{13}, acetic acid-d_4, furfural-d_3, linalool-d_3, d_3-methylisoborneol and 3-methyl-1-butyl alcohol-d_4. Volatile compounds were extracted using a 2-cm grey fibre coated with 50-30 µm Divinylbenzene/Carboxen/Polydimethylsiloxane. Extraction was performed at 60 °C (25 min, 500 rpm). Volatile compounds were desorbed for 5 min to an open tubular DB-Wax column (Polyethylene glycol, 60 m X 0.25 mm i.d. X 0.25 µm film thickness; SGE, Austin, TX, USA) using a splitless injector set at 270 °C. The oven temperature was programmed as follows: isothermal at 30 °C for 1 min; increased to 40 °C at a rate of 10 °C/min; increased to 240 °C at a rate of 3.5 °C/min; isothermal for 2 min; increased to 250 °C at a rate of 20 °C/min, and isothermal for 5 min. Helium was used as carrier gas under constant flow (1 mL/min). Volatile compounds were identified by comparing retention time, retention indices and mass abundance of the selected ions with authentic standards and by matching spectral data with the NIST Spectral Library.

5. Berry sensory analyses

Berry sensory analyses were conducted according to the method of Rousseau and Delteil (2000) modified by Pedneault (2012). The panel comprised eight women and four men in 2012, and sixteen women and eight men in 2013. During three pre-tasting sessions, the panel was 1) familiarised with the berry testing method and the eight descriptors (colour, pulp aroma, pulp sweetness, pulp acidity, skin aroma, skin astringency, skin resistance and seed colour; Table S6), 2) trained on the scaling of sugar, astringency and acidity levels, and 3) familiarised with the evaluation grid and berry sensory analysis. The analyses were carried out the day after the berries had been sampled. The berries were stored at 4°C in a sensory room in individual boxes. The samples, labelled with randomised three-digit numbers, were presented to each member of the panel randomly. In 2012, the panelists rated each descriptor on a 1 to 4 intensity scale, while a 150 mm-band scale was used in 2013 to increase precision. The panelists attended three sessions for each grape variety.

6. Statistical analyses

Data were analysed with the JMP software (version 11.0.0; SAS Institute Inc., Cary, NC, USA) using analysis of variance (ANOVA) to analyse the main effects of the factors and their interactions at $p \leq 0.05$. Data were analysed in the same way in 2012 and 2013 by Crop load* Sampling date, but the rows were blocked in 2013 following the loss of some of the experimental sites due to spring frost. The Standard Least Squares personality within the Fit Model platform was used and pairwise comparisons of least squares means using Tukey HSD ($\alpha = 0.05$) was performed to find significant difference between treatments. A principal component analysis (PCA) was also performed using the JMP software to resume the effect of the crop load and the harvest date on the vine physiology and the grape quality. Only variables significant to the ANOVA were selected for the PCA.

RESULTS

Vine physiological parameters, grape basic metrics, phenolic and aroma content and berry sensory results are presented in Tables 1-4 and Figure 1. The volatile compounds were classified according to their aroma families, corresponding to their primary descriptor, to simplify aroma profile analysis. Only the data corresponding to the effects of single factors (Crop load and Sampling date) are presented, since the effects of interactions (Crop load*Sampling date, $p \leq 0.05$) were not significant for most variables.

1. Crop load

The total number of clusters per plant significantly decreased by ≈19 to 45 % in relation to the control in the 70 and 40 % crop load treatments for both cultivars (Table 1). In 2012, reducing crop load from 100 to 40 % of total clusters resulted in significantly larger cluster weight in Seyval blanc but such result was not observed in Vandal-Cliche. In contrast, leaf to fruit ratio and yield per plant were significantly affected in Vandal-Cliche over the two seasons, but not in Seyval blanc. Furthermore, no impacts were observed on the must composition (basic metrics and polyphenol content) for both cultivars and years (Table 2).

The cluster thinning treatments significantly affected the concentration of certain volatile compounds (Table 3). The effects were slight in 2012 in both cultivars, whereas larger impacts were observed in Vandal-Cliche in 2013. In Seyval blanc (2012), linalool - known for its floral and citrus aroma - significantly increased in the most severe crop load treatment (40 % cluster-thinned), whereas the herbaceous compound, hexanal, decreased. In Vandal-Cliche, cluster thinning had no significant impact in 2012; whereas in 2013 the berries from cluster thinned grapevines showed significantly higher levels of C_6-compounds (*cis*-3-hexenal, *trans*-2-heptenal, hexanol, *cis*-3-hexenol, *trans*-2-hexenol and *trans*-2-*cis*-6-nonadienal) than the control berries, and approximately 1.3 times lower concentrations of 2-methoxy-4-vinylphenol and *α*-terpineol.

The crop adjustment treatments significantly impacted the sensory perception of Vandal-Cliche berries in both years (Figure 1), with differences being more perceptible in 2013 than in 2012. In 2012, skin astringency was found to significantly decrease for the lower crop load. In 2013, in comparison to the 100 % crop load treatments, the cluster-thinned berries were perceived as being yellow (rather than yellow-green) with browner (rather than yellow-green) seeds, sweeter, more aromatic and less acidic pulp, and more aromatic (e.g., fruitier) and softer skin. Some of these differences were perceptible at 70 % crop load (i.e., in terms of berry and seed colour, pulp aroma and acidity, skin aroma and softness) and other attributes further improved at the 40 % crop level (berry colour and pulp sweetness).

2. Sampling date

While sampling date showed few impacts on physiological measurements it significantly impacted berry chemistry. Cluster weight, but not berry weight, significantly decreased by about 1.3 times between Date 1 and Date 2 in Seyval blanc in 2012 and Vandal-Cliche in 2013 (Table 1). In both varieties and both seasons, total soluble solids content showed a 1.2-fold increase in the periods between the first and the second and/or the third sampling dates, while TA decreased during the same periods (Table 2). In both 2012 and 2013, differences in the levels of hydroxycinnamic esters and flavonoids were only detected in Vandal-Cliche, with an increase between the first and the second sampling date.

The profiles of the volatile compounds exhibited distinct alterations across both cultivars and over the years. In Seyval blanc (2012), aromas with fatty notes, such as *trans*-2-*cis*-4-heptadienal and *trans*-2-*trans*-4-heptadienal, showed a 1.5-fold increase in the period between the first and the last sampling dates, while the fruity 2-undecanone decreased by about half (Table 4). Similarly, C_{13}-norisoprenoid compounds (*β*-damascenone, *α*-ionone, *α*-ionol, *β*-ionone and citronellol, which contribute to the floral and fruity notes in berries) showed a significant 6.3-fold decrease in the period between the first and the last sampling dates, whereas the floral terpene linalool increased approximately 4.1-fold. Herbaceous compounds comprising C_6-alcohols (i.e., hexanol, *cis*-3-hexenol and *trans*-2-hexenol) decreased significantly during ripening (i.e., approximately 2.9-fold between Dates 1 and 3), while the C_6-aldehydes (i.e., hexanal, *trans*-2-hexenal, *trans*-2-heptanal and *cis*-3-hexenal) showed a significant 5.8-fold increase.

In 2012, the harvest date significantly impacted several aroma compounds in the Vandal-Cliche berries (Table 4). The content of the citrus-flavoured compound R-(+)-limonene increased approximately 3.7-fold between the first and third sampling dates, while most fatty and herbaceous compounds peaked at the second sampling date, which corresponds to the commercial harvest date. Floral/fruity C_{13}-norisoprenoids *β*-damascenone and *α*-ionone content peaked on the first and the last sampling dates (Date 1 and Date 3), whereas the spicy terpene *β*-myrcene reached its maximal concentration on the second sampling date and remained stable until the last date. In 2013, more than half of the volatile compounds quantified in the Vandal-Cliche berries showed a significant difference from one harvest date to the other, but patterns slightly differed from those observed in 2012. Most compounds, including floral and fruity compounds such as linalool, *α*-ionol, *β*-ionone, *β*-damascenone and ethyl hexanoate, and herbaceous compounds such as hexanol and *trans*-2-hexenol, significantly increased in concentration between the first and the last sampling date. In contrast, the concentration of the herbaceous compounds hexanal, *cis*-3-hexenal, *trans*-2-hexenal and *cis*-3-hexenol significantly decreased during the same period.

While crop adjustment did not result in significant changes to the sensory characteristics of Seyval blanc berries, significant differences were observed between the first and the last sampling date in terms of berry colour (yellow rather than yellow-green) and skin resistance (softer skin as berries ripened) in 2012 (Figure 1). In Vandal-Cliche, the 1 to 4 scale used in 2012 showed a significant decrease in pulp

TABLE 1. Impact of crop load level (100 %, 70 %, and 40 % cluster-thinned) and harvest date (Dates 1, 2 and 3) on grapevine physiological parameters (leaf:fruit ratio, yield, clusters per plant, cluster and berry weight) of the interspecific hybrid *Vitis* varieties Seyval blanc (2012) and Vandal-Cliche (2012, 2013) grown in Quebec, Canada. *p*-values of the main effects are presented, see Supplementary Material for *p*-values of the interactions.

		Leaf:fruit ratio (m^2 leaf/ kg fruit)		Yield (kg/plant)		Number of clusters/plant		Cluster weight (g)		Berry weight (g)	Berry water content (% w/w)	
						Crop *load level*						
	100 %	1.17		2.75		17.9	a*	148	b	1.86	77.8	
	70 %	1.52		2.35		13.9	ab	176	b	1.90	76.6	
	40 %	1.55		2.20		10.6	b	226	a	1.90	75.8	
						Sampling date						
Seyval blanc, 2012	Date 1	1.24		2.47		12.5		227	a	1.76	78.3	a
	Date 2	1.33		2.44		14.4		179	b	1.95	76.6	ab
	Date 3	1.67		2.35		15.0		153	b	1.93	75.8	b
						p-values						
	Crop load	0.2125		0.1320		0.0008		0.0007		0.7308	0.0632	
	Sampling date	0.1593		0.8430		0.3709		0.0013		0.1219	0.0087	
	Crop load*Sampling date	0.8934		0.8210		0.8546		0.9869		0.3898	0.6323	
						Crop load level						
	100 %	1.31	b	2.97	a	40.9	a	75.3		1.87	79.4	
	70 %	1.45	b	2.84	a	33.1	b	81.0		1.95	78.6	
	40 %	2.20	a	1.89	b	22.6	c	82.0		1.96	78.9	
						Sampling date						
Vandal-Cliche, 2012	Date 1	1.61		2.67		32.4		81.9		1.91	79.7	
	Date 2	1.62		2.58		31.0		79.7		1.95	78.6	
	Date 3	1.74		2.46		33.1		76.6		1.92	78.6	
						p-values						
	Crop load	0.0047		0.0011		≤ 0001		0.5722		0.5048	0.4962	
	Sampling date	0.8553		0.7143		0.3886		0.7284		0.8238	0.1673	
	Crop load*Sampling date	0.9902		0.9358		0.6116		0.5921		0.8562	0.6564	
						Crop load level						
	100 %	3.29	b	1.25	a	32.9	a	31.5		1.72	n.a.	
	70 %	3.90	ab	1.09	ab	24.7	b	36.4		1.74	n.a.	
	40 %	6.03	a	0.82	b	18.1	c	37.7		1.65	n.a.	
						Sampling date						
Vandal-Cliche, 2013	Date 1	4.01		1.07		25.2		41.3	a	1.72	n.a.	
	Date 2	4.94		1.09		25.3		31.7	b	1.68	n.a.	
	Date 3	4.27		1.01		25.2		32.7	b	1.71	n.a.	
						p-values						
	Crop load	0.0393		0.0211		≤ 0001		0.2978		0.2551	–	
	Sampling date	0.6810		0.8387		0.9961		0.0482		0.7460	–	
	Crop load*Sampling date	0.5997		0.7523		0.8681		0.0680		0.5374	–	

* For a given variable or treatment (Crop load or Sampling date, in bold), different letters indicate significant differences at $p \leq 0.05$, according to Tukey's honest significant difference test.

TABLE 2. Impact of crop load level (100 %, 70 % and 40 % cluster-thinned) and harvest date (date 1, 2 and 3) on the grape quality attributes (total soluble solids; titratable acidity; pH; yeast assimilable nitrogen and yeast assimilable nitrogen) and extractible grape phenolic compounds (hydroxycinnamic esters and flavonoids) of the interspecific hybrid *Vitis* varieties Seyval blanc (2012) and Vandal-Cliche (2012, 2013) grown in Quebec, Canada. *p*-values of the main effects are shown; see Supplementary Material for *p*-values of the interactions.

		Total soluble solids (°Brix)		pH		Titratable acidity (g/L tartaric acid eq.)		Yeast assimilable nitrogen (mg/L)		Hydroxy cinnamic esters (mg/L, cafeic acid eq.)		Flavonoids (mg/L, quercetin eq.)	
						Crop load level							
Seyval blanc, 2012	100 %	19.6		2.93		10.4		108		2.31		1.61	
	70 %	19.6		2.96		10.4		137		2.42		1.69	
	40 %	20.8		3.00		10.1		148		2.78		1.61	
						Sampling date							
	Date 1	18.0	b*	2.92	b	12.3	a	133		1.99		1.63	
	Date 2	20.8	a	2.89	b	9.63	b	125		2.66		1.69	
	Date 3	21.1	a	3.09	a	9.20	b	139		2.83		1.60	
						p-values							
	Crop load	0.1890		0.4084		0.7854		0.2536		0.3449		0.7601	
	Sampling date	0.0028		0.0075		0.0017		0.8345		0.0733		0.7653	
	Crop load*Sampling date	0.7646		0.9733		0.9990		0.5243		0.9569		0.0564	
						Crop load level							
Vandal-Cliche, 2012	100 %	18.4		2.88		12.8		118		4.93		2.16	
	70 %	18.8		2.87		12.2		106		4.64		2.04	
	40 %	18.7		2.89		13.1		138		4.66		2.06	
						Sampling date							
	Date 1	17.7	b	2.85		13.3		102		3.95	b	1.79	b
	Date 2	19.2	a	2.91		12.6		137		5.31	a	2.30	a
	Date 3	19.0	ab	2.89		12.1		124		4.97	a	2.17	a
						p-values							
	Crop load	0.7357		0.8796		0.2784		0.2990		0.4382		0.5532	
	Sampling date	0.0193		0.3830		0.0963		0.2253		≤.0001		0.0005	
	Crop load*Sampling date	0.5496		0.9856		0.7529		0.6877		0.8056		0.8739	
						Crop load level							
Vandal-Cliche, 2013	100 %	17.2		2.72		19.2		213		60.5**		59.5	
	70 %	17.5		2.75		18.8		217		62.4		61.5	
	40 %	16.9		2.77		19.2		229		65.5		63.7	
						Sampling date							
	Date 1	15.1	c	2.63	b	21.5	a	176	b	51.6	b	35.2	b
	Date 2	17.8	b	2.82	a	17.9	b	220	ab	66.2	a	74.3	a
	Date 3	18.7	a	2.78	a	17.7	b	263	a	70.6	a	75.1	a
						p-values							
	Crop load	0.0883		0.0532		0.6588		0.7893		0.4101		0.5151	
	Sampling date	≤.0001		≤.0001		≤.0001		0.0042		≤.0001		≤.0001	
	Crop load*Sampling date	0.6469		0.9827		0.6163		0.8941		0.9612		0.7762	

* For a given variable and treatment (Crop load or Sampling date, in bold), different letters indicate significant differences at $p \leq 0.05$, according to Tukey's honest significant difference test.

** Different methodologies were used to measure hydroxycinnamic esters and flavonoids contents in 2012 and 2013, which explains the different ranges of values obtained.

TABLE 3. Impact of crop load level (100 %, 70 % and 40 % cluster-thinned) on the free aroma content of grape (µg/L, in must) of the interspecific hybrid *Vitis* varieties Seyval blanc (2012) and Vandal-Cliche (2012 and 2013) grown in Quebec, Canada.

		Seyval blanc 2012						Vandal-Cliche 2012						Vandal-Cliche 2013					
	Crop load levels	100 %		70 %		40 %		100 %		70 %		40 %		100 %		70 %		40 %	
Citrus	R-(+)–limonene	0.10		0.10		0.11		0.99		0.87		0.83		0.30		0.33		0.39	
	decanal	1.79		1.76		1.72		1.56		1.58		1.65		1.08	b*	1.10	b	1.14	a
	citral	n.d.		n.d.		n.d.		n.d.		n.d.		n.d.		4.04		4.04		4.09	
Earthy	2-octanone	0.07		0.06		0.06		0.07		0.07		0.08		0.16		0.24		0.15	
	1-octen-3-ol	0.43		0.51		0.6		0.62		0.71		1.16		0.93		0.95		1.18	
Fatty	*trans*-2-*cis*-4-heptadienal	0.40		0.38		0.37		0.41		0.41		0.44		0.43		0.40		0.40	
	trans-2-*trans*-4-heptadienal	2.14		2.12		2.16		2.27		2.33		2.51		2.35		2.34		2.19	
Fermented	ethyl crotonate	n.d.		n.d.		n.d.		47.8		47.0		50.0		93.6		102		84.3	
Floral	linalool	1.19	b	1.39	ab	1.82	a	30.6		27.2		37.8		6.30		7.22		7.49	
	phenylacetaldehyde	55.4		102		58.6		n.d.		n.d.		n.d.		n.d.		n.d.		n.d.	
	α-terpineol	47.4		47.2		47.3		29.5		28.8		28.0		44.6	a	44.8	a	40.5	b
	citronellol	0.91		0.95		1.15		n.d.		n.d.		n.d.		n.d.		n.d.		n.d.	
	nerol	n.d.		n.d.		n.d.		0.88		0.68		1.36		n.d.		n.d.		n.d.	
	β-damascenone	3.35		4.31		4.68		8.5		9.62		8.59		8.1		9.23		8.67	
	α-ionone	0.7		0.81		0.9		0.62		0.68		0.64		n.d.		n.d.		n.d.	
	α-ionol	2.85		3.03		3.36		2.04		2.07		2.11		10.2		10.2		10.2	
	β-ionone	0.24		0.24		0.24		0.24		0.23		0.24		0.24		0.25		0.24	
Fruity	ethyl acetate	22.0		34.6		296		2 682		2 443		2 811		4 848		5 777		5 446	
	ethyl propanoate	n.d.		n.d.		n.d.		12.2		10.6		10.9		14.5		14.9		14.9	
	ethyl butyrate	n.d.		n.d.		n.d.		180		180		184		285		302		286	
	ethyl 2-methylbutanoate	n.d.		n.d.		n.d.		1.17		1.54		1.44		2.72		3.42		3.21	
	ethyl isovalerate	n.d.		n.d.		n.d.		n.d.		n.d.		n.d.		0.27		0.31		0.31	
	ethyl hexanoate	n.d.		n.d.		n.d.		19.2		20.2		21.5		25.4		37.8		29.6	
	2-undecanone	0.67		0.61		0.7		0.51		0.52		0.56		n.d.		n.d.		n.d.	
Green	hexanal	115	a	95.2	ab	48.8	b	54.8		53.2		75.0		30.4		41.7		37.6	
	cis-3-hexenal	38.8		42.2		25.4		80.9		85.4		96.6		49.0	b	64.0	a	65.5	a
	trans-2-hexenal	596		609		435		813		872		922		657		805		837	
	trans-2-heptenal	1.34		1.45		1.88		1.13		1.31		1.40		1.53	b	2.21	ab	3.23	a
	hexanol	335		351		409		259		267		378		131	b	211	a	215	a
	cis-3-hexenol	62.0		70.0		58.9		25.3		22.8		36.4		8.66	b	10.0	b	14.7	a
	rose oxide	n.d.		n.d.		n.d.		0.06		0.06		0.09		0.17		0.27		0.24	
	sorbaldehyde	32.2		27.0		22.0		37.9		41.3		44.0		34.7		46.0		48.0	
	trans-2-hexenol	477		502		570		618		545		812		497	b	652	a	684	a
	trans-2-*cis*-6-nonadienal	0.18		0.15		0.17		0.39		0.39		0.44		0.26	a	0.30	b	0.32	b
Spicy	β-myrcene	1.85		1.85		1.86		3.09		2.94		3.13		2.15		2.24		2.25	
	2-methoxy-4-vinylphenol	1.17		0.78		1.07		n.d.		n.d.		n.d.		2.07	a	1.55	b	1.75	ab

* For a given variable, variety*vintage and crop load treatment (100 %, 70 % and 40 %), different letters indicate significant differences at $p \leq 0.05$, according to Tukey's honest significant difference test.

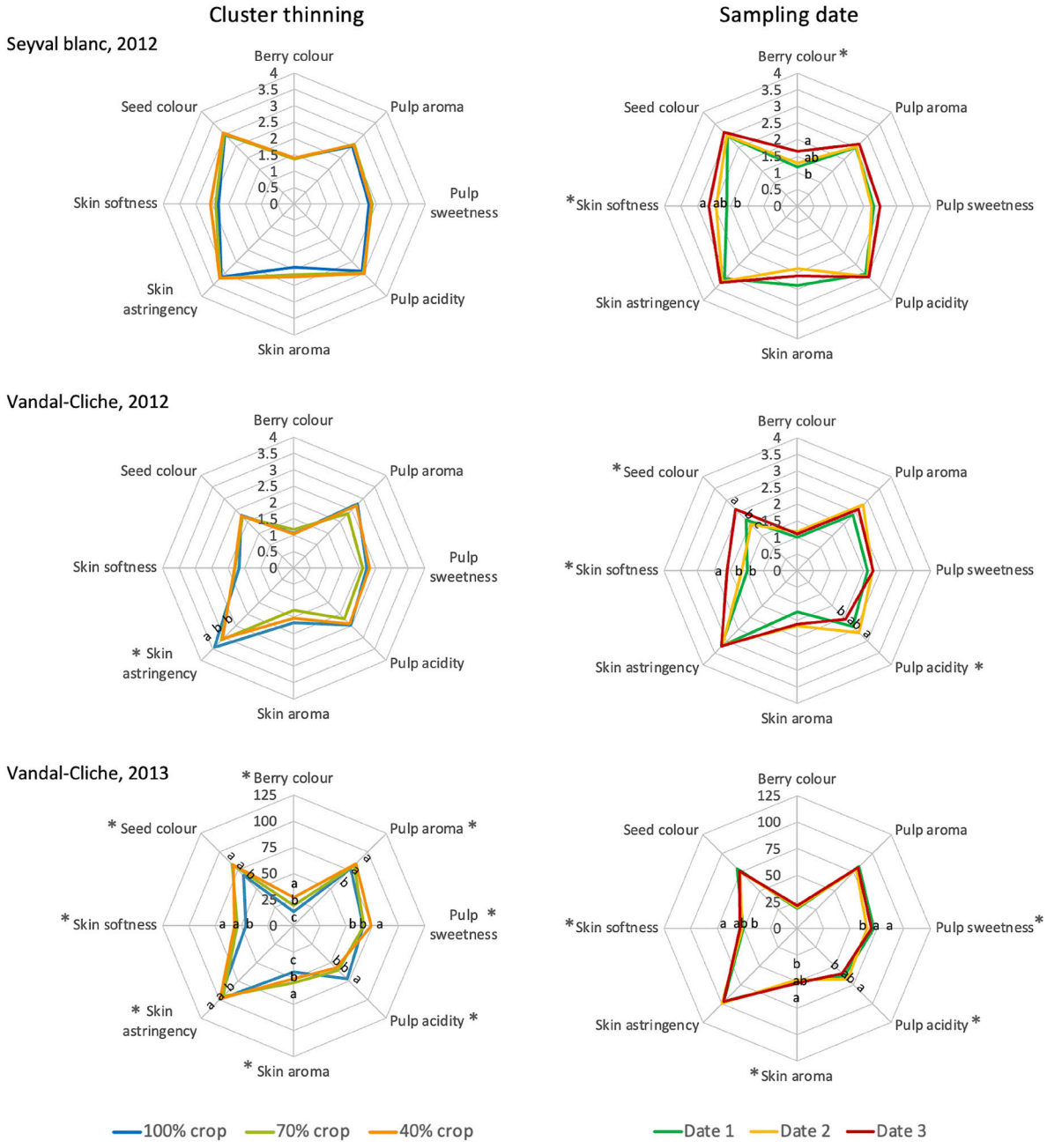
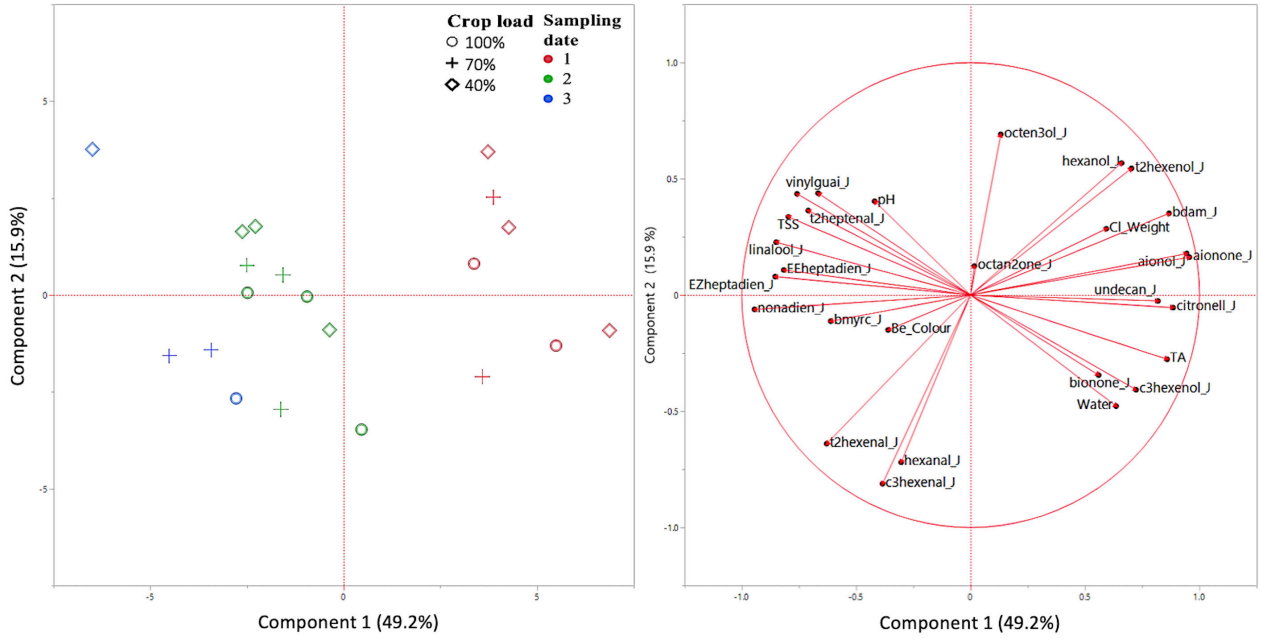


FIGURE 1. Impact of crop load level (100 %, 70 % and 40 % cluster-thinned) and harvest date (Dates 1 to 3, one week interval between sampling) on the berry sensory descriptors of the interspecific hybrid *Vitis* varieties Seyval blanc (2012) and Vandal-Cliche (2012, 2013) grown in Quebec, Canada. Descriptors identified with an asterisk (*) showed significant differences between treatments (cluster thinning or sampling date) at $p \leq 0.05$, according to Tukey's honest significant difference test; different letters indicate differences between means. Detailed values are available in Table S7.

Table 4. Impact of harvest date (Dates 1 to 3, one week interval between each sampling) on the grape free aroma content (µg/L, in must) of the interspecific hybrid *Vitis* varieties Seyval blanc (2012) and Vandal-Cliche (2012, 2013) grown in Quebec, Canada.

		Seyval blanc 2012						Vandal-Cliche 2012						Vandal-Cliche 2013					
Sampling date		Date 1		Date 2		Date 3		Date 1		Date 2		Date 3		Date 1		Date 2		Date 3	
Citrus	R-(+)limonene	0.09		0.1		0.12		0.38	b*	0.94	b	1.38	a	0.35	ab	0.22	a	0.44	b
	decanal	1.77		1.71		1.8		1.62		1.53		1.66		1.10		1.10		1.12	
	citral	n.d.		n.d.		n.d.		n.d.		n.d.		n.d.		4.05		4.06		4.05	
Earthy	2-octanone	0.05	b	0.10	a	0.02	b	0.05	b	0.09	a	0.07	b	0.08	b	0.05	a	0.42	c
	1-octen-3-ol	0.59	a	0.42	b	0.54	ab	1.01		0.79		0.7		0.81	a	1.07	b	1.19	c
Fatty	*trans*-2-*cis*-4-heptadienal	0.29	b	0.42	a	0.43	a	0.39	b	0.54	a	0.34	b	0.36	a	0.42	b	0.46	c
	trans-2-*trans*-4-heptadienal	1.63	c	2.27	b	2.46	a	2.18	b	3.1	a	1.84	b	2.03	a	2.24	b	2.61	c
Fermented	ethyl crotonate	n.d.		n.d.		n.d.		53.5		36.4		54.5		87.1		103		89.9	
Floral	linalool	0.57	c	1.42	b	2.33	a	23.6		44.4		27.5		3.82	a	7.74	b	9.45	b
	phenylacetaldehyde	104		91.3		26.1		n.d.		n.d.		n.d.		n.d.		n.d.		n.d.	
	α-terpineol	47.5		47.3		47.0		31.5		26.2		28.5		44.8		44.1		41.0	
	citronellol	1.82	a	0.84	b	0.37	b	n.d.		n.d.		n.d.		n.d.		n.d.		n.d.	
	nerol	n.d.		n.d.		n.d.		0.82		1.43		0.66		n.d.		n.d.		n.d.	
	β-damascenone	8.15	a	2.97	b	1.76	c	9.3	ab	6.14	b	11.27	a	7.39	a	8.86	ab	9.75	b
	α-ionone	1.72	a	0.53	b	0.27	c	0.63	ab	0.47	b	0.84	a	n.d.		n.d.		n.d.	
	α-ionol	5.43	a	2.38	b	1.72	b	2.47	a	1.77	b	1.97	b	0.30	a	15.2	b	15.2	b
	β-ionone	0.25	a	0.24	a	0.23	b	0.23	b	0.24	a	0.23	b	0.22	a	0.25	b	0.26	b
Fruity	ethyl acetate	321		31.1		37.7		3146		1853		2937		2844	a	7669	c	5557	b
	ethyl propanoate	n.d.		n.d.		n.d.		12.2		8.76		12.69		10.1	a	19.6	c	14.5	b
	ethyl butyrate	n.d.		n.d.		n.d.		200		158		187		174	a	316	b	382	c
	ethyl 2-methylbutanoate	n.d.		n.d.		n.d.		0.74	b	0.95	b	2.46	a	0.91	a	2.80	b	5.64	c
	ethyl isovalerate	n.d.		n.d.		n.d.		n.d.		n.d.		n.d.		n.d.		0.43	b	0.46	b
	ethyl hexanoate	n.d.		n.d.		n.d.		18.6		19.5		22.9		15.2	a	39.2	b	38.5	b
	2-undecanone	1.02	a	0.47	b	0.52	b	0.54		0.47		0.59		n.d.		n.d.		n.d.	
Green	hexanal	49.0	b	52.4	b	150	a	36.7	b	133	a	13.0	b	37.4	ab	46.9	b	25.4	a
	cis-3-hexenal	20.0	b	32.9	ab	51.4	a	49.4	b	168	a	45.2	b	69.4	a	58.8	ab	50.3	b
	trans-2-hexenal	253	c	492	b	857	a	608	b	1 545	a	454	b	799	b	916	b	583	a
	trans-2-heptenal	0.39	c	1.92	ab	2.25	a	1.30	ab	1.84	a	0.71	b	3.75	b	1.69	a	1.53	a
	hexanol	529	a	290	b	298	b	210	b	439	a	255	ab	109	a	203	b	245	b
	cis-3-hexenol	110	a	48.0	b	37.9	b	17.2	b	48.3	a	19.1	b	14.6	b	10.2	ab	8.64	a
	rose oxide	n.d.		n.d.		n.d.		0.05	b	0.11	a	0.05	b	0.07	a	0.24	b	0.37	b
	Sorbaldehyde	19.5		27.1		32.7		34.3	b	67.9	a	20.9	b	61.2	c	47.0	b	20.4	a
	trans-2-hexenol	812	a	456	b	319	b	488	b	913	a	573	b	353	a	625	b	854	c
	trans-2-*cis*-6-nonadienal	n.d.	c	0.21	b	0.27	a	0.35	b	0.62	a	0.25	b	0.30		0.32		0.28	
Spicy	β-myrcene	1.84	b	1.86	ab	1.87	a	2.10	b	3.74	a	3.33	a	2.02	a	2.15	b	2.47	c
	2-methoxy-4-vinylphenol	0.46	b	1.09	b	1.35	a	n.d.		n.d.		n.d.		1.95		1.84		1.57	

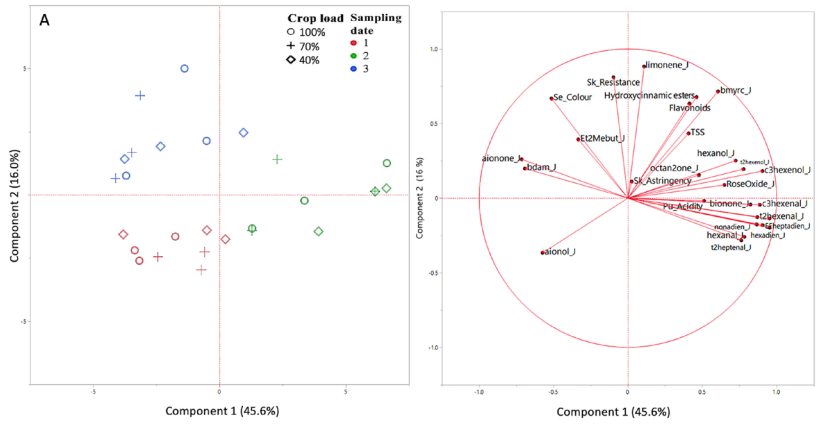
* For a given variable, variety X vintage and sampling date (date 1, 2 and 3), different letters indicate significant differences at $p \leq 0.05$, according to Tukey's honest significant difference test.



Variables - Seyval blanc (2012)

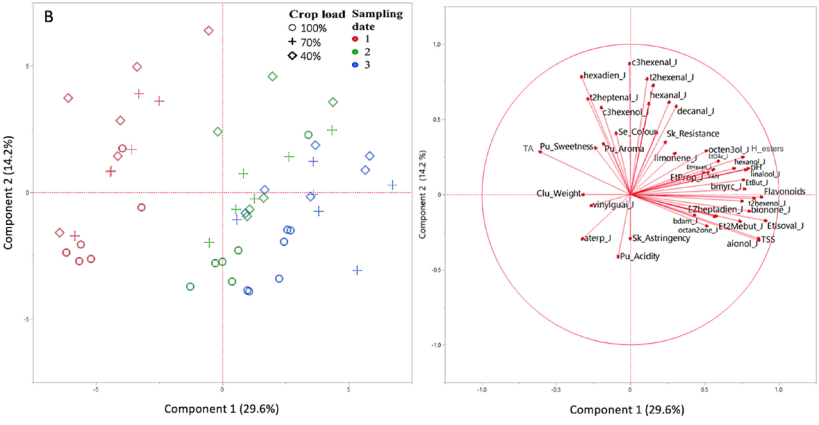
Physiological parameters		Must basic metrics		Aroma compounds		Berry sensory metrics	
Cluster weight	*Cl_Weight*	pH	*pH*	2-octanone	*octan2one_J*	Berry colour	*Be_Colour*
Water content	*Water*	Titratable acidity	*TA*	1-octen-3-ol	*octen3ol_J*	Skin resistance	*Sk_Resistance*
		Total soluble solids	*TSS*	2-undecanone	*undecan_J*		
				hexanal	*hexanal_J*		
				trans-2-hexenal	*t2hexenal_J*		
				cis-3-hexenal	*c3hexenal_J*		
				trans-2-*cis*-4-heptadienal	*EZheptadien_J*		
				trans-2-*trans*-4-heptadiena	*EEheptadien_J*		
				trans-2-*cis*-6-nonadienal	*nonadien_J*		
				trans-2-heptenal	*t2heptenal_J*		
				hexanol	*hexanol_J*		
				trans-2-hexenol	*t2hexenol_J*		
				cis-3-hexenol	*c3hexenol_J*		
				linalool	*linalool_J*		
				β-myrcene	*bmyrc_J*		
				citronellol	*citronell_J*		
				β-damascenone	*bdam_J*		
				α-ionone	*aionone_J*		
				α-ionol	*aionol_J*		
				β-ionone	*bionone_J*		
				2-methoxy-4-vinylphenol	*vinylguai_J*		

FIGURE 2. Principal component analysis of vine physiological parameters (leaf:fruit ratio, cluster weight and berry weight), must basic metrics (total soluble solids, titratable acidity, pH, yeast assimilable nitrogen), must phenolic (hydroxycinnamic esters and flavonoids) content and must free aroma content (on the right) plotting according to the crop load treatments (100 %, 70 % and 40 %) and the sampling dates (Date 1, 2 and 3) (on the left) of the interspecific hybrid *Vitis* variety Seyval blanc, grown in Quebec, Canada, in 2012. Variables significant to the ANOVA selected for the PCA are listed at bottom with their respective abbreviation.



Variables, Vandal-Cliche (2012)

Must basic metrics		Aroma compounds		Berry sensory metrics	
Total soluble solids	*TSS*	ethyl 2-methylbutanoate	*Et2Mebut_J*	Pulp acidity	*Pu_Acidity*
Hydroxycinnamic esters	*Hydroxycinnamic esters*	2-octanone	*octan2one_J*	Skin astringency	*Sk_Astringency*
Flavonoids	*Flavonoids*	hexanal	*hexanal_J*	Skin resistance	*Sk_Resistance*
		trans-2-hexenal	*t2hexenal_J*	Seed colour	*Se_Colour*
		cis-3-hexenal	*c3hexenal_J*		
		trans-2-heptenal	*t2heptenal_J*		
		sorbaldehyde	*hexadien_J*		
		trans-2-*cis*-4-heptadienal	*EZheptadien_J*		
		trans-2-*trans*-4-heptadiena	*EEheptadien_J*		
		trans-2-*cis*-6-nonadienal	*nonadien_J*		
		hexanol	*hexanol_J*		
		trans-2-hexenol	*t2hexenol_J*		
		cis-3-hexenol	*c3hexenol_J*		
		r-limonene	*limonene_J*		
		β-myrcene	*bmyrc_J*		
		β-damascenone	*bdam_J*		
		α-ionone	*aionone_J*		
		α-ionol	*aionol_J*		
		β-ionone	*bionone_J*		
		rose oxide	*RoseOxide_J*		



Variables, Vandal-Cliche (2013)

Physiological parameters		Must basic metrics		Aroma compounds		Berry sensory metrics	
Cluster weight	Clu_Weight	Total soluble solids	*TSS*	ethyl acetate	*EtOAc_J*	Berry colour	*Be_Colour*
		pH	*pH*	ethyl propanoate	*EtProp_J*	Pulp aroma	*Pu_Aroma*
		Titratable acidity	*TA*	ethyl butyrate	*EtBut_J*	Pulp sweetness	*Pu_Sweetness*
		Yeast assimilable nitrogen	*YAN*	ethyl 2-methylbutanoate	*Et2Mebut_J*	Pulp acidity	*Pu_Acidity*
		Hydroxycinnamic esters	*H_esters*	ethyl isovalerate	*Etisoval_J*	Skin aroma	*Sk_Aroma*
		Flavonoids	*Flavonoids*	ethyl hexanoate	*EtHexan_J*	Skin astringency	*Sk_Astringency*
				2-octanone	*octan2one_J*	Skin resistance	*Sk_Resistance*
				1-octen-3-ol	*octen3ol_J*	Seed colour	*Se_Colour*
				hexanal	*hexanal_J*		
				trans-2-hexenal	*t2hexenal_J*		
				cis-3-hexenal	*c3hexenal_J*		
				sorbaldehyde	*hexadien_J*		
				trans-2-heptenal	*t2heptenal_J*		
				trans-2-*cis*-4-heptadienal	*EZheptadien_J*		
				trans-2-*trans*-4-heptadiena	*EEheptadien_J*		
				trans-2-*cis*-6-nonadienal	*nonadien_J*		
				hexanol	*hexanol_J*		
				trans-2-hexenol	*t2hexenol_J*		
				cis-3-hexenol	*c3hexenol_J*		
				decanal	*decanal_J*		
				r-limonene	*limonene_J*		
				linalool	*linalool_J*		
				α-terpineol	*aterp_J*		
				β-myrcene	*bmyrc_J*		
				β-damascenone	*bdam_J*		
				α-ionol	*aionol_J*		
				β-ionone	*bionone_J*		
				rose oxide	*RoseOxide_J*		
				2-methoxy-4-vinylphenol	*vinylguai_J*		

FIGURE 3. Principal component analysis of vine physiological parameters (leaf:fruit ratio, cluster weight and berry weight), must basic metrics (total soluble solids, titratable acidity, pH and yeast assimilable nitrogen), must phenolic (hydroxycinnamic esters and flavonoids) content and must free aroma content (on the right) plotting according to the crop load treatments (100 %, 70 % and 40 %) and the sampling dates (Date 1, 2 and 3) (on the left) of the interspecific hybrid *Vitis* variety Vandal-Cliche, grown in Quebec, Canada, in 2012 (A) and 2013 (B). Variables significant to the ANOVA selected for the PCA are listed at the bottom of each PCA with their respective abbreviation.

acidity, an increase in skin softness and brown seeds during berry ripening (between Date 1 and Date 3). In 2013, similar sweetness and acidity of the pulp and similar skin aroma were perceived in berries from the first and last sampling dates compared to the second sampling date, but the skin was perceived as being softer on the last sampling date.

3. Principal component analyses

To summarise the effect of crop load and harvest date on grapevine physiology and grape physicochemical and sensory properties, a principal component analysis (PCA) per cultivar and year was carried out, using only the variables that showed significant differences according to the analysis of variance (Figures 2 and 3). For both varieties and vintages, the principal components (PC) 1 and 2 explained 43.8 (Vandal-Cliche, 2013) to 65.1 % (Seyval blanc, 2012) of the variation between samples.

In the PCA, the samples of both varieties and from both vintages are mostly grouped according to sampling date, rather than crop load treatment. In Seyval blanc, high TA, C_6-alcohols and C_{13}-norisoprenoids are mostly associated with low ripening, whereas high TSS, terpenes (e.g., linalool, *β*-myrcene) and C_6-aldehydes are associated with later ripening stages (Dates 2 and 3). In Vandal-Cliche in 2012, TSS and C_6-aldehydes peaked at Date 2, whereas high levels of the C_{13}-norisoprenoids *β*-damascenone and *a*-ionone are associated with full ripening (Date 3). A similar pattern can be seen in 2013, with Date 3 being associated with higher levels of TSS, C_{13}-norisoprenoids (*β*-damascenone and *β*-ionone, among others) and terpenes (linalool, *β*-myrcene).

DISCUSSION

1. Impact of cluster thinning and harvest date on yield components

Cluster thinning is a common practice in northern viticulture (Province of Quebec, Canada; Midwestern and Northeastern United States; and Northern Europe), and historically it has been recommended for controlling Seyval blanc yield in Michigan and other areas (Edson *et al.*, 1995). In contrast to other canopy management practices, such as leaf removal, the aim of cluster thinning is to alter leaf to fruit ratio; reducing the number of clusters increases leaf to fruit ratio thus reducing yield (i.e., a larger canopy leads to the ripening of a lower amount of fruit).

In this study, significant differences in the number of clusters per plant were observed between the crop load treatments (40 %, 70 % and 100 %) for both of the interspecific *Vitis* cultivars, Seyval Blanc and Vandal-Cliche. Additionally, a similar number of clusters per plant was observed between the flowering and full maturity stages for each treatment. These results show the effective reduction in number of clusters per plant through cluster thinning. However, the efficiency of the treatment in terms of successfully altering the leaf to fruit ratio varied depending on the cultivar. In Vandal-Cliche, thinning the clusters to 40 % significantly decreased yield by 36.1 % and 33.8 % in 2012 and 2013 respectively, significantly increasing leaf to fruit ratio in both years as well. In Seyval blanc, cluster thinning did not reduce yield as this cultivar compensated for the low number of clusters by producing very large clusters (up to 52 % larger), hence resulting in similar yields in cluster-thinned and control grapevines; consequently, the leaf to fruit ratio was not significantly increased in this variety. Such compensation has been documented in interspecific hybrid varieties, including Seyval blanc (Berkey *et al.*, 2011; Edson *et al*., 1995; Reynolds and Heuvel, 2009) and in certain *V. vinifera* varieties such as Carignan (Bravdo *et al*., 1984), but multiple year studies have not always produced significant results (Reynolds *et al*., 1986a). The occurrence of compensation may be due to a larger number of berries per cluster and/or to the production of larger berries. In our study, cluster thinning resulted in larger clusters without an increase in average berry weight; therefore, the weight gain was likely attributable to a larger number of berries on each cluster rather than to larger berries. Edson *et al.* (1995) obtained similar results for Seyval blanc. In both our study and the latter study cluster thinning was conducted at the flowering stage. By contrast, Berkey *et al.* (2011) conducted cluster thinning at the pea-size stage and, while they also observed compensation in terms of cluster weight, this result was attributable to higher berry weight. Thus, the outcome of cluster thinning in Seyval blanc would seem to strongly depends on the timing of the operation (i.e., flowering vs pea-size stage), cluster thinning at the flowering stage resulting in improved fruit set (i.e., more berries per cluster) rather than larger berries. Indeed, cluster thinning at the flowering stage can contribute to reducing disorders related to poor reproductive performance, such as coulure, without significantly reducing yield at harvest. The occurrence of coulure is strongly related to the environmental conditions (e.g., low temperature and rain) during flowering (Grimplet *et al*., 2019; Lebon *et al*., 2005), and it has been observed to frequently occur in northern vineyards, especially in cloudy, rainy and/or cold conditions during the flowering stage.

Besides physiological disorders that can affect grape production, attaining full ripeness level is another yearly concern in cold climate vineyards. Indeed, the reduced photoperiod in autumn, along with cooler temperatures, increased rainfall and occasional frosts all hamper ripening and may even result in an early harvest when risks of damages, such as berry splitting and fungal infections (e.g., *Botrytis*), are high. In the present study, a decrease in cluster weight in Seyval blanc (2012) and Vandal-Cliche (2013) was observed in the period between the first and last sampling dates. In Seyval blanc, this decrease was concomitant with a decrease in berry water content, which likely resulted from dehydration due to the warm temperatures of the 2012 season. A similar decrease in cluster weight was observed in Vandal-Cliche (2013) in the period between the first and last sampling dates, likely attributable to water loss, although this variable was not measured in 2013.

2. Impact of cluster thinning and harvest date on basic berry chemistry

The cluster thinning treatments on both Seyval blanc and Vandal-Cliche had little or no impact on the must technological parameters or on the extractible phenolic compounds in both seasons. Studies on *V. vinifera* (Bravdo *et al*., 1984; Guidoni *et al*., 2002; Gutiérrez-Gamboa *et al*., 2019; Kliewer and Dokoozlian, 2005; Martínez-Lüscher and Kurtural, 2021; Rossouw *et al*., 2017) and hybrid varieties (Berkey *et al*., 2011; Dami *et al*., 2006; Reynolds *et al*., 1986a; Sun *et al*., 2012) have shown that increasing the leaf to fruit ratio through cluster thinning often increases sugar accumulation in berries, but positive impacts seem to vary depending on cultivar, season and growing conditions (Martínez-Lüscher and Kurtural, 2021; Mota *et al*., 2010; Rossouw *et al*., 2017), with cooler years being more likely to give positive results (Berkey *et al*., 2011).

Ripening had a much higher impact than cluster thinning on berry quality parameters. Both cultivars showed significant increases in TSS and pH and a decrease in TA in the period between the first and last sampling dates. YAN also significantly increased in Vandal-Cliche (2013), but no significant changes were observed in Seyval blanc and Vandal-Cliche in 2012. Nitrogen tends to accumulate during ripening, but can sometimes stabilise before reaching full maturity (Bell and Henschke, 2005). Nitrogen accumulation largely depends on the variety, especially among IHG varieties that tend to accumulate significantly higher levels of YAN than *V. vinifera*, with significant annual and regional variations (Pedneault and Provost, 2016; Stewart, 2013).

The berry content in extractable flavonoids and hydroxycinnamic esters significantly increased with ripening in Vandal-Cliche in 2012 and 2013, but no changes occurred in Seyval blanc. Although differences linked to variety can occur, the sustained increase in the content of flavonoids and hydroxycinnamic esters is typical during berry ripening, except near full ripening, when concentrations will stabilise or decrease due to oxidation processes (Ribéreau-Gayon *et al*., 2018). Vandal-Cliche was harvested from a cool area, whereas Seyval blanc benefitted from warm conditions (area and season) in 2012, which may have affected the production of flavonoids and hydroxycinnamic esters in the berries and their concentrations at harvest. In Seyval blanc, these phenolic compounds may have already stabilised in the samples by the time of the third harvest, whereas they were still accumulating in the cooler conditions under which Vandal-Cliche was grown. These results are consistent with a previous study we carried out on the interspecific hybrids Frontenac and Marquette, which revealed a sharp increase in hydroxycinnamic esters and flavonoids on a cool site, whereas inconsistent accumulation patterns were observed on a warmer site (Pedneault *et al*., 2013).

3. Impact of cluster thinning and harvest date on berry volatile compounds

In our study, not only did cluster thinning result in little improvement of basic berry characteristics, even in the cooler year of 2013, but when treatments affected the volatile compounds profile, as was the case in Vandal-Cliche 2013, the cluster-thinned berries had higher levels of herbaceous C_6-compounds than the control. These results suggest that cluster thinning does not improve and could even be detrimental to Seyval blanc and Vandal-Cliche quality, as the level of C_6 in berries is known to affect the levels of C_6-compounds in wine (Slegers *et al*., 2015). Although certain C_6-compounds (e.g., hexan-1-ol, hexenal, (E)-2-hexen-1-ol and (E)-2-hexenal) from grapes are transformed during fermentation, and can contribute to wine fruitiness (Dennis *et al*., 2012), many remain in the wines and can affect wine quality (Mozzon *et al*., 2016; Slegers *et al*., 2015, Chapman *et al*., 2004). Different studies have shown varied results regarding the impact of cluster thinning on herbaceous compounds (e.g., C_6-alcohols and aldehydes) in berries, either increasing or decreasing their concentrations (Alba *et al*., 2022; Sun *et al*., 2011; Wang *et al*., 2019; Xi *et al*., 2020). Similar to our results, cluster thinning increased the concentration of C_6-compounds in berries of the Chinese variety Jumeigui (Xi *et al*., 2020), whereas it significantly decreased the concentration of C_6-compounds in Sangiovese and Cabernet Sauvignon berries (Alba *et al*., 2022; Wang *et al*., 2019). However, in a study by Alba *et al*. (2022), most of the changes in volatile compounds measured in berries, despite being significant, had ultimately little impact on wine aroma; this indicates that any gains achieved from cluster thinning at any point in the wine production chain may not be enough to overcome the negative impact of yield losses or labour costs associated with cluster thinning. Regarding our study, however, part of the results can be explained by the initially low crop load of the control vines, which left a range of less than 1 kg between full crop (100 % clusters) and the 40 % cluster-thinned grapevines, indicating that, from a physiological point of view, there was little room for tangible improvement. A "natural" reduction in crop load in northern vineyards regularly occurs in many cultivars due to winter and spring frost events and, in some cases, to poor fruit set (e.g., *coulure*), a physiological issue that was observed in the experimental parcels in both 2012 and 2013.

In contrast to cluster thinning, berry ripening significantly affected the profile of the volatile compounds in the berry in both cultivars. In Seyval blanc during ripening, floral aromas, such as linalool, increased significantly, while other compounds, such as C_{13}-norisoprenoids (citronellol, *β*-damascenone, *α*-ionone, *α*-ionol and *β*-ionone), decreased. In Vandal-Cliche, changes in the concentrations of floral compounds were inconsistent during maturation in the two years of study. The progression of the concentrations of floral volatile compounds, such as terpenes (linalool) and C_{13}-norisoprenoids *(β*-damascenone, α-ionone, *α*-ionol, *β*-ionone), is not always linear during grape ripening. These compounds will often accumulate until a particular stage of maturity is reached and will then remain stable or decrease until

full maturity (Campos-Arguedas *et al.*, 2022; Pedneault *et al.*, 2013). Furthermore, a three-week window is relatively too small to be able to gain a comprehensive understanding of the changes in volatile compounds, especially when the changes in environmental conditions are limited to this window, as is often the case in northern wine production, as the accumulation of growing-degree days slows down quickly in September. Furthermore, any changes observed during ripening are not necessarily applicable from one season to another. For example, in wines made from Maréchal Foch berries of different ripeness levels over two years, Sun *et al.* (2011) observed higher levels of citronellol and *α*-terpineol (a breakdown product from linalool) in the earliest wine in the first year, whereas the highest levels of citronellol were observed in the most mature wines the following season. Such variability in patterns results from interactions between different seasonal conditions and small sampling windows.

The concentration of herbaceous compounds, mainly C_6-compounds resulting from the degradation of unsaturated fatty acids (linoleic and linolenic acids), is usually affected by berry ripening (Kalua and Boss, 2009; Pedneault *et al.*, 2013). In Seyval blanc, a significant increase in aldehydes, including hexanal, *trans*-2-hexenal, *trans*-2-heptanal and *cis*-3-hexenal, during ripening was accompanied by a significant decrease in C_6-alcohols (e.g. hexanol, *cis*-3-hexenol, and *trans*-2-hexenol). We observed a similar trend in the interspecific hybrid varieties Marquette and Frontenac in a previous study (Pedneault *et al.*, 2013). C_6-aldehydes can bring green aromas and sometimes bitterness to wines, but most are converted into their respective alcohols during fermentation, which have less impact on the aromas because of their high odour threshold (García *et al.*, 2003; Kalua and Boss, 2009). In Vandal-Cliche, the concentration of C_6-compounds showed a very different trend in 2012 and 2013, and a different profile from that observed in Seyval blanc. In 2012, both C_6-alcohols and C_6-aldehydes followed the same trend in Vandal-Cliche, increasing in the second harvest and decreasing later, whereas in 2013, C_6-alcohols increased during ripening while C_6-aldehydes decreased. Such variations between varieties and years suggest significant differences in the catabolism of unsaturated fatty acids, and possibly in the enzymatic activity leading to the biosynthesis of alcohols from aldehydes (Kalua and Boss, 2009; Pedneault *et al.*, 2013). Besides genetic-related variations, those processes are also affected by temperature: higher temperatures can increase the oxidation of unsaturated fatty acids into aldehydes and alcohol derivatives (i.e., C_6 and others), whereas lower temperatures can trigger an increase in the level of C_6-precursors (e.g., unsaturated fatty acids). In our case, some of the observed variations may be due to differences in environmental conditions between the areas in Quebec where Vandal-Cliche (cooler area) and Seyval blanc (warmer area) are grown, and between seasonal conditions, which were warmer in 2012 than in 2013.

4. Relationships between berry sensory properties, ripening and cluster thinning

Cluster thinning mostly impacted skin and pulp-related descriptors, such as skin astringency and softness and pulp sweetness and aroma, and changes were only detected in Vandal-Cliche, especially in 2013, when the scale was adapted. Overall, lower crop loads of Vandal-Cliche grapevines resulted in browner seeds, more aromatic berries and less acidic berries, with softer and less astringent skin. Studies on the impact of crop load on the sensory profile of berry are very scarce. In contrast to our results, in a study in which crop load treatments were applied to the *V. vinifera* Sémillon grape variety just after flowering (30 % of clusters removed at EL-29; peppercorn-sized berries) no significant differences were found between the sensory profiles of the treated berries and the control in terms of berry colour, pulp sweetness and flavour, and skin astringency and flavour (Lohitnavy *et al.*, 2010).

Skin softness evaluation via skin grinding allowed us to obtain a reliable and clear discrimination of the maturity level of both the cultivars during the two study years, and overall skin softness was the most reliable descriptor of those tested. Berry skins significantly softened during berry ripening; these changes in berry firmness during maturation are mainly due to a shift in cell wall mechanical properties, involving components like hemicellulose, pectin and cellulose (Goulao and Oliveira, 2008). The changes in firmness are influenced by the grapevine's genotype and its interactions with the environment (Rihan *et al.*, 2017). Although the skin of interspecific hybrid varieties is typically harder than that of *V. vinifera* varieties - which also contributes to their generally higher resistance to fungal diseases - our data shows that the degradation process that occurs during ripening is scalable and could be used as a maturity marker. Skin softness also impacts tannin and aroma extraction during winemaking, which is relevant to white wine production, as these compounds give body and length to wine and contribute to its quality (Hanlin *et al.*, 2010).

Differences related to skin and pulp aroma were only detected in the Vandal-Cliche 2013 berries. In this variety/year, cluster-thinned grapevine produced fruitier berries (both skin and pulp aroma) than the control, and the ripest berries (Date 3) had a fruitier skin aroma than the berries from Date 1. This is consistent with the results of the chemical analyses: the ripest berries (Date 3) had significantly higher levels of floral and fruity compounds, such as linalool, ethyl butyrate and ethyl hexanoate, among others, and lower levels of herbaceous compounds than the berries harvested on Date 1. By contrast, the cluster-thinned berries showed little to no significant differences in their aroma profile, and even higher levels of herbaceous compounds than the control, which contrasts with the results of the berry sensory analyses. These contrasting results indicate that cluster thinning may have affected other volatile compounds to those we measured and that, consequently, berry metabolism was affected in a different way by cluster thinning and the ripening process.

CONCLUSION

Flower cluster thinning treatments on Seyval blanc grapevines resulted in neither a significant decrease in yield per plant, nor a significant improvement in berry quality; however, it improved fruit set, indicating that this practice could help to reduce coulure without negatively impacting yield in northern vineyards. In Vandal-Cliche, the reduction of crop load to 40 %, while efficiently reducing yield, did not improve basic must chemistry and negatively affected the grape volatile compounds profile, especially in the cooler season of 2013, when cluster-thinned berries contained significantly higher levels of herbaceous volatile compounds, such as C_6-alcohols and aldehydes. The minor differences observed between the cluster thinning treatments were likely due to the already low yield observed in the control plants, which was too low to be able to carry out effective crop load reduction by cluster thinning; "natural" crop reduction is a phenomenon that is frequent in northern viticulture, occurring in response to winter and spring frosts, as well as other stresses. Adjusting crop load is time-consuming and costly and, overall, our results indicate that this practice may not be consistently profitable for Quebec's growers and winemakers in terms of berry quality. While crop control is still essential for controlling yield and vigour in hybrid cultivars, other approaches, such as bud removal and shoot thinning, may be more appropriate for these cultivars.

Harvest date had a much larger impact on fruit quality than cluster thinning, especially on the profile of the volatile compounds. In Seyval blanc, C_6-alcohols and C_{13}-norisoprenoids content decreased significantly during ripening, while C_6-aldehydes and the monoterpene linalool increased. In Vandal-Cliche, fatty and herbaceous volatile compounds reached a maximum at commercial harvest in 2012, a particularly warm season; meanwhile, in 2013, herbaceous compounds, such as *trans*-2-hexenal, *trans*-2-heptenal and *cis*-3-hexenol, reached their lowest levels at the last ripening stage. Therefore, delayed harvest may have a more positive impact on the aroma profile of Seyval blanc and Vandal-Cliche berries than cluster thinning. "Aromatic maturity" is a concept that has been poorly developed in hybrid grape varieties and it would need attention to fully develop the potential of those varieties in the wine industry. Our results, along with the high genotypic variability of these cultivars, indicate that it would be useful to identify specific maturity markers for them. For instance, the results of the berry sensory analyses show that differences in skin astringency allow a reliable assessment to be made of berry quality and ripening level for Seyval blanc and Vandal-Cliche but other descriptors were not useful. Overall, interspecific hybrid grape varieties show different biochemical patterns to those of *V. vinifera* varieties. Thus, further knowledge is needed to support the development of those varieties within the wine industry.

ACKNOWLEDGEMENTS

The authors thank the Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec (MAPAQ). They also thank the Centre de recherche bioalimentaire du Québec (CDBQ), the Conseil de recherche en Sciences Naturelles et en Génie du Canada (CRSNG) and the Fonds de recherche Nature et Technologies du Québec (FQRNT) for supporting the scholarship of Catherine Barthe, MSc student. They would like to thank the wineries who provided the experimental parcels and grapes, the Association des vignerons du Québec (now "Conseil des vins du Québec") who supported this project, and the panelists who participated in the sensory analyses.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Alba, V., Natrella, G., Gambacorta, G., Crupi, P., & Coletta, A. (2022). Effect of over crop and reduced yield by cluster thinning on phenolic and volatile compounds of grapes and wines of 'Sangiovese' trained to Tendone. *Journal of the Science of Food and Agriculture*, *102*(15), 7155–7163. https://doi.org/10.1002/jsfa.12081

Ames, Z. R., Olmstead, M., Sims, C., & Rebecca, D. (2002). Effect of shoot and cluster thinning on vine performance, fruit and wine quality of "Blanc du Bois." *Journal of the American Pomological Society*, *70*(1), 2–15.

Atucha, A., Hedtcke, J., & Workmaster, B. A. (2018). Evaluation of cold-climate interspecific hybrid wine grape cultivars for the upper Midwest. *Journal of the American Pomological Society,* 72, 80-93.

Bell, S.-J., & Henschke, P. A. (2005). Implications of nitrogen nutrition for grapes, fermentation and wine. *Australian Journal of Grape and Wine Research*, *11*(3), 242–295. https://doi.org/10.1111/j.1755-0238.2005.tb00028.x

Berkey, T. G., Mansfield, A. K., Lerch, S. D., Meyers, J. M., & Heuvel, J. E. V. (2011). Crop Load Adjustment in 'Seyval Blanc' Winegrape: Impacts on Yield Components, Fruit Composition, Consumer Wine Preferences, and Economics of Production. *HortTechnology*, *21*(5), 593–598. https://doi.org/10.21273/horttech.21.5.593

Bravdo, B., Hepner, Y., Loinger, C., Cohen, S., & Tabacman, H. (1984). Effect of Crop Level on Growth, Yield and Wine Qualityof a High Yielding Carignane Vineyard. *American Journal of Enology and Viticulture*, *4*(35), 247–252.

Campos-Arguedas, F., Sarrailhé, G., Nicolle, P., Dorais, M., Brereton, N. J. B., Pitre, F. E., & Pedneault, K. (2022). Different Temperature and UV Patterns Modulate Berry Maturation and Volatile Compounds Accumulation in *Vitis* sp. *Frontiers in Plant Science*, *13*, 862259. https://doi.org/10.3389/fpls.2022.862259

Chapman, D. M., Matthews, M. A., & Guinard, J.-X. (2004). Sensory Attributes of Cabernet Sauvignon Wines Made from Vines with Different Crop Yields. *American Journal of Enology and Viticulture*, *55*(4), 325–334.

Conde, C., Silva, P., Fontes, N., Dias, A. C. O., Tavares, R. M., Sousa, M. J., Agasse, A., Delrot, S., & Gerós, H. (2007). Biochemical Changes throughout Grape Berry Development and Fruit and Wine Quality. *Food*, *1*(1), 1–22.

Dami, I., Ennahli, S., & Scurlock, D. (2013). A Five-year Study on the Effect of Cluster Thinning and Harvest Date on Yield, Fruit Composition, and Cold-hardiness of 'Vidal Blanc' (*Vitis* spp.) for Ice Wine Production. *HortScience*, *48*(11), 1358–1362. https://doi.org/10.21273/hortsci.48.11.1358

Dami, I., Ferree, D., Prajitna, A., & Scurlock, D. (2006). *A Five-year Study on the Effect of Cluster Thinning on Yield and Fruit Composition of `Chambourcin' Grapevines* (Vol. 41). https://doi.org/10.21273/hortsci.41.3.586

Dennis, E. G., Keyzers, R. A., Kalua, C. M., Maffei, S. M., Nicholson, E. L., & Boss, P. K. (2012). Grape Contribution to Wine Aroma: Production of Hexyl Acetate, Octyl Acetate, and Benzyl Acetate during Yeast Fermentation Is Dependent upon Precursors in the Must. *Journal of Agricultural and Food Chemistry*, *60*(10), 2638–2646. https://doi.org/10.1021/jf2042517

Dubé, G., & Turcotte, I. (2011). *Guide d'identification des cépages cultivés en climat froid : cépages de cuve*, Richard Grenier Éditeur, Montréal, 215 pp.

Edson, C. E., Howell, G. S., & Flore, J. A. (1995). Influence of Crop Load on Photosynthesis and Dry Matter Partitioning of Seyval Grapevines. III. Seasonal Changes in Dry Matter Partitioning, Vine Morphology, Yield, and Fruit Composition. *American Journal of Enology and Viticulture*, *46*(4), 478–485.

Fenoll, J., Manso, A., Hellin, P., Ruiz, L., & Flores, P. (2009). Changes in the aromatic composition of the *Vitis vinifera* grape Muscat Hamburg during ripening. *Food Chemistry*, *114*(2), 420–428. https://doi.org/10.1016/j.foodchem.2008.09.060

Frioni, T., Zhuang, S., Palliotti, A., Sivilotti, P., Falchi, R., & Sabbatini, P. (2017). Leaf Removal and Cluster Thinning Efficiencies Are Highly Modulated by Environmental Conditions in Cool Climate Viticulture. *American Journal of Enology and Viticulture*, *68*(3), 325–335. https://doi.org/10.5344/ajev.2017.16098

García, E., Chacón, J. L., Martínez, J., & Izquierdo, P. M. (2003). Changes in Volatile Compounds during Ripening in Grapes of Airén, Macabeo and Chardonnay White Varieties Grown in La Mancha Region (Spain). *Food Science and Technology International*, *9*(1), 33–41. https://doi.org/10.1177/1082013203009001006

Gatti, M., Bernizzoni, F., Civardi, S., & Poni, S. (2012). Effects of Cluster Thinning and Preflowering Leaf Removal on Growth and Grape Composition in cv. Sangiovese. *American Journal of Enology and Viticulture*, *63*(3), 325–332. https://doi.org/10.5344/ajev.2012.11118

Girard, B., Fukumoto, L., Mazza, G., Delaquis, P., & Ewert, B. (2002). Volatile Terpene Constituents in Maturing Gewürztraminer Grapes from British Columbia. *American Journal of Enology and Viticulture*, *53*(2), 99–109. http://www.ajevonline.org/content/53/2/99.short

Goulao, L. F., & Oliveira, C. M. (2008). Cell wall modifications during fruit ripening: when a fruit is not the fruit. *Trends in Food Science & Technology*, *19*(1), 4–25. https://doi.org/10.1016/j.tifs.2007.07.002

Grimplet, J., Ibáñez, S., Baroja, E., Tello, J., & Ibáñez, J. (2019). Phenotypic, Hormonal, and Genomic Variation Among *Vitis vinifera* Clones With Different Cluster Compactness and Reproductive Performance. *Frontiers in Plant Science*, *9*, 1917. https://doi.org/10.3389/fpls.2018.01917

Guidoni, S., Allara, P., & Schubert, A. (2002). Effect of Cluster Thinning on Berry Skin Anthocyanin Composition of *Vitis vinifera* cv. Nebbiolo. *American Journal of Enology and Viticulture*, *53*(3), 224–226. https://doi.org/10.5344/ajev.2002.53.3.224

Gutiérrez-Gamboa, G., Díaz-Galvéz, I., Verdugo-Vásquez, N., & Moreno-Simunovic, Y. (2019). Leaf-to-Fruit Ratios in *Vitis vinifera* L. cv. "Sauvignon Blanc", "Carmenère", "Cabernet Sauvignon", and "Syrah" Growing in Maule Valley (Chile): Influence on Yield and Fruit Composition. *Agriculture*, *9*(8), 176. https://doi.org/10.3390/agriculture9080176

Haggerty, L. L. (2013). *Ripening Profile of Grape Berry Acids and Sugars in University of Minnesota Wine Grape Cultivars, Select Vitis vinifera, and Other Hybrid Cultivars*. University of Minnesota, St. Paul, USA.

Hanlin, R. L., Hrmova, M., Harbertson, J. F., & Downey, M. O. (2010). Condensed tannin and grape cell wall interactions and their impact on tannin extractability into wine. Australian *Journal of Grape and Wine Research*, 16(1), 173-188.

Howell, G. S. (2001). Sustainable Grape Productivity and the Growth-Yield Relationship: A Review. *American Journal of Enology and Viticulture*, *52*(3), 165–174.

Ivanišević, D., Kalajdžić, M., Drenjančević, M., Puškaš, V., & Korać, N. (2020). The impact of cluster thinning and leaf removal timing on the grape quality and concentration of monomeric anthocyanins in Cabernet-Sauvignon and Probus (*Vitis vinifera* L.) wines. *OENO One*, *54*(1), 63–74. https://doi.org/10.20870/oeno-one.2020.54.1.2505

Jackson, D. I., & Lombard, P. B. (1993). Environmental and Management Practices Affecting Grape Composition and Wine Quality - A Review. *American Journal of Enology and Viticulture*, *44*(4), 409–430. http://www.ajevonline.org/content/44/4/409.short

Kalua, C. M., & Boss, P. K. (2009). Evolution of volatile compounds during the development of cabernet sauvignon grapes (*Vitis vinifera* L.). *Journal of Agricultural and Food Chemistry*, *57*(9), 3818–3830. https://doi.org/10.1021/jf803471n

Kliewer, W. M., & Dokoozlian, N. (2005). Leaf Area/Crop Weight Ratios of Grapevines: Influence on Fruit Composition and Wine Quality. *American Journal of Enology and Viticulture*, *56*(2), 1–12.

Kontoudakis, N., Esteruelas, M., Fort, F., Canals, J. M., & Zamora, F. (2010). Comparison of methods for estimating phenolic maturity in grapes: Correlation between predicted and obtained parameters. *Analytica Chimica Acta*, *660*(1–2), 127–133. https://doi.org/10.1016/j.aca.2009.10.067

Lebon, G., Brun, O., Magné, C., & Clément, C. (2005). Photosynthesis of the grapevine (*Vitis vinifera*) inflorescence. *Tree Physiology*, *25*(5), 633–639. https://doi.org/10.1093/treephys/25.5.633

Lohitnavy, N., Bastian, S., & Collins, C. (2010). Berry sensory attributes correlate with compositional changes under different viticultural management of Semillon (*Vitis vinifera* L.). *Food Quality and Preference*, *21*(7), 711–719. https://doi.org/10.1016/j.foodqual.2010.05.015

Martínez-Lüscher, J., & Kurtural, S. K. (2021). Same Season and Carry-Over Effects of Source-Sink Adjustments on Grapevine Yields and Non-structural Carbohydrates. *Frontiers in Plant Science*, *12*, 695319. https://doi.org/10.3389/fpls.2021.695319

Miller, D.P., Howell, G.S, et Flore, J.A. (1996). Influence of Shoot Number and Crop Load on Potted Chambourcin Grapevines.I. Morphology and Dry Matter Partitioning. *American Journal of Enology and Viticulture*, *47*(4), 380-388.

Moigne, M. L., Maury, C., Bertrand, D., & Jourjon, F. (2008). Sensory and instrumental characterisation of Cabernet Franc grapes according to ripening stages and growing location. *Food Quality and Preference*, *19*(2), 220–231. https://doi.org/10.1016/j.foodqual.2007.03.004

Morris, J. R., Main, G. L., & Oswald, O. L. (2004). Flower Cluster and Shoot Thinning for Crop Control in French-American Hybrid Grapes. *American Journal of Enology and Viticulture*, *55*(4), 423–426.

Mota, R. V. da, Souza, C. R. de, Silva, C. P. C., Freitas, G. de F., Shiga, T. M., Purgatto, E., Lajolo, F. M., & Regina, M. de A. (2010). Biochemical and agronomical responses of grapevines to alteration of source-sink ratio by cluster thinning and shoot trimming. *Bragantia*, *69*(1), 17–25. https://doi.org/10.1590/s0006-87052010000100004

Mozzon, M., Savini, S., Boselli, E., Thorngate, J.H. (2016). The herbaceous character of wines. *Italian Journal of Food Science,* 28, 190–207.

Palomo, E. S., Díaz-Maroto, M. C., Viñas, M. A. G., Soriano-Pérez, A., & Pérez-Coello, M. S. (2007). Aroma profile of wines from Albillo and Muscat grape varieties at different stages of ripening. *Food Control*, *18*(5), 398–403. https://doi.org/10.1016/j.foodcont.2005.11.006

Pedneault, K., Dorais, M., & Angers, P. (2013). Flavor of cold-hardy grapes: impact of berry maturity and environmental conditions. *Journal of Agricultural and Food Chemistry*, *61*(44), 10418–10438. https://doi.org/10.1021/jf402473u

Pedneault, K., & Provost, C. (2016). Fungus resistant grape varieties as a suitable alternative for organic wine production: Benefits, limits, and challenges. *Scientia Horticulturae*, *208*, 57–77. https://doi.org/10.1016/j.scienta.2016.03.016

Reeve, A. L., Skinkis, P. A., Vance, A. J., Lee, J., & Tarara, J. M. (2016). Vineyard Floor Management Influences 'Pinot noir' Vine Growth and Productivity More than Cluster Thinning. *HortScience*, *51*(10), 1233–1244. https://doi.org/10.21273/hortsci10998-16

Reynolds, A. G., & Heuvel, J. E. V. (2009). Influence of Grapevine Training Systems on Vine Growth and Fruit Composition: A Review. *American Journal of Enology and Viticulture*, *60*(3), 251–268.

Reynolds, A. G., Pool, R. M., & Mattick, L. R. (1986a). Effect of Shoot Density and Crop Control on Growth, Yield, Fruit Composition, and Wine Quality of 'Seyval blanc' Grapes. *Journal of the American Society for Horticultural Science*, *111*(1), 55–63. https://doi.org/10.21273/jashs.111.1.55

Reynolds, A. G., Pool, R. M., & Mattick, L. R. (1986b). Influence of cluster exposure on fruit composition and wine quality of Seyval blanc grapes. *Vitis*, *25*, 85–95. https://core.ac.uk/download/pdf/235693024.pdf

Ribéreau-Gayon, P. P., Dubourdieu, D., Donèche, B., & Lonvaud, A. (2018). *Handbook of Enology* (2nd Ed., Vol. 1). Wiley. https://doi.org/10.1002/0470010363

Rihan, H. Z., Al-Issawi, M., & Fuller, M. P. (2017). Advances in physiological and molecular aspects of plant cold tolerance. *Journal of Plant Interactions*, *12*(1), 143–157. https://doi.org/10.1080/17429145.2017.1308568

Rossouw, G. C., Smith, J. P., Barril, C., Deloire, A., & Holzapfel, B. P. (2017). Carbohydrate distribution during berry ripening of potted grapevines: Impact of water availability and leaf-to-fruit ratio. *Scientia Horticulturae*, *216*, 215–225. https://doi.org/10.1016/j.scienta.2017.01.008

Rousseau, J., & Delteil, D. (2000). Présentation d'une méthode d'analyse sensorielle des baies de raisin. Principe, méthode, interprétation. *Revue Française d'oenologie*, *183*(Juillet/Août), 10–13.

Slegers, A., Angers, P., Ouellet, É., Truchon, T., & Pedneault, K. (2015). Volatile Compounds from Grape Skin, Juice and Wine from Five Interspecific Hybrid Grape Cultivars Grown in Québec (Canada) for Wine Production. *Molecules*, *20*(6), 10980–11016. https://doi.org/10.3390/molecules200610980

Stewart, A. C. (2013). *Nitrogen Composition of Interspecific Hybrid and Vitis Vinifera Wine Grapes From the Eastern United States*. Purdue University, West Lafayette, IN, USA.

Sun, Q., Sacks, G. L., Lerch, S. D., & Heuvel, J. E. V. (2012). Impact of Shoot and Cluster Thinning on Yield, Fruit Composition, and Wine Quality of Corot noir. *American Journal of Enology and Viticulture*, *63*(1), 49–56. https://doi.org/10.5344/ajev.2011.11029

Sun, Q., Sacks, G., Lerch, S., & Heuvel, J. E. V. (2011). Impact of Shoot Thinning and Harvest Date on Yield Components, Fruit Composition, and Wine Quality of Marechal Foch. *American Journal of Enology and Viticulture*, *62*(1), 32–41. https://doi.org/10.5344/ajev.2010.10023

Wallis, A., Martinson, T., Pashow3, L., Lamoy, R., & Lungerman, K. (2017). *Wine Grapes for New York's North Country: The Willsboro Cold Climate Variety Trial* [Newletter]. https://ecommons.cornell.edu/bitstream/handle/1813/103652/Research-Focus-2017-2-wine-grapes-for-New-Yorks.pdf?sequence=1

Wang, Y., He, Y.-N., He, L., He, F., Chen, W., Duan, C.-Q., & Wang, J. (2019). Changes in global aroma profiles of Cabernet Sauvignon in response to cluster thinning. *Food Research International*, *122*, 56–65. https://doi.org/10.1016/j.foodres.2019.03.061

Watrelot, A. A., Vavra, C., Gapinski, A., & Cheng, Y. (2023). What are the challenges to producing high quality red wines from interspecific grapes? *BIO Web of Conferences*, *56*, 02016. https://doi.org/10.1051/bioconf/20235602016

Xi, X., Zha, Q., He, Y., Tian, Y., & Jiang, A. (2020). Influence of cluster thinning and girdling on aroma composition in 'Jumeigui' table grape. *Scientific Reports*, *10*(1), 6877. https://doi.org/10.1038/s41598-020-63826-7.