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CARBOHYDRATE RESERVES AND GRAPEVINE RESILIENCE UNDER CLIMATIC VARIABILITY: A TWO-YEAR STUDY FROM BLAJ VITICULTURAL CENTER

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Abstract

This study investigates how carbohydrate reserves vary in both grapevine and rootstock canes over two consecutive years (2023–2024) and explores their relationship with environmental conditions, assessing cultivar performance and resilience patterns. Seven grapevine cultivars (Fetească albă, Fetească regală, Fetească neagră, Italian Riesling, Neuburger, Traminer roz and Sauvignon blanc) and three rootstocks (C-26, C-71 and SO4-4) were analyzed, quantifying non-structural carbohydrate (NSC) reserves in one-year-old canes. The results revealed significant differences between cultivars, vintages, and their interaction. Total NSC levels varied between 11.59±0.95 % and 17.94±0.41 %. Generally, fruit-bearing cultivars accumulated more NSC reserves than rootstocks. Almost all cultivars showed higher NSC reserves in 2023 than in 2024*. Starch content remained relatively stable across years, while soluble sugars were more sensitive to environmental variation. In terms of performance and resilience, Traminer roz and Fetească regală emerged as the top fruit-bearing cultivars, and Crăciunel 71 proved to be the most resilient rootstock.*

Key words*: grapevine, rootstock, carbohydrate reserves, climatic resilience, cultivar performance.*

INTRODUCTION

With a decreasing trajectory of area harvested and grape production (Figure 1), illustrated by the latest available statistics and time-series trends over the past two decades (FAOSTAT, 2025), Romania maintains a significant role within the European viticulture.

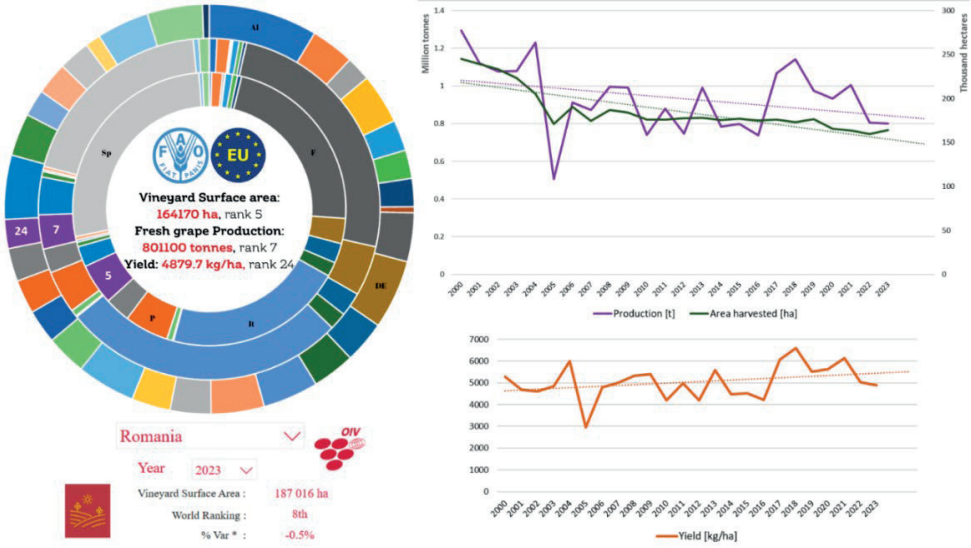

Figure 1. Statistics of Romania`s viticulture

Recent FAOSTAT data show that Romania ranks 5th in vineyard area and 7th in fresh grape production among the European Union (EU) countries (Figure 1) (FAOSTAT, 2025). Also, Romania ranked in 8th globally in 2023, with more than 187,000 hectares of vineyard area (Figure 1) (Country Statistics | OIV, 2025). Despite Romania's extensive vineyard area, productivity metrics reveal a relatively low average yield of 4879.7 kg/ha, positioning it only in 24th place in the EU (Figure 1) (FAOSTAT, 2025). Such discrepancies between vineyard potential and realized yield point to underlying physiological and management-related constraints.

Among the key internal factors influencing grapevine performance is the status of non-structural carbohydrate (NSC) reserves, particularly in perennial organs such as one-year-old canes. Research indicates that higher carbohydrate content in grapevine canes can significantly enhance grapevine resilience serving as vital energy sources during periods of stress, such as after pruning, during adverse weather conditions, or in response to pest attacks (Căpruciu et al., 2024; Falchi et al., 2019; Vuerich et al., 2023; Zufferey et al., 2012). These reserves support critical functions such as healing wounds, regenerating tissues, and maintaining vital metabolic processes. Specifically, increased carbohydrate reserves improve overall grapevine vigor and resilience by facilitating rapid recovery from stress-related damage (Ferrandino et al., 2023; Pellegrino et al., 2014; Rogiers et al., 2011). Additionally, they contribute to better tolerance of environmental stressessuch as drought or extreme temperatures, as the stored energy provides a buffer to sustain metabolic activities when photosynthetic capacity is compromised (Gambetta et al., 2020).

The NSC reserves serve as critical energy sources during early-season growth phases, especially budburst and shoot development, and are essential for buffering the grapevine against environmental stress and variable annual conditions (Zufferey et al., 2012).

Studies have shown that the seasonal dynamics of carbohydrate storage - largely in the form of starch and soluble sugars - are influenced by climatic variables, source-sink relations, and post-harvest management (Călugăr et al., 2022; Greven et al., 2016). Moreover, variations in starch levels during dormancy have been correlated with bud viability and cane maturity (Calugar et al., 2010; Călugăr et al., 2019), both of which are key indicators of grapevine resilience.

This study focuses on a two-year evaluation of carbohydrate reserves in one-year-old canes from selected cultivars in Blaj Viticultural Center, part of the prestigious Târnave vineyard in Romania.

By tracking interannual variations in NSC accumulation during the dormant season, our study aims to elucidate patterns that may explain grapevine adaptation and performance under temperate continental conditions. Such data not only deepen our understanding of grapevine physiology in Transylvanian terroirs but also support targeted vineyard management strategies that align with climate resilience and sustainable yield optimization.

MATERIALS AND METHODS

Experimental design

The present study was conducted in Blaj Viticultural Center, a cool-climate region favorable for grapevine cultivation and the production of quality white wines with PDO and PGI. The specific ecoclimatic conditions of this area are suitable for producing dry, semi-sweet or sweet wines, semi-aromatic and aromatic wines, and also sparkling wines (Călugăr et al., 2018; Chedea et al., 2021).

The research aimed to evaluate carbohydrate reserves across diverse grapevine genotypes over two consecutive years (2023-2024) and explore their relationship with environmental conditions. For this purpose, eleven cultivars were selected for analysis, including fruit-bearing grapevine cultivars (*Vitis vinifera* L.) and rootstock cultivars (*Berlandieri x Riparia*) (Table 1), which are representative of the Blaj region and among the most widely cultivated in local vineyards.

The selected cultivars were distributed across three vineyard plots (P1, P2, P3), in two different locations (Crăciunelu de Jos and Blaj). Table 1 provides detailed information on cultivar identity, and Table 2 summarizes the vineyard plots characteristics.

Table 1. Sample details

Crt no.	Cultivar Name	Type	Loc.	Plot	Planting year	Sample code
1	**Italian Riesling**	G	Cr	P_1	2010	**RI_P1**
2	**Traminer roz**	G	Cr	P_1	2007	**TR_ P1**
3	**Sauvignon blanc**	G	Cr	P_1	2014	**SB_ P1**
4	**Fetească neagră**	G	Cr	P_1	2010	**FN_ P1**
5	**Fetească regală**	G	Cr	P_2	2012	**FR_ P2**
6	**Fetească albă**	G	Cr	P_2	2007	**FA_ P2**
7	**Neuburger**	G	Cr	P_2	2012	**Nb_ P2**
8	**Italian Riesling**	G	Cr	P_2	2012	**RI_ P2**
9	**Crăciunel 26**	R	Bj	P_3	2008	**C26**
10	**Crăciunel 71**	R	Bj	P_3	2008	**C71**
11	**Oppenheim 4sel**	R	Bj	P_3	2008	**SO4-4**

*Notes: Loc. = location; G = fruit-bearing grapevine cultivar; R = rootstock cultivar; Cr = Crăciunelu de Jos; Bj = Blaj.

Table 2. Experimental plots characteristics

Plot	GPS coord.	Soil type	Soil manag.	Planting Distance	Training sist.
P_1	46.1733 23.8484	Alluvial soil	Grass strips	2.0 x 1.0	Demi-high Guyot system with periodic replacement arms
P_2	46.1782 23.8187	Coluvisoil		2.0 x 1.2	
P_3	46.1732 23.9350	Saline alluvial soil	Alt. grass strips	2.0 x 1.6	Diagonal support system

*Notes: Alt = alternative; Coord. = coordinates; Sist. = system; Planting distance is expressed in meters.

One-year-old canes were collected during winter dormancy (on 16.01.2023 and 11.12.2024) from both fruit-bearing grapevine cultivars and rootstock cultivars. Due to their greater length, each rootstock cane was divided into three distinct segments: base, middle, and tip. Each segment was treated and analyzed as an individual sample to accurately assess the distribution of non-structural carbohydrate reserves along the cane. Fruit-bearing cultivar canes were analyzed as whole samples without segmentation.

The collected samples were cut into convenient sizes (15-20 cm) and oven-dried at 55°C to a constant mass (approx. 48 h). The dried material was finely ground until the cellular structure was destroyed and passed through a 0.7 mm sieve. The samples thus prepared were stored at room temperature until analysis (NSC quantification).

Assessment of non-structural carbohydrate (NSC) reserves.

Standards and reagents preparation

Glucose standard: 0.1 g glucose dissolved in 1000 mL distilled water; diluted to 50 µg/mL for use; freshly prepared for each assay.

The assessment of non-structural carbohydrate (NSC) reserves was done by determining the total content of hydrocarbons (soluble sugars + starch) using the spectrophotometric method with the anthrone reagent described by Cimpoi et al. (2020). The method is based on the soluble sugars and starch extraction and their quantification after anthrone dosing.

Sample preparation and carbohydrates extraction

A precisely weighed amount of 0.25 g (±0.01 g) dried powder was mixed with approximately 0.25 g of quartz sand and 2.5 ml of 80% ethanol. The mixture was homogenized with a mortar and pestle to form a uniform paste. Then, 15 ml of distilled water (5 ml initially, followed by 10 ml for rinsing) was added, and the mixture was transferred to a centrifuge tube. After centrifugation at 6000 rpm for 20 minutes, the supernatant was collected into a 100 ml volumetric flask.

The residue was re-extracted three times with warm 80% ethanol (2.5 mL, then 10 mL in each cycle) followed by centrifugation, and all supernatants were combined. The final volume was adjusted to 100 ml with distilled water. From this solution, 50 mL were transferred to another 100 mL volumetric flask, treated with 0.5 mL of lead acetate, allowed to react (for 5 min), brought to volume with distilled water and filtered. Then, 50 ml of the filtrate was neutralized with 0.5 ml sodium sulfate (saturated solution), brought to volume with distilled water (100 ml) and filtered again. The obtained sugar extract can be stored at 4°C up to 5 days.

The centrifuge residue from the sugar extraction was homogenized with 2.5 mL of distilled water, and then treated with 3.3 ml of 52% perchloric acid (dropwise) under stirring for 15 minutes. After adding 10 mL of distilled water and centrifugation (6000 rpm, 20 minutes), the supernatant was collected. This extraction step was repeated once more. The combined supernatants were brought to 250 mL with distilled water, forming the starch extract (which can be stored at 4°C up to 5 days).

Anthrone reagent (0.2%): 0.2 g anthrone dissolved in 100 mL 95% sulfuric acid, freshly prepared at least 4 hours before use and protected from light.

Carbohydrate quantification by anthrone dosing

In labeled test tubes (14 mm diameter), the following solutions were prepared:

(a) Blank control: 2 mL distilled water;

(b) Standard: 1 mL distilled water + 1 mL glucose standard;

(c) Sugar extract: 1 mL distilled water + 1 mL sugar extract;

(d) Starch extract: 1 mL distilled water + 1 mL starch extract.

To each tube, 4 mL anthrone reagent was added dropwise in an ice-water bath. Tubes were gently mixed, heated in a boiling water bath for 10 minutes, and then cooled in an ice bath for 15 minutes. Absorbance was measured at 620 nm using a ScanDrop2 (AnalytikJena AG, Germany) UV-Vis spectrophotometer.

Calculations

Glucose concentrations in extracts were calculated by:

$$Z = \frac{Ec - Ea}{Eb} \times 50 \quad [\mu g/mL] \qquad (1)$$

$$A = \frac{Ed - Ea}{Eb} \times 50 \quad [\mu g/mL] \qquad (2)$$

Where Ea, Eb, Ec, Ed are the absorbance values of blank, standard, sugar extract, and starch extract solutions, respectively.

Final sugar and starch contents, expressed as glucose equivalents in percent dry weight (% w/w DW), were calculated as follows:

$$\text{Sugars} = \frac{Z \times Vs \times DF \times 100}{m \times 10^6} \quad [\%] \quad (3)$$

$$\text{Starch} = \frac{A \times Vp \times 100}{m \times 10^6} \quad [\%] \quad (4)$$

Where:

Z = sugar content in the extract [µg/mL];

A = starch content in the extract [µg/mL];

m = dry mass of the sample used for analysis;

DF = 4 (dilution factor used in the sugar extraction protocol);

Vs = 100 = volume of sugar extract [mL];

Vp = 250 = volume of starch extract [mL].

Carbohydrate contents reported as percentages (%) correspond to grams of glucose equivalents per 100 grams of dry sample, thus normalizing for sample moisture and allowing direct comparison. The analysis was conducted in duplicate to ensure statistical validity.

Agroclimatic context and weather data

Weather data were recorded daily by an iMetos 3.3 weather station (Pessl Instruments GmbH; Weiz, Austria), located between P1 and P2 in Crăciunelu de Jos at the following coordinates: 46.174372 N latitude and 23.85257 E longitude. The viticultural years 2023 and 2024 were characterized in comparison with the reference period between 1990-2022. The following parameters were recorded and analyzed:

- Vegetation period length (VP): Number of days from budbreak to leaf fall.
- Average annual temperature (°C): Mean temperature over the entire calendar year.
- Average temperature during the vegetation period (°C): Mean temperature recorded during the active growing season.
- Global heat units (∑t˚G, °C): The sum of daily positive mean (>0 °C) temperatures, representing total heat accumulation.
- Active heat units (∑t˚A, °C): Calculated as the sum of daily mean temperatures above the base threshold of 10°C.
- Useful heat units (∑t˚U, °C): Portion of heat units effectively utilized by grapevines, calculated as the sum of differences between daily average temperature > 10°C and the biological threshold required for the vegetation start (10ºC).
- Absolute minimum temperature (°C): Lowest recorded temperature during the study period.
- Average minimum temperature (°C): Mean of daily minimum temperatures.
- Absolute maximum temperature (°C): Highest recorded temperature during the study period.
- Average maximum temperature (°C): Mean of daily maximum temperatures.
- Relative humidity (RH, %): Average atmospheric moisture content.
- Annual precipitation (∑Ppt, mm/m²): Total rainfall over the year.
- Precipitation during the vegetation period (Vp∑Ppt, mm/m²): Total rainfall accumulated during the active growing season.
- Sunlight during the vegetation period (hours): Total hours of solar radiation received during the growing season.
- Huglin Index (°C): Provides a measure of heat accumulation over the growing season, integrating temperature and day length to assess climatic suitability. Was calculated according to Irimia et al. (2013).

Statistical analysis

The data were analysed using Minitab 17 (Minitab Inc., State College, PA, USA). One-way ANOVA with Fisher's LSD test ($p < 0.05$) was applied to assess differences between cultivars. Main effects analysis evaluated factor influences. A General Linear Model examined cultivar performance and resilience. Two-sample t-tests compared each vintage's climatic data to the historical reference period (1990-2022). Normality and variance assumptions were verified prior to testing. Statistical significance was set at $p < 0.05$.

RESULTS AND DISCUSSIONS

Overview of NSC accumulation

A general overview of NSC accumulation is presented in Table 3 as mean ± standard deviation. The results are expressed as grams of glucose equivalents/100 grams of dry matter. Total carbohydrate levels varied between 12.55% and 17.94% with an average of 15.23% in 2023 and between 11.59% and 15.53% with an average of 13.89% in 2024. Almost all cultivars showed higher average reserves in 2023 exceptions being Neuburger (Nb_P2), Crăciunel 71 (C71_P3) and Oppenheim 4sel (SO4-4). This trend indicates favorable reserve accumulation during the 2023 season. Soluble sugars maintained the same trend, declining from an average of 9.32% in 2023 to an average of 8.12% in 2024. Starch content showed the greatest stability across years, registering an average of 5.92% in 2023 and 5.76% in 2024. The relative stability of starch across vintages suggests a buffering role in reserve dynamics, while the decline in soluble sugars reflects higher sensitivity to environmental variation (Nawaz et al., 2025; Zepeda et al., 2023).

Table 3. Results regarding the carbohydrate content

Crt no.	Sample code	2023			2024		
		Sugars	Starch	Total_NSC	Sugars	Starch	Total_NSC
1	**RI_P1**	10.20±0.97^{ab}	6.31±0.24^{c}	16.51±0.74^{abc}	7.94±0.66^{cd}	5.67±0.63^{de}	13.61±0.11^{cd}
2	**TR_P1**	8.79±1.19^{cd}	6.88±0.37^{bc}	15.67±0.82^{bc}	7.81±0.26^{cd}	7.29±0.26^{b}	15.10±0.44^{ab}
3	**SB_P1**	8.96±0.71^{bcd}	6.31±0.43^{c}	15.27±1.13^{c}	8.39±0.33^{bc}	5.74±0.30^{d}	14.13±0.03^{bc}
4	**FN_P1**	9.53±0.78^{bc}	7.34±0.11^{b}	16.87±0.68^{ab}	7.64±0.47^{cde}	6.80±0.60^{bc}	14.44±1.06^{abc}
5	**FR_P2**	8.19±098^{d}	8.48±0.25^{a}	16.67±1.21^{abc}	8.04±0.44^{cd}	6.22±0.45^{cd}	14.26±0.87^{abc}
6	**FA_P2**	10.97±0.76^{a}	6.97±0.35^{bc}	17.94±0.41^{a}	7.40±0.46^{de}	4.61±0.34^{f}	12.01±0.80^{ef}
7	**Nb_P2**	9.24±0.95^{bcd}	3.39±0.27^{f}	12.63±0.68^{e}	6.81±0.43^{c}	8.72±0.65^{a}	15.53±1.08^{a}
8	**RI_P2**	10.89±0.18^{a}	5.24±0.12^{de}	16.13±0.30^{bc}	7.18±0.72^{de}	4.40±1.25^{f}	11.59±0.95^{f}
9	**C26_P3**	8.41±0.59^{d}	5.52±0.46^{d}	13.93±0.86^{d}	9.48±0.64^{a}	3.27±0.44^{g}	12.76±0.76^{de}
10	**C71_P3**	8.69±0.62^{cd}	4.79±0.44^{e}	13.40±1.00^{de}	9.72±0.64^{a}	4.94±0.34^{ef}	14.66±0.80^{abc}
11	**SO4-4_P3**	8.66±0.87^{cd}	3.89±0.49^{f}	12.55±1.20^{e}	8.91±0.47^{b}	5.74±0.77^{d}	14.65±0.96^{abc}

Note: *Different letters indicate statistically significant differences according to Fisher's LSD test ($p < 0.05$).

Similar carbohydrate contents are reported by Călugăr et al. (2010, 2019) and by Iliescu et al. (2012) in the same area.

The main effect analysis shows significant influences of studied factors on the sugar (Figure 2), starch (Figure 3), and total NSC levels (Figure 4). Sugar content was consistently higher in rootstocks than in fruit-bearing cultivars, and in samples from the Blaj location (Bj). Among the plots, P3 exhibited the highest average sugar concentration, while P2 showed the lowest (Figure 2).

Fruit bearing cultivars accumulated more starch than rootstocks, and Crăciunelu location (Cr) registered higher starch levels than Blaj (BJ). Among the plots, P1 recorded the highest starch content, while P3 had the lowest starch content (Figure 3). In terms of total NSC, fruit bearing cultivars accumulated more reserves than rootstocks; the Crăciunelu location (Cr) and P1 plot registered the highest average carbohydrate values (Figure 4).

A consistent reduction from 2023 to 2024 was observed across all three parameters, reinforcing the strong influence of the meteorological conditions of each vintage on the grapevines' reserve dynamics.

Cimpoi et al. (2020), reports a total carbohydrate content in dormant canes of both rootstock and fruit bearing cultivars ranging from 12.02% to 15.64%. Soluble sugars were the major fraction (8.63-11.38%), with starch contributing 2.44-5.41%. Lower levels of total NSC were determined in the rootstock cultivars.

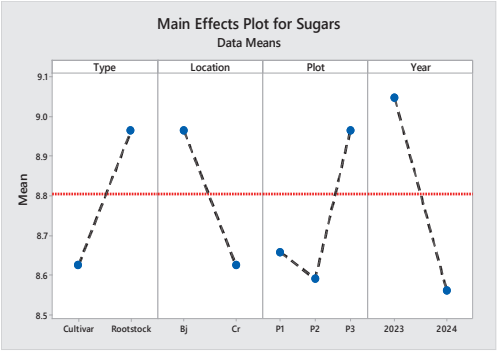

Figure 2. Main effect plot for soluble sugars content

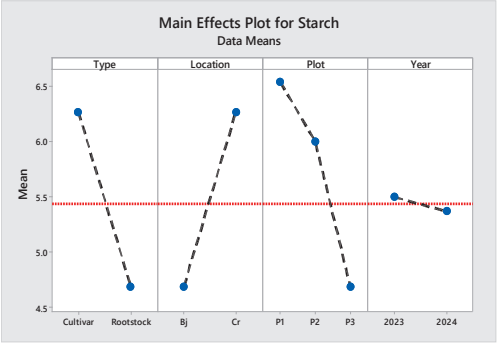

Figure 3. Main effect plot for starch content

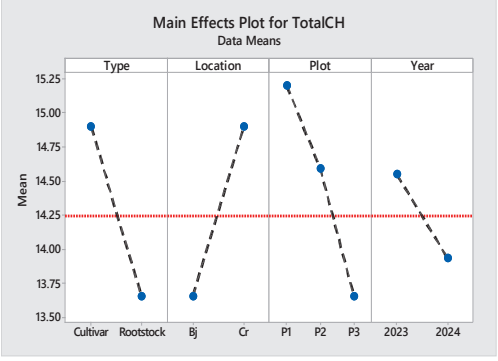

Figure 4. Main effect plot for total carbohydrate content

Cultivar performance and resilience patterns

Grapevine resilience refers to a cultivar's ability to maintain physiological performance despite seasonal variability (e.g., heat, drought, and yield stress). In our study, resilience is indicated by stable total NSC levels across 2023 and 2024, the ability to recover or maintain reserves regardless of climate conditions, and smaller carbohydrate declines in 2024 under more stressful conditions.

Fruit bearing cultivars

In evaluate how each cultivar performed and how performance changed depending on the year, a General Linear Model (GLM) was applied. This allows the evaluation of both main effects and interactions while adjusting for environmental variability. The General Linear Model (GLM) including cultivar, year, and their interaction explained 84.2% of the variance in total NSC content and confirmed significant effects of cultivar ($P = 0.022$), year ($P < 0.001$), and their interaction ($P < 0.001$).

Traminer roz and Fetească regală emerged as the top cultivars. Traminer roz maintained the most stable carbohydrate reserves across years, with only a minimal decrease from 15.67% in 2023 to 15.10% in 2024 (Table 3 and Figure 5). Fetească regală consistently accumulated high carbohydrate levels, with means of 16.67% and 14.26%, respectively, reflecting strong performance with moderate resilience (Table 3 and Figure 5). Fetească neagră also showed solid performance, decreasing from 16.87% to 14.44%, and retained relatively stable reserves (Table 3 and Figure 5). Sauvignon Blanc showed moderate performance and stability with 15.27% total NSC content in 2023 and 14.13% total NSC content in 2024 (Table 3 and Figure 5).

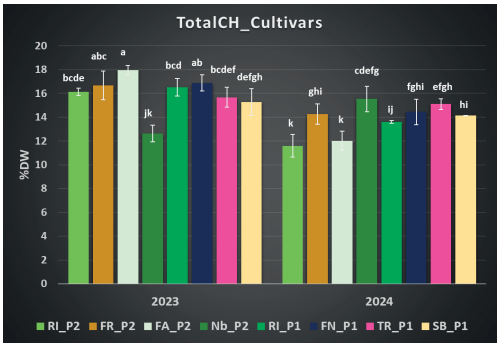

Figure 5. Graphical representation of the fruit-bearing cultivars (RI - Italian Riesling, FR - Fetească regală, FA - Fetească albă, Nb - Neuburger, FN - Fetească neagră, TR - Traminer roz, SB - Sauvignon Blanc; *Different letters indicate statistically significant differences according to Fisher's LSD test, $p < 0.05$)

Italian Riesling, while reaching high total NSC content in 2023, registered a significant drop in 2024 in both plots (Table 3 and Figure 5). This decline indicates a strong year effect and

positions it as a vintage-responsive cultivar, potentially vulnerable under adverse conditions. Fetească albă, despite having the highest carbohydrate content in 2023 (17.94%), showed a sharp decline in 2024 (12.01%), underscoring its sensitivity to climatic or physiological stress (Table 3 and Figure 5). Neuburger is the only fruit bearing cultivar that showed a moderate increase from 12.63% to 15.53% (Table 3 and Figure 5), suggesting a recovery dynamic possibly linked to physiological depletion from prior yield (Muntean et al., 2023).

Similar NSC levels are reported in the literature. Holzapfel & Smith (2012), and Zufferey et al. (2015), report non-structural carbohydrate (NSC) reserves in dormant grapevines canes ranging between 10 and 15% DW, with slight variation depending on cultivar, and stress exposure. Also, the study of Călugăr et al. (2022), analyzing eight *Vitis vinifera* varieties (Muscat de Hamburg, Napoca, Cardinal, Perla de Csaba, Fetească regală, Muscat Ottonel, Pinot noir, Fetească neagră) during dormancy (October-February 2019-2020) reveals total NSC levels ranging from 12.77% (Cardinal cultivar) to 16.03% (Fetească regală cultivar). Higher total NSC levels were observed in October (12.93-16.03%) while minimum levels were highlighted in January (11.70-13.70%) (Călugăr et al., 2022).

Rootstock cultivars

Usually, the canes of the studied rootstock cultivars reach 5 m long therefore we analyzed them into three longitudinal segments: base, middle and tip. This helps to better understand the distribution and dynamics of carbohydrate reserves in grapevine rootstocks and may also provide insights into how environmental stressors or previous crop loads influence reserve partitioning. A uniform carbohydrate distribution might suggest sustained metabolic activity and a good vascular connectivity, while pronounced differences could indicate localized storage or transport limitations. Interannual variation in segmental carbohydrate levels may reflect rootstock specific physiological strategies or responses to climatic conditions (Chandra Dahal, 2019; Falchi et al., 2019; Martínez-Lüscher & Kurtural, 2021).

The General Linear Model for the rootstock cultivars included cultivar, cane part, year and their interaction. The model explains 63% of the total variation in NSC levels, which is moderate but typical in field-based viticultural studies. According to the GLM, the effect of year was highly significant ($P = 0.006$), with 2023 generally recording lower carbohydrate levels than 2024. The cane part factor was also significant ($P = 0.026$), with the base section consistently showing higher carbohydrate content than middle and tip. This reflects the natural gradient of reserve accumulation along the cane, the base of the cane, being closest to the main vascular connection and older lignified tissues, is typically richer in stored reserves, while the tip often represents the youngest, least lignified segment with lower reserve density (Chandra Dahal, 2019; Frioni et al., 2016; Rogiers et al., 2011; Toolo, 2022).

The cultivar effect approached significance ($P = 0.085$), suggesting meaningful but slightly variable differences among rootstocks. The Cultivar × Year interaction was highly significant ($p < 0.001$), confirming that total NSC responses differed across years depending on the cultivar (Figure 6).

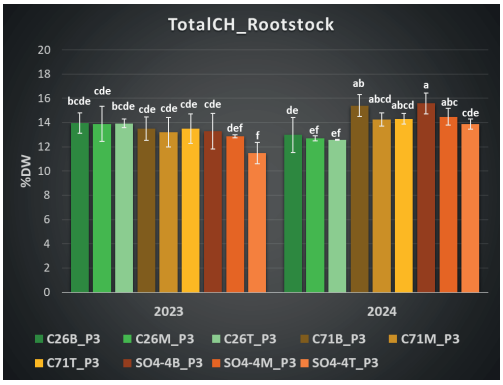

Figure 6. Graphical representation of the rootstock cultivars performance (C26 - Crăciunel 26, C71 - Crăciunel 71, SO4-4 - Oppenheim 4sel; B - base cane segment, M - middle cane segment, T - tip cane segment; *Different letters indicate statistically significant differences according to Fisher's LSD test, $p < 0.05$)

In terms of performance and resilience, Crăciunel 71 proved to be the top-performing and most resilient rootstock cultivar. It maintained relatively high carbohydrate reserves in both years (13.40% in 2023, 14.66% in 2024) and a balanced carbohydrate distribution across cane segments. SO4-4 showed the most

pronounced increase (+2.10%), after registering the lowest total NSC level in 2023 (12.55%). This indicates strong recovery potential but greater interannual variability.

Crăciunel 26 began with moderately high carbohydrate reserves in 2023 (13.93%), but declined to 12.76% in 2024, suggesting greater sensitivity to annual environmental or physiological stressors.

Our findings are in agreement with other studies from the available literature. Cimpoi et al. (2020) studied pre-grafting dormant canes of three rootstocks cultivars: Riparia Gloire, SO4-4 and Crăciunel 2 Selection. They found the highest total NSC content in Riparia gloire (13.49%), followed by Crăciunel 2 (12.78%) and SO4-4 (12.02%). Iliescu et al. (2012) studied SO4-4 rootstock canes, sampled from plantation (autumn, winter) and from storage (spring) and found total NSC levels between 11-13% observing that the NSC content remained stable across seasons and storage, with a slight gradient from base to tip segments.

Meteorological Conditions and Climatic Stressors

The key indicators for the meteorological conditions of the two studied vintages are presented in Table 4. The 2023 and 2024 growing seasons in Blaj Viticultural Center were marked by statistically significant deviations from the 1990-2022 climatic reference period, with 2024 in particular standing out as an extreme vintage.

Both years showed significantly higher average annual temperatures (11.6 °C in 2023 and 12.1 °C in 2024, $p < 0.001$), with 2024 also exhibiting a significantly extended vegetation period (205 days, $p < 0.001$) and the highest cumulative global heat units ($\Sigma t^{\circ}G = 3763.9$ °C, $p < 0.001$). Sunshine hours during the vegetation period increased dramatically in 2024 (1987 hours, $p < 0.001$).

These climate patterns, especially the combination of increased temperature, longer growing seasons, and greater solar radiation, are known to elevate grapevine respiration and accelerate phenological stages, often at the expense of reserve accumulation (Colibaba et al., 2024; Dominguez et al., 2024; Hall et al., 2016).

The observed reduction in Tmax. combined with an increase in Tmin. clearly shows a narrowing of the thermal amplitude during recent vintages. This combination results in a lower carbon surplus available for allocation to perennial storage organs such as roots and canes (Smith et al., 2009). Cooler daytime temperatures can reduce photosynthetic carbon assimilation, while warmer nights elevate respiration rates, increasing carbon demand (D. Greer & Weedon, 2014; Zufferey et al., 2015).

Table 4. Meteorological conditions of the studied vintages

Parameter	Average		
	1990-2022	2023	2024
January	-1.5	3.3	0.9
February	1.0	1.1	6.7
Mars	5.4	6.9	8.8
April	11.2	9.1	13.2
May	16.0	15.8	16.1
June	19.6	19.2	22.3
Iuly	21.2	21.9	23.0
August	21.0	21.9	22.5
September	15.9	18.5	17.7
October	10.7	12.8	9.6
November	4.7	6.3	2.8
December	-0.2	2.4	2.2
Vegetation period length, VP [days]	187	$187^{n.s}$	205^{***}
Average annual temperature [°C]	10.4	11.6^{***}	12.1^{***}
Average annual temperature during VP [°C]	17.5	17^{***}	$17.7^{n.s}$
Global heat unit, $\sum t^{\circ}G$ [°C]	3456.7	3649.3^{***}	3763.9^{***}
Active heat unit, $\sum t^{\circ}A$ [°C]	3312.4	3517.6^{***}	3676.3^{***}
Usefull heat unit, $\sum t^{\circ}U$ [°C]	1464.8	1577.6^{***}	1736.3^{***}
Absolute minimum temperature [°C]	-24.7	-14.8^{***}	-12.2^{***}
Average minimum temperature [°C]	-9.3	-0.3^{***}	-0.2^{***}
Absolute maximum temperature [°C]	41.6	36.5^{*}	38.5^{***}
Average maximum temperature [°C]	30.1	24.9^{***}	26.7^{***}
Relative humidity, RH [%]	80.6	77.5^{*}	$79.2^{n.s}$
Annual precipitations $\sum Ppt$ [mm/ m^2]	619.9	547.6^{**}	$606.4^{n.s}$
Precipitations during the vegetation period, $Vp\sum Ppt$ [mm/m^2]	430.1	385.2^{*}	$442.2^{n.s}$
Sunlight during the vegetation period [hours]	1355	1563.0^{***}	1987.0^{***}
Huglin Index	-	2590.2	3023.0

Although total precipitation in 2024 was not significantly different from the historical mean,

2023 exhibited significantly lower annual and vegetation period rainfall ($p < 0.05$), paired with a significant drop in relative humidity. Moderate water deficit and optimal temperature regimes during the growing season promote carbohydrate accumulation in grapevines (Chaves et al., 2007; Holzapfel et al., 2010). In contrast, prolonged periods of high precipitation and humidity tend to favor vegetative growth, reducing the allocation of resources to carbohydrate reserves (Palliotti & Poni, 2016).

The Huglin Index, which measures heat accumulation relevant for grapevine development, was 2590.2 in 2023 and increased to 3023.0 in 2024, indicating a shift towards warmer and potentially more stressful conditions. Table 5 presents the climatic stressors recorded in Blaj Viticultural Center during the two studied vintages. The frequency of critical stress events in 2023 and 2024 was evaluated using thresholds relevant to grapevine damage and physiological disruption.

Critical winter frost (minimum temperatures below –15 °C) did not occur in any of the core winter months (December, January, or February) in either 2023 or 2024 (Table 5). This contrasts with historical patterns in Blaj Viticultural Center, where extreme lows of –24.7 °C have previously been recorded (Table 4). In 2023, five days in March fell below the late frost threshold of –2 °C, accounting for 16% of March days. No spring frost events occurred in 2024.

Table 5. Stress factors frequency recorded in 2023 and 2024

Risk/stress factor	Critical level	Month	Days with critical levels/month		Risk factor frequency (%)	
			2023	2024	2023	2024
Winter frost	Minimum temperature **< -15°C**	Dec.	0	0	0	0
		Jan.	0	0	0	0
		Feb.	0	0	0	0
Late spring frost	Minimum temperature **< -2°C**	March	5	0	16	0
		April	0	0	0	0
		May	0	0	0	0
Drought	Maximum temperature **> 30°C**	June	3	17	10	56.7
		July	18	16	58	51.6
		Aug.	17	24	55	77.4
		Sept.	3	7	10	23.3

Heat stress, defined here as days with maximum temperatures exceeding 30 °C, occurred with greater frequency in 2024, especially during June and August (Table 5). In total, 2024 recorded 64 days over 30 °C, compared to 41 days in 2023. These high temperatures are likely to have reduced stomatal conductance and limited photosynthetic activity during key periods of carbohydrate accumulation (Escalona et al., 2000; D. H. Greer & Weedon, 2013; D. Greer & Weedon, 2012), especially if combined with limited soil moisture (Soar et al., 2006; Tombesi et al., 2015) . The stress is particularly significant in June, when shoot growth is still vigorous and the grapevines carbohydrate demand is high (Kizildeniz et al., 2021; Lebon et al., 2008).

Taken together, the results indicate that 2024 posed the highest level of climatic stress over the two-year study period, with probable consequences on the NSC reserves accumulation affecting the grapevines capacity for resilience and recovery.

CONCLUSIONS

This two-year study provides insight into dormant-season non-structural carbohydrate (NSC) accumulation in grapevine canes highlighting the influence of climatic variability on grapevine reserves status and cultivar-specific resilience patterns.

Across both years, non-structural carbohydrate (NSC) levels in dormant canes fell within ranges previously reported. Generally, 2023 - significantly warmer and drier than the reference period (1990-2022) - favored higher total NSC accumulation, whereas 2024 - characterized by even higher average temperatures, increased frequency of days >30°C, and a narrower thermal amplitude - led to a consistent decline in total reserves in most cultivars. This confirms that interannual climate variability is a major driver of perennial reserve accumulation.

Soluble sugars were more sensitive to climate variability than starch. Sugars declined substantially from 2023 to 2024, while starch content remained relatively stable, supporting its role as a buffering reserve pool. Warmer night temperatures in 2024 likely increased respiration rates, contributing to reduced sugar availability for storage.

In terms of cultivar-specific resilience the following patterns emerged: Traminer roz and Fetească regală displayed the highest combined performance and stability, maintaining high NSC levels across both vintages. In contrast,

Fetească albă and Italian Riesling showed large interannual declines, indicating greater sensitivity to climate stress. Neuburger was the only fruit-bearing cultivar to increase NSC in 2024, suggesting a recovery dynamic after potential depletion in 2023. Rootstock cultivars exhibited clear reserve gradients along the cane. Carbohydrate content was consistently highest in the basal cane segments and lowest at the tips, reflecting storage physiology and vascular connectivity. Crăciunel 71 showed the highest and most stable NSC levels across years, while SO4-4 demonstrated strong recovery potential despite low reserves in 2023.

The climatic stressors from 2024 that most likely restricted NSC reserve accumulation are the following: intensified heat, extended vegetation period, increased solar radiation, and high cumulative temperatures. The combination of these climatic stressors, is known to elevate grapevine respiration and accelerate phenological stages, suggesting an intensified metabolic load, likely leading to greater consumption of non-structural carbohydrates (NSCs) during the ripening and post-harvest phases at the expense of reserve accumulation.

Reduced NSC reserves can compromise budburst, early shoot growth, and flowering in the following season, potentially influencing yield and fruit composition. Cultivars with higher resilience (e.g., Traminer roz, Fetească regală) may better sustain consistent wine quality under warming scenarios, whereas more sensitive cultivars (e.g., Fetească albă) may require targeted management - such as moderated crop loads, optimized irrigation, and postharvest leaf area maintenance - to protect reserve status.

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REFERENCES

Călugăr, A., Babeş, A. C., Bunea, C. I., Pop, T. I., Tomoiagă, L., & Iliescu, M. (2018). Oenological characterization of wines from grape clones created at Research Station for Viticulture and Enology Blaj, Romania. *CZU*, *663*(2), 50–56.

Călugăr, A., Cordea, I., Babeş, A., & Fejer, M. (2019). Dynamics of starch reserves in some grapevine varieties (*Vitis vinifera* L.) during dormancy. *BulletinUASVM Horticulture*, *76*(2), 1843–5394. https://doi.org/10.15835/buasvmcn-hort

Călugăr, A., Cordea, M., Babeş, A., Fejer, M. , Comsa, M. , & Popescu, D. (2022). The measurements of starch and total sugars content in some grapevine varieties (*Vitis vinifera* L.) during dormancy through different methods. *Scientific Papers. Series B. Horticulture*, *66*(1). https://ibn.idsi.md/sites/default/files/j_nr_file/vol2022_1_1.pdf#page=230

Calugar, A., Pop, N., Farago, M., Babeş, A. , Bunea, C. I. , Hodor, D. , & Cioabanu, F. (2010). Buds viability and carbohydrates canes content of some varieties created at SCDVV Blaj during winter 2009-2010. *Lucrări Ştiinţifice USAMVB, Seria B,* 548-553. https://www.researchgate.net/profile/Anca-Babes/publication/289916057_Buds_viability_and_carbohydrates_canes_content_of_some_varieties_created_at_SCDVV_Blaj_during_winter_2009-2010/links/5693735508aec14fa55e876b/Buds-viability-and-carbohydrates-canes-content-of-some-varieties-created-at-SCDVV-Blaj-during-winter-2009-2010.pdf

Căpruciu, R., Cichi, D. D., Costea, C. D., & Mărăcineanu, C. L. (2024). Carbohydrate dynamics in some grapevine (Vitis Vinifera L.) cultivars during dormancy. *Scientific Papers. Series B. Horticulture*, *68*(1).

Chandra Dahal, K. (2019). *Insights into seasonal yield variation in subtropical table grape production* [CQUniversity]. https://doi.org/10.25946/13468785

Chaves, M. M., Santos, T. P., Souza, C. R., Ortuño, M. F., Rodrigues, M. L., Lopes, C. M., Maroco, J. P., & Pereira, J. S. (2007). Deficit irrigation in grapevine improves water-use efficiency while controlling vigour and production quality. *Annals of Applied Biology*, *150*(2), 237–252. https://doi.org/10.1111/J.1744-7348.2006.00123.X

Chedea, V. S., Dragulinescu, A. M., Tomoiaga, L. L., Balaceanu, C., & Iliescu, M. L. (2021). Climate change and internet of things technologies -sustainable premises of extending the culture of the amurg cultivar in transylvania - a use case for târnave vineyard. *Sustainability*, *13*(15), 8170. https://doi.org/10.3390/su13158170

Cimpoi, V. I., Rotaru, L., Colibaba, L. C., Scutărașu, E. C., Călin, I., & Alexandru, C. L. (2020). Influence of carbohydrate content on grafting in wine grape varieties "Aromat de Iași" and "Golia." *Scientific Papers. Series B. Horticulture*, *LXIV*(1), 248–254. https://www.researchgate.net/publication/352781959

Colibaba, L. C., Bosoi, I., Pușcalău, M., Bodale, I., Luchian, C., Rotaru, L., & Cotea, V. V. (2024). Climatic projections vs. grapevine phenology: a regional case study. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca*, *52*(1), 13381. https://doi.org/10.15835/nbha52113381

Country Statistics | OIV. (n.d.). Retrieved May 27, 2025, from https://www.oiv.int/what-we-do/country-report?oiv

Dominguez, D. L. E., Cirrincione, M. A., Deis, L., & Martínez, L. E. (2024). Impacts of Climate Change-Induced Temperature Rise on Phenology, Physiology, and Yield in Three Red Grape Cultivars: Malbec, Bonarda, and Syrah. *Plants*, *13*(22), 3219–3219. https://doi.org/10.3390/PLANTS13223219

Escalona, J. M., Flexas, J., & Medrano, H. (2000). Stomatal and non-stomatal limitations of photosynthesis under water stress in field-grown grapevines. *Functional Plant Biology*, *27*(1), 87. https://www.publish.csiro.au/FP/PP99019_CO

Falchi, R., Petrussa, E., Zancani, M., Casolo, V., Beraldo, P., Nardini, A., Sivilotti, P., Calderan, A., Herrera, J. C., Peterlunger, E., & Braidot, E. (2019). Summer drought stress: differential effects on cane anatomy and non-structural carbohydrate content in overwintering Cabernet Sauvignon and Syrah vines. *BIO Web of Conferences*, *13*, 03007. https://doi.org/10.1051/BIOCONF/20191303007

FAOSTAT. (n.d.). Retrieved May 27, 2025, from https://www.fao.org/faostat/en/#data/QCL

Ferrandino, A., Pagliarani, C., & Pérez-Álvarez, E. P. (2023). Secondary metabolites in grapevine: crosstalk of transcriptional, metabolic and hormonal signals controlling stress defence responses in berries and vegetative organs. *Frontiers in Plant Science*, *14*, 1124298. https://doi.org/10.3389/FPLS.2023.1124298/XML/NLM

Frioni, T., Tombesi, S., Silvestroni, O., Lanari, V., Bellincontro, A., Sabbatini, P., Gatti, M., Poni, S., & Palliotti, A. (2016). Postbudburst spur pruning reduces yield and delays fruit sugar accumulation in Sangiovese in central Italy. *American Journal of Enology and Viticulture, 67*(4), 419–425. https://www.ajevonline.org/content/67/4/419.abstract

Gambetta, G. A., Carlos Herrera, J., Dayer, S., Feng, Q., Hochberg, U., & Castellarin, S. D. (2020). The physiology of drought stress in grapevine: towards an integrative definition of drought tolerance. *Journal of Experimental Botany*, *71*(16), 4658–4676. https://doi.org/10.1093/jxb/eraa245

Greer, D. H., & Weedon, M. M. (2013). The impact of high temperatures on *Vitis vinifera* cv. Semillon grapevine performance and berry ripening. *Frontiers in Plant Science*, *4*, 491. https://doi.org/10.3389/fpls.2013.00491

Greer, D., & Weedon, M. (2012). Modelling photosynthetic responses to temperature of grapevine (Vitis vinifera cv. Semillon) leaves on vines grown in a hot climate. *Plant, Cell & Environment*, *35*(6), 1050–1064. https://doi.org/10.1111/J.1365-3040.2011.02471.X

Greer, D., & Weedon, M. (2014). Does the hydrocooling of *Vitis vinifera* cv. Semillon vines protect the vegetative and reproductive growth processes and vine performance against high summer. *Functional Plant Biology*, *41*(6), 620–633. https://doi.org/10.1071/FP13286

Greven, M. M., Neal, S. M., Tustin, D. S., Boldingh, H., Bennett, J., & Vasconcelos, M. C. (2016). Effect of Postharvest Defoliation on Carbon and Nitrogen Resources of High-Yielding Sauvignon blanc Grapevines. *American Journal of Enology and Viticulture*, *67*(3), 315–326. https://doi.org/10.5344/AJEV.2016.15081

Hall, A., Mathews, A. J., & Holzapfel, B. P. (2016). Potential effect of atmospheric warming on grapevine phenology and post-harvest heat accumulation across a range of climates. *International Journal of Biometeorology*, *60*(9), 1405–1422. https://doi.org/10.1007/S00484-016-1133-Z

Holzapfel, B., Smith, J., Field, S., & Hardie, W. (2010). Dynamics of Carbohydrate Reserves in Cultivated Grapevines. *Horticultural Reviews*, *37*, 1–399. https://doi.org/10.1002/9780470543672

Holzapfel, B., & Smith, J. P. (2012). Developmental stage and climatic factors impact more on carbohydrate reserve dynamics of Shiraz than cultural practice. *American Journal of Enology and Viticulture*, *63*(3), 333–342. https://www.ajevonline.org/content/63/3/333.short

Iliescu, M., Popescu, D., & Comşa, M. (2012). Studies on the Quality of Rootstocks in the Viticultural Centre Blaj. *Bulletin of University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca. Horticulture*, *69*(1), 395. https://ftp.cramagiurgea.ro/index.php/horticulture/article/view/8555

Irimia, L., Patriche, C. V, & Quénol, H. (2013). Viticultural zoning: A comparative study regarding the accuracy of different approaches in vineyards climate suitability assessment. *Cercetări Agronomice În Moldova*, *XLVI*(3).

Kizildeniz, T., Pascual, I., Irigoyen, J. J., & Morales, F. (2021). Future CO2, warming and water deficit impact white and red Tempranillo grapevine: Photosynthetic acclimation to elevated CO2 and biomass allocation. *Physiologia Plantarum*, *172*(3), 1779–1794. https://doi.org/10.1111/PPL.13388

Lebon, G., Wojnarowiez, G., Holzapfel, B. , Fontaine, F. , Vaillant-Gaveau, N. , & Clément, C. (2008). Sugars and flowering in the grapevine (*Vitis vinifera* L.). *Journal of Experimental Botany*, *59*(10), 2565–2578. https://journals.aai.org/jxb/article/59/10/2565/437545

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*. https://doi.org/10.3389/FPLS.2021.695319/FULL

Muntean, M.-D., Sîrbu, A. D., Botea, V., Răcoare, H. S., Tomoiagă, L. L., Comșa, M., & Chedea, V. S. (2023). Carbohydrate reserves in some grapevine cultivars from SCDVV Blaj. *Acta Agricola Romanica*, *2*(5).

Nawaz, A. F., Gargiulo, S., Pichierri, A., & Casolo, V. (2025). Exploring the Role of Non-Structural Carbohydrates (NSCs) Under Abiotic Stresses on Woody Plants: A Comprehensive Review. *Plants*, *14*(3), 328. https://doi.org/10.3390/PLANTS14030328

Palliotti, A., & Poni, S. (2016). Grapevine under light and heat stresses. *Grapevine in a Changing Environment: A Molecular and Ecophysiological Perspective*, 148–178. https://doi.org/10.1002/9781118735985.

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Pellegrino, A., Clingeleffer, P., Cooley, N., Walker, R., Mcdowell, N., Alamos, L., Arndt, S., & Holzafel, B. P. (2014). Management practices impact vine carbohydrate status to a greater extent than vine productivity. *Frontiers in Plant Science 5*, *5*, 283. https://doi.org/10.3389/fpls.2014.00283

Rogiers, S. Y., Smith, J. P., Holzapfel, B. P., & Hardie, W. J. (2011). Soil temperature moderates grapevine carbohydrate reserves after bud-break and conditions fruit set responses to photoassimilatory stress. *Functional Plant Biology*, *38*(11), 899–909. https://doi.org/10.1071/FP10240

Smith, J., Viticulture, B. H.-A. J. of E. and, & 2009, undefined. (2009). Cumulative responses of Semillon grapevines to late season perturbation of carbohydrate reserve status. *American Journal of Enology and Viticulture,* *60*(4), 461–470. https://www.ajevonline.org/content/60/4/461.short

Soar, C. J., Speirs, J., Maffei, S. M., Penrose, A. B., McCarthy, M. G., & Loveys, B. R. (2006). Grape vine varieties Shiraz and Grenache differ in their stomatal response to VPD: apparent links with ABA physiology and gene expression in leaf tissue. *Australian Journal of Grape and Wine Research*, *12*(1), 2–12. https://doi.org/10.1111/J.1755-0238.2006.TB00038.X

Tombesi, S., Nardini, A., Frioni, T., Soccolini, M., Zadra, C., Farinelli, D., Poni, S., & Palliotti, A. (2015). Stomatal closure is induced by hydraulic signals and maintained by ABA in drought-stressed grapevine. *Scientific Reports*, *5*(1), 12449. https://doi.org/10.1038/srep12449

Toolo, K. B. (2022). *Effect of post-harvest summer pruning on carbohydrate reserve status, bud break and fertility of Sultanina H5 in the Lower Orange River region.* [Stellenbosch University]. https://scholar.sun.ac.za/handle/10019.1/126058

Vuerich, M., Petrussa, E., Boscutti, F., Braidot, E., Filippi, A., Petruzzellis, F., Tomasella, M., Tromba, G., Pizzuto, M., Nardini, A., Secchi, F., & Casolo, V. (2023). Contrasting Responses of Two Grapevine Cultivars to Drought: The Role of Non-structural Carbohydrates in Xylem Hydraulic Recovery. *Plant and Cell Physiology*, *64*(8), 920–932.

Zepeda, A. C., Heuvelink, E., & Marcelis, L. F. M. (2023). Carbon storage in plants: a buffer for temporal light and temperature fluctuations. *In Silico Plants*, *5*(1), 1–12. https://doi.org/10.1093/INSILICOPLANTS/DIAC020

Zufferey, V., Murisier, F., Belcher, S., Lorenzini, F., Vivin, P , Spring, J. L., & Viret, O. (2015). Nitrogen and carbohydrate reserves in the grapevine (*Vitis vinifera* L.'Chasselas'): the influence of the leaf to fruit ratio. *Vitis-Journal of Grapevine Research*, *54*(4), 183–188. https://doi.org/10.5073/vitis.2015.54.183-188

Zufferey, V., Murisier, F., Vivin, P., Belcher, S., Lorenzini, F., Spring, J. L., & Viret, O. (2012). Carbohydrate reserves in grapevine (*Vitis vinifera* L. 'Chasselas'): the influence of the leaf to fruit ratio. *Vitis: Journal of Grapevine Research*, *51*(3), 103–110. https://doi.org/10.5073/VITIS.2012.51.103-110