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Research Article

Quantifying the Effects of Water Status on Grapevine Vegetative Growth, Yield, and Grape Composition Through a Collaborative Analysis

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The consolidation of scientific knowledge is based on the accumulation and understanding of previous findings. Nowadays, reviews of the scientific literature have become more effective through the use of meta-analyses, which are systematic evaluations of the results from multiple studies. Similarly, mega-analyses, which combine raw data from many studies into a single sample for processing and statistical analysis, are a very powerful tool for analyzing results of heterogeneous origin but require a high level of collaboration between the researchers contributing data. In the framework of a collaborative methodology between different Spanish viticultural research groups, this work uses a mega-analytical approach to quantify the effects of changes in vine water status on vine vegetative growth, yield, and grape composition, integrating a wide range of growing conditions to obtain robust general trends of vine performance under water deficit. The mean seasonal stem water potential data from the different studies allowed a classification into five levels of water status (no deficit ⟶ mild ⟶ moderate ⟶ high ⟶ severe). A progressive decrease in vegetative growth with increasing deficit was observed, while yield decreased more markedly as water deficit progressed from moderate to high. On the other hand, titratable acidity was more sensitive to variation in water status than sugar concentration, with a greater decrease in titratable acidity when changing from no to moderate deficit. Conversely, increasing water deficit from moderate to high resulted in the greatest increases in grape anthocyanin in the red varieties explored. The results obtained in this work provide solid information on general trends in grapevine response to water deficit that can be used in simulation models or incorporated by grape growers in their decision-making processes in relation not only to irrigation management but also on other agronomic tools to impact grapevine water status.

Keywords: grapevine; irrigation; midday stem water potential; must composition; plant–water status

1. Introduction

Science is fundamentally cumulative, with new findings built upon prior knowledge to expand our understanding. Historically, this integration relied on narratives referencing earlier work, frequently compiling and consolidating it in book chapters or in review articles in journals. The development of article databases has allowed the development of systematic literature reviews (SLRs), where a systematic and replicable methodology aims to identify and evaluate all relevant literature on a given topic. SLRs overperform nonsystematic reviews, as they provide (i) a holistic portrayal of the current state of knowledge within a research domain, which includes defining the scope, identifying discrepancies and their causes, and constructing a framework to synthesize past research, and (ii) a guidance for future research by pinpointing gaps in the existing understanding [1]. Although SLRs have some limitations [2], they should always be considered when addressing any research question. The use of SLRs in viticulture is still relatively scarce, though the number of papers published with this approach has grown in recent years [3–7].

Building upon the principles of SLRs, science has increasingly turned to quantitative methods that synthesize results from multiple studies to further enhance efficiency and insight [8]. Cumulative approaches to science are garnering growing interest and involve the integration of information rather than the analysis of results from individual experiments. One such approach is meta-analysis, with over 50 years of the literature supporting its usefulness [9] and has become relatively common in agricultural sciences [10]. Meta-analyses have also been incorporated into viticulture and are a useful tool that has contributed to improving our understanding of how field practices affect plant growth, yield, and berry composition (e.g., [11–14]). Additionally, and very interestingly, researchers also have the option of pooling raw data from multiple studies and integrating their analysis using a single preprocessing and statistical analysis pipeline, thus performing a mega-analysis [8]. This approach differs from meta-analyses in that fact the raw data, and not summary statistics, are combined into a larger dataset, more detailed information being retained. As a consequence, some authors claim that mega-analysis can be the "gold standard" of empirical research [15]. While both methods aim to synthesize research findings, they differ in data requirements, analytical flexibility, and resource demands. Meta-analysis is more feasible when only summary data are available and is less resource-intensive, making it a common choice in many research fields. In contrast, mega-analysis offers greater analytical depth and accuracy but requires access to raw data and significant collaboration among researchers [8].

Therefore, to apply a mega-analytic approach, collaborative efforts that bring together the expertise of multiple investigators in each area of research are required. The tendency of researchers to work independently and/or in competition with one another, a pattern reinforced by academic and research cultures, is still present [16]. However, there is a movement toward a more open data management in research, and the FAIR principles [17] for scientific data management and stewardship are being increasingly implemented by public funding agencies. Three broad issues challenging the sharing and synthesizing of existing data have been identified: data ownership, data protection, and data interpretation. To overcome these limitations, it makes sense to provide structures that promote data sharing and synthesis efforts in terms of building partnerships and collaborations [16].

This research stands as an example of formal-based partnership collaboration, established within the framework of publicly funded programs at the national level in Spain. This collaboration originated in two consecutive networking initiatives (RedVitis and RedVitis 2.0) and took place within the WANUGRAPE4.0 project. This collaborative methodology ensures due recognition of data ownership through authorship, while data interpretation is a product of collective discussion. This collaborative structure already resulted in the publication of an analysis of the discrimination ability of leaf and stem water potential (SWP) measured at different times during the day after sharing water potential values of > 65,000 leaves [18], in addition to some other collaborations in the form of critical revision articles [19], water status modeling [20], and other ongoing works.

The objective of this paper is to present a mega-analysis examining the effects of changes in vine water status on vineyard vegetative growth, yield, and grape composition. This topic holds significant relevance both in Spain and globally [21–23], especially under a climate change context [24–27]. It is worth noticing the important implications that the generated knowledge could have on vineyard management, marketing strategies, and winemaking logistics. Some recent reviews have been published on this topic, highlighting its implications for grape yield and composition [28–30]. The originality of our approach lies not only in the use of a mega-analytic procedure but also in the classification of each replicate within each experiment and year into five deficit levels, enabling a detailed evaluation of vineyard performance and grape composition across incremental changes in water status.

2. Materials and Methods

2.1. Creation of the Database. The database was compiled using the original research data collected in field trials conducted by the 11 research groups participating in the project AGL2017-90759-REDT and was further extended within the WANUGRAPE4.0 project. In total, the data were gathered from 41 trials (Table 1), each one spanning 2–6 years (3-4 years for ≈80% of the trials). They were conducted between 1996 and 2020 in nine Spanish Autonomous Communities (Castilla La Mancha, Castilla y León, Cataluña, Comunidad Valenciana, Extremadura, Galicia, Islas Baleares, La Rioja, and Navarra), over a wide range of edaphoclimatic and growing conditions representative of the Spanish viticulture (Figure 1, Table S1). The database consists of 1381 entries, each corresponding to a replicate of a trial and containing information on the source of data, trial, field site, variety/rootstock, year, season-average midday SWP (Ψ_{stem}), and 14 response variables (Table 2). All trials included at least one irrigated treatment, and although precise records of the timing of SWP measurements relative to irrigation events were not available for all trials, measurements were generally taken midway between irrigations. SWP data were used directly, not being corrected for meteorological conditions due to the size of the dataset and considering that the objective was to evaluate grapevine response in a wide range of conditions.

SWP values over the season from each of the replicates within each trial were averaged to obtain a single integrative indicator of vine water status. This approach allowed us to synthesize the overall water availability experienced by the vine throughout the growing season, facilitating comparisons across trials with varying measurement frequencies, timings, and environmental conditions (Figure S1). These average values were used to classify them into five water deficit levels as defined by Linares et al. [31] and adapted by Baeza [32]. This classification was created as a combination of the literature and adapted to Spanish viticultural conditions through expert knowledge, setting the following threshold values: no deficit (> −0.411 MPa), mild (−0.411 to −0.674 MPa), moderate (−0.674 to −0.936 MPa), high (−0.936 to −1.2 MPa), and severe (< −1.2 MPa). An observation was defined as the pool of replicates classified with the same deficit level within each trial and year of study. Subsequently, within each observation, the mean and standard deviation of the replicates were calculated for each response variable.

Table 1: Varietal distribution of the trials included in this mega-analysis.

Variety (color)	Number of		
	Trials	Years	Replicates
Airen (W)[1]	2	6	84
Albariño (W)	2	9	86
Bobal (R)	2	6	154
Brancellao (R)	1	3	18
Cabernet Sauvignon (R)	3	10	109
Cigüente (W)	1	3	48
Garnacha Tinta (R)	2	6	126
Godello (W)	2	6	54
Graciano (R)	1	3	18
Macabeo (W)	2	5	72
Mazuelo (R)	1	3	18
Merlot (R)	1	2	30
Monastrell (R)	2	5	22
Moscatel (W)	1	3	48
Sousón (R)	1	3	18
Tempranillo (R)	13	43	365
Tempranillo blanco (W)	1	3	21
Treixadura (W)	1	3	18
Verdejo (W)	2	6	72
Total	41	128	1381

Note: The number of trials, years, and replicates are indicated for each variety.
[1]Berry skin color: W, white varieties; R, red varieties.

2.2. Statistical Analysis. Response ratios (RR_i) were calculated to quantify the effect of increasing vine water deficit in one level within each trial and year [33]:

$$RR_i = \ln X_{\text{hs}} - \ln X_{\text{ls}}, \quad (1)$$

where X_{ls} is the mean value of the response variable for the lower deficit level and X_{hs} is the mean value for the immediately higher deficit level (e.g., increasing from high to severe stress). Although this metric becomes undefined if either X_{ls} or X_{hs} is zero, which would indicate an absence of measurable yield or other response variable under the corresponding deficit level, such conditions were not encountered in our dataset. Afterward, a weighting factor ω_i was calculated for each RR_i as follows [33]:

$$\omega_i = \frac{1}{\left(\left(s_{ls}^2\right)/\left(n_{ls} \times X_{ls}^2\right)\right) + \left(\left(s_{hs}^2\right)/\left(n_{hs} \times X_{hs}^2\right)\right)}, \quad (2)$$

where s is the standard deviation and n is the number of replicates included within each observation. The weighted mean response ratio (RR_w) was calculated as follows [34]:

$$RR_w = \frac{\sum_{i=1}^{j} \omega_i \times RR_i}{\sum_{i=1}^{j} \omega_i}, \quad (3)$$

where j is the total *RR* calculated over the set of trials and years and ω_i is the weighting factor of the RR_i response ratio. The variance of RR_w (Var) was calculated as follows [35]:

$$\text{Var} = \frac{1}{\sum_{i=1}^{k} \omega_i}. \quad (4)$$

To identify significant differences in the effect sizes, the 95% confidence interval of RR_w (95% CI) was calculated as follows:

$$95\%\text{CI} = RR_w \pm 1.96\sqrt{\text{Var}}, \quad (5)$$

when the RR_w (95% CI) did not include the zero, the effect of increasing the deficit in one level was considered significant ($p < 0.05$). An increase in water deficit effect is considered positive if $RR_w > 0$, negative if $RR_w < 0$, or no effect if

Figure 1: Geographic location of the field trials included in this mega-analysis. Letters correspond to the codes for the representation of country names and their subdivisions (ISO 3166 standard). The values within the solid circles indicate the number of trials performed on each Autonomous Community. For a more comprehensive overview of the general characteristics of the respective trials, consult Table S1 in the supporting information.

Table 2: Variables analyzed in this study, indicating the number of available replicates (Reps) and observations (Obs) for each variable.

Type	Variable	Units	Number of Reps	Number of Obs
Vegetative growth	Leaf area	m^2 $vine^{-1}$	585	124
	Pruning weight	Mg ha^{-1}	821	160
Yield components	Yield	Mg ha^{-1}	1046	225
	Bunches per vine		961	190
	Bunch weight	g	961	190
	Berry weight	g	924	202
	Ravaz index (yield:pruning weight)		821	160
Berry composition	Soluble solid content (SSC)	°Bx	1076	224
	Ion concentration	10^{-pH}	1056	224
	Titratable acidity (TA)	g L^{-1}	1083	212
	SSC:TA ratio		1072	172
	Malic acid	g L^{-1}	853	224
	Total polyphenols[1]	mg L^{-1}	322	74
	Total anthocyanins[1]	mg L^{-1}	322	74

[1]In red varieties only.

$RR_w = 0$. For better understanding, the percent of change (C %) on the investigated variables induced by the increase in the deficit level was calculated as follows [33]:

$$C\% = \left(e^{RR} - 1\right) \times 100. \quad (6)$$

The mega-analysis was performed in the R environment [36], and the results were plotted by means of *RStudio* [37] using the *forestploter* 1.1.1 package [38].

3. Results and Discussion

The generated database compiled a broad corpus of observations for 19 grapevine varieties, nine white and 10 red (Table 1), and 14 variables, associated with vegetative growth (leaf area and pruning weight), production (yield, number of bunches per vine, bunch, and berry weights), and berry composition (soluble solid content [SSC], pH, titratable acidity [TA] malic acid in must, and anthocyanins and total polyphenols in berries). These variables also allowed the calculation of two indicators associated to grapevine balance: yield to pruning weight ratio (Ravaz index, RI) and soluble solid to TA ratio (SSC:TA). The number of replicates available for each variable ranged between 322 and 1076, the average being 850 (Table 2).

The average number of replicates that were pooled on each observation was 5.0 ± 1.3, so that observations between 160 and 225 were available for most variables (Table 2). All variables were thus similarly represented, except for leaf area, which was only evaluated in 60% of the trials, and those associated to phenolic maturity, which were the less represented ones (74 observations each), since they are not measured in white cultivars. The distribution of information between red and white varieties was relatively balanced, with observation proportions around 40% for the white ones.

Finally, the distribution of observations according to their deficit level (Figure 2) followed a normal pattern, with most of the observations representing moderate deficit conditions, the no-deficit situations being the least represented. Lower deficit situations were more frequent in white than in red varieties, whereas severe deficit conditions were mainly recorded in red varieties. This is likely because white grapevine varieties are more abundant in cooler regions.

3.1. Vegetative Growth and Yield. Increasing the level of water deficit resulted in a reduction in vegetative growth, which could be observed for both leaf area and pruning weight (Figure 3). To ease understanding, from here on, the effects are commented by their *C%* value, rather than by their logarithmic values (RR).

For each step of increasing the level of water deficit, an average reduction of leaf area of at least ≈10% was observed (Figure 3(a)), the most marked decrease being recorded when deficit changed from high to severe, where 18.2 ± 5.2% of leaf reduction was reached. The trend observed for the reduction in pruning weight (Figure 3(b)) was slightly different to that in leaf area, with an average decrease for this variable at every step of vine water status change of 13.8 ± 3.8%, the most salient effect being observed when conditions changed from moderate to high deficit (26.0 ± 2.3% of reduction). The different behavior of these two variables is probably explained by the fact that severe deficit conditions could cause early defoliation [39–41], a phenomenon that is not detected through pruning weight measurements but directly recorded when leaf area is measured. Globally, vine vegetative growth decreases in a similar proportion from one water deficit status to the next through all the steps of change analyzed (no deficit ⟶ mild ⟶ moderate ⟶ high ⟶ severe), although there is a slight trend to an increasing effect as changes in water deficit occur between more severe situations.

Yield (Figure 3(c)) was influenced by changes in vine water status and the magnitude, and even the direction of the effect was affected by the water deficit leaps considered. Thus, an increase of 12.6 ± 9.7% in yield was observed when deficit increased from null to mild, showing that sustained high-water availability over the growing season can cause significant yield reductions. The information in the dataset does not allow for a detailed analysis of the reasons that explain this fact. While waterlogging is known to negatively affect vine performance [42], we consider it unlikely in our dataset given the nature and management of the experimental plots. In our context, it can be hypothesized that the yield decrease from mild deficit to no deficit could be an indirect consequence of increased leaf area (Figure 3(a)), as dense canopy densities may increase the incidence of fungal diseases that lead to harvest losses [43, 44]. Under those conditions, despite stomatal aperture is maximum, which signifies maximizing photosynthesis, yield can be reduced due to the appearance of rots associated with decreased aeration and increased relative humidity increases in the cluster zone. Additionally, the dense canopies that develop

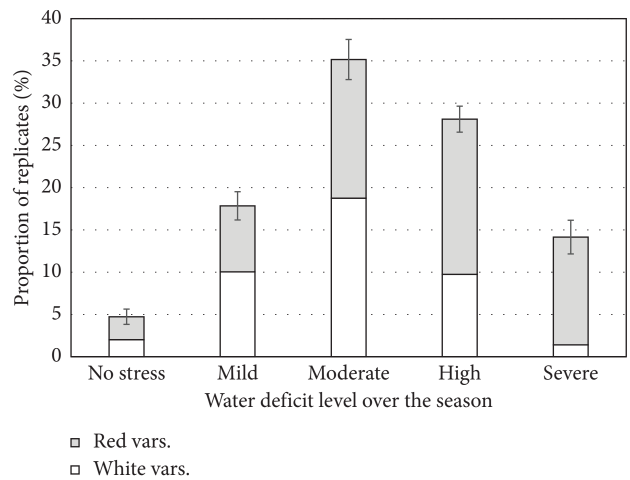

FIGURE 2: Proportion of replicates (%) available for each vine water deficit level in the database, indicating the contribution of red and white varieties. The mean value and the standard deviation for all the variables analyzed are provided.

when there are no water constraints may hinder bunch formation as they decrease the incidence of solar radiation [45, 46], which could limit inflorescence induction and differentiation. In fact, our analysis shows that the number of bunches per vine increased 7 ± 7%, when conditions went from no deficit to mild deficit (Figure 3(d)). Since most experimental designs include treatments that are repeated on the same vines from 1 year to the following, certain carryover effects can be behind the increase in yield observed in the null ⟶ mild deficit step of change, associated to a better inflorescence differentiation in the previous season.

When water deficit changed from mild to moderate, from moderate to high, and from high to severe, the effect on yield was always detrimental. However, yield reduction percentage was different in every deficit leap, with an average loss of 14.2 ± 2.2% from mild to moderate, of 26.6 ± 2.5% from moderate to high, and only of 5% from high to severe. These different percentages of change caused by water deficit as conditions are more severe which probably result from a combination of factors. First, the abovementioned change in inflorescence differentiation could partially explain this observation, as carbohydrate reserves are known to affect bud fertility [47–49], and water deficit has been recurrently shown to affect it [29, 30, 50]. In fact, the number of bunches per vine decreased when the steps of change occur in the higher deficit conditions (8.8 ± 2.1, 6.7 ± 1.8, and 2.6 ± 2.9%, respectively), although these differences cannot completely explain the changes in yield. Among the other yield components, the greatest changes are observed for bunch weight (Figure 3(e)), that showed reductions of ≈15 ± 2% when deficit increased from mild to moderate and from moderate to severe but did not change between high and severe. Berry weight sensitivity also largely changed with the degree of water deficit experienced (Figure 3(f)), with only slight reductions in weight (1.9 ± 2.4%) when water deficit increased from null to mild, followed by progressively larger reductions when

Parameter	Deficit change	N° reps/level Lower	N° reps/level Higher	Change (%)	95 % CI
a) Leaf area	No Deficit to Mild	22	18	−12.82	[−20.15, −4.82]
	Mild to Moderate	72	115	−9.70	[−12.52, −6.80]
	Moderate to High	177	134	−9.54	[−11.76, −7.28]
	High to Severe	81	78	−18.25	[−23.45, −12.69]
b) Pruning weight	No Deficit to Mild	30	36	−7.71	[−13.72, −1.28]
	Mild to Moderate	105	125	−10.00	[−13.42, −6.44]
	Moderate to High	166	121	−25.96	[−28.27, −23.58]
	High to Severe	96	112	−11.70	[−15.15, −8.12]
c) Yield	No Deficit to Mild	48	42	12.57	[2.84, 23.22]
	Mild to Moderate	124	177	−14.25	[−16.46, −11.98]
	Moderate to High	233	186	−26.60	[−29.14, −23.98]
	High to Severe	117	137	−4.96	[−8.83, −0.92]
d) Bunches per vine	No Deficit to Mild	30	36	7.36	[0.01, 15.24]
	Mild to Moderate	118	171	−8.80	[−10.90, −6.66]
	Moderate to High	224	171	−6.74	[−8.50, −4.94]
	High to Severe	106	124	−2.59	[−5.49, 0.40]
e) Bunch weight	No Deficit to Mild	30	36	3.49	[−2.22, 9.52]
	Mild to Moderate	118	171	−16.11	[−17.78, −14.41]
	Moderate to High	224	171	−14.78	[−17.24, −12.25]
	High to Severe	106	124	2.60	[−1.31, 6.67]
f) Berry weight	No Deficit to Mild	42	28	−1.90	[−4.30, 0.57]
	Mild to Moderate	114	159	−6.77	[−8.50, −5.00]
	Moderate to High	216	170	−11.24	[−12.83, −9.63]
	High to Severe	80	85	−5.16	[−7.57, −2.68]
g) Ravaz index	No Deficit to Mild	30	36	18.75	[4.78, 34.57]
	Mild to Moderate	105	125	2.86	[−2.62, 8.64]
	Moderate to High	166	121	−0.24	[−3.93, 3.59]
	High to Severe	96	112	16.24	[8.57, 24.45]

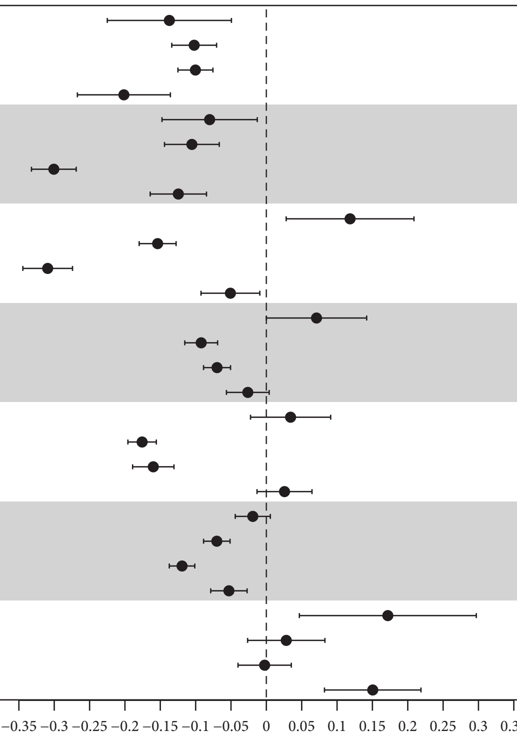

Figure 3: Forest plots for the effects of increasing vine water deficit level on vegetative growth and yield components. Horizontal bars stand for the mean value of the response ratio (RR) and the 95% confidence interval (CI); thus, effects are significant at $p = 0.05$ when bars do not cross the zero-response ratio (vertical dashed line).

moving from mild to moderate (6.8 ± 1.7%) and from moderate to high (11.2 ± 1.6%), and showing a lesser effect (5.2 ± 2.4%) when shifting from high to severe deficit conditions. Berry size is known to be very sensitive to water stress [51, 52], as both cell division and enlargement are decreased even at relatively mild water deficit levels [53, 54], which is supported by our results.

The characteristics of our dataset do not allow to discern the reasons behind the changes in yield to the smallest detail, since we are considering season-average water deficit, not the specific effect of water deficit at different moments of the plant cycle. However, the information on the sensitivity of grape yield to water deficit that can be inferred is certainly valuable for decision-making in vineyard management. Yield reductions are relevant, but probably not crucial, when deficit increases from mild to moderate (14.3 ± 2.2%), and therefore restrictions in irrigation may be tolerable if resources are limited. However, when deficit goes from moderate to high, yield decrease is much higher (26.6 ± 2.5%), and if we consider it accumulatively (i.e., from mild to high), it causes a decrease in yield > 40% that likely goes beyond profitability. Therefore, irrigation or other management practices that allow reducing the level of water deficit experienced by the vines should be used to avoid remaining in the two highest status of water deficit. When vine water deficit shifts from high to severe, yield losses are not relevant, so only grape quality or plant survival need to be considered.

Finally, the implications of water deficit for the balance between vegetative growth and yield could be analyzed through the RI. For this index (Figure 3(g)), changes were relatively small, with no variation in balance being observed when deficit increased from mild to moderate or from moderate to high. On the contrary, an increase of water deficit in the two extreme steps (from no deficit to mild and from high to severe) caused a similar increase in the RI (16%–18%), which indicates certain imbalance toward greater production compared to vegetative development [55].

3.2. Grape Composition. The effect of changes in vine water status affected nearly all the berry traits considered (Figures 4 and 5). In the case of SSC, the effect was significant (Figure 4(a)), but its intensity and direction depended on the specific steps of change in water deficit. When the plant–water status changed from null to mild and from mild to moderate deficit, SSC increased between 1.1 ± 1.1 and 1.5 ± 1.0%, whereas a slight decrease (0.74 ± 0.5%) was found when deficit changed from moderate to high, and no significant changes were found when deficit changed from high to severe. This trend demonstrates that, in general conditions, dilution phenomena occur when vines are subjected to null or mild stress, and that increasing deficit causes SSC to increase. Therefore, the positive effect that higher water availability has in photosynthesis, which should translate into more sugar being allocated in berries, counter balanced due to the increase in yield and/or later ripening when water

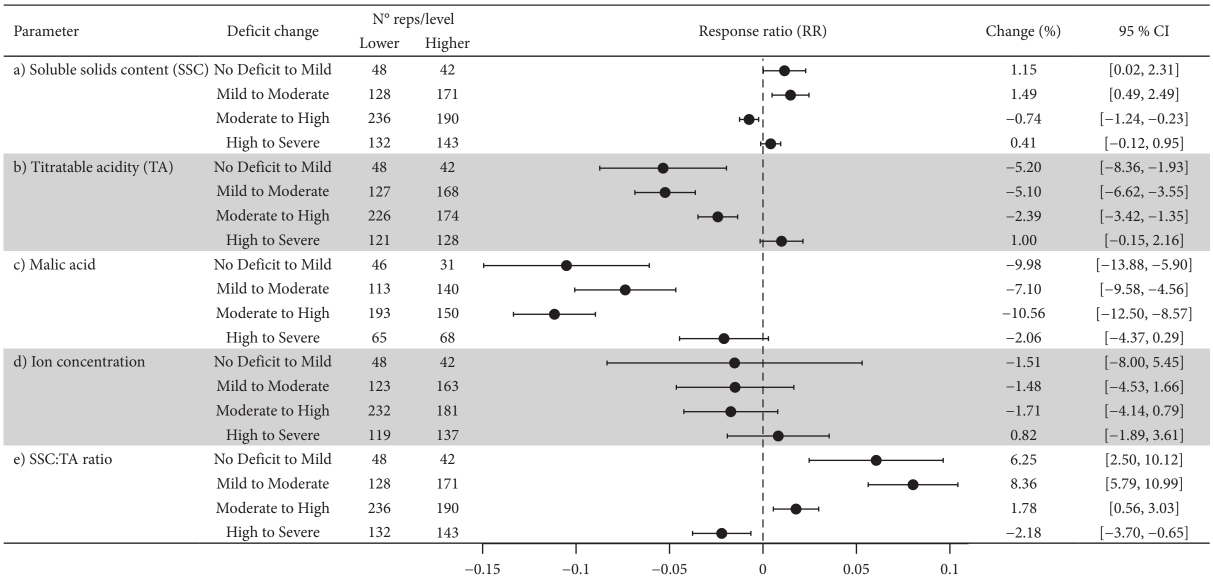

Figure 4: Forest plots for the effects of increasing vine water deficit level on grape composition traits. Horizontal bars stand for the mean value of the response ratio (RR) and the 95% confidence interval (CI); thus, effects are significant at $p = 0.05$ when bars do not cross the zero-response ratio (vertical dashed line).

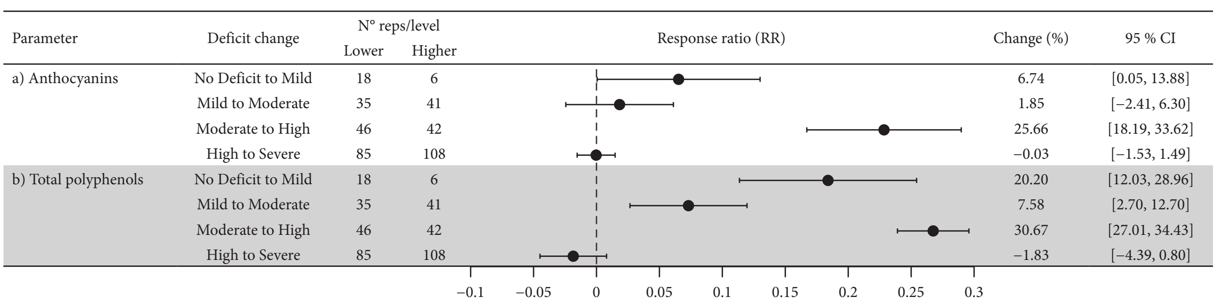

Figure 5: Forest plots for the effects of increasing vine water deficit level on anthocyanin and polyphenol contents. Horizontal bars stand for the mean value of the response ratio (RR) and the 95% confidence interval (CI); thus, effects are significant at $p = 0.05$ when bars do not cross the zero-response ratio (vertical dashed line).

is more abundant [56–58]. However, when water deficit shifts from moderate to severe, photosynthetic limitations become dominant, and grape SSC decreases. The lack of change when passing from high to severe deficit is possibly associated, to some extent, to the appearance of partial berry shriveling, which is frequently observed in severely stressed vineyards [59, 60]. Partial berry shriveling causes concentration of solutes and, therefore, can be hiding an additional effect of photosynthesis blockage in severely stressed vines.

The variables associated with acidity were generally affected by changes in water deficit. TA was decreased in all the steps of water deficit change, except for the high to severe deficit (Figure 4(b)). Thus, going from no deficit to mild deficit or from mild to moderate deficit resulted in a ≈5% decrease of TA for each variable. This decrease was smaller (2.4 ± 1.0%), though significant, when deficit increased from moderate to high, and disappeared, nearly reaching a slight increase when going from high to severe. The effect of water deficit on TA is well known and is associated primarily with an advanced maturity and to higher malic acid degradation [61–63]. In fact, we observed this trend when changes in malic acid concentration were analyzed (Figure 4(c)), so this effect appears to be more sensitive in situations of moderate, mild, or no water deficit. The apparently anomalous behavior observed for TA at the highest water deficit situations may be due to the concentration phenomena associated to partial shriveling mentioned above for SSC. Malic acid levels at high water stress situations are very low, and changes in berry size can result in increased concentrations of tartaric acid, which is known to be very stable [64, 65] and whose final concentration depends relevantly on dilution/concentration phenomena. Finally, pH (expressed here as concentration of protons) showed similar trends, but no significant differences were found. This lack of effect may be partly explained by the important influence of potassium on the pH of the must, which depends not only on vine water status but also on soil type and fertilization [66].

Changes in the water deficit level also affected the balance between sugar and acidity as estimated with the SSC:TA ratio (Figure 4(e)). The increases in deficit from null to mild or from mild to moderate caused an increase in this ratio (6%–8%), a slight increase when going from moderate to high deficit (1.8 ± 1.2%), and another slight decrease from high to severe deficit (2.2 ± 1.5%). These changes mainly reflect the effects observed for TA, as the impacts observed for SSC were slight and, therefore, contributed less to the variation in this ratio.

Regarding phenolics, anthocyanin, and total polyphenols content (Figure 5), significant effects of plant water status were observed. For total polyphenols, a quantitatively positive effect of increasing water deficit was observed for all the steps up to the high deficit level. This trend was less clear for anthocyanins, for which the only significant increase (25.7 ± 7.5%) was observed when deficit went from moderate to high, but not changing for the remaining steps. It must be noted that the variability observed for the RRs of these parameters is much higher than that of other berry composition variables due to the fact that their concentration depends on a very complex set of biological (yield, berry size, and variety) and environmental circumstances (temperature and light regimes) that can make more difficult to discern the implications of water deficit.

3.3. Water Deficit Effects and Irrigation Guidelines. Water deficit influences grapevine performance and grape composition, implying relevant considerations for vineyard management. Water deficit is known to affect phenolic synthesis through different processes, some being the direct consequence of metabolism shifts [67–69] and some others being associated to changes in bunch microclimate occurring because of a more dense or sparse canopy due to water status changes [70–72]. In addition, changes in yield and berry size due to water status modify the phenolic concentration in the must [50, 73, 74]. Although the changes in grape phenolics are the result of complex interactions, some general insights can still be extracted from the analysis of our results. If high phenolics and anthocyanin concentration are sought, the greatest gain can be obtained if vine water deficit increases from moderate to high. However, as discussed above, this change is also associated to the greatest yield loss. Therefore, a specific trade-off analysis should be made for each circumstance to determine if it is worth in terms of vineyard profitability. However, reaching the next level of severe deficit conditions would not be efficient at all, as no gains are obtained for either anthocyanins or for total phenolics. High water deficit levels cause blockage in plant metabolism, and, therefore, impair phenolic synthesis [71, 75] and can even lead to their degradation [76]. However, in those situations of null to mild deficit, the use of cover crops could drive water status toward more suitable conditions for the synthesis of phenolics, increasing their concentration [77].

The examination of the impact of vine water status performed in this collaborative work provides growers with actionable information to optimize their practices and adapt them to their specific needs. For example, our analysis reveals that moderate levels of water deficit can result in optimal vine balance, leading to improved grape quality without sacrificing yield. With this knowledge, growers can implement targeted irrigation strategies to maintain a certain water status level throughout the growing season, thereby maximizing both quality and quantity of grape production. This could be achieved using, in parallel, vineyard water balance models such as the one recently validated by Mirás-Avalos et al. [20] where seasonal vine water status could be simulated and different irrigation scenarios could be then implemented.

We have thus outlined the fact that irrigation needs to be managed considering specifically for each water status level and vineyard variable the implications of going one step up or down in a water deficit scale. In some contexts, despite some detrimental consequences for vineyard performance, they could be assumed to be due to environmental constraints, but in some others, the prejudice caused by increased water deficit would justify allocating water resources for vineyard irrigation. This trade-off–based decision-making is not simple, even less in the context of climate change.

Concerning irrigation decision-making with regards to grape composition, reducing vine water deficit by irrigating can lead to more acidic wines, which are undoubtedly a necessity in warm conditions, nowadays exacerbated by climate change, and could contribute to maintain typicity in seasons that are drier and warmer than usual. However, the degree of change hence obtained would be admissible from an environmental point of view only in those circumstances where water is not limited. Regarding phenolic content, decisions should be taken majorly focused on the perspective of the trade-off between yield and grape/wine characteristics, since the use of less water results, in general terms, in increased phenolic contents.

4. Concluding Remarks

The collaborative approach described in this article, in which a network of 11 research groups across Spain combined their previous results to perform a mega-analysis, has proven to be an effective way to model vine responses and extract valuable information for decision-making in viticulture. This collaborative effort exemplifies the power of integrating data and expertise from multiple sources to derive meaningful insights. This is not, however, a straightforward process, since during collaborative analysis, some problems, such as data variability and the need for careful interpretation of results, arise. However, our experience also emphasizes the opportunities of collaborative research, including the ability to capture diverse perspectives and address complex research questions. In this research, collaboration allowed for the inclusion of research data from many different sites, leading to a dataset that encompasses a broad range of vineyard conditions, which is highly important when analyses are intended to reveal general trends.

In any case, we must keep in mind that the mega-analytical approach also has some limitations. Compared to single large-scale studies, data coverage may be uneven for some situations and variables analyzed, and the variability of the measurements may be inflated because it is rare that independent field experiments can be considered exact replicates. Therefore, it is important to note that the obtained results should be considered general trends rather than specific predictions and that they are subject to variation due to factors such as soil, climate, viticulture management, cultivar, and rootstock.

While our analysis has provided valuable insights into the relationship between water deficit and vineyard performance, there remain areas where further investigation is needed. The approach considered has some intrinsic methodological limitations associated. On the one side, although averaging midday SWP over the growing season allowed us to synthesize vine water status into a single integrative indicator for each replicate, facilitating comparisons across trials, it can somehow be overlooking some effects of temporal dynamics of vine water status. It is well known that grapevine responses to water deficit vary depending on the phenological stage at which the deficit occurs [52, 78–80]. Therefore, results may differ from those presented here in situations where vine water status changes markedly between phenological stages, which were not the case in the experiments considered in our dataset (Figure S1). Another methodological limitation is that SWP values were not corrected for meteorological conditions such as air temperature or vapor pressure deficit. In recent years, several modeling approaches have been developed to adjust SWP (e.g., [81]), and future studies could benefit from incorporating such correction models when data availability permits.

Globally, there is a need for the wine grape industry and science to integratively understand vineyard management implications under diverse environmental conditions, particularly in the context of global change. Collaboratively, large-scale analyses such as this one provide valuable insights and represent a promising approach, even though they involve methodological challenges that future research will need to address. Incoming research efforts could focus on exploring the longer-term impacts of water deficit on vine health and productivity, and also on the impact of other practices related to soil, nutrition, and canopy management for which, despite a wide corpus of research being available, relatively little integrative work has been carried out.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

David Uriarte and Luis Gonzaga Santesteban have equally contributed to this work.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. *(Supporting Information)*

Table S1: Main characteristics of the vineyards studied in each region, number of trials, location, years of study, varieties, grape color, rootstock, soil texture, annual reference evapotranspiration (ETo), and annual rainfall.

Figure S1: Range of water deficit values found before and after veraison (V.) in the observations used in this study, according to the overall water deficit level experienced by them throughout the growing season.

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