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Decision support system for selecting the rootstock, irrigation regime and nitrogen fertilization in winemaking vineyards: WANUGRAPE4.0

F. Visconti[1], M. de la Fuente[2], I. Buesa[3], J.M. Escalona[3], H. Medrano[3], C. Miranda[4], J.M. Mirás Avalos[5], J. Palacios[6], J.G. Pérez-Pérez[7], J.M. Ramírez-Cuesta[1], P. Romero[8], L.G. Santesteban[4], N. Torres[4], D. Uriarte[9], M. Parra[10], and D.S. Intrigliolo[1]

[1]Centro de Investigaciones sobre Desertificación-CIDE (CSIC, UVEG, GVA), Moncada, Spain
[2]Plataforma Tecnológica del Vino-PTV, Madrid, Spain
[3]Instituto de Investigaciones Agroalimentarias y de Economía del Agua, Universidad de las Islas Baleares INAGEA-UIB, Palma, Spain
[4]Universidad Pública de Navarra-UPNA, Pamplona, Spain
[5]Centro de Investigación y Tecnología Agroalimentaria de Aragón-CITA, Zaragoza, Spain
[6]Viticultura Viva, San Martín de Unx, Spain
[7]Instituto Valenciano de Investigaciones Agrarias-IVIA (GVA), Moncada, Spain
[8]Instituto Murciano de Investigación y Desarrollo Agrario y Medio Ambiental-IMIDA, La Alberca, Spain
[9]Centro de Investigaciones Científicas y Tecnológicas de Extremadura (CICYTEX), Guadajira, Spain
[10]Centro de Edafología y Biología Aplicada del Segura (CEBAS-CSIC), Murcia, Spain

Abstract. We aim to develop and transfer to the wine sector a decision support system (DSS) in the frame of WANEGRAPE4.0 project that, integrated into a geographic information system, helps wine growers in i) selecting the most suitable rootstock given some agroecological conditions and oenological objectives; and ii) managing irrigation and nitrogen fertilization in the most suitable way for the selected rootstock and agroecological conditions. The following goals have been achieved. First, the modular structure and information flow of the DSS has been defined. Second, the main algorithms of the water balance module (DSS core part) have been formulated and the module coded in a spreadsheet. Third, this water balance module has been tested with data from field experiments in several regions of Spain. Fourth, the relationships between grapevine water status and production and harvest quality variables have been established, revealing an always-significant effects of the decrease in water stress on vegetative development, yield, and grape composition. Fifth, the nitrogen fertilizer effects on vine performance has been assessed. Sixth, the effects rootstocks have on 5 parameters of vine production and grape quality for winemaking have been established too by doing another meta-analysis of rootstock trials. Seventh, a rootstock selection module has been defined. The WANUGRAPE4.0 project goes on with the integration of all its modules, their coding in a World Wide Web language and their publication on an Internet portal.

1 Introduction

Grapevine (*Vitis vinifera* L.) is widely cultivated, though particularly in semi-arid areas, such as the Mediterranean basin. Currently vineyards spread over more than 7.4 million ha worldwide yielding around 78 Mt, which correspond to 292 million hL of wine, 27.3 and 1.3 Mt of, respectively, table grape and dried grapes [1]. Spain, with almost 1 million ha is the country with the largest vineyard area, yielding 6.8 Mt, which lead to 40 million hL of wine, 278,000 t of table grapes and 1000 t and dried grapes [2]. During the last decades, the Spanish viticulture has increased yields despite the vine surface has decreased. Boosting this higher productivity, there is the expansion of irrigation and fertilization practices, and the use of new genotypes, cultivars and rootstocks.

In Mediterranean areas, grapevine had been traditionally grown under rain-fed conditions. However, irrigation has been gradually introduced in these areas during the last decades as a way to alleviate the severe summer drought stress that negatively affects grape and wine quality, and thus to ensure more regular and predictable yields [3]. Nevertheless, given the large area under vine cultivation, particularly in Spain, and its high water requirements [4], water resources may get overexploited thus leading to side environmental and economic impacts [5]. Moreover, according to the climate projections into the middle of this century for Southern Europe [6,7], temperature, aridity and water stress are expected to increase thus threatening vine yields [8,9].

The adaptation to the climate change challenge involves a more reasonable use of water. However, this is not a simple matter of irrigation reduction because the overall grapevine response to soil water depends on soil nitrogen content and also, on vine genotype, climate, other soil characteristics, and the interactions among them. Specifically, the nitrogen use efficiency (NUE) depends on plant water status and vice-versa, and a valuable insight on how both interact has been gained in recent decades [10]. Therefore, the improvement at large scale of both the actual WUE and NUE will require a major effort of knowledge transfer to the vine grower.

In addition to the complexity the interacting effects between water status and nitrogen nutrition introduce for vine cropping, there are the rootstock effects on both, which are modulated by soil and climate conditions [11,12]. Viticulturists are often not enough aware of the profound effects rootstocks have on vine growing, because traditionally more attention is paid to the aerial part of the plants than to the underground one. However, the latest knowledge acquired on both traditional and new rootstocks can be advantageously used by vine growers to face the climate change threat and, furthermore, to address the environmental demands for a sustainable viticulture.

Consequently, there is a growing need for vine cropping adaptation. This will prompt viticulturists to adopt proper water management and nitrogen fertilization practices, and to substitute present plant materials, remarkably including rootstocks better adapted to the soil and climate conditions according to their variation throughout the territory. In this regard, Decision Support Systems (DSS) will play an important role to convey the scientific knowledge into a practical solution to assist vine growers in the decision making for adaptation. The DSSs are computer-based tools able to retrieve, interconnect data from a variety of sources and further process them to deliver meaningful information to their users [13].

WANUGRAPE4.0 tackles the issue of how the vine research results can be turned into effective recommendations for vineyard management, from the general planning, e.g., use of the most appropriate plant material, till the daily decisions about water and nitrogen management. Therefore, the main aim of the WANUGRAPE4.0 project is to develop a DSS for Spanish viticulture. This DSS will enable users to i) select the most appropriate rootstock material depending on soil and climate conditions and target oenological objectives, and ii) obtain recommendations for irrigation and nitrogen management, including the assessment of the adequacy of certain viticulture areas to sustain or not a rain-fed regime. In this communication, the on-going WANUGRAPE4.0 project is presented to an international audience, by summarizing its development status so far.

2 Overview of the DSS

2.1 Structure and uses of the DSS

The decision support system will have three distinct modules: i) the water balance one, ii) the nitrogen fertilization one, and iii) the rootstock selector. Moreover, the DSS will have at least two different uses: i) vineyard assessment, and ii) vineyard planning.

For the vineyard assessment, the DSS may be used to estimate the water status of vineyards based on soil and climate data obtained from the respective georeferenced databases to which it will be linked. This application of the DSS may be performed for specific vineyards or for larger vine growing areas, particularly in Spain, though note that it may be easily widen to other countries. In this regard, it is envisioned that the DSS will enable the estimation of the vineyard water status under different scenarios, either in the present, e.g., rain-fed viticulture, or in the future, e.g., viticulture under different globally shared socioeconomic pathways leading to climate change, i.e., greenhouse gases emission scenarios.

For the vineyard planning, the DSS may be used to obtain recommendations of irrigation and nitrogen fertilization regimes to attain the desired vine production and grape quality aims in specific fields intended for vine growing. Additionally, the rootstock selector of the DSS may be used to obtain recommendations about the most appropriate plant root material to cope with the soil, water and climate constraints the viticulturist face in those specific fields.

2.2 DSS workflow

For the vineyard assessment, only the water balance module will be needed, whereas for the vineyard planning, the three modules may be used in conjunction or in isolation depending on the user needs and convenience. Whatever the case, the water module is central to the DSS, being its key output the midday stem water potential (Ψ_{stem}) (Fig. 4). How the Ψ_{stem} is calculated from the water balance is explained in Sect. 3. How the DSS works for vineyard planning as a result of the coupling of the three modules with the different input data, i.e., soil and climate information and vine production parameters, as well as grape quality traits, is shown in Fig. 1 and explained thereafter.

Since the working hypothesis is that vine production parameters and grape quality traits are mainly related to Ψ_{stem} [14], the desired values for these data will be associated to a suitable Ψ_{stem} value, which will become the target Ψ_{stem}, i.e., $\Psi_{stem,t}$. The calculation of this $\Psi_{stem,t}$ will be made by using the relationships derived from the meta-analysis of water status effects on vine production and grape quality (Fig. 1). Then, this $\Psi_{stem,t}$ will be compared with the Ψ_{stem} calculated by the water balance module on the basis of the soil, climate and vine data, as well as the irrigation regime (Fig. 1), including none, i.e., rain-fed conditions. If the difference Ψ_{stem} - $\Psi_{stem,t}$, i.e., $\Delta\Psi_{stem}$, is positive, i.e., $\Delta\Psi_{stem} > 0$, then, to attain the desired aims of vine production and grape quality, the irrigation should be adjusted and, specifically, decreased (Fig. 1). If, conversely, the difference is negative, i.e., $\Delta\Psi_{stem} < 0$, then, to attain the desired aims of vine production and grape quality, the irrigation should be also adjusted, but this time it should be increased (Fig. 4).

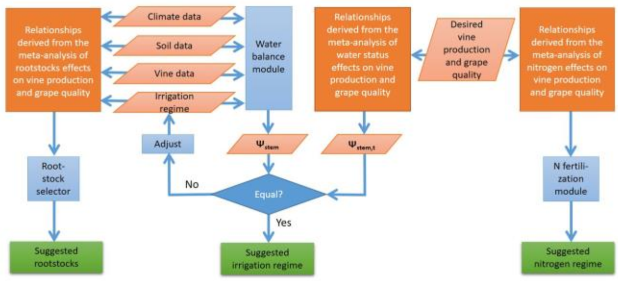

Figure 1. Flow of information in the WANUGRAPE4.0 decision support system when used for vineyard planning.

The irrigation regime will be readjusted and the $\Delta\Psi_{stem}$ calculation reassessed until it becomes zero ($\Delta\Psi_{stem} = 0$) or irrigation cannot be decreased any more, i.e., rain-fed conditions are attained. Then, the DSS has converged to an irrigation regime and this is presented as a recommendation to the user. In case irrigation cannot be decreased any more, the probable values for the vine production parameters and grape quality traits that would result as a consequence are evaluated. These probable values will be presented to the user in parallel with the desired values, so they can compare both.

Additionally, in sequence or in parallel, the nitrogen fertilization recommendation may also be obtained from the desired vine production parameters and grape quality traits. In this case, this will be made by using the relationships derived from the meta-analysis of nitrogen effects on all these (Fig. 1) along with other relevant relationships obtained from the literature. Finally, and also in sequence or in parallel with the other two modules, a suggestion of suitable rootstocks for the soil and climate conditions, as well as the vine characteristics and irrigation regime, particularly, water availability, may be obtained too (Fig. 1). In this case, this will be made by using the relationships derived from the meta-analysis of rootstocks effects on vine production and grape quality.

3 Water balance module development

3.1 Module description

The soil-vine-atmosphere continuum has been described according to Lebon et al. [15]. Briefly, soil is considered as a finite reservoir with a given amount of total transpirable soil water (*TTSW*), which is obtained from soil texture, percentage of stoniness and depth. Vine canopy is represented as a geometric structure according to Riou et al. [16] and the atmosphere is characterized by weather variables.

For initialization, the model considers that the soil has stored rainfall from the beginning of the year until the budburst date. Then, it keeps a daily update of soil water content by calculating the soil transpirable water in the rootzone (TSW_d) as:

$$TSW_d = (TSW_{d\text{-}1} + P_d - ES_d - TV_d) \qquad (1)$$

where $TSW_{d\text{-}1}$ is the transpirable soil water remaining from the previous day, P_d, ES_d and TV_d are, respectively, rainfall, evaporation from the soil and transpiration from the vine canopy, on that day. The model calculates the fraction of transpirable soil water (*FTSW*) at any given date as the ratio of TSW_d to *TTSW* [15].

Vine daily transpiration is closely related to the absorbed global radiation, which is computed from canopy dimensions and vineyard features [16]. In this model, the canopy is defined by three parameters: *H* and *L*, denoting the height and width of the foliage, respectively, and *Po*, the proportion of foliage gaps [16]. To simulate canopy development, the increase of *H* and *L*, and the decrease of *Po* are linked to cumulative thermal time (THT). The model assumes that *H* and *L* reach maximum values at a given thermal time (THT_{max}) since budburst. However, *Po* continues to decrease up to veraison, approximately, (THT_{min}).

In the absence of water deficit, *TV* is computed as:

$$TV = TV_p = \{R_{gv}/[(1-\alpha) \times R_g]\}ETP \qquad (2)$$

where TV_p is the potential vine transpiration, R_{gv} is the global radiation absorbed by the canopy, α is the albedo of the vineyard, R_g is the measured incident global radiation, and *ETP* is reference evapotranspiration. The feedback of water stress on vine transpiration is simulated with a bilinear function [15]. When *FTSW* falls below a threshold (φ), the ratio of *TV* to TV_p declines linearly with *FTSW* down to zero [15].

Evaporation from the soil is estimated using a two-stage approach as reported by Brisson and Perrier [17]. In the first stage, energy at the soil surface drives the actual evaporation. This stage lasts until cumulative evaporation reaches a threshold, equal to the amount of water stored in the topsoil layer (*U*). In the second stage, the evaporation is reduced because of the decrease in the water content at the soil surface and by the increase in hydraulic resistance near the soil surface. This stage depends on weather (b_1) and soil texture (b_2) according to Brisson and Perrier (1991) [17].

Then, several physiological variables, including predawn leaf water potential (Ψ_{pd}), are computed [18]. As a novelty, in this upgraded version, an empirical equation derived from data collected in eight grapevine varieties (n = 456, $R^2 = 0.599$) transforms Ψ_{pd} into midday stem water potential (Ψ_{stem}) values:

$$\Psi_{stem} = 1.2038 \times \Psi_{pd}^2 + 2.74 \times \Psi_{pd} - 0.254 \qquad (3)$$

Figure 2 shows a schematic representation of the model.

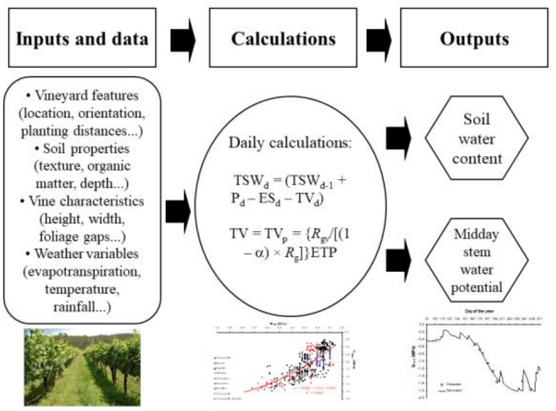

Figure 2. Scheme of the vineyard water balance model.

3.2 Input data

Values of model inputs can be either taken from the literature or estimated from experimental data. The climate and soil components for the equations describing evaporation of water from the soil (b_1, b_2, U) were calculated for the soil and climate data collected in each vineyard following Brisson and Perrier [17]. The threshold of FTSW at which vine transpiration begins to decline (φ) was estimated from measurements of stomatal conductance and soil water content in several experimental vineyards, whereas the value proposed by Lebon et al. [15] (φ = 0.40) was used in the vineyards where no gas exchange measurements were available.

Daily weather data (solar radiation, temperature, relative humidity, wind speed and reference evapotranspiration) were collected from automated stations located nearby the experimental vineyards. Data on vineyard features (geographical location, elevation, row orientation, spacings and canopy dimensions) and soil properties (texture, bulk density, organic matter content and depth) were collected in-situ in the experimental vineyards. Finally, THT_{max} and THT_{min} were obtained by combining phenological and weather data collected in each experimental vineyard over several years. Table 1 summarizes the inputs needed for running the model.

4 Water balance module validation

4.1 Experimental vineyards

The water balance module was tested with data from 10 vineyards featuring several cultivar × rootstock combinations, which were located in regions of Spain differing in climate (dry sub-humid to semi-arid), rootstocks, plant ages, soil classes, and water regimes (Table 2), totalling 129 different scenarios. In each one, Ψ_{stem} was measured approximately fortnightly using a pressure chamber on 4-9 representative vines. In the vineyards with white grapevine cultivars (Albariño, Godello and Treixadura) and in those of Palma with red (Tempranillo and Garnacha), stomatal conductance was also determined.

The differences between observed and simulated values of Ψ_{stem} were evaluated by means of linear regression and coefficients of determination (R^2). Additionally, the model performance was assessed through the calculation of the mean bias error (ME), the root mean-square error (RMSE) and the index of agreement (d) [19].

Table 1. Input parameters needed for running the vineyard water balance model.

Input	Abbre-viation	Units
Referred to vineyard location		
Longitude	Long	Coordinates
Latitude	Lat	
Elevation	Elev	m
Referred to soil		
Sand	Sand	%
Clay	Clay	
Organic matter	OM	
Bulk density	BD	t m^{-3}
Depth	Depth	m
Soil albedo	α_s	-
Parameter referred to climate	b_1	-
Parameter referred to soil	b_2	-
Amount of water stored in the topsoil	U	mm
Threshold between unlimited and limited transpiration	φ	-
Referred to vineyard		
Row orientation		Radian
Date of budburst	BB	Day of the year
Distance between plants		m
Distance between rows		
Maximum height of the canopy	H	
Maximum width of the canopy	L	
Minimum proportion of foliage gaps	P_o	-
Vine albedo	α_v	-
Cumulative thermal time at which the canopy is developed	THT_{max}	ºC
Cumulative thermal time at cessation of shoot growth	THT_{min}	

4.2 Validation results

The water module simulated Ψ_{stem} with average values of R^2, ME, RMSE and d for all the grapevine cultivars of, respectively, 0.94, 0.022 MPa, 0.266 MPa and 0.75. Goodness-of-fit indicators showed that the model provided adequate estimations of Ψ_{stem} in most scenarios, and although absolute values of Ψ_{stem} tended to be slightly overestimated, the evolution of this variable over the growing season was correctly simulated (Fig. 3). Specifically, in the vineyards of Garnacha in Palma and of Treixadura in Leiro, the simulated Ψ_{stem} values reproduced fairly well the seasonal trend (Figs. 3a and

3b). Nevertheless, in the vineyards of Monastrell in Yecla and Tempranillo in Requena, overestimations of Ψ_{stem} were overall observed but at the end of the season the Ψ_{stem} was underestimated (Figs. 3a and 3d).

Overall, goodness-of-fit indicators showed that the module provides adequate estimations of Ψ_{stem} under a wide range of conditions, confirming the robustness and reliability of this upgraded water balance module for simulating vineyard water balance in Spanish vineyards. Therefore, this module was able to simulate the vineyard water status satisfactorily enough to be the core of the decision support system (DSS) for vineyard water management.

Table 2. General characteristics of the experimental vineyards.

Site (autonomous region)	Plan-tation year	Grapevine cultivar (color)	Rootstock
Requena (Valencian Com.)	1991	Tempranillo (red)	Courdec 161-49
Moncada (Valencian Com.)	2018	Tempranillo (red)	Paulsen 1103
Yecla (Murcia)	1984	Monastrell (red)	Richter 110
Jumilla (Murcia)	1994	Monastrell (red)	Paulsen 1103
Badajoz (Extremadura)	2001	Tempranillo (red)	Richter 110
Palma (Balearic Islands)	2009	Tempranillo & Garnacha (red)	Richter 110
Olite (Navarra)	2001	Tempranillo (red)	Ruggeri 140
O Rosal (Galicia)	1996	Albariño (white)	Richter 110
Leiro (Galicia)	1998	Treixadura (white)	Castel 196-17
A Rúa (Galicia)	1997	Godello (white)	Richter 110

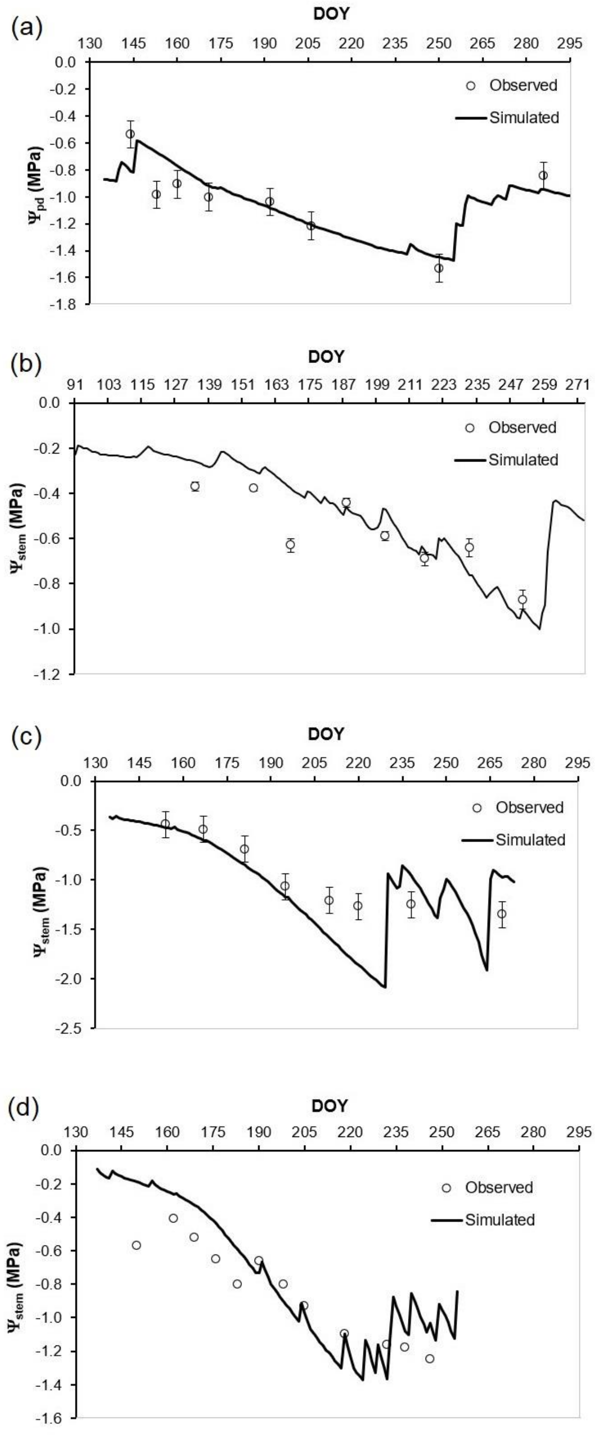

Figure 3. Seasonal trends of observed and simulated values of midday stem water potential (Ψ_{stem}) for several datasets displaying different irrigation strategies in vineyards of: (a) Garnacha in Palma in 2022, (b) Treixadura in Leiro in 2014, (c) rain-fed vineyards of Tempranillo in Requena in 2003 and (d) Monastrell in Yecla in 2019.

5 Meta-analysis of irrigation effects

5.1 The irrigation effects database

A database compiled during the AGL2017-90759-REDT project "New advances in viticulture - RedVitis 2.0" has been extended within the WANUGRAPE4.0 project. In total, information from 41 trials conducted between 1996 and 2020 by the research groups participating in the project was collected. The database includes information on vegetative development, yield, grape quality characteristics at harvest and water potential, for around 1,400 replicates, covering 19 varieties (9 whites and 10 reds) over a wide range of soil and climate and growing conditions that can be regarded as representative of the Spanish viticulture.

5.2 Statistical analysis

Response ratios (*RR*) were calculated to quantify the effect of increasing the stress in one level within each trial and year as:

$$RR = \ln X_{ls} - \ln X_{hs} \quad (4)$$

where X_{ls} is the mean value of the response variable for the lower stress level and X_{hs} is the mean value for the immediately higher stress level (e.g., increasing from High to Severe stress). Then, a weighting factor ω was calculated for each *RR* as:

$$\omega = \frac{1}{\frac{s_{ls}^2}{n_{ls} \times X_{ls}^2} + \frac{s_{hs}^2}{n_{hs} \times X_{hs}^2}} \quad (5)$$

where *s* is the standard deviation and *n* the number of replicates included within each observation. The weighted mean response ratio (RR_p) was calculated as:

$$RR_p = \frac{\sum_{i=1}^{j} \omega_i \times RR_i}{\sum_{i=1}^{j} \omega_i} \quad (6)$$

where *j* is the total *RR* calculated over the set of trials and years, ω_i is the weighting factor of the RR_i response ratio. Then, the percent of change (*C*%) of the investigated variables induced by the increase of the stress level were calculated as:

$$C\% = (e^{RR} - 1) \times 100 \quad (7)$$

The results were plotted in *R* [21], by means of RStudio [22] using the forestplotter 1.0.0 package [23].

5.3 Results of the irrigation meta-analysis

The replicates were grouped into ≈500 observations. The number of observations comprising the bottom and top levels of each comparison was uniform in all cases (Figs. 4 and 5). In general, the shift from a situation of ‘No stress’ to one of ‘Mild stress’ was the one for which the smallest number of observations was available (between 30 and 48 observations). Conversely, for the other responses the number of observations was much higher (between ≈100 and ≈250), with the shifts from ‘Mild’ to ‘Moderate’ and from ‘Moderate’ to ‘High’ being the best represented.

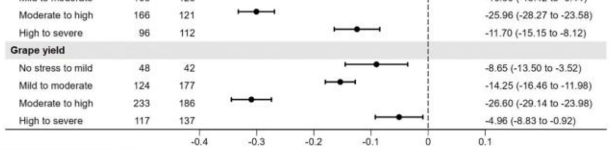

Figure 4. Forest plots for the effects of increasing water stress level on pruning wood weight and vineyard yield. Horizontal bars stand for the mean value of the response ratio (*RR*) and the 95% confidence interval (CI); thus effects are significant at p = 0.05 when bars do not cross the zero-response ratio vertical dashed line.

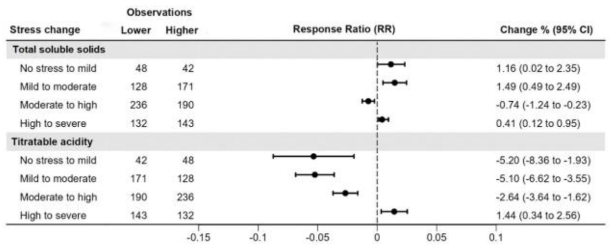

Figure 5. Forest plots for the effects of increasing water stress level on the soluble solids content and the titratable acidity of berries. Horizontal bars stand for the mean value of the response ratio (*RR*) and the 95% confidence interval (CI), thus effects are significant at p = 0.05 when bars do not cross the zero-response ratio vertical dashed line.

In relation to vine growth and yield, increasing water stress always has a significant ($p < 0.05$) negative effect, as the intervals at the 95% confidence level for the response ratios never contained the zero (*RR* = 0). The intensity of this effect (between ≈-5 ± 4% and -15 ± 3%) can be considered constant, as the confidence intervals cover a very similar range, for stress increases when it is still mild or is already high. However, when shifting from moderate to high stress levels, much more severe reductions in growth or yield are observed (≈-26 ± 3%), i.e., around 2.5-3 times more intense than in the other situations. A similar pattern is found for the TSS, although in this case increased water stress has enhanced TSS accumulation in berries at an almost constant rate (up to 1.5%, which means up to +0.5 ºBrix) except when moving from moderate to high stress, where it is slightly impaired (between -0.1 and -0.3 ºBrix), as it decreased by -0.74 ± 0.5%. Finally, the pattern for the titratable acidity differs from the others. Increases in stress up to moderate levels have a strong depressive effect (between -2.6% and -5.2%), whereas it is increased (1.4 ± 1%) when shifting from high to severe stress levels. The results show the overall impact of vine water status management on the agronomic response of the vineyard and constitute a valuable tool for water management in these agroecosystems and the development of decision support systems.

6 Meta-analysis of nitrogen effects

6.1 Creation of the nitrogen trials database

The first step in the meta-analysis consisted in selecting significant vine characteristics that may be affected by nitrogen nutrition. These were six vine production parameters and eight grape quality traits. The parameters of vine production were grape yield, pruning wood weight, bunch number, bunch weight, berry number and berry weight, whereas, the quality traits were TSS, titratable acidity (TA), pH, malic acid concentration, tartaric acid concentration, anthocyanins concentration, total polyphenol index and yeast assimilable nitrogen (YAN).

The terms ‘grapevine nitrogen fertili(z, s)ation’ were searched in the indexes of summaries Clarivate Web of

Science™ and Elsevier Scopus® giving in 283 results. This selection was narrowed down by removing duplicates, as well as by removing articles not related to vines for winemaking but rather for production of table grapes, those reporting none of the target variables, and review papers. Therefore, 122 articles were finally collected, from which the whole text of 117 was got.

In each of the articles, different nitrogen fertilization trials were isolated depending on all the factors, not only the nitrogen rate, which had been used in the experimental designs and that may affect the target variables: irrigation regime, soil characteristics, vine variety, rootstock and vintage, among others. As a result, the information of 374 nitrogen fertilization trials was extracted and, within each one, to ease comparisons among trials, a normalized value ($x_{n\ ij}$) was calculated for every target variable x by means of:

$$x_{n,ij} = 100\ x_{ij}/x_{\max j} \tag{8}$$

where x_{ij} is the value the variable x presents in the treatment i of the trial j, and $x_{\max j}$ is the maximum value the variable x presents in the trial j.

6.2 Data representativeness

The works were mostly carried out in Europe with France (15%), Spain (14%) and Italy (12%) on the lead, followed by the Americas with Brazil standing out (18%), thus being the collection fairly representative of the world vitiviniculture where France (15%), Spain (14%) and Italy (18%) lead wine production, and Brazil ranks third among the American producers (FAO, 2023). Cropping conditions were mostly open-air (95%) over glasshouse (5%), and directly on soil (81%) or pot (14%), with no irrigation support in most reported instances (48%). Planting density was between 1,250 and 10,000 vines ha^{-1} with average of 3,800 ± 400 vines ha^{-1}. Vine age ranged from 1 to 32 years with average of 11 ± 2 years. The number of rootstocks used was 25 with SO4 (23%) and Paulsen 1103 (16%) leading, whereas the share of non-grafted varieties was noticeable (9%). The number of varieties was 36, mostly red (63%) over white (33%), and with Cabernet Sauvignon (23%) and Syrah (11%) on top. In the works, the objective was mostly to try different rates of mineral N (69%), then different types of mineral N fertilizers (10%) and finally different rates of organic N (9%). Among the works featuring the testing of different rates of mineral N, the applications through soil (64%) and fertigation (26%) stood out and, consequently, they were the ones used for the meta-analysis.

6.3 Results of the nitrogen meta-analysis

The Mitscherlich's law of diminishing returns [24] was tried to describe how the normalized vine production and grape quality variables change with the annual nitrogen rate. Since the direct fitting to the scatter plots failed to satisfactorily fulfil the aim, these graphs were replaced by the corresponding point density surfaces, which were assessed by Kernel smoothing (Fig. 6). Therefore, five out of six vine production parameters, in addition to the yeast assimilable nitrogen, were shown to adapt to the Mitscherlich's law. The variables that did not adjust to the Mitscherlich's law followed either a logistic curve or neither known curve (Fig. 6). Among the former there were the anthocyanins concentration and the total polyphenol index, and among the latter, there were the berry weight, the TSS, the TA, the hydrogen ion activity (H), and the concentrations of tartaric acid (TcA) and malic acid (MA).

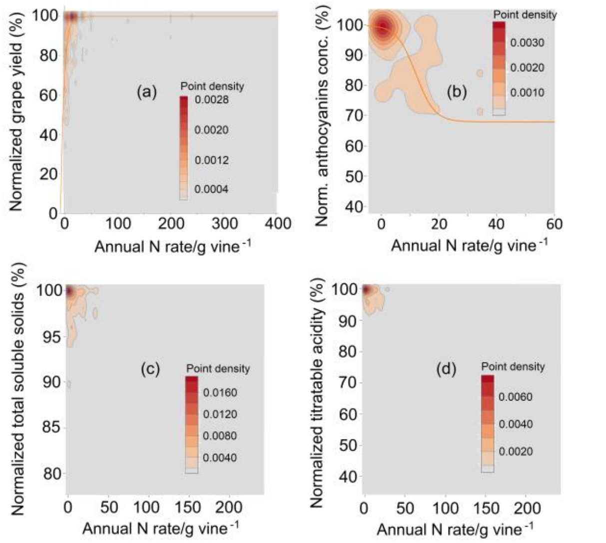

Figure 6. Adaptation of the density point data of the vine characteristics to the various curves that were tried: (a) Mitscherlich's law of diminishing returns for grape yield, (b) logistic curve for the anthocyanins concentration, (c) none curve for total soluble solids and (d) none curve for titratable acidity.

Based on the fitted Mitscherlich's curves, to attain maximum grape yield on the average viticultural conditions previously addressed, between 30 and 40 kg$_N$ ha^{-1} are required, thus leading to nitrogen use efficiency (NUE) values ranging from 0.27 to 0.36 t kg$_N$$^{-1}$. Despite no curve could be fitted to the normalized TSS and TA against annual nitrogen rate, a rate between 20 and 25 kg$_N$ ha^{-1} could still be estimated for maximizing technological quality while additionally keeping phenological quality at its best in red grapes, thus leading to NUE values between 0.41 and 0.47 t kg$_N$$^{-1}$.

7 Rootstock selector development

For the development of the logical part of the WANUGRAPE4.0 Rootstock Selector (W4RS), a search was carried out for already available dynamic on-line rootstock selectors in English, Spanish, French, Italian, Portuguese and German. In the Internet there were found many tables to manually make the rootstock selection, but only two selector tools: the Grapevine Rootstock Selector Tool (GRST) from Wine Australia (https://www.grapevinerootstock.com/), and the *Árbol de decisión para elección de portainjertos* (ADEP) from the *Diputación de Álava* in Spain (https://web.araba.eus/es/agricultura-ganaderia/eleccion-de-portainjertos).

In the logical functioning, the GRST and the ADEP selectors present similitudes. They start from a set of rootstocks (Table 3), and several questions, each one with some answer options, are presented to the user. These questions are about the desired vine tolerance to several stress factors about climate, soil and water, as well as desired vine development characteristics (Table 4). In the case of the GRST, the starting set is made up of 22 rootstocks, and the number of questions is six, from which five are related to climate, soil and water characteristics and only one to vine development features (Table 4). In the case of the ADEP, the starting set is made up of 14 rootstocks and the questions are four, all dealing with climate, soil and water characteristics (Table 4).

Table 3. Collections of rootstocks recommended by the Spanish Ministry of Agriculture (MAPA, 2018): RSMA; and used in the different selectors: GRST, Grapevine Rootstock Selector Tool; ADEP, *Árbol de decisión para elección de portainjertos* and W4RS, WANUGRAPE4.0 Rootstock Selector.

Id	Rootstock	Collection of rootstocks			
		RSMA	GRST	ADEP	W4RS
1	Blanchard BC-1	✓			
2	Börner		✓		
3	Castel 196-17	✓			✓
4	Castel 6736	✓			
5	Couderc 161-49	✓		✓	✓
6	Couderc 1616	✓			✓
7	Couderc 3306		✓		
8	Couderc 3309	✓	✓	✓	✓
9	Dog Ridge		✓		
10	Ecole de Montpellier 333	✓			✓
11	EVE Jerez 13-5	✓			
12	Fercal	✓	✓	✓	✓
13	Freedom		✓		
14	Gravesac		✓	✓	✓
15	Kober 5BB*	✓	✓		✓
16	Martínez Zaporta 5-A	✓		✓	
17	Merbein 5489		✓		
18	Merbein 5512		✓		
19	Millardet 101-14	✓	✓		✓
20	Millardet 19-62	✓			
21	Millardet 41-B	✓	✓	✓	✓
22	Millardet 420-A	✓	✓	✓	✓
23	Paulsen 1103	✓	✓	✓	✓
24	Paulsen 775		✓		
25	Ramsey		✓		
26	Richter 110	✓	✓	✓	✓
27	Richter 31	✓			
28	Richter 99	✓	✓	✓	✓
29	Riparia Gloire de Mont.			✓	✓
30	Ruggeri 140	✓	✓	✓	✓
31	Rupestris du Lot	✓		✓	✓
32	Schwarzmann		✓		
33	SO4	✓	✓	✓	✓
34	Teleki 5C		✓		

*Also known as Teleki 5A or Teleki 5BB.

In the logical functioning, the GRST and the ADEP selectors present also differences, which are worth commenting. In the case of the GRST the questions are presented in one go, and the user can respond or not, and in the order they wish. This way of working has several advantages. First, it allows the user to obtain a selection even if they do not answer questions because of lack of information or convenience. Second, it allows the user to see how the initial set of rootstocks is gradually narrowed down as they answer the questions. In the case of the ADEP the questions are presented in a specific order and the user has no choice but to answer all if they want to obtain a selection. This way of working has several disadvantages. First, it does not allow the user to obtain a selection if all questions are not answered. Second, it does not allow the user to see how the initial set of rootstocks is progressively narrowed down. Therefore, the GRST has not only more questions and more options to each one (Table 4) and hence is more information rich than the ADEP, the GRST is also more flexible and transparent than the ADEP. Consequently, the GRST was chosen as the starting point from which the logical part of the rootstock selector in the WANUGRAPE4.0 was developed.

Table 4. Questions and number of answer options presented to the user in the different rootstock selectors: GRST, Grapevine Rootstock Selector Tool; ADEP, *Árbol de decisión para elección de portainjertos*; W4RS, WANUGRAPE4.0 Rootstock Selector. A zero record means the rootstock selector does not ask that question.

Id	Question about...	Rootstock selector		
		GRST	ADEP	W4RS
1	Water availability	9	2	9
2	Vine vigour	3	0	3
3	Soil or water salinity	4	2	4
4	Soil drainage ease	2	0	0
5	Soil pH	5	0	5
6	Nematodes tolerance	2	0	2
7	Soil organic matter	0	3	0
8	Soil active lime	0	4	7
9	*Indice du pouvoir chlorosant**	0	0	7

*10^4 percent active lime/ppm extractable Fe.

The relevance for Spanish winegrape growing of the six questions originally featured in the GRST were reviewed with the counselling of the *Vitis Navarra* staff, one of the most important vine nurseries in Spain (https://vitisnavarra.com/). Therefore, five out of the six questions from the GRST were used in the W4RS, and two additional questions were attached as alternatives to the soil pH one (Table 2). These latter two questions enable the user to refine the rootstock selection if the soil pH is from neutral to strongly alkaline and if, besides, they have data about the soil active lime or the *indice du poivoir chlorosant* (IPC) as defined by Juste and Pouget (1972) [25]:

$$\text{IPC} = 10^4 \text{ percent active lime/ppm extractable Fe} \quad (9)$$

In addition to the questions, the rootstocks that should constitute the pool from which to make the selection were also discussed. These should be representative of the Spanish vitiviniculture and, in this regard, an adequate

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starting point was the collection of 22 rootstocks recommended by the Spanish Ministry of Agriculture [26] (Table 3). Because of the counselling from *Vitis Navarra*, six rootstocks were dismissed from the recommended set and two were added, specifically, the Gravesac and the Riparia Gloire de Montpellier, which had been included in the GRST, only the former, and in the ADEP, both (Table 3). As a result, a collection of 18 rootstocks was obtained for the W4RS.

Next, the level of tolerance of the rootstocks to the stress factors of climate, soil and water, as well as vine development characteristics were discussed. In this stage of the DSS development, it was decided to use already worked out data, which was taken from the *Vitis Navarra* vine variety and rootstock catalogue, from Hidalgo and Hidalgo [27] and from the GRST (Table 5).

Finally, the W4RS was coded and a graphical user interface designed in Spanish (Fig. 7).

Table 5. Sources of information about the rootstock tolerance to several stress factors of climate, soil and water, as well as vine development characteristics: VN, *Vitis Navarra* catalogue; H&H, Hidalgo and Hidalgo (2019) and GRST, Grapevine Rootstock Selector Tool.

Id	Characteristic	Source of rootstock information used		
		VN	H&H	GRST
1	Tolerance to soil nematodes	✓		
2	Tolerance to soil acidity			✓
3	Tolerance to soil lime	✓		
4	Tolerance to water scarcity	✓		
5	Vine vigour	✓		
6	Tolerance to salinity	✓	✓	✓

8 Meta-analysis of rootstock effects

8.1 Creation of the rootstocks database

A database was created aimed at compiling research done in Spanish vineyards on rootstock performance. This database included research articles from both technical national journals and international journals with peer review, as this source can be considered useful for such a global analysis considering the particulars of experimentation in viticulture. A variety of documents that were deemed appropriate for the database and consequently for the subsequent meta-analysis, including 20 technical documents in total, were all incorporated into the database. Overall, the database included rootstock experimentation performed on 36 different varieties, 47 different rootstocks, and at 59 different sites. The total number of records that were kept for the meta-analysis was 312. The five variables that showed up more frequently in these documents were yield, pruning wood weight, Ravaz index, sugar concentration, and pH, and were therefore included in the meta-analysis.

8.2 Statistical analysis

Response ratios (*RR*) were calculated to quantify the effect of each rootstock and rootstock crossing on yield, pruning wood weight, Ravaz index, sugar concentration and pH. The procedure that was followed to calculate and create the figures was the same described in Sect. 5 for the meta-analysis of water status on vineyard performance.

Figure 7. Screenshot of the WANUGRAPE4.0 Rootstock Selector as of the date this communication was written.

8.3 Results of the rootstocks meta-analysis

The response ratio values depicted in the forest plots offered a clear picture of the overall impact of each rootstock and *Vitis* sp. crossings on agronomic performance. Due to space limitations, Fig. 8 summarizes the effect of the major *Vitis* sp. crossings, as an example of the potentiality of this database, which will be explored in subsequent publications. The crossing affected all the variables considered, *Vitis berlandieri* x *V. riparia* providing higher yields and pruning weight and lower sugar content and pH than the average, *V. berlandieri* x *V. rupestris* higher pruning weight and sugar content, and lower Ravaz Index than the average, whereas for *V. berlandieri* x *V. vinifera* we observe lower yield, pruning weight, sugar concentration and pH, and higher Ravaz Index. It must be noticed that the individual behaviour of some of the rootstocks differed from the average trend for its crossing, and that other rootstocks not belonging to these crossings were considered for the statistical analysis, but have not been included in the figures due to space limits.

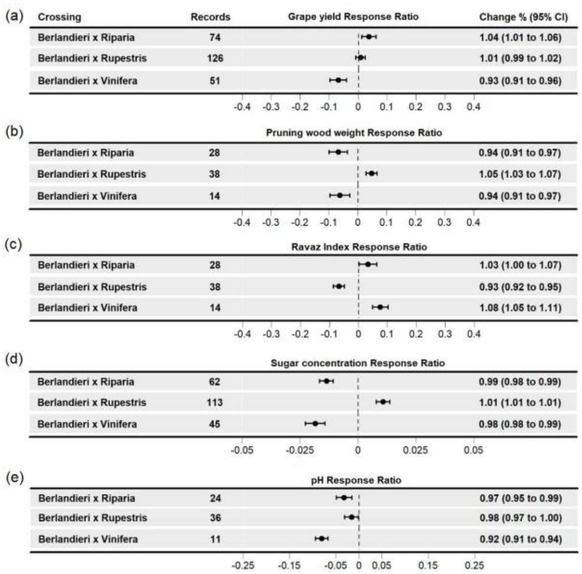

Figure 8. Forest plot showing the Response Ratio observed for (a) yield, (b) pruning weight (c) Ravaz Index, (d) sugar content and (e) pH for the main *Vitis* sp. crossings leading to currently used tootstocks. Horizontal bars stand for the 95% confidence intervals (CI); thus effects are significant at $p = 0.05$ when bars do not cross the zero-response ratio vertical dashed line.

9 Conclusions

The WANUGRAPE4.0 Proof-of-Concept project is of importance to capitalize the results obtained in previous research projects. The developments, under finalization, will be of aid to the grape and wine industry to choose the best adapted rootstock type. In addition, the DSS for water and nitrogen fertilization recommendation, will be useful for a first approximation to the fertirrigation regime to be applied seasonally considering the desired oenological and agronomic objectives and the environmental conditions in the area of study.

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