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ARAŞTIRMA MAKALESİ RESEARCH ARTICLE

# Effects of restricted irrigation on root morphological properties of wine grapes (*Vitis vinifera* L.)

Su kısıtı uygulamalarının şaraplık üzüm çeşitlerinde (*Vitis vinifera* L.) kök morfolojik özellikleri üzerine etkileri

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Ö Z E T / A B S T R A C T

***Aims***: This study sought to determine the effects of the application of water restrictions on the morphological characteristics of the roots of wine grape varieties grown in the Thrace region.
***Methods and Results***: The experiment was conducted in 14 L pots and perlite growth medium using a computerised irrigation and nutrition system. Different water restrictions were applied to 'Adakarası', 'Papazkarası', 'Vasilaki', 'Yapıncak' and 'Cabernet Sauvignon' cultivars, including 4 different daily total water amounts and no irrigation. At the end of 2 growing seasons, plants were removed and the parameters of number, length, diameter, weight of fine and coarse roots and trunk diameter were determined.
***Conclusions***: Although none of the studied parameters is sufficient to define exactly the drought tolerance of the cultivars, it shows that they are important for defining the genotypic response of the cultivars to water stress. The cultivar 'Adakarası' responds to decreasing water content similarly to 'Cabernet Sauvignon'. The high number of roots in the 'Papazkarası' cultivar can be considered an advantage in terms of adaptation to drought conditions. On the other hand, the 'Yapıncak' and 'Vasilaki'' cultivars respond to low water with reduced vegetative growth.
***Significance and Impact of the Study***: In this study, root morphological characteristics of traditionally grown wine cultivars in the Thrace region were investigated for the first time. Knowledge of these traits is important for the adaptability and to take advantage of genetic diversity of local cultivars for the sustainability of viticulture under current climate change conditions.

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## INTRODUCTION

The devastating effects of the climate crisis have been felt in the world's traditional wine-growing regions for years (Jones, 2007; Tóth and Végvári, 2016; Candar et al., 2019; Santos et al., 2020). It is an indisputable fact that recent predictions have come true. Climate changes, especially the increase in average temperatures, the change in the amount of precipitation and the timing of the growing season, elevated $CO_2$ content in the atmosphere and the increase in unusual weather events have had an impact on viticulture in almost all wine regions in the last decade, (Webb et al., 2008; Fraga et al., 2012; Vrsic and Vodovnik, 2012; IPCC, 2014; Kizildeniz et al., 2021) and these changes affect the quality standards of grapes and wine. Drought, soil erosion and salinity are some of the main indirect effects of climate change, limiting productivity and affecting the composition of grapes. Areas with Mediterranean climate characteristics where current winemaking regions risk losing their viticultural sustainability in future scenarios (Fraga et al., 2016; Santos et al., 2020). Despite, traditional vineyard areas will not disappear. However, it means that vignerons in these regions will have to consider drastic changes to adapt to the effects of the climate crisis and rising temperatures. It also opens up new opportunities for winemaking in regions that were previously unsuitable for winemaking, such as northern and eastern Europe and parts of North America and Asia. Traditionally, the vast majority of fine wines are produced between the 30˚ and 50˚ latitudes in each hemisphere. However, the consequences of the climate crisis are cause these growing regions to shift further north in the Northern Hemisphere and further south in the Southern Hemisphere.

Today, global warming is accepted as inevitable. In this case, short-term strategies such as canopy management, use of sunscreens, supplemental drip irrigation, tillage and preparation for new vineyard pests and diseases should be considered. In addition, researchers have long expressed preferences such as changing the training system, changing the clone or rootstock, changing the cultivar and changing the location (Carbonneau and Bahar, 2009; OIV, 2014).

The biodiversity of the viticulturist countries offers important opportunities for clonal, rootstock and varietal changes in viticulture. The possibilities offered by this diversity and the autochthonous *V. vinifera* L. cultivars have been extensively studied (Vouillamoz et al., 2006; Ergül et al., 2011; Hizarci et al., 2012; Balda et al., 2014; Yılmaz et al., 2020).

It is required to benefit from the adaptability and genetic diversity of local cultivars, both to ensure the sustainability of viticulture in the Mediterranean region and for future-oriented sustainable winemaking in new vineyard zones (Bernardo et al., 2018; Candar et al., 2021). The selection of appropriate rootstocks and cultivar; supports sustainability by influencing input costs and waste management processes in the vineyard, e.g. through labour management, water management, nutrient elimination and soil management, and reduction of vehicle traffic between vineyard rows.

The root morphology and physiology of grapevine may be considered a key element of adaptation.

The root system (RS), as the interface element between the vine and the soil, fixes the vine to the ground, supports it and is responsible for the absorption of water and nutrients dissolved in water. The root is also the storage organ for the carbohydrates produced by photosynthesis. These storage substances protect the vine from frost in winter and are the main source of nourishment for newly formed roots and shoots during bud break. It is also the organ where some plant hormones such as cytokinins and abscisic acids are produced (Keller, 2015; Creasy and Creasy, 2018). In plants that reproduce by seed, the primary roots develop from the hypocotyl of the embryo. However, the root system of the grapevine consists of adventitious roots from woody cuttings. The adventitious roots then form the main roots of the new plant. The lateral roots formed on the main root make many branches and constantly form new roots. The number and placement of lateral roots is not predetermined, as it depends on many soil factors, especially the availability of water and nutrients (Malamy and Benfey, 1997). Moreover, unlike many other plant species, the formation of lateral roots in grapevines is not restricted to the unbranched apical zone. Grapevines are also able to form new lateral roots on older parts of the roots that have already developed a vascular cambium (Keller, 2015).

In rootstocks and cultivars of the genus *Vitis*, the size of the root system, i.e. its horizontal and vertical depth distribution, is important for the ability to absorb water and nutrients (Smart et al., 2006).

The most important structure of the root system is the root apex. The root apex is the structure that allows the vine to collect the water and nutrients it needs to survive and to find new soil layers to expand the root system. The root tip consists of the maturation zone, the elongation zone, the meristematic zone and the structures called the root cap or caliptra, which allow the root to move forward and protect it in the soil. Root hairs or sucking hairs, which appear in the maturation zone at the root tip every growing season, are specialised structures that grow from epidermal cells. The uptake of water and dissolved nutrients by the root is mainly via the suction hairs. The quantity and length of the absorption hairs vary depending on many factors such as cultivar, soil structure, climate, water content of the soil and chemical properties of the soil. The water-soluble nutrients absorbed by the suction hairs via their cell membranes are passed on to the root bark and then to the vascular bundles. In perennial plants, due to their natural cycle, the root hairs constantly die within 1-2 weeks of their emergence. Then the root hairs constantly replaced by new ones that appear nearby as long as the soil conditions are suitable (Mullins et al., 1992; Helmisaari et al., 2009; Zhang et al., 2016).

There are many elements that influence the formation, development and movement of the root in the soil. Factors such as the physical and chemical properties of the soil, tillage, water absorption and transport, the presence of impermeable, compacted layers, rootstocks and cultivars, planting density, root diseases and weed species in the vineyard lead to an unusual diversification of the architecture of the root system and increase the plasticity (Smart et al., 2006; Bauerle et al., 2008; Hochholdinger and Zimmermann, 2009; Eshel and Beeckman, 2013).

Primary root development begins with the appearance of fine roots (Ø < 2 mm), which have a function in water and nutrient seeking and uptake and are often mycorrhizal. These roots are analogous to the roots of herbs and consist of exodermis, cortex, endodermis, pericycle as well as xylem and phloem tissues (Comas et al., 2000; Keller, 2015; Freschet et al., 2021). As the root matures, the vascular cambium produces secondary xylem and phloem, and the cork cambium (arising from the pericycle) forms the periderm. The original exodermis, cortex and endodermis are lost through secondary growth in the mature root (de Herralde et al., 2010; Keller, 2015; Richards, 2011). When mature roots ripen, they form the original structure, the root stem, from which all other roots sprout. These coarse (woody) roots represent a high percentage of the root biomass and have structural, water and nutrient transporting and storing functions (Richards, 1983; de Herralde et al., 2010; Keller, 2015).

Coarse roots are classified as roots larger (Ø > 2 mm) than 2 mm in diameter (Cuneo et al., 2021; Freschet et al., 2021), however some other sources report them as roots larger (Ø > 4 mm) than 4 mm in diameter (Ollat N et al., 2016). Therefore, these values may not be able to capture the diversity of form and function of all grapevines (McCormack et al., 2015; Freschet et al., 2021).

Understanding the relationships between grapevine, root functions, genetic diversity and water in order to cope with climate change under such extreme conditions and increase adaptive capacity is now an even more important challenge for fruit production. This is because plant roots control the metabolic activity of above-ground organs by sensing stimuli such as gravity, moisture, light, pressure and hardness, sound, nitrogen, phosphorus, potassium, salinity, toxic substances, bacteria, and chemical and electrical signals from neighbouring plants (Mancuso and Viola, 2015).

Vines are almost exclusively propagated vegetatively by cuttings and the vast majority are grafted. In areas infested by phylloxera, the establishment of vineyards with self-rooted vines is impossible. To cope with phylloxera, most vines worldwide have to be grafted onto a rootstock. In addition, rootstock vines are an important underground structure for the plant to resist various pests and diseases and to adapt to different soil types. In modern viticulture, grafting commercial grapevine cultivars onto interspecific rootstocks is a common practise required to make the plant resistant to many biotic and abiotic stresses (Korkutal et al., 2011; Corso et al., 2016; Ollat N et al., 2016; Loureiro et al., 2020). However, some parts of Australia and Chile are free of phylloxera and grapevines are own-rooted (Mullins et al., 1992; Jackson, 2014; Keller, 2015). Also in Turkey, many old vineyard plantations in viticulture regions consisting of local cultivars are still own-rooted. Moreover, the effects of rootstocks on grapevine cultivars are a widely studied research topic (Mccully, 1999; Jones, 2012; Marguerit et al., 2012; Zhang et al., 2016; Peccoux et al., 2018; Marín et al., 2021), and when it comes to lesser known local cultivars, these effects suppress a detailed understanding of the genotypic characteristics of the scion. Therefore, this experiment attempts to determine the performance of the cultivars by studying them independently of the rootstock effect. Thus, variations in the structure, development and distribution of the root system of grapevine may have a genetic component (Smart et al., 2006; Yıldırım et al., 2018).

As drought adaptation is a complex trait that can be controlled by a cultivar of physiological processes, understanding the functional and morphological differences between genotypes seems to be related with better understanding of the contribution of cultivars to drought adaptation. Measurements on whole root systems, independent of root diameter or topology, can be useful to describe the functioning of the whole plant (Freschet et al., 2021).

In this study, the changes in root morphology of wine grape cultivars grown in the Thrace region of Turkey under different limited irrigation applications were investigated.

## MATERIAL and METHODS

### *Location, plant material and trial design*

The experiment was conducted during the 2019-2020 vegetation periods on cv. ‘Adakarası’, ‘Papazkarası’, ‘Vasilaki’, ‘Yapıncak’ and ‘Cabernet Sauvignon’ grapevines (*Vitis vinifera* L.) at the coordinates 40.96 °N - 40.97 °N latitude and 27.46 °E - 27.47 °E longitude and, 30-35 m altitude in Tekirdag, Turkey.

Local wine grape cultivars that have been traditionally grown in the region for a long time were cultivated as the interest of growers has increased, as well as 'Cabernet Sauvignon' as a control cultivar due to its resilience under dry conditions (Simonneau et al., 2017). A computer-controlled irrigation and nutrient system (Teori Yazılım Ltd. İstanbul, Turkey) was installed in the open field. Cuttings with 7-8 buds were taken from healthy mother plants previously tested for important viruses from the experimental vineyards of Tekirdağ Viticulture Research Institute (TVRI). Grapevines rooted and grew in 14-L plastic pots in perlite medium (Kale Perlit, Turkey) until they reached 14-16 leaves, EL 29-31 (Lorenz et al., 1995). Before the EL 15-17 stage, all clusters and supernumerary main shoots were removed, 2-3 shoots were left on each individual vine. Until the end of the experiment, the main shoots of the vines were kept at a length of 170-175 cm and the lateral shoots were removed except for 3-4 leaves. At the end of the first vegetation period, the vines were pruned back to 2-3 buds. The same cultivation procedure was used in the second year (Table 1).

*Table 1. Phenological development stages of cultivars*

| **Cultivars** | **EL 4** | | **EL 17-19** | | **EL 33-35** | | **EL 43-47** | |
|---|---|---|---|---|---|---|---|---|
| | **2019** | **2020** | **2019** | **2020** | **2019** | **2020** | **2019** | **2020** |
| 'Adakarası' | 04.04 | 17.04 | 24.06 | 16.07 | 26.07 | 15.07 | 17.11 | 25.11 |
| 'Papazkarası' | 02.04 | 18.04 | 24.06 | 16.07 | 24.07 | 17.07 | 16.11 | 27.11 |
| 'Vasilaki' | 04.04 | 16.04 | 26.06 | 17.07 | 24.07 | 15.07 | 15.11 | 02.12 |
| 'Yapıncak' | 03.04 | 18.04 | 25.06 | 14.07 | 27.07 | 15.07 | 14.11 | 27.11 |
| 'Cabernet Sauvignon' | 01.04 | 19.04 | 25.06 | 16.07 | 26.07 | 17.07 | 15.11 | 29.11 |

Water constraints period, WCT; Water constraint treatments, DWA; Daily water amount.

When all the vines had reached the level to have a homogeneous shoot length (EL 29-31), the water holding capacity of perlite was calculated and irrigated in standard amounts up to this point, the irrigation amount was predicted and the daily irrigation schedule per pot was started to create water stress for the plants. A daily maximum irrigation amount (8 L) was set according to Ilahi and Ahmad (2017) and other reduced water amounts were applied at the rate of 6 L, 4 L and 2 L according to the reference evapotranspiration (ETo). In addition, another application was made without irrigation. The amount of water to be applied per application was determined by a computerised system by dividing 5 during the day by the daily total. In this way, conditions of water scarcity are simulated in a controlled way (Table 2).

*Table 2. Irrigation schedule during experimental years*

| **Irrigation amount (L)** | **Irrigation time (min)** | **Dates of year 2019** | **Dates of year 2020** | **WCP of 2019** | **WCP of 2020** | **WCT of experimental years** | **DWA of experimental years** |
|---|---|---|---|---|---|---|---|
| 5.00 | 75 | 15.05-14.06 | 29.06-01.07 | 28.07.2019 – 16.09.2019 | 18.07.2020 – 02.10.2020 | 100% | 8.00 |
| 7.33 | 110 | 14.06-28.06 | 01.07-18.07 | | | 75% | 6.00 |
| 8.00 | 120 | 28.06-16.09 | 18.07-02.10 | | | 50% | 4.00 |
| 6.67 | 100 | 16.09-04.10 | 02.10-14.10 | | | 25% | 2.00 |
| 2.67 | 40 | 04.10-11.10 | 14.10-24.10 | | | 0% | 0.00 |
| 2.00 | 30 | 11.10-31.10 | 24.10-30.10 | | | | |

Water constraints period, WCT; Water constraint treatments, DWA; Daily water amount.

The experimental design was a completely randomised block trial with a total of 600 vines, consisting of 3 replicates and 8 vines for each replicate and 5 treatments, following the pattern of the randomised block trial.

***Sample collection and definitions***

At the end of two years of vegetation, 5 plants were uprooted at each repetition of each application. The roots were first shaken and then carefully washed under fresh water to remove adhering perlite particles. The following morphological measurements were made.

In these measurements, adventitious root formations were assessed about 3 cm below the soil line where the root formation took place. Since fine and coarse roots have been classified differently depending on the references (Morlat and Jacquet, 2003; Somkuwar et al., 2012; Ollat et al., 2016; Cuneo et al., 2021; Freschet et al., 2021), in this study fine roots (absorptive roots) were identified as roots with a diameter of less than 3 mm (Ø < 3 mm) and coarse roots as roots with a diameter of more than 3 mm (Ø > 3 mm). In order not to confuse terminology, primary roots (PR) were defined as roots that form adventitiously from buds of the cutting with branches. Fine roots (FR) were defined as roots that branch from the primary root. Depth roots (DR) are roots that develop vertically from the second and subsequent nodes below the soil line. Surface roots (SR, intercepting roots), refer to roots that form horizontally developing primary roots from the first node below the soil.

***Measurements***

Regardless of root classification, all root numbers were determined by cutting and counting the roots of 5 grapevines at each replicate of each application. To determine root lengths, 20 root pieces from 5 grapevines were measured at each replicate of each application and the mean was recorded. For root diameter, the average of 20 root pieces from 5 grapevines was measured at each replicate of each application using a digital caliper (Mitutoyo, Japan). The cut and counted roots from 5 grapevines in each replicate of each application were weighed on a precision scales (Vibra, Japan) and the total fresh root weight per grapevine was recorded. To determine the total dry weight of the roots, the roots were dried in an oven (Elektro-mag, Turkey) at 65°C for 72 hours, and the dry weights were stabilized. The diameter of the grapevine trunk was measured 3 cm above the ground with a digital caliper.

***Statistical analysis***

The significance of differences between treatments was determined using one-way analysis of variance (ANOVA), and significant differences were grouped using the LSD test at a 5% significance level.

**RESULTS and DISCUSSION**

***Root umber***

The effect of irrigation treatments on the number of roots was statistically significant ($p < 0.05$) for both the main effects of irrigation treatment (IT) and the main effects of cultivar for the number of fine depth root (FDR). While the irrigation treatment with 4 L per day achieved the highest FDR number with 58.25 pieces in the IT main effect, the lowest FDR number with 24.50 was obtained in the treatment with 0 L per day without irrigation. 'Cabernet Sauvignon' cultivar reached the highest average FDR number and 'Papazkarası' and 'Adakarası' were determined as the following cultivars. The lowest FDR number was found in the cv. 'Yapıncak'. The interaction between cultivar and IT was found to be not significant in terms of FDR number (Figure 1α). Both IT and the main effect of cultivar were found to be statistically significant for the number of coarse depth root (CDR). Among cultivars, the highest number of CDRs was found in 'Adakarası' cultivar and the lowest number in 'Vasilaki' cultivar. Among the irrigation treatments, the highest CDR number was obtained in applications of 8 L per day, while the lowest CDR number was obtained in applications without irrigation (Figure 1β).

Irrigation treatments were not statistically significant in both Fine surface root (FSR) and Coarse surface root (CSR) treatments. The highest number of FSRs was obtained in 'Cabernet Sauvignon' and 'Papazkarası' cultivars. The 'Adakarası' cultivar followed these cultivars. Although there is no statistically significant differences for ITs, the 4 L day application achieved the highest number of FSRs. The 2 L day irrigation application remained numerically at the lowest average FSR number (Figure 2α). The CSR numbers are also statistically insignificant with respect to the IT applications. The 'Adakarası' cultivar achieved the highest CSR number. 'Cabernet Sauvignon' and 'Papazkarası' are the following cultivars. The lowest CSR number was obtained for the cultivar 'Vasilaki'. 'Vasilaki' and 'Yapıncak' cultivars were statistically calculated in the same group (Figure 2β).

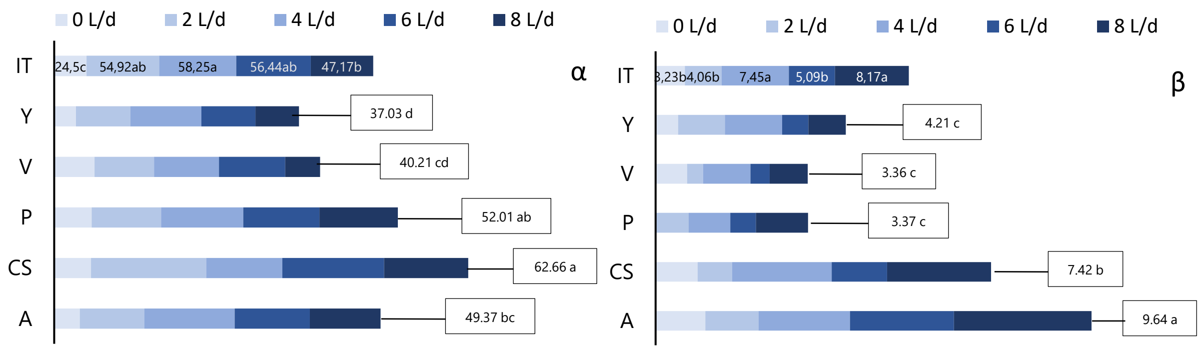


Figure 1. The effect of cultivars and irrigation treatments on the fine and coarse depth root number.

Values expressed with different letters are statistically significant at the p≤0.05 level according to LSD test. The data were shared with their means of repetitions. Treatment and cultivar interactions are presented in the figures with cumulative lines. IT; Irrigation treatment main effect; Y; 'Yapıncak', V; 'Vasilaki', P; 'Papazkarası', CS; 'Cabernet Sauvignon', A; 'Adakarası'. α: Fine depth root (FDR) number; β: Coarse depth root (CDR).
FDR Cultivar $LSD_{0.05}$: 10.87; FDR IT $LSD_{0.05}$: 10.87
CDR Cultivar $LSD_{0.05}$: 1.94; CDR IT $LSD_{0.05}$: 1.94

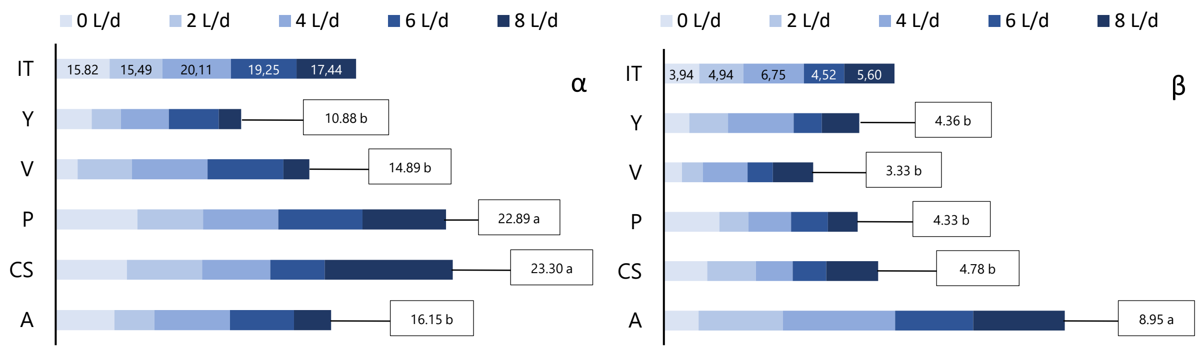


Figure 2. The effect of cultivars and irrigation treatments on the fine and coarse surface root number.

Values expressed with different letters are statistically significant at the p≤0.05 level according to LSD test. The data were shared with their means of repetitions. Treatment and cultivar interactions are presented in the figures with cumulative lines. IT; Irrigation treatment main effect; Y; 'Yapıncak', V; 'Vasilaki', P; 'Papazkarası', CS; 'Cabernet Sauvignon', A; 'Adakarası'. α: Fine surface root (FSR, n) number; β: Coarse surface root (CSR, n).
FSR Cultivar $LSD_{0.05}$: 6.08
CSR Cultivar $LSD_{0.05}$: 2.01

The number of roots of a grapevine cultivar may be one of the determinants of the total amount of roots. In this case, of course, the proportional distribution of surface roots or depth roots and fine and coarse root numbers is also important. Although no root parameter is the sole determinant (Fort et al., 2017), the highest FDR count of 'Cabernet Sauvignon' could be related to the drought resistance of the cultivar. Fine roots have received much attention because of their function in water and nutrient uptake (Bassirirad, 2000; Ma et al., 2014). Similarly, the number of CDRs is highest in 'Adakarası' grape cultivar, followed by 'Cabernet Sauvignon'. This may indicate that both cultivars behave similarly in terms of resistance to drought conditions. When generalization is made in terms of number of roots, it is found that 'Cabernet Sauvignon', 'Adakarası', and 'Papazkarası' cultivars respond similarly to each other. However, when the number of CSRs is examined, it is found that the difference between high and low values decreases. In this case, it can be assumed that water is easier to find in the region near the surface of the growing medium and surface roots can multiply more easily.

***Root length***

Under field conditions, longer roots are expected to be found in drier growing environments if canopy size is considered to be the same (Schenk and Jackson, 2002a, 2002b). However, according to the available data, root length was found to increase with increasing water volume, although this was not statistically significant. It is suspected that this is due to the fact that the grapevines was grown in a potted environment and the volume was limited. The effect of irrigation treatments on root length was found to be statistically non-significant for the main effect of irrigation treatment for both FDR and CDR (Figure 3α).

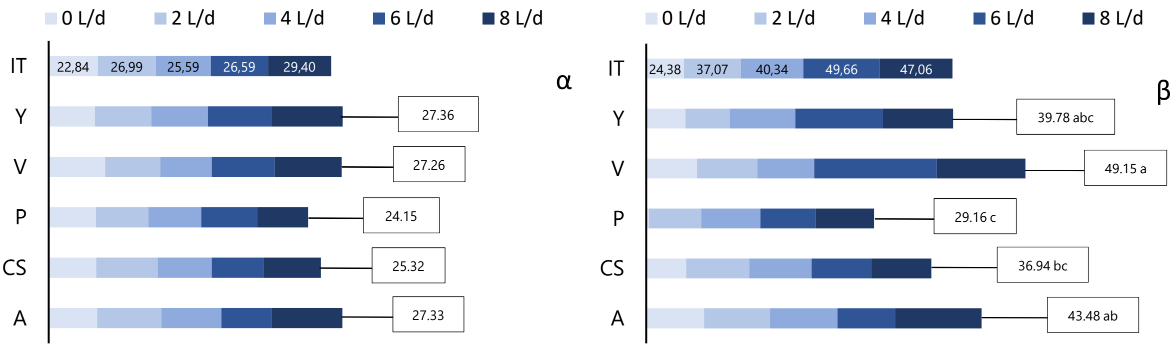


Figure 3. The effect of cultivars and irrigation treatments on the fine and coarse depth root lenght.

Values expressed with different letters are statistically significant at the p≤0.05 level according to LSD test. The data were shared with their means of repetitions. Treatment and cultivar interactions are presented in the figures with cumulative lines. IT; Irrigation treatment main effect; Y; 'Yapıncak', V; 'Vasilaki', P; 'Papazkarası', CS; 'Cabernet Sauvignon', A; 'Adakarası'. α: Fine depth root (FDR, cm) length; β: Coarse depth root (CDR, cm) length. CDR Cultivar $LSD_{0.05}$: 11.49

However, when the criterion of root length at coarse depth, it is considered that 'Vasilaki' and 'Adakarası' cultivars produce longer CDRs and the results are statistically significant. When root length is considered as an expression of the total root volume, it has been reported that an increase in the growth of the root system also means an increase in the canopy (Steudle, 2000; Schenk and Jackson, 2002b; Comas et al., 2005). It was found that the main effects of cultivar were statistically significant for coarse depth root (CDR) length. With respect to cultivars, the longest CDRs were found in the 'Vasilaki' cultivar and the 'Adakarası' cultivar. This result was evaluated in agreement with the results of previous studies for the 'Adakarası' cultivar. Longer roots increase the canopy growth. However, it does not seem possible to correlate root length with canopy development in the same way for the 'Vasilaki' cultivar. This was because 'Vasilaki' is considered a weak cultivar in terms of vegetative development under both arid and non-arid conditions (Candar, 2022). On the other hand, weak and slow development of the shoot system development is a distinctive feature of abiotic stress resistance (Chapin, 1991).

The main effects and interaction between irrigation treatment (IT) and cultivar main effects made no statistical difference in surface root lengths. Although there was no statistical difference, it was found that the 0 L day had the shortest fine surface root length of 28.91 cm in relation to the IT main effect. The 6 L day IT had the longest fine surface root length of 33.18 cm. There was no linear relationship between the increase in water content and fine surface root length. As for the main effect of cultivar, the longest fine surface roots were found in 'Adakarası' cultivar with 32.40 cm and the shortest fine surface roots were found in 'Vasilaki' cultivar with 29.19 cm (Figure 4α). The lengths of coarse surface roots increased linearly, although with small differences, with increasing water volume, although not statistically significant. The longest cooarse surface roots were measured in the 'Adakarası' cultivar and the shortest coarse surface roots in the 'Papazkarası' cultivar (Figure 4β). As in Fort et al. (2017), no simple positive correlation between total root length and drought tolerance was found in this study. Plasticity of the root system may allow more water to be utilised from soil depth, and vertical root growth is also typically a strong genotypic character (Doussan et al., 2003). However, a general review of the literature reports that while it is difficult to make simple, strong, and always consistent generalizations for the genus *Vitis*, root distribution, which is a variable dependent on root length, should be evaluated in drought tolerance studies as a function of external factors (Smart et al., 2006).

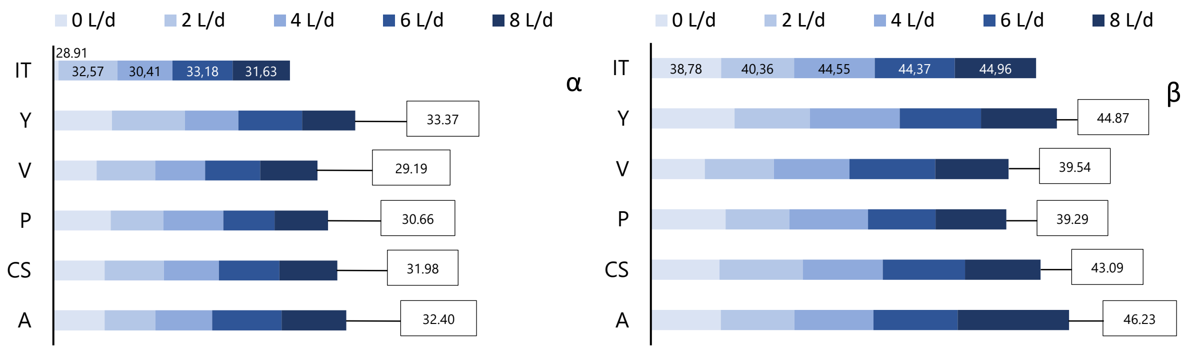


Figure 4. The effect of cultivars and irrigation treatments on the fine and coarse surface root lenght.
Values expressed with different letters are statistically significant at the p≤0.05 level according to LSD test. The data were shared with their means of repetitions. Treatment and cultivar interactions are presented in the figures with cumulative lines. IT; Irrigation treatment main effect; Y; 'Yapıncak', V; 'Vasilaki', P; 'Papazkarası', CS; 'Cabernet Sauvignon', A; 'Adakarası'. α: Fine surface root (FSR, cm) length; β: Coarse surface root (CSR, cm) length.

***Root diameter***

Under field conditions, longer roots are expected to be found in drier growing environments if canopy size is The increase in root diameter in grapevine is considered to reflect the accumulation of storage carbohydrates, a product of photosynthesis. And it is important for the next year's newly formed roots and shoots. Low values of root diameter can also mean that the following growing season may be affected by climatic and abiotic stress factors. On the other hand, this situation is also influenced by genetic factors.

The effects of irrigation treatments on root diameter were statistically significant ($p < 0.05$) for both cultivar main effects for FDR and CDR diameter. While the cultivar 'Adakarası' reached the highest FDR number of 1.77 cm in the cultivar main effect, the lowest FDR number of 1.38 cm was obtained for the cultivar 'Papazkarası'. IT main effect was not statistically significant for fine depth root diameter (Figure 5α). In the 'Adakarası' x 8 L day interaction, coarse depth root diameter of roots at 4.84 cm as the highest diameter with 4.84 cm. 'Adakarası' x 2 L day interaction and 'Cabernet Sauvignon' x 2 L day interactions were the followers. The lowest coarse depth root diameter was measured in the 'Papazkarası' x 0 L day interaction at 3.10 cm (Figure 5 β).

Both IT and cultivar main effects also were found to be statistically significant for coarse depth root (CDR) diameter. With respect to cultivars, the highest CDR diameter was again found in the 'Adakarası' cultivar, 'Cabernet Sauvignon' was the follower, and the lowest diameter in the 'Papazkarası' cultivar. In the irrigation treatments, the highest CDR diameter was obtained in the 2 L day treatment, while the lowest CDR diameter was obtained in the application without irrigation (Figure 5β).

Although applications other than the 0 L day treatment are in the same statistical group, it is interesting to note that the 2 L day treatment achieves the highest coarse depth root diameter (Figure 5β).

All interactions of 2 L day x 'Cabernet Sauvignon', 'Adakarası' and 'Vasilaki' cultivars had relatively high root diameters. This situation might have been caused by the relatively lower daily water amount and higher water use efficiency (WUE) of the cultivars, which increased the accumulation of photosynthesis products in the root tissue. The allocation of carbon to the root system to form 'expensive' roots with a well-developed exodermis and endodermis, as described by North and Nobel (1991), has also been shown to limit root desiccation in dry soils. WUE, which increases as the amount of water decreases, is thought to be an adaptation mechanism to climatic and abiotic stressors.

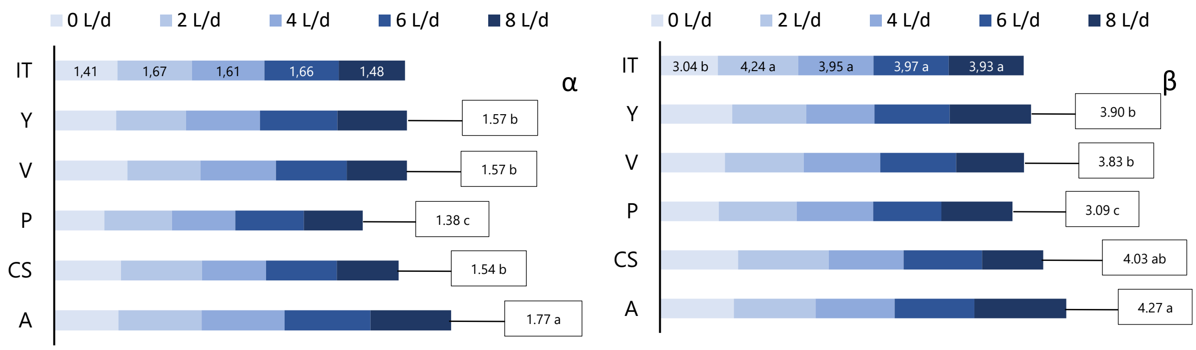


Figure 5. The effect of cultivars and irrigation treatments on the fine and coarse depth root diameter.

Values expressed with different letters are statistically significant at the p≤0.05 level according to LSD test. The data were shared with their means of repetitions. Treatment and cultivar interactions are presented in the figures with cumulative lines. IT; Irrigation treatment main effect; Y; 'Yapıncak', V; 'Vasilaki', P; 'Papazkarası', CS; 'Cabernet Sauvignon', A; 'Adakarası'. α: Fine depth root (FDR, cm) diameter; β: Coarse depth root (CDR, cm) diameter.
FDR Cultivar $LSD_{0.05:}$ 0.15
CDR Cultivar $LSD_{0.05:}$ 0.36; CDR IT $LSD_{0.05:}$ 0.61; CDR Cultivar x IT $LSD_{0.05:}$0.82

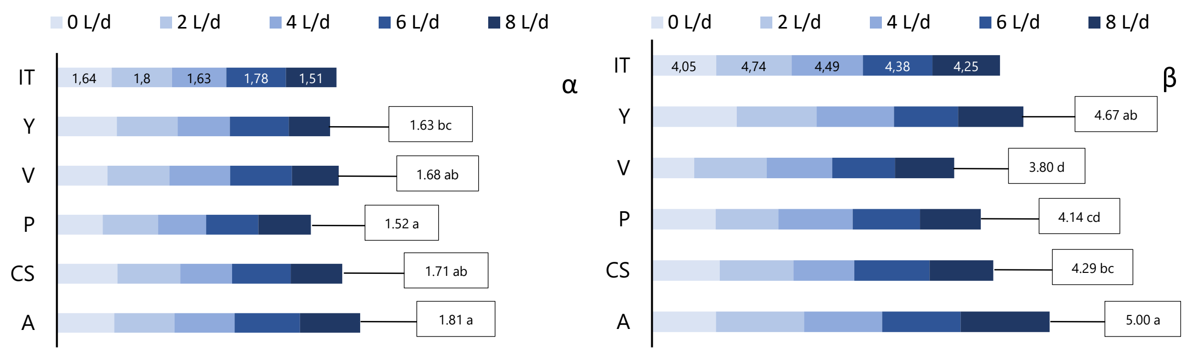


Figure 6. The effect of cultivars and irrigation treatments on the fine and coarse surface root diameter.

Values expressed with different letters are statistically significant at the p≤0.05 level according to LSD test. The data were shared with their means of repetitions. Treatment and cultivar interactions are presented in the figures with cumulative lines. IT; Irrigation treatment main effect; Y; 'Yapıncak', V; 'Vasilaki', P; 'Papazkarası', CS; 'Cabernet Sauvignon', A; 'Adakarası'. α: Fine surface root (FSR, mm) diameter; β: Coarse surface root (CSR, mm) diameter.
FSR Cultivar $LSD_{0.05:}$ 0.14
CSR Cultivar $LSD_{0.05:}$ 0.49; CSR Cultivar x IT $LSD_{0.05:}$1.09

Both main effects of cultivar were found to be statistically significant for surface root diameter of fine and coarse roots (Figure 6β). Fine surface root diameters were found to be the thickest at 1.81 cm for the 'Adakarası' cultivar and thinnest at 1.51 cm for the 'Papazkarası' cultivar (Figure 6α). Coarse surface root diameters were also thickest in 'Adakarası' cultivar at 5.00 cm and thinnest in 'Vasilaki' at 3.80 cm (Figure 6β). The interaction between the main effects of Cultivar x IT was statistically significant ($p < 0.05$) for coarse surface root diameter. The 8 L day x 'Adakarası' interaction was thickest at 5.60 cm diameter, and the 2 L day x 'Adakarası' interaction was follower. The interaction 0 L day x 'Vasilaki' had the thinnest coarse surface root diameter at 2.65 cm. The fact that the 2 liters per day treatment showed numerically high values in both surface and depth root diameters, as reported in Baeza et al. (2019), may be due to the negative effect of the severe water restriction and constant saturation conditions of the grapevines on root growth.

***Root weight***

In addition to increasing soil hardness and acidity, poor water infiltration also reduces the number of roots and thus total root weight (Van Zyl, 1988; Morlat and Jacquet, 1993). As expected, the highest values for total fresh and dry root weight were obtained with irrigation of 8 litres per day, while the lowest values were obtained with irrigation of 0 litres per day. The root weights of the IT main effects were found to vary in the 4 L day and 6 L day treatments. In terms of cultivar main effect, 'Adakarası' cultivar achieved the highest values for total fresh root weight and root dry weight. The lowest value for total fresh root weight was measured in 'Vasilaki' cultivar, and the lowest value for total dry root weight was measured in 'Yapıncak' cultivar (Figure 7α and β).

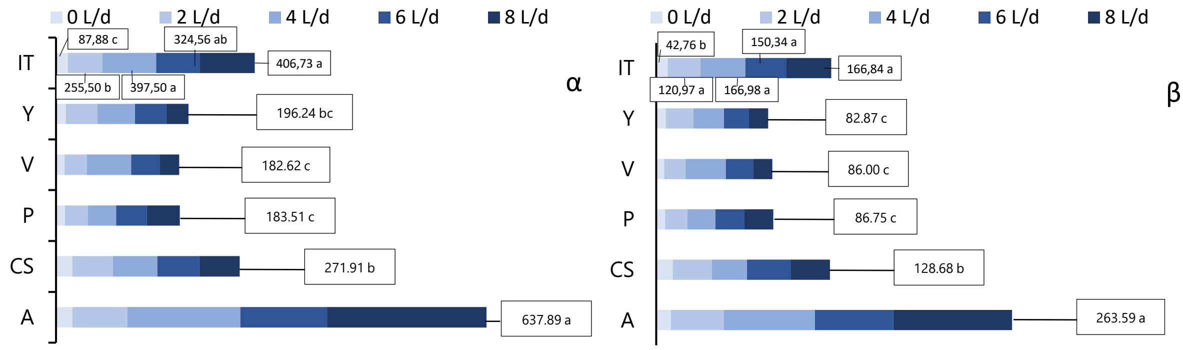


Figure 7. The effect of cultivars and irrigation treatments on the total fresh and dry root weight.
Values expressed with different letters are statistically significant at the p≤0.05 level according to LSD test. The data were shared with their means of repetitions. Treatment and cultivar interactions are presented in the figures with cumulative lines. IT; Irrigation treatment main effect; Y; 'Yapıncak', V; 'Vasilaki', P; 'Papazkarası', CS; 'Cabernet Sauvignon', A; 'Adakarası'. α: Total fresh root weight (TFRW, g); β: Total dry root weight (TDRW, g).
TFRW Cultivar LSD$_{0.05:}$ 84.57; TFRW IT LSD$_{0.05:}$ 121.00
TDRW Cultivar LSD$_{0.05:}$ 34.13; TDRW IT LSD$_{0.05:}$ 49.91; TDRW Cultivar x IT LSD$_{0.05:}$76.35

The interaction of the main effects of Cultivar x IT proved statistically significant ($p < 0.05$) for total root dry weight. The interaction of all irrigation levels except the 0 L day treatment with the 'Adakarası' cultivar resulted in the highest total dry root weights, in the order of 8 L day, 4L day, 6 L day, and 2L day. In the 0 L day treatments, on the other hand, the interaction is listed as 'Cabernet Sauvignon', 'Adakarası', 'Yapıncak', 'Papazkarası' and 'Vasilaki', depending on the variety, from heavy to light. In this application, where the water is completely cut off, the fact that 'Cabernet Sauvignon' and 'Adakarası' cultivars reach relatively high total dry root weights gives an indication of the drought tolerance of the cultivars.

***Trunk diameter***

Trunk diameter of grapevine is also one of the indicators of vigor and accumulation and translocation of photosynthetic carbohydrate reserves. Diameter growth correlates with water potential of grapevine and can be related to vigor (Ton and Kopyt, 2004). Regarding the IT main effect, the lowest trunk diameter was measured in 0 L day treatments with a main effect of 13.70 cm.

Although other ITs were statistically in the same group, the highest diameter was found to be the main effect at 4 L day. Although other ITs are statistically in the same group, the highest diameter at 4 L day was found to be the main effect. This situation can be considered consistent with the statement of Baeza et al. (2019) that severe water deficit and irrigation negatively affect root growth. This is because the nutrient medium maintained at the saturation point negatively affects WUE and assimilation of carbohydrates and reduces the cumulative effect of trunk growth.

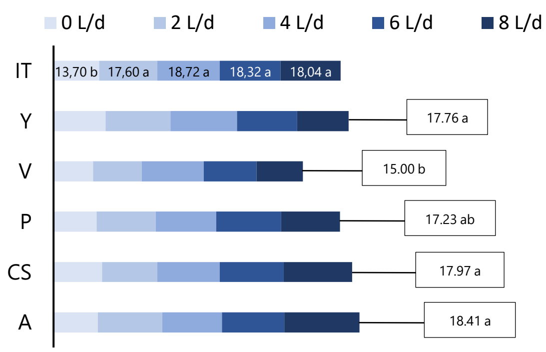


Figure 8. The effect of cultivars and irrigation treatments on the trunk diameter.
Values expressed with different letters are statistically significant at the p≤0.05 level according to LSD test. The data were shared with their means of repetitions. Treatment and cultivar interactions are presented in the figures with cumulative lines. IT; Irrigation treatment main effect; Y; 'Yapıncak', V; 'Vasilaki', P; 'Papazkarası', CS; 'Cabernet Sauvignon', A; 'Adakarası'. Trunk diameter (TD, cm).
TD Cultivar LSD$_{0.05:}$ 2.24; TD IT LSD$_{0.05:}$ 2.76

As with some of the other criteria examined in this study, the lowest trunk diameter was measured for the main effect of the 'Vasilaki' cultivar. The highest trunk diameter was recorded for the cultivar 'Adakarası'. As for some other criteria, the 'Adakarası' cultivar obtained the highest value in trunk diameter. Considering the function of fine roots are more important than other types of roots for the rapid absorption of nutrients and water and for better grapevine growth and development, (Hendrick and Pregitzer, 1993; Somkuwar et al., 2012) the higher values of 'Adakarası' cultivars in higher fine roots in many criteria, makes this result significant.

And also, higher trunk diameter of 'Adakarası' could be due to highly significant anatomical differences, especially in one-year roots, according to genotype (Ollat et al., 2016). On the other hand, drought-resistant genotypes may respond to abiotic stress conditions by increasing root hydraulic conductance and leaf-specific hydraulic conductance under dry conditions, unlike the sensitive genotype Alsina et al. (2011).

In conclusions, the root system of grapevine performs important functions for growth and development. The results presented here aim to identify some morphological characteristics related to drought response in the roots of autochthonous wine grape cultivars.

In this study, anatomical parameters and varying daily water volumes applied to growing media were investigated together to better understand the drought resistance of four local grape cultivars and 'Cabernet Sauvignon'.

Based on the available data, no single root morphological criterion proved to be a superior means of distinguishing genotypes. However, it can be concluded that the 'Adakarası' cultivar has higher values in almost all criteria studied and responds similarly to 'Cabernet Sauvignon' in terms of daily water amounts. On the other hand, the 'Papazkarası' cultivar stands out for its high number of fine roots. However, it is not possible to state that this fact provides drought resistance under low soil water conditions. 'Yapıncak' and 'Vasilaki', on the other hand, can be evaluated as cultivars with relatively weak vigour and limited water tolerance due to low root parameters.


## ÖZET

***Amaç***: Bu çalışmada, Trakya bölgesinde yetiştirilen şaraplık üzüm çeşitlerinin köklerinin morfolojik özellikleri üzerine su kısıtı uygulamalarının etkilerinin belirlenmesi amaçlanmıştır.

***Yöntem ve Bulgular***: Deneme, bilgisayar kontrollü sulama ve bitki besleme sistemi kullanılarak 14 L saksılarda ve perlit yetiştirme ortamında gerçekleştirilmiştir. 'Adakarası', 'Papazkarası', 'Vasilaki', 'Yapıncak' ve 'Cabernet Sauvignon' çeşitlerine günlük 4 farklı toplam su miktarı ve sulama yapılmaması dahil olmak üzere farklı su kısıtlamaları uygulanmıştır. 2 yetiştirme sezonu sonunda bitkiler sökülerek, emici ve kalın köklerin sayısı, uzunluğu, çapı, ağırlığı ve gövde çapı parametreleri belirlenmiştir.

***Genel Yorum***: Çalışılan parametrelerin hiçbiri çeşitlerin kuraklık toleransını tam olarak tanımlamada tek başına yeterli olmasa da çeşitlerin su stresine karşı genotipik tepkisini tanımlamada önemli oldukları belirlemiştir. 'Adakarası' çeşidi, azalan su içeriğine 'Cabernet Sauvignon''a benzer şekilde tepki vermiştir. 'Papazkarası' çeşidinde kök sayısının fazla olması susuz koşullara uyum açısından bir avantaj olarak değerlendirilebilir. Diğer yandan, 'Yapıncak' ve 'Vasilaki' çeşitleri düşük suya vejetatif büyümeyi azaltarak tepki vermektedir.

***Çalışmanın Önemi ve Etkisi***: Bu çalışmada, Trakya bölgesinde geleneksel olarak yetiştirilen şaraplık üzüm çeşitlerinin kök morfolojik özellikleri ilk kez araştırılmıştır. Bu özelliklerin bilinmesi, mevcut iklim değişikliği koşullarında bağcılığın sürdürülebilirliği için yerel çeşitlerin adapte edilebilirliği ve genetik çeşitlilikten yararlanılması açısından önemlidir.


***Anahtar Kelimeler***: *Vitis*, iklim değişikliği, yerel üzüm çeşitleri, adaptasyon, abiotik stres.

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## CONFLICTS OF INTEREST

The authors declare no conflict of interest.

## AUTHOR CONTRIBUTION

Authors SC and EB were planned and designed the trial. SC, EKD, ME and TA performed the field experiments and measurements. İK and EB made critical revisions of the manuscript for intellectual content. All authors read and approved the final manuscript.

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