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RESPONSES OF GRAPEVINES TO PLANTING DENSITY AND TRAINING SYSTEMS IN SEMIARID ENVIRONMENTS

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Aim. To investigate the physiological and agrobiological responses of grapevines on different systems of training systems in row plantations depending on the planting density and the possibility of adjusting plants for non-irrigated crop cultivation under cold semiarid climate. **Methods**. The field two-way experiment of 2 × 4 was applied to study the effect of two planting density variants (3 × 1.5 m; 3 × 1 m) and four vine training systems (when the horizontal cordon is located at the height of 0.4 m, 0.8 m, 1.2 m, 1.6 m) on the parameters of the leaf area, leaf index, water loss through transpiration, activity of the photosynthetic apparatus of leaves and the yield of Zahrei wine grape cultivar *(Vitis vinifera* L.*)*. The experiment data were processed using the analysis of variance. **Results.** The increase in the density of vine row plantations per area units from 3 × 1.5 m to 3 × 1 m enlarges the total leaf area, the exposed leaf area, water loss through transpiration, and yield weight, but these indices decrease in the evaluations per plant. The responses of grapevine to the training systems are similar and independent from the experimental variants of planting density. At the height of the cordon of 0.4 and 0.8 m, the vertical shoot positioning enhances the potential of the photosynthetic capacity of the plantations, but this potential is realized only during the years with lower water deficit for plants. Free-growing shootings on the cordons, located at the height of 1.2 m, form the canopy architecture with relatively low water loss through transpiration which has a positive effect on the activity of the photosynthetic apparatus and yield, especially in dry years. The downward shoot positioning on the cordons of 1.6 m decreases the leaf area of the vines and creates the canopy architecture with increased transpiration which enhances the effect of the water deficit and has a negative effect on the productivity of plants. **Conclusions.** The agronomic methods of planting and training systems for grapevines ensure the management of the character of spatial shoot location, the formation of certain canopy architecture, and setting the parameters of the leaf area; their optimization mitigates the negative effect of water deficit and provides for adapting the plants for non-irrigated crops under semiarid climate. The positive effect of compacting plantations on crop yield was determined without irrigation in semiarid environments. The variant of planting density of 3 × 1 m decreases the yield on the vines on average by 12.1–31.0 %, as compared to the variant of 3 × 1.5 m. Yet, more dense plantations are remarkable for their yield, which is 18.5–61.3 % higher depending on the training system for vines. Under dry conditions, the most efficient system is the training system with the formation of the horizontal cordon at the height of 1.2 m and free-growing shoots. The system optimizes the leaf area density, and forms the canopy architecture with rather low water loss through transpiration which has a positive effect on the activity of the photosynthetic apparatus of leaves during droughts. Under free growth, the yield of the plantations increases by 4.3–12.3 % on average as compared to the vertical shoot positioning and by 21.3 % – under their downward positioning.

Key words: grapes, planting density, training system, leaf area, transpiration, photosynthetic apparatus, productivity, yield.

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INTRODUCTION

Grapevine (*Vitis vinifera* L.), as an industrial crop, are common for the hot and cold semiarid climates. The dry conditions of these territories pose risks for stable viticulture production (Jones G, 2015). This problem is aggravated by a rapid change in climate conditions – a global increase in the temperature and its negative effect on the grapes yield and the quality of the winemaking products, especially those for terroir production (Schultz, 2000; Keller, 2010; Webb et al, 2013; Davis et al, 2019; Bois et al, 2018; Molitor et al, 2019; Leeuwen et al, 2019).

While in the area with a sufficient regime of natural irrigation, the climate risks are mainly related to the deterioration of product quality (Gambetta et al, 2021; Bucur et al, 2017; Deloire et al, 2004), the semiarid environment pose economic risks for the grapevine culture. Firstly, it is related to unstable and sometimes even the very low yield of plantations due to droughts (Zarrouk et al, 2015).

The irrigation of a vineyard solves the problem of low yield in semiarid environments, but freshwater resources and irrigation systems of many viticulture regions are very limited. The priority of their utilization is given to the crops, whose cultivation is impossible without irrigation (Edwards et al, 2013; Phogat et al, 2020).

The increase in the efficiency of using natural water resources in vineyards is of decisive significance for the stable development of viticulture in semiarid regions (Medrano et al, 2015). This purpose may be achieved in the existing vineyards using such agrotechnologies as soil tillage with low physical moisture evaporation with mulching or using the black fallow system (Cataldo et al, 2020; Porto et al, 2018; Șerdinescu et al, 2014); canopy manipulation (Hunter et al, 2004; Wang et al, 2019; Bucur, 2021), leaf shadowing (Oliveira et al, 2014; Lu et al, 2021), which decrease water loss through transpiration.

While starting a vineyard, it would be reasonable to select drought-resistant cultivars and their rootstock (Serra et al, 2014; Ollat et al, 2015; Cameron et al, 2020; Mezei et al, 2021; 2020; Marín et al, 2021), to locate trellis rows in the east-west direction (Campos et al, 2017; Lu et al, 2021), decrease the planting density (Leeuwen et al, 2019; Keller et al, 2021); and use the adaptive training systems (Leeuwen et al, 2019).

The possibility of optimizing the elements of vineyard structural organization in the semiarid climatic zone is an urgent problem that has not been studied sufficiently. The grapevine training system determines the nature of green shoot location in space, the distance from the vines to the soil surface, and changes the lights regime for the plantations. The parameters of vine training affect the water regime (Scholasch et al, 2019; Zufferey et al, 2020), and the processes of photosynthesis and respiration of plants (Colova et al, 2007; Vlasov et al, 2016); define the yield rates of grapes (Dry, 2000; Sommer K et al, 2000; Clingeleffer, 2006; Carbonneau et al, 2004) and wine quality (Minnaar et al, 2020); manual labor requirements, material resources, and the cost of products (Deloire et al, 2004; Strub et al, 2021), which conditions the fundamental nature of the studies.

Grapevine plantations should ensure rather a high potential for plant productivity and relatively low water loss through transpiration. These requirements for the vineyard are related to the fact that high insolation and the deficit of water available for plants are notable for semiarid territories. During the vegetation period, there are frequent disruptions in the water regime for plants and, as a result, a yield reduction and deterioration of grape quality (Simonneau et al, 2017). It becomes practically relevant to coordinate the needs of plants in water with the energy factors which define the water regime (Amirdzhanov, 1980).

The aim of this study was to investigate the physiological and agrobiological responses of grapevines on different systems of training systems in row-type plantations depending on the planting density and the possibility of adapting plants for non-irrigated crops in cold semiarid environments.

It is envisaged that the responses of grapevine to different variants of training systems and planting density would allow managing the character of spatial shoot location, forming specific canopy architecture, and setting the parameters of the leaf area. Some parameters of the mentioned indices may be involved in mitigating the negative effect of water deficit on plants due to the reduced water loss through transpiration and serve as a mechanism of increasing the activity of the photosynthetic apparatus of leaves and the yield of plantations.

MATERIALS AND METHODS

The place of conducting studies. Different variants of planting density and vine training systems were tested on the experimental plot of the National Scientific Center “V.Ye. Tairov Institute of Viticulture and Winemaking” (46.35° N; 30.65° W; Alt. 36 m). The terrain of the plot is plain, with a slope of up to 2 degrees towards the west. The vineyard was started in 2013 with young grafted plants of Zahrei cultivar using rootstock *PxP* 101-14. The vines are trained on the unilateral trellis of 1.8 m with poles near vine trunks. The rows are oriented north-south. It is a non-irrigated crop. Black fallow is used for soil maintenance.

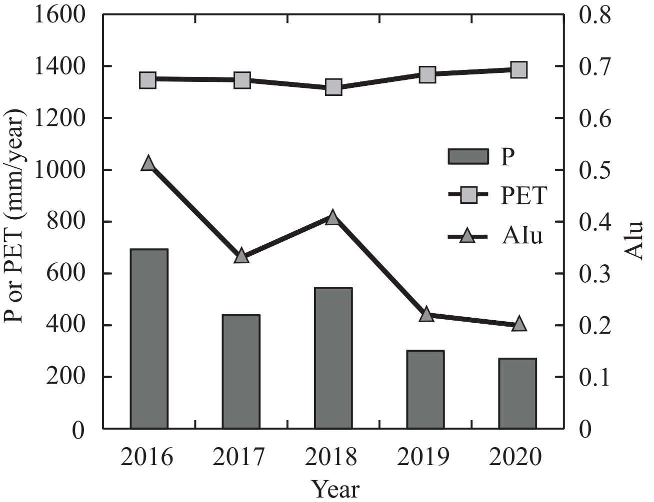

Fig. 1. The variation in the indices of the annual precipitation amount (P), potential evapotranspiration (PET), and aridity index (AI_u) in 2016–2020 according to the data of the meteorological station at the National Scientific Center "V. Ye. Tairov Institute of Viticulture and Winemaking"

Agrobiological specificities of the cultivar. Zahrei is a grapevine cultivar *(Vitis vinifera* L.*)* of hybrid breeding at the National Scientific Center "V.Ye. Tairov Institute of Viticulture and Winemaking". It was added to the State Register of Plant Varieties of Ukraine in 2006. The cultivar is notable for ecologic plasticity. The ripening is medium to late. The vine vigor is average, the shoot ripening is good, and winter hardness and frost hardness are increased. The variety is resistant to fungal diseases and droughts. The fruits are average, round, and white; the texture is rich; the taste is plain; the yield is used to produce grape wine and juices (Vlasov V et al, 2014).

Soil cover. The experimental plot was started on southern heavy-loamy chernozem on loess. The capacity of the humus horizon is 45 cm; humus content in the arable horizon is 2.3 %. The reaction of water suspension in the horizon from 0 to 120 cm is weakly alkaline (pH 7.5–8.6). The total exchangeable bases are 17.0–21.5 mmol/100 g of soil; Ca prevails in the composition of bases (80–90 %); soil alkalinity is very low. The content of carbonates changes from 1.3 to 17.6 %, and the content of active lime – 1.2–13.6 %; the risk of chlorosis is low in upper soil layers, average – in the horizon of the accumulation of carbonates. The content of nitrogen in the arable horizon is very low (56 mg/kg by Kornfeld), the content of phosphorus is average (22.4 mg/kg by Machyhin), the content of potassium is increased (219.4 mg/kg by Machyhin). The granulometric composition of the soil is heavy loamy; the sum of fractions of <0.01 mm varies in the horizons from 41 to 48 %.

Agroclimatic conditions. During the studies in 2016–2020, the average temperature of the coldest month, January, fluctuated from 1.8 °C (2020) to –4.2 °C (2018). In January–February, the air temperature dropped shortly down to –7.9…–19.0 °C. The temperature minimum was registered on January 25, 2016. Under such conditions, the overwintering of plantations is good, with the damage to wintering buds irrelevant for yield loss of up to 15 %.

The duration of the warm period with temperatures of >10 °C varied from 179 to 206 days. The dates of last spring frosts were observed in the air on March 18–April 07, which coincided with the phenological phase of sap flow. No damage to vines from spring frosts was observed during the studies.

The veraison of Zahrei comes on September 12–18. The early term of harvesting was observed during the first fruit-bearing of the vines and during drier conditions in 2019–2020.

The dates of autumn frosts in the air came from October 28 to November 22 and coincided with the phenological phase in November; they didn't have any relevant effect on the maturation of the vine.

The average annual air temperature varied from 11.5 to 13.0 °C. The amount of precipitation during the year fluctuated from 271 mm to 693 mm (Fig. 1).

The excess in the level of evapotranspiration as compared to the precipitation amount decreases the aridity index (AI_u). For instance, during the period of studies, AI_u varied in the interval from 0.2 to 0.5 and characterized the territory as semiarid according to the classification accepted in the UN environmental program (Middleton, 1997). According to Köppen-Geiger classification, the region of studies belongs to the cold semiarid climate (Beck, 2018).

Field experiment. The two-way experiment of 2 × 4, set in five consecutive repeats, studied the effect of two main planting density variants (3 × 1.5 m; 3 × 1 m) and four different vine training systems on the indices of leaf area, water loss through transpiration, the activity of photosynthetic apparatus of leaves, yield and grape quality.

The training systems differ in the height of the horizontal cordon location (0.4, 0.8, 1.2, and 1.6 m) and the character of spatial shoot positioning. For instance, on the cordons of 0.4 m and 0.8 m there was vertical shoot positioning, at 1.2 m – free-growing shoots, at 1.6 m – downward shoot positioning.

The experimental plot was started on the area of 4,752 sq.m. under the plantations; it consists of 16 trellis rows of 100 m. The experimental variants are divided into equal areas, 2 trellis rows each, with the area of 594 sq.m. The number of plants under registration is 132 plants in one experimental variant with the planting density of 3 × 1.5 m, 198 vines – 3 × 1 m.

Measurements of the leaf area. The quantitative description of the canopy of the row plantations involved the following phytometric characteristics: the number of shoots and leaves on plants on one line meter of the row, length, width, and height of the canopy.

The registration was done during the phenological phase of fruit maturation when the vine growth processes were completed. The number of shoots per plant was counted on five registration plants, typical for the training systems. When the obtained value is divided by the vine planting density in the rows (D, m), it shows the density of shoots per line meter of the row (N). The relative diameter of each leaf blade was determined on twenty shoots of the plants under registration, average in growth capacity.

The area of the average leaf was calculated under laboratory investigation (Ivanchenko VI et al, 2004):

$$W\,(\mathrm{cm}^2) = \frac{\pi \times d^2}{4}$$

where W – the area of the circle, relatively accepted as the leaf area (sq.cm.); d – the length (relative diameter) of the leaf, defined from the upper to the lower lamina of the leaf blade (cm); π – 3.14.

The area of the leaves on the shoot was calculated (F, sq.m.), and the leaf area of one line meter of the row was calculated by the equation:

$$N \times F\,(\frac{m^2}{m}).$$

Considering the number of rows: $\frac{100}{E}$, where E – the distance between the rows (m) and their total length on one hectare under plantations: $\frac{10\,000}{E}$, the leaf area (SF) is calculated by the equation (Carbonneau , 1983):

$$SF(\frac{m^2}{ha}) = \frac{10\,000 \times N \times F}{E}.$$

The potential of photosynthetic capacity of the plantations was evaluated by the index of the exposed leaf area (SFe) per one hectare and calculated by the equation (Schneider C, 1989):

$$SFe(\frac{m^2}{ha}) = \frac{10\,000}{E} \times (1-t) \times S.$$

The light regime of the canopy was evaluated by the level of the leaf index (IF). The index is determined as the ratio between the area of the external surface of the leaf canopy and the actual area of the leaves during the period of completing the grapevine growth processes and filling the space of the trellis with the annual growth (Schneider C, 1989):

$$IF(\frac{m^2}{m^2}) = \frac{(1-t) \times S}{N \times F}$$

where t – the lumens in the canopy per one meter of the row: t = T/D, where D – the vine planting density (m); S – the relative external area of the canopy (sq.m.). Under orthogonal intersections S = 2 × H + e, where H – canopy height (m); e – canopy width (m). The average height and width of the canopy were determined using 20 measurements (Amirdzhanov, 1980).

N – the number of shoots per one meter of the row;

F – the average area of the shoot leaves (sq.m.).

Determining water loss through transpiration. The method of energy balance was used for comparative characteristics of the transpiration of vines. Potential water losses through transpiration were calculated based on the equation for the total solar energy absorption by plants during the day and the quantitative heat loss through water evaporation (Amirdzhanov, 1980):

$$T(\frac{mm}{ha} \times day) = \frac{Q_A}{E} \times 10^{-4}$$

where T – the potential water loss through transpiration; Q_A – the total solar energy absorption by plants in the daytime at the area of 1 ha under row plantations (kilojoule); E – the energy of vaporescence (2.42 kilojoule/g H_2O at 20–25 °C); 10^{-4} – the coefficient for the conversion of the water amount into millimeters.

Q_A was determined during the phenological phase of wine growth (July), when the canopy on trellis rows closed to the complete pattern, using the equation:

$$Q_A = \Sigma(S_i \times Q \times k_Q)$$

where ΣS_i – the total area of the canopy projection on 1 ha under plantations (sq.m.):

$$\Sigma S_i = (\frac{10\,000}{E} \times e) + (2 \times \frac{10\,000}{E} \times H) + (2 \times \frac{100}{E} \times H \times e);$$

Q – the total amount of solar energy coming in the short-wave spectrum (0.3–3.0 mcm) to the horizontal surface $(\frac{kj}{m^2} \times day)$, according to the data of POWER Data Access Viewer v2.0.0; k_Q – the coefficient of solar energy absorption by the leaves, calculated by the average daily relative radiation flows in 46 ºN in the second decade of July for the horizontal surface – 0.80; vertical northern surface – 0.07; southern – 0.27; eastern and western surfaces – 0.30 (Amirdzhanov AG, 1980).

The activity of the photosynthetic apparatus of the leaves was evaluated by the method of chlorophyll fluorescence induction (FI) using the single-beam fluorometer Floratest (V.M. Glushkov Institute of Cybernetics of the NAS of Ukraine). The device can determine the effect of environmental stress factors on the photosynthesis process in real-time without damaging plants (Brajon OV et al, 2000).

The representative plants were selected for the analysis in each specific experimental variant. FI was measured on five leaves located in the area of nodes 6–8 of the shoot under direct solar light. The device sensor was located under the main ribs of the lamina. Prior to measuring FI, the leaves were subjected to dark adaptation for at least 20 minutes.

The obtained induction curves were used to determine the levels of chlorophyll fluorescence at F_0, F_{pl}, F_p, and F_t. The relative content of Q_B-non-reducing complexes of Photosystem II (PS2) was calculated by the ratio between the points: $\frac{F_{pl}-F_0}{F_p-F_0}$ (Brajon et al, 2000).

Yield registration. While harvesting, the number and weight of clusters with the distinctiveness of 1 g were counted and weighed on the plants under registration, located around the entire plot, except for peripheral and non-typical forms of vines. The number of plants under registration is at least 15.

The yield of the grapevine was calculated as follows:

$$Yield\ (\frac{kg}{vine}) = \frac{N_{clusters}}{vine} \times W_{clusters} \times 10^{-3},$$

where $\frac{N_{clusters}}{vine}$ – the average number of clusters per plant; $W_{cluster}$ – the average weight of a cluster (g); 10^{-3} – the coefficient for recalculating the yield weight into kilograms.

The average productivity of 1 ha of plantations was calculated as follows (t):

$$Yield\ (\frac{t}{ha}) = \frac{10\,000}{E \times D} \times Y_A \times 10^{-3},$$

where $\frac{10\,000}{E \times D}$ – the number of vines in the area of 1 ha under plantations; Y_A – the average yield of a vine during the study period (kg); 10^{-3} – the coefficient for recalculating the yield weight into tons.

Determining the grape quality. While harvesting, two average samples of clusters with a weight of 1–2 kg were selected from each experimental variant. The juice was obtained from the wine using the hand press. The must sugariness was determined by its density, using calibrated densimeters with a scale from 1,000 to 1,080 and 1,080–1,160. The total sugars in the must were determined in g/dm^3.

The must acidity was determined by titration of 0.1 N with the solution of NaOH. The mass concentration of the titrated acids was determined in g/l as calculated per tartaric acid (Ivanchenko et al, 2004).

The gluco-acidometric index was calculated by the ratio between the must sugariness (%) and titrated acidity (g/l).

Grapevine vigor. In the autumn-winter period after the phenological phase of leaf fall, ten average plants were selected on the experimental plot to measure the thickness of annual shoots in the area of shoot internodes 3–4 using the callipers. The data obtained were used to calculate the number of average shoots per plant $(N\frac{shoots}{vine})$ by the equation (Vlasov et al, 2018):

$$N(h) = \Sigma < 7 \times 0.3 + \Sigma 7.1-10 + \Sigma > 10 \times 2.3\Sigma,$$

where $\Sigma_{<7}$ – the total of low-vigor shoots of up to 7 mm; $\Sigma_{7.1-10}$ – the total of average shoots of 7.1–10 mm; $\Sigma_{>10}$ – the total of vigorous shoots of over 10 mm; Σ_{vines} – the number of plants under registration; 0.3; 2.3 – the coefficients for recalculation per average shoots.

Statistical analysis. The data were processed by the two-way analysis of variance (ANOVA). Duncan's multiple range test was used to determine statistically reliable differences between the experimental variants, $P \leq 0.05$. The mean data and standard deviation are presented (±SE).

RESULTS

Parameters of vineyard canopy. Table 1 presents the mean data of the indices of the vineyard canopy. The dispersion analysis of the data demonstrates the reliable effect ($p \leq 0.05$) of the planting density and training system on the total canopy (SF), the exposed leaf area (SFe), and leaf index (IF). The effect of the interaction between the experimental factors is observed for IF index and is absent for SF and SFe.

It was determined that the thickening of the plantations densities from 3 × 1.5 m to 3 × 1 m increases the SF index by 2.2–24.6 %. After the increase in the height of the vine cordon from 0.4 m to 1.6 m, there is a decrease in SF by 55.8 % at the planting density of 3 × 1.5 m and 53.2 % at – 3 × 1 m.

The SFe index varies within 6.9–9.9 sq.m.×10^{-3}/ha depending on the training system and planting density. The maximal levels of SFe are set in the plantations with the vertical shoot positioning at the cordon of 0.4 m. The enlargement of the cordon to 0.8 m decreases SFe by 8.8–11.1 %, up to 1.2 m – by 24.2–27.3 %, up to 1.6 m – by 22.0–22.2 %.

The cultivation of grapevine in row plantations creates a canopy well-exposed on the outside and shadowy inside. Shadowed leaves lose more organic substances for breathing than they produce during photosynthesis (parasitize on the plant).

The ratio between the area of exposed and shadowed leaves or the density of the canopy of row plantations is characterized by the IF index. The IF levels in the range from 0.75 to 1 is optimum; up to 0.75 the canopy is characterized as highly compacted, with a large share of shadowed leaves, and above 1 – as thinned, with insufficiently filled space on trellis rows (Irimia, 2006).

The data, presented in Table 1, demonstrate that at the cordon of 0.4 m or 0.8 m, vertical shoot positioning creates a relatively dense canopy on trellis rows, with the average IF for the period of studies at the level of 0.63–0.67 at the planting density of 3 × 1.5 m, 0.59–0.61 at 3 × 1 m.

The optimal density of the canopy with IF of 0.76–0.78 was determined for free-growing shoots at the cordon of 1.2 m regardless of the planting density.

The enlargement of the cordon up to the height of 1.6 m with downward shoot positioning at the planting density of 3 × 1.5 m creates the thinned canopy, with IF at the level of 1.11, and at 3 × 1 m there is a decrease in the index down to 0.95.

Water loss through transpiration. The canopy architecture on trellis rows determines the area of radiation for grapevines in the form of direct, scattered, and reflected short-wave radiation and the levels of its absorption. The calculated data demonstrate that during one day in the second decade of July, T in row plantations changes within 3.43–4.14 mm/ha depending on the planting density and the height of placing the horizontal cordon. The enlargement in the planting density from 3 × 1.5 m to 3 × 1 m increases T by 5.7–9.4 % depending on the training system (Fig. 2).

The minimal water loss through transpiration for Zahrei vines with a planting density of 3 × 1–1.5 m is determined for placing the horizontal cordon at 1.2 m and free-growing shoots. The reduction in the vine cordon height down to 0.4 m or its enlargement to 1.6 m increases the transpiration by 10.6–13.3 % and 10.0–10.7 %, respectively.

The activity of the photosynthetic apparatus of leaves. The grapevine training system affects the activity of the photosynthetic apparatus of leaves during the period of the highest water deficit. Statistically reliable differences were determined between the fluorescence levels in the curve points F_0, F_{pl}, F_p and F_t under different grapevine training systems. The effect of planting

Table 1. The parameters of Zahrei wine grape cultivar canopy *(Vitis vinifera* L.*)* under different planting densities and training systems. The mean data for 2016–2020 are presented

Planting density/ Training system	SF $(\frac{m^2 \times 10^{-2}}{ha})$	SFe $(\frac{m^2 \times 10^{-2}}{ha})$	IF $(\frac{m^2}{m^2})$
3 × 1.5 m			
Cordon at the height of 0.4 m	14.7 ± 0.9 bc	9.1 ± 0.3 cd	0.63 ± 0.03 a
–0.8 m	12.6 ± 0.7 b	8.3 ± 0.3 bc	0.67 ± 0.04 a
–1.2 m	9.0 ± 0.2 a	6.9 ± 0.2 a	0.76 ± 0.01 a
–1.6 m	6.5 ± 0.3 a	7.1 ± 0.2 a	1.11 ± 0.03 b
3 × 1 m			
Cordon at the height of 0.4 m	17.3 ± 1.9 c	9.9 ± 0.3 d	0.59 ± 0.04 a
–0.8 m	14.6 ± 1.2 bc	8.8 ± 0.2 c	0.61 ± 0.04 a
–1.2 m	9.2 ± 0.2 a	7.2 ± 0.3 ab	0.78 ± 0.01 a
–1.6 m	8.1 ± 0.3 a	7.7 ± 0.1 ab	0.95 ± 0.3 b

Note. The data present the mean values ± SE (n = 5). Different letters indicate reliable differences between the experimental variants by Duncan's new multiple range test with several ranges ($p \leq 0.05$).

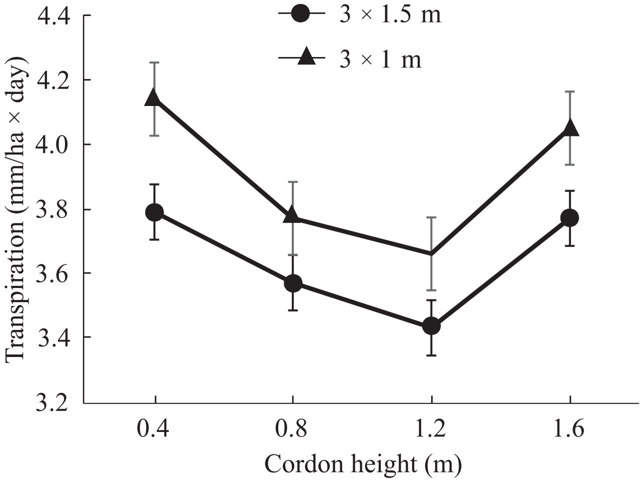

Fig. 2. The effect of the cordon height on water loss through transpiration depending on the planting density. The mean data for 2016–2020. The curves show the deviation threshold ± SE

density on FI parameters of leaves was not determined ($p > 0.05$) (Table 2).

Numerous indices, determined by the ratio between fluorescence intensity between specific points on FI curves, are used to define the state of the photosynthetic apparatus of plant leaves. In our experiment, noteworthy was the ratio between the points , which shows the relative content of Q_B, not reduced by PS2. These complexes are not involved in the linear transportation of electrons, so the efficiency of accumulating primary photosynthesis products in chloroplasts and plant productivity may depend on their number. The increase in the relative number of Q_B-non-reduced complexes of PS2 may be used as an index of stress and response of plants to unfavorable environmental factors, including drought, increased or decreased temperature, etc. (Korneev, 2002).

During the driest vegetative period (July 2020), the relatively low levels of the content of Q_B-non-reduced complexes of PS2 were determined in the grapevine leaves at the cordon height of 0.8 m and 1.2 m at the planting density of 3 × 1.5 and 3 × 1 m, respectively. The decrease or increase in the cordon height increases the ratio of regardless of the planting density.

Grapevine yield and grape quality. During five years of plantation fruit-bearing, from year four till year eight, a significant effect ($p \leq 0.05$) of the planting density and training system was found along with that of the interaction of factors on grapevine productivity in some years (2016, 2018).

There is some dependence of the yield rates not only on the factors under investigation (planting density and training system) but also the age of vines and agroclimatic conditions of the year.

When the grapevines entered the fruit-bearing period (2016), their productivity was relatively low, and varied depending on the training system within 2.05–3.91 kg at the planting density of 3 × 1.5 m, 1.83–2.55 kg at 3 × 1 m.

The productive (fruit-bearing) use of the vineyard, according to the regulations (Vlasov, 2006), starts in the fifth year since the vines were planted. In 2017–2018, the productivity was the highest for the investigation period, at the level of 5.67–7.91 kg at the planting density of 3 × 1.5 m, 5.25–7.11 kg at 3 × 1 m. In these

Table 2. The relative fluorescence levels in points F_0, F_{pl}, $F_{p,}$ and F_t on FI curves of the leaves under different planting density and training systems during the drought (2020, the 2nd decade of July)

Planting density/Training system	F_0	F_{pl}	F_p	F_t
3 × 1.5 m				
Cordon at the height of 0.4 m	0.33 ± 0.01 ab	0.73 ± 0.01 b	1.39 ± 0.02 bcd	0.34 ± 0.1 abc
–0.8 m	0.38 ± 0.01 c	0.80 ± 0.03 b	1.51 ± 0.05 d	0.38 ± 0.02 c
–1.2 m	0.32 ± 0.03 a	0.63 ± 0.05 a	1.11 ± 0.05 a	0.29 ± 0.02 a
–1.6 m	0.31 ± 0.00 a	0.77 ± 0.01 b	1.21 ± 0.01 ab	0.35 ± 0.1 abc
3 × 1 m				
Cordon at the height of 0.4 m	0.31 ± 0.01 a	0.76 ± 0.01 b	1.26 ± 0.01 abc	0.30 ± 0.02 a
–0.8 m	0.34 ± 0.02 ab	0.74 ± 0.01 b	1.21 ± 0.01 ab	0.37 ± 0.01 bc
–1.2 m	0.32 ± 0.01 a	0.62 ± 0.01 a	1.25 ± 0.04 abc	0.31 ± 0.01 ab
–1.6 m	0.36 ± 0.01 bc	0.73 ± 0.01 b	1.43 ± 0.03 cd	0.32 ± 0.01 ab

Note. The data present the mean values ± SE (n = 5). Different letters indicate reliable differences between the experimental variants by Duncan's new multiple range test with several ranges ($p \leq 0.05$).

years, the precipitation amount exceeded the average norms, at the level of 438.8–542.6 mm, and the aridity index – 0.33–0.41.

In 2019 and 2020, the precipitation amounts per year were lower than average – 301.4 mm and 270.7 mm, and the aridity indices – 0.22 and 0.20. As compared to the average productivity in 2017–2018, the yield from one vine decreased by 17.3–35.3 % in 2019, and in 2020 – by 61.2–69.2 % depending on the planting density and training system (Table 3).

During less dry years, the grapevine productivity is observed under vertical shoot positioning on the horizontal cordons of 0.4–0.8 m. In the driest years, relatively high productivity was observed on the vines with the cordon of 0.8 m at the planting density of 3 × 1.5 m, at the height of 1.2 m at 3 × 1 m.

The planting density of 3 × 1 m decreases the productivity of grapevines, but as recalculated per area unit, it is more efficient compared to the planting density of 3 × 1.5 m regardless of the training system.

On average, for the investigated years, the maximal level of the yield for Zahrei plantations (at the level of 14.1 t/ha) was determined under planting density 3 × 1 m and the cordon height of 1.2 m. The reduction or enlargement in the height of the vine cordon, and the decrease in the planting density to 3 × 1.5 m decreases the yield of plantations by 12.3–21.1 %.

Our results demonstrate that in case of cultivating in row plantations, the yield rates for Zahrei cultivar correlate with the number of shoots (Fig. 3). This dependence was established for the number of shoots with average vigor and the width of 7–10 mm (Vlasov et al, 2018).

The planting density and training system affect the rates of shoot load and, thus, the yield of plantations. However, it is reasonable to analyze the norm of shoot load in connection to the shoot productivity index, which reflects the yield weight per average shoot. The data in Fig. 4 demonstrate that the shoot productivity changes under the effect of the training system and depends on the planting density. Under the planting density of 3 × 1.5 m, the maximal productivity rates of 225 g/shoot are observed on grapevines with a cordon height of 0.8 m. Thicker planting of 3 × 1 m increases the productivity, its peak of 236 g/shoot is observed on the vines with the cordon of 1.2 m. The decrease or increase in the cordon height reduces the shoot productivity by 4.9–27.1 %, depending on the planting density.

The taste qualities of grapevine and its suitability for technical processing are mostly determined by the content of sugar and organic acids in wine. On average, during the investigation period, the total sugars in the must of Zahrei cultivar changed from 192 to 205 g/dm^3, that of titrated acids – 5.3–6.1 g/l depending on the planting density and training system. It is remarkable that in most arid years, the decrease in the plantation productivity increases the total sugars and decreases the acidity of the must. Putting the grape cluster off the soil surface with the increase in the height of the

Table 3. The effect of the planting density and training system on the yield weight of Zahrei wine grape cultivar *(Vitis vinifera* L.)

Year	Cordon height (m)			
	0.4	0.8	1.2	1.6
		3 × 1.5 m		
2016	2.1 ± 0.2 a	3.9 ± 0.4 b	2.7 ± 0.2 a	2.1 ± 0.1 a
2017	7.9 ± 0.6 c	7.9 ± 0.7 c	6.7 ± 0.6 abc	5.7 ± 0.5 ab
2018	6.7 ± 0.3 d	8.5 ± 0.6 e	6.9 ± 0.4 d	5.1 ± 0.3 bc
2019	5.9 ± 0.4 d	6.0 ± 0.2 d	5.6 ± 0.5 cd	3.6 ± 0.4 ab
2020	2.2 ± 0.1 d	2.7 ± 0.2 e	2.6 ± 0.1 e	2.0 ± 0.1 bcd
		3 × 1 m		
2016	2.2 ± 0.3 a	2.4 ± 0.2 a	2.6 ± 0.4 a	1.8 ± 0.3 a
2017	7.1 ± 0.4 bc	5.8 ± 0.3 ab	5.8 ± 0.4 ab	5.3 ± 0.3 a
2018	3.4 ± 0.4 a	5.8 ± 0.3 cd	6.1 ± 0.3 cd	4.7 ± 0.2 b
2019	4.0 ± 0.6 ab	4.3 ± 0.3 ab	4.5 ± 0.2 bc	3.2 ± 0.4 a
2020	1.8 ± 0.1 ab	1.9 ± 0.1 abc	2.1 ± 0.1 cd	1.6 ± 0.1 a

The data present the mean values ± SE (n = 5). Different letters indicate reliable differences between the experimental variants by Duncan's new multiple range test with several ranges ($p \leq 0.05$).

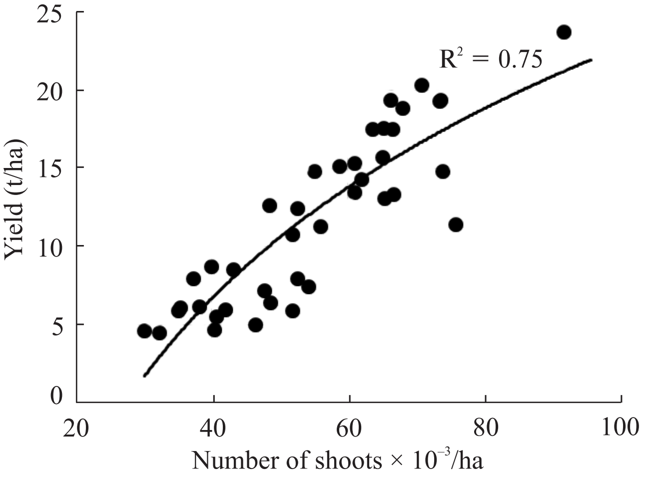

Fig. 3. The dependence between the number of average shoots and the yield of row plantations of grapevines

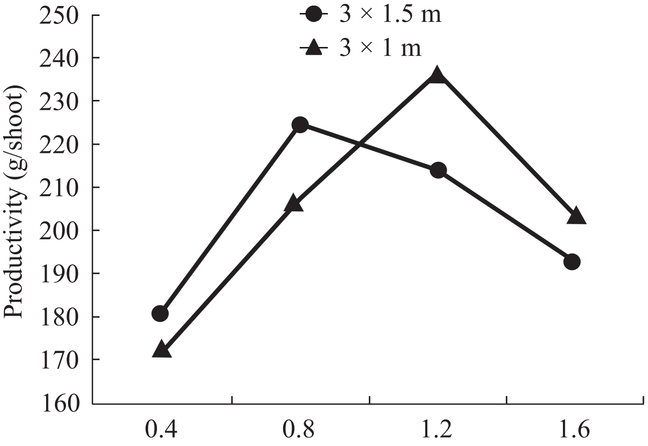

Fig. 4. The effect of the training system on shoot productivity depending on the planting density. The mean data for 2016–2020

horizontal cordon delays the veraison, and decreases the gluco-acidometric index regardless of the planting density. This effect is clearly traced in the veraison period during drought.

DISCUSSION

In the area of insufficient natural moisture supply, the change in the planting density and training system for grapevine affects the processes of growth and fruit-bearing of grapes. Its productivity of plants is ensured by specific parameters of canopy architecture of the plantations, leaf canopy, and shoot load as well as a related decrease in water loss through transpiration and an increase in the activity of the photosynthetic apparatus of leaves.

Different scientists have introduced numerous variants of planting density into viticulture considering different environments (Winkler, 1974). In the area with sufficient moisture supply, the planting density is high – the number of plants per one hectare is 5,000–8,000, sometimes up to 10,000. For these conditions, it is recommended to decrease the planting density in order to adapt plants to dry vegetation settings (Leeuwen et al, 2019; Keller et al, 2021).

In the zone of insufficient moisture supply, the planting density is much lower – 2,000–4,000 vines per hectare (Stoev, 1984). According to our data, in these conditions, the effect of aridity on grapevines during the vegetation is lower at a higher density of the plantations – 3,333 as compared to 2,222 plants per hectare. In our opinion, this effect is related to the decrease in the shoot load and yield as per one plant.

In viticulture, the shoot load is one of the main agrotechnical methods to regulate the growth and fruit-bearing of vines. The standardization of shoots per plant induces an increase or decrease in the grapevine vigor (Badr et al, 2018), a change in the leaf area and the ratio between leaves and clusters (Parker et al, 2015), as well as the photosynthetic activity of plants and the productivity of plantations (Reynolds et al, 1994). The results of our studies demonstrate that the effect of the shoot load on vines is manifested in the change in the cluster amount, the average cluster weight, and in the preservation or change in the yield quality indices.

The increase in the number of normally developed shoots on vines may help to implement the measures to increase the plantation productivity. However, it is possible to increase the shoot load on vines up to a specific or optimal level under specific cultivation conditions. The increase in the shoot load above optimal values may decrease the productivity due to the thickening of the canopy and an increase in the share of shadowed leaves or the effect of the limiting environmental factor observed in the experimental conditions.

Among the solutions to the problem of adapting the crop to arid conditions, it is suggested to use adaptive training systems for vines. The increase in the height of the yield location allows for decreasing the negative effect of high temperatures of the surface layer (Leeuwen et al, 2019). Our data demonstrate that the increase or decrease in the height of the grapevine cordon, except for the determined one, changes the canopy architecture, and its parameters allow the regulation of the rate of solar energy absorption and water loss through transpiration.

It is known that the productivity of the plantation is determined by the level of absorption and use of solar energy for photosynthesis. These indices are in straight-line correlation. This tendency is not critical for the sufficient moisture supply for plants (Amirdzhanov AG, 1980).

For semiarid conditions without irrigation, the productivity of grapevines may be increased up to the maximal rate only in case of the correspondence between the water and light regime of plants. The increase in the potential of the photosynthetic capacity of the plantations under insufficient moisture supply does not increase productivity, its rate is limited by the functional activity of the photosynthetic apparatus.

Under water deficit, high rates of solar energy collection may cause excessive tissue heating of the exposed leaves. Due to this effect, there is a significant change in physiological-biochemical processes, mainly related to photosynthesis inhibition and intensified respiration in plants, especially the ones from C-3 photosynthesis group. Two main processes in plants – transpiration and photosynthesis – are closely interrelated: if transpiration, which is the flow of water via stomata, decreases due to the shortage of soil moisture and further closing of stomata, then the photosynthesis will decrease as well, first of all, due to the intake of CO_2 to the leaf. So transpiration and productivity of plants are in close correlation (Shul'gin, 2013).

Based on the determined dependence between the parameters of the leaf area, water loss through transpiration, activity of the photosynthetic apparatus of leaves and productivity indices for plantations, it is possible to formulate the optimal elements of the structural vineyard organization for the non-irrigated crop in the semiarid climatic zone:

– the decrease in the shoot load on vines with some increase in the plantation density;

– the decrease in the height of the canopy with an insignificant increase in its width in row plantations and the training system on a unilateral vertical trellis;

– the optimization of canopy density due to the decrease in the share of shadowed leaves.

The optimal elements of the structural organization of Zahrei plantations for the non-irrigated crops are ensured by the planting density of 3 × 1 m under the horizontal cordon at the height of 1.2 m and free-growing shoots. Such vineyard structure enhances the efficiency of using the resource, limiting the productivity under a semiarid climate – soil moisture available for plants.

CONCLUSIONS

The agronomic methods of planting and training systems for grapevines ensure the management of the character of spatial shoot location, the formation of a specific canopy architecture, setting the parameters of the leaf area; their optimization mitigates the negative effect of water deficit and provides for adapting the plants for non-irrigated crops under semiarid climate.

The positive effect of compacting plantations on the yield of Zahrei wine grape cultivar was determined in the non-irrigated crop in semiarid environments. The variant of planting density of 3 × 1 m decreases the yield load on the vines on average by 12.1–31.0 %, as compared to the variant of 3 × 1.5 m. Yet, more dense plantations are remarkable for their yield, which is 18.5–61.3 % higher depending on the training system for vines.

Under dry conditions, the most efficient system is the training system with the formation of the horizontal cordon at the height of 1.2 m and free-growing shoots, the cultivation of grapevines in row plantations with a planting density of 3 × 1 m. The system optimizes the leaf area density, and forms the canopy architecture with rather low water loss through transpiration which has a positive effect on the activity of the photosynthetic apparatus of leaves during droughts. Under free growth, the yield of the plantations increases by 4.3–12.3 % on average as compared to the vertical shoot positioning and by 21.3 % – under their downward positioning.

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Реакція винограду на щільність садіння та систему ведення кущів у семіаридних умовах

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Мета. Дослідження фізіологічних і агробіологічних реакцій винограду на різні системи ведення кущів у рядкових насадженнях залежно від щільності садіння та можливості пристосування рослин для культури без зрошення в умовах холодного семіаридного клімату. **Методи.** Дослідження проведено польовим методом. У двофакторному досліді 2 × 4 вивчено дію двох варіантів щільності садіння (3 × 1,5 м; 3 × 1 м) і чотирьох систем ведення кущів (при розташуванні горизонтального кордону на висоті 0,4; 0,8; 1,2; 1,6 м) на параметри площі листкової поверхні, листковий індекс, витрати води на транспірацію, активність фотосинтетичного апарату листків і врожай технічного сорту винограду Загрей *(Vitis vinifera* L.*)*. Результати досліду обробляли за допомогою дисперсійного аналізу. **Результати.** Збільшення щільності рядових насаджень винограду на одиниці площі з 3 × 1,5 м до 3 × 1 м підвищувало загальну листкову поверхню, площу світлових листків, витрати води на транспірацію, масу врожаю, але у перерахунку на один виноградний кущ зазначені показники знижуються. Реакція винограду на систему ведення кущів аналогічна та незалежна від дослідних варіантів щільності садіння. Вертикальне ведення пагонів кущів при висоті розташування кордону 0,4 та 0,8 м збільшує потенціал фотосинтетичної потужності насаджень, але цей потенціал реалізується тільки в роки з меншим дефіцитом доступної вологи для рослин. Вільне ведення пагонів на кордонах, розташованих на висоті 1,2 м, формує архітектуру листкового пологу з відносно низькими витратами води на транспірацію, що позитивно впливає на активність фотосинтетичного апарату та врожайність, особливо в посушливі роки. Звисаюче положення пагонів на кордонах заввишки 1,6 м зменшує площу листкової поверхні кущів та створює архітектуру листкового пологу з підвищеною транспірацією, що посилює дію водного дефіциту та негативно впливає на продуктивність рослин. **Висновки.** Агроприйоми щільність садіння та система ведення кущів винограду дають змогу управляти характером розташування пагонів у просторі, формувати певну архітектуру листкового пологу, задавати параметри площі листкової поверхні; їх оптимізація пом’якшує негативну дію водного дефіциту та дає можливість пристосовувати рослини для культури без зрошення в умовах семіаридного клімату. Встановлений позитивний вплив ущільнення насаджень на врожайність культури без зрошення в семіаридних умовах. Варіант щільності садіння 3 × 1 м зменшує навантаження кущів врожаєм у середньому на 12,1–31,0 %, у порівнянні з варіантом – 3 × 1,5 м. Але більш щільні насадження відрізняються підвищеною врожайністю на 18,5–61,3 % залежно від системи ведення кущів. У посушливих умовах найефективнішою є система ведення кущів з формуванням горизонтального кордону на висоті 1,2 м і вільним розташуванням пагонів. Система оптимізує щільність листкової поверхні, формує архітектуру пологу з відносно низьким рівнем витрати води на транспірацію, що позитивно впливає на активність фотосинтетичного апарату листків у періоди дії посухи. Урожайність насаджень при вільному розташуванні приросту в середньому збільшується на 4,3–12,3 % у порівнянні з вертикальним веденням пагонів, на 21,3 % у звисаючим їхнім положенням.

Ключові слова: виноград, щільність садіння, система ведення, листкова поверхня, транспірація, фотосинтетичний апарат, продуктивність, урожай.

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