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RESEARCH ARTICLE

Performance of sweet cherry trees trained to a central leader and pergola system

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ABSTRACT

Sweet cherry (*Prunus avium* (L.) L.) cultivation has expanded remarkably in Chile, surpassing 80 000 ha, driving the need for orchard management strategies that enhance precocity, profitability, fruit quality, and operational efficiency. This study evaluated the effect of two training systems with permanent wood renewal: Central leader and pergola, on light interception, leaf gas exchange, vegetative growth, and fruit production of 'Lapins'/'Colt' sweet cherry trees. Light interception by the trees was higher in pergola (83%) than in central leader (36%). Leaf transpiration rate and stomatal conductance in trees trained in the pergola system were 32% and 39% lower, respectively, compared with the central leader, although no differences were observed in photosynthetic rate. The leaf area per tree was 66% higher in the pergola system than that observed in central leader. Fruit production per tree did not differ between systems; however, pergola produced 49% more fruit per branch and 73% more leaf area per fruit than central leader. Fruit from trees trained on pergola were larger, but showed slightly less intense color and higher acidity compared to those from central leader, suggesting delayed ripening. These results provide relevant production indicators for decision-making in the establishment of new commercial sweet cherry orchards.

Key words: Fruit size, leaf area, light interception, *Prunus avium*, trunk cross-sectional area, yield efficiency.

INTRODUCTION

In the past, sweet cherry trees (*Prunus avium* (L.) L.) were trained with a central leader architecture on their own roots or on very vigorous rootstocks, with a planting density of no more than 400-500 trees ha^{-1}. These trees developed tall, voluminous canopies, which led to low yield efficiency, smaller fruit size, and slow entry into production, reaching full production 8 yr after planting (Long et al., 2005; Whiting et al., 2005; Robinson and Hoying, 2014).

Orchard modernization has introduced various techniques to reduce tree size and induce early fruit production, such as the use of dwarfing rootstocks and new training systems that favor high density, which allowed for the creation of pedestrian orchards (Musacchi et al., 2015). High density training systems seek to increase light interception and distribution into the canopy, maximize tree productivity, and optimize labor efficiency. However, these methods require constant renewal of productive branches (Radunić et al., 2011; Long et al., 2015; Musacchi et al., 2015). In this regard, pruning is a complex task due to the difficulty of selecting which branches to remove (Long et al., 2021; Soysal et al., 2025).

Sweet cherry has an acrotonic growth habit with limited lateral shoot development, which makes it challenging to establish training systems. The tabletop central leader (TTP) system was developed in The Netherlands. It consists of a pergola with a central leader and two rows of horizontal fruit-bearing branches that are renewed every 3 yr. This system is formed in spring by pruning the central leader to stimulate the growth of fruit-bearing branches. These branches are broken at their base, which induces new growth that will replace the productive branch in the next cycle (Long et al., 2021). This pruning was introduced in Chile under the name Head System or Sistema de Renovación Permanente (SRP). However, to date, no studies have been conducted comparing the performance of sweet cherry trees in this new formation with traditional training systems. Therefore, the objective of this study was to compare the photosynthetic performance, vegetative growth, and productivity of 'Lapins'/'Colt' sweet cherry trees trained on central leader and pergola systems and using the head system.

MATERIALS AND METHODS

Study site and plant material

The study was conducted in a commercial orchard located in Chimbarongo (34°38' S, 71°01' W; 356 m a.s.l.), O'Higgins Region, Chile, during the 2022-2023 season. The study compared 5-yr-old sweet cherry trees (*Prunus avium* (L.) L.) 'Lapins' on 'Colt' rootstock trained using the central leader and pergola systems, both formed using the head system. The trees on central leader were planted at 4.5 × 2.5 m (889 trees ha^{-1}) and the trees on pergola at 4.5 × 2.0 m (1111 trees ha^{-1}). In the formation of the central leader, the branches were broken and arranged pendulously along the leader; in the case of the pergola, the branches were broken and arranged horizontally in opposite directions (Figure 1).

Figure 1. Sweet cherry trees 'Lapins' in two training system: Central leader (left) and pergola (right).

The experiment followed a non-randomized comparative design. Within each training system, six trees were randomly selected as sampling units. The measurements were taken from trees located in the central row and central position of each plot in order to avoid border effects. All evaluations were conducted within a 3 ha experimental area of the commercial orchard.

The orchard was managed according to conventional export-oriented practices in terms of fertilization, irrigation, pruning, and phytosanitary control. The plots were irrigated with two drip lines per row with four emitters per tree. The soil is structured around basins and plains derived from sedimentation from the Andes Mountains and deposits from the Tinguiririca River. The climate is Mediterranean template with winter rains, with precipitation concentrated in winter, leading to a dry season lasting 7 to 8 mo as a result of the Pacific anticyclone. Meteorological conditions of the evaluated season are summarized in Table 1. During the research, conditions were favorable for pollination and fruit growth, with no frost during blooming and average maximum and minimum temperatures between October and December of 24 and 9 °C, respectively.

Table 1. Climatic data during the evaluated season. [1]Richardson et al., 1974. [2]Anderson and Seeley, 1992.

Season	Period	Variable	
Rest	Apr-Jul	Mean air T (°C)	8.6
		Chill units[1]	2 343.0
		Rain (mm)	239.0
Fruit growing season	Sep-Dec	Mean air T (°C)	15.9
		Growing degree hours (GDH)[2]	27 448.0
		Maximum solar radiation (W m^{-2})	741.0

Light interception and gas exchange

Intercepted light was measured using a ceptometer (AccuPAR LP-80; Decagon Devices, Pullman, Washington, USA). Readings were taken 1.7 m above soil level and in the directions of the four cardinal points of the canopy, with three replicates. Light interception (%) was calculated as the ratio between the radiation received under the canopy and that measured in full sun. All measurements were made between 12:00 and 13:00 h, on a fully sunny day (28 November 2022).

Net photosynthetic rate (P_n; µmol m^{-2} s^{-1}), transpiration rate (E; mmol m^{-2} s^{-1}) and stomatal conductance (g_s; mmol m^{-2} s^{-1}) were measured using a portable infrared gas analyzer LCpro (ADC BioScientific Ltd., Herts, UK). Water use efficiency (WUE; µmol CO_2 $mmol^{-1}$ H_2O) was calculated as the quotient of P_n and E. All measurements were made between 12:00 and 14:00 h, in six sun-exposed healthy leaves per replicate, with a photosynthetic photon flux density ≈ 1700 µmol m^{-2} s^{-1}, on a fully sunny day (24 November 2022).

Vegetative growth

Vegetative parameters were evaluated after fruit harvest (28 December 2022). Trunk diameter (cm) was measured 20 cm above the graft union, from which the trunk cross-sectional area (TCSA) was calculated. The canopy volume (m^3) of trees trained on central leader was calculated using the following equation:

$$V_e = \frac{\pi r^2 h}{3} \qquad (1)$$

where, V_e is the canopy volume, r is the base radius (calculated from the average width and depth of the canopy), and h is the canopy height.

The canopy volume of trees trained on pergola was calculated using the following equation:

$$V_p = \frac{\pi r^2 h_s}{3} + w \cdot d \cdot h \qquad (2)$$

where, V_p is the canopy volume, r is the base of the radius and h_s is the height of the vertical branches above the canopy. In addition, w is the width, d is the depth and h is the effective height of the horizontal branches of the canopy.

The total number of vegetative and productive branches per tree was recorded. For each branch, length (cm) was measured and the number of spurs as well as the number of leaves on the annual shoots were counted. Diameter of branch (cm) was measured 10 cm above of the breaking of the branch, from which the branch trunk cross-sectional area (BCSA) was calculated.

Subsequently, a sample of five spurs and five annual shoots per tree was collected, and the leaf area (cm^2) was estimated using LI-3100 equipment (LI-COR, Lincoln, Nebraska, USA) and the number of leaves was counted. Finally, a subsample of 50 g leaves was taken to measure their weight (g) and DM (%) after 72 h in a forced-air drying oven at 60 °C.

The foliar indicators estimated using gravimetric relationships were the number of leaves per tree and leaf area per tree. The leaf area index (LAI) was determined as the ratio between the leaf area per tree and the soil area allocated to each tree, according to 1111 trees ha^{-1}.

Fruit production and fruit quality

At harvest (7 December 2022), all fruits of each replicate were collected and weighed individually to determine production per tree (kg). In addition, a 50 g fruit sample was taken to determine dry weight (g) and DM (%) after 72 h in a forced-air drying oven at 60 °C. Fruit production per tree was used to determine fruit yield per branch, TCSA (kg cm^{-2}), canopy volume (kg m^{-3}) and leaf area (kg m^{-2}).

A sample of 60 fruits per treatment was taken at harvest to analyze weight (g) measured using a balance, diameter (mm) using a vernier caliper in the equatorial zone of the fruit, color visually classified using scale (red = 1, mahogany red = 2, mahogany = 3, dark mahogany = 4 and black = 5), firmness (g mm^{-1}) with a FirmTech II (BioWorks, Wamego, Kansas, USA), soluble solids content (°Brix) with a digital refractometer PAL-1 (Atago, Tokyo, Japan), and titratable acidity (% malic acid; TitroLine easy, Schott AG, Mainz, Germany). The fruit diameter distribution (mm) of a sample of 500 fruits per treatment was compared.

Statistical analysis

A one-way ANOVA was performed to evaluate if there were significant differences between treatments. Data analysis was performed using Statgraphics Centurion software 16.1.03 (Statgraphics Technologies, The Plains, Virginia, USA). Figures were generated using SigmaPlot 10 software (WPcubed GmbH, München, Germany).

RESULTS

Light interception and leaf gas exchange

Light interception differed between the training systems, with 39% recorded in central leader and 83% in pergola (Figure 2).

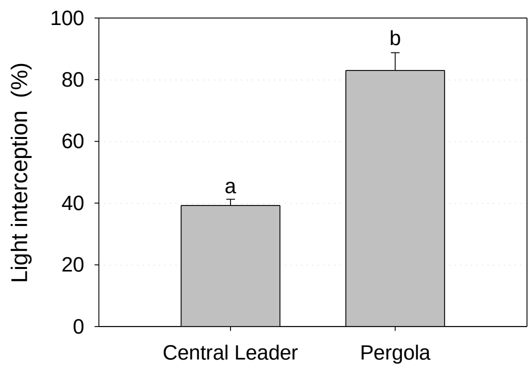

Figure 2. Light interception (%) in 'Lapins' sweet cherry trees trained on central leader and pergola systems. Different letters on bars indicate significant differences between training system according to Tukey test ($P < 0.05$). Means + standard error ($n = 24$).

The photosynthetic rate (P_n) did not differ between the training systems, with an average value of 9.1 µmol m^{-2} s^{-1}. In contrast, the transpiration rate (E) and stomatal conductance (g_s) of trees trained on pergola were 32% and 39% lower, respectively, than those trained on the central leader. Water use efficiency (WUE), calculated as the ratio of P_n and E, tended to be higher in trees trained on pergola, although differences were nonsignificant compared to the central leader system (Table 2).

Table 2. Photosynthetic performance and water use efficiency in 'Lapins' sweet cherry trees trained on central leader and pergola systems. ^{ns}Nonsignificant; **Significant difference ($P < 0.01$).

Treatment	Photosynthetic rate	Transpiration rate	Stomatal conductance	Water use efficiency
	µmol m^{-2} s^{-1}	mmol m^{-2} s^{-1}	mmol m^{-2} s^{-1}	µmol CO_2 mmol H_2O^{-1}
Central leader	9.9	3.1	115	3.3
Pergola	8.2	2.1	70	3.8
Significance	ns	**	**	ns

Vegetative growth

Sweet cherry trees grown on pergola showing greater canopy volume (86%), ΣBCSA (16%) and ΣBCSA/TCSA (28%) compared to those grown on central leader. However, TCSA was not affected by the training systems, reaching an average of 71 cm^2 (Table 3). The number of productive branches on trees trained on a pergola was approximately half that of trees trained on a central leader; however, total number of spurs per tree did not differ between training systems.

At the branch level, trees trained on pergola showed more vigorous growth than those trained on central leader, showing greater length (18%), BCSA (33%), and number of shoots (33%) (Table 4). At the leaf level, no differences were observed between treatments in leaf size or DM, with an average spur leaf area of 164 cm^2. However, the leaf area per tree and leaf area index (LAI) of the pergola system were 39% and 52% higher, respectively, than those of the central leader (Table 5).

Table 3. Vegetative growth of ‘Lapins’ sweet cherry trees trained on central leader and pergola systems. CV: Canopy volume; TCSA: trunk cross-sectional area; BCSA: branch cross-sectional area. ^{ns}Nonsignificant; *Significant difference ($P < 0.05$); **Significant difference ($P < 0.01$).

Treatment	Planting density	CV	TCSA	ΣBCSA	ΣBCSA/TCSA	Fruiting branches per tree	Spurs per tree
	Trees ha^{-1}	m^3	cm^2	cm^2	cm^2 cm^{-2}	Nr tree^{-1}	Nr tree^{-1}
Central leader	889	2.2	77	48	0.63	25	725
Pergola	1111	4.1	65	57	0.88	16	672
Significance	-	*	ns	**	**	**	ns

Table 4. Vegetative growth of productive branches of ‘Lapins’ sweet cherry trees trained on central leader and pergola systems. BCSA: Branch cross-sectional area. **Significant difference ($P < 0.01$).

Treatment	Branch				Spurs per meter
	Longitude	Diameter	BCSA	Spurs	
	m	mm	cm^2	Nr	Nr m^{-1}
Central leader	1.4	15	1.8	20	15
Pergola	1.7	18	2.7	30	19
Significance	**	**	**	**	**

Table 5. Foliar indicators for ‘Lapins’ sweet cherry trees trained on central leader and pergola systems. LAI: Leaf area index. ^{ns}Nonsignificant; *Significant difference ($P < 0.05$). [1]LAI was calculated considering the same number of trees in each training system (1111 trees ha^{-1}).

Treatment	Leaf				Tree		
	Annual shoot leaf area	Spur leaf area	Total spur leaf area	DM	Total leaves	Total leaf area	LAI[1]
	cm^2	cm^2	cm^2	%	Nr tree^{-1}	m^2	
Central leader	57	21	138	40.1	5214	13.7	1.5
Pergola	51	28	190	37.7	6041	22.8	2.5
Significance	ns	ns	ns	ns	ns	*	*

Fruit production

At the individual tree level, fruit yield per year in the fifth season was 17.5 kg tree^{-1}, with no differences between training systems. In addition, trees trained in pergola system showed higher yield per fruiting branch (49%) and yield per TCSA (21%) than those trained in the central leader system (Table 6).

Table 6. Fruit production of ‘Lapins’ sweet cherry trees trained on central leader and pergola systems. TCSA: Trunk cross-sectional area; VC: canopy volume. ^{ns}Nonsignificant; *Significant difference ($P < 0.05$); **Significant difference ($P < 0.01$).

Treatment	Yield/Fruiting branch	Yield/TCSA	Yield/VC	Yield
	g	kg cm^{-2}	kg m^{-3}	kg tree^{-1}
Central leader	0717	0.212	8.0	17.9
Pergola	1071	0.256	4.4	17.1
Significance	**	*	**	ns

The fruit/leaf ratio differed between training systems, with trees trained on a pergola showing a lower yield/leaf area (43%) and a higher leaf area per fruit (73%) compared to the central leader. These variations in the leaf/fruit ratio were reflected in DM distribution, as the fruit dry weight/leaf dry weight ratio in trees trained on a central leader was 1.6 times higher than that recorded in the pergola system (Table 7).

Table 7. Productive efficiency of 'Lapins' sweet cherry trees trained on central leader and pergola systems. FW: Fruit weight; LW: leaf weight; FWD: fruit dry weight; LWD: leaf dry weight. *Significant difference ($P < 0.05$).

Treatment	Yield/Leaf area	Leaf area per fruit	FW/LW	FDW/LDW
	kg m^{-2}	cm^2	g g^{-1}	g g^{-1}
Central leader	1.34	77	6.6	3.0
Pergola	0.77	133	3.8	1.9
Significance	*	*	*	*

Fruit quality

The fruits from trees trained on pergola exhibited less intense coloration than those produced on the central leader, along with 20% higher titratable acidity. However, no differences were observed between the training systems in fruit firmness or soluble solids concentration (Table 8).

Table 8. Fruit quality of 'Lapins' sweet cherry trees trained on central leader and pergola systems at harvest. SSC: Soluble solids concentration; TA: titratable acidity. nsNonsignificant; *Significant difference ($P < 0.05$); **Significant difference ($P < 0.01$).

Treatment	Color	Firmness	SSC	TA	Weight	DM
	(1-5)	g mm^{-1}	°Brix	% malic acid	g	%
Central leader	3	369	18.3	0.74	10.3	18.5
Pergola	2	380	17.5	0.92	10.9	19.1
Significance	**	ns	ns	**	*	ns

The distribution of sweet cherry size differed between training systems (Figure 3). In the pergola system, 55% of the fruit reached diameters of 28 mm or greater, whereas in the central leader system this proportion was close to 35%.

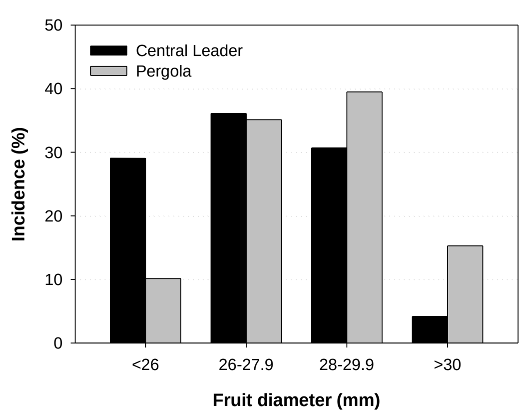

Figure 3. Size distribution (%) of fruits from 'Lapins' sweet cherry trees trained on central leader and pergola systems.

DISCUSSION

The results of this study indicate that tree architecture plays a central role in determining light interception and distribution within the canopy. In this context, the pergola training system promotes a more uniform light environment due to its planar and compact canopy structure, whereas the central leader system generates a more heterogeneous light profile associated with its conical architecture (Figure 1). Studies conducted on vertical 2D training systems have reported average light interception levels ranging from 52% to 66%, depending on the number and arrangement of branches within each system (Stone et al., 2022), as well as differences in light interception between the two sides of the tree (Coye et al., 2024).

Training systems with a central leader that produce branches with tighter insertion angles have less light interception than those with more open and compact arrangements (Gascón-Casanova et al., 2019; Zhang et al., 2023). In turn, trees with very high canopy density reduce light penetration into the interior parts of the tree (Hrotkó, 2013; Stone et al., 2022). Steiner et al. (2015) indicate that, for denser conical canopies, a canopy radius of 70-80 cm could be considered optimal for light penetration to support photosynthesis.

Another relevant factor to consider when comparing different tree architectures is the variation in light interception throughout the day, which is more variable in vertical training systems, i.e., those arranged in a fruiting wall (Zhang et al., 2015; 2016). In contrast, this variable would not be affected in trees trained on pergola.

Training systems can affect the overall photosynthetic performance of the canopy, given their ability to influence light distribution (Afonso et al., 2017; Anthony and Minas, 2021; 2025). The most efficient systems are those in which the greatest distribution of photoassimilates goes to the fruit rather than vegetative growth. In sweet cherry trees, the net photosynthetic rate (P_n) range varies between 8 and 14 µmol m^{-2} s^{-1} depending on the cultivar, with light saturation reaching 1000-1100 µmol m^{-2} s^{-1} (Blanke et al., 2017; Jorquera-Fontena et al., 2022; Pino et al., 2023), levels equivalent to half the maximum daily incident light in central Chile.

In the present study, the lower transpiration rate (E) and stomatal conductance (g_s) of trees trained on pergola could be attributed to greater control of stomatal opening compared to those on central leader, associated with a cooler microclimate. The g_s reaches its maximum level near harvest and is influenced each season by atmospheric vapor demand and water availability (Marsal et al., 2010; Blanco et al., 2018).

Water use efficiency (WUE) is used as a physiological indicator of plant response to water stress conditions (Mininni et al., 2022). The photosynthetic performance of trees grown on pergola would indicate that this tends to favor WUE over the central leader system.

The training system affected the vegetative growth of the trees (Table 3). The observed differences in canopy volume per hectare are explained by the different tree shapes and the distribution of branches along the axis in each training system. Hence, the planting distance of trees trained on a central leader proved to be very wide, given that, when their branches were broken (unlike in a traditional), the canopy covered a width of only 2 m, leaving a large amount of unused space.

In sweet cherry trees trained on central leader, canopy volumes between 13-18 m^3 have been observed (Pino et al., 2023), while in high-density training systems with branch renewal, using dwarfing rootstocks such as super slender axe, canopy volume values reach 3-6 m^3, with 10 to 15 lateral branches of moderate vigor (Long et al., 2015; Aglar et al., 2024).

The vegetative growth expressed as trunk cross-sectional area (TCSA) and leaf development of a tree is influenced by the rootstock, soil fertility, water availability, and environmental conditions during the season (Usenik et al., 2006; Robinson et al., 2017; Blanco et al., 2020).

Previous studies show that systems with permanent branch renewal improve precocity, productivity, and fruit quality compared to traditional systems (Long et al., 2015), given that in sweet cherry trees, as the branch ages, productivity (flower bud density) and fruit size decrease (Whiting and Lang, 2004; Bondarenko et al., 2023). In this sense, head system (SRP) using the break technique has an advantage over traditional pruning, given that sweet cherry trees have marked apical dominance and tend to produce few branches with closed angles (Long et al., 2021).

In this study, the pergola had thicker branches (≈ 18 mm diameter) than the central leader system. In trees trained on pergola, all new branches originated from horizontal leaders, which did not generate heterogeneity in their growth. In contrast, in trees trained on central leader, new shoots emerged at different levels of the trunk, with greater growth in the upper ones than in the lower ones, and thus higher competition for photoassimilates due to the greater number of branches per tree.

The selection of vigorous branches would favor productive potential, given the development of a more extensive vascular network and greater capacity for photosynthesis and the transport of water and nutrients (Smith, 2008). These factors would contribute to the storage of more carbohydrates and the production of more fruitful buds than small branches.

In previous studies of sweet cherry trees conducted using the table top (TTP) system branch vigor was low, with diameters between 8-10 mm, which was associated with the use of dwarfing rootstocks and the fact that branching was allowed in the lower part of the canopy (Long et al., 2021).

The different leaf populations (spur or shoot) contribute to the supply of carbohydrates to the fruit, although their relative contribution is still under debate (Whiting and Lang, 2004; Cittadini et al., 2008). The leaf area index (LAI) of trees trained on pergola system was 67% higher than that of trees trained in the central leader system when calculated at the same plant density. Previous studies on 'Lapins'/'Colt' sweet cherry trees trained on traditional central leader reported a leaf area per tree of 22 m^2 and LAI values of 2.0, as well as 3.7 in Kym Green Bush (KGB) systems (Yuri et al., 2021). Meanwhile, 'Royal Dawn'/'Maxma 14' sweet cherry trees grown on Y-trellises had a leaf area of 30 m^2 per tree and an LAI of 3.3 (Blanco et al., 2019). The differences in vegetative growth presented by training systems must be considered when determining planting distance, as well as for pruning strategy, fruit load control, and mineral nutrition.

The space allocated in the row for trees trained on a central leader was greater than necessary for this system, given that it generates a pendulous arrangement of branches. If the trees were located at a distance of 2 m in the row, their production would increase by 4 t ha^{-1}. However, increasing planting density does not always lead to higher orchard profitability; thus, in studies conducted on sweet cherry trees with ultra-high-density training systems (> 2800 trees ha^{-1}), fruit yield at full production did not exceed an average of 10 t ha^{-1}, due to very compact and low-vigor canopies (Musacchi et al., 2015). In Chile, 'Lapins' sweet cherry trees planted at moderate densities (889-1250 trees ha^{-1}) can achieve yields exceeding 25 t ha^{-1} yr^{-1}.

Trees trained on pergola showed higher yield/fruiting branch (49%) and yield/TCSA (21%) than those trained on central leader (Table 6). The productive efficiency values (kg cm^{-2} TCSA) for the training systems studied were moderate to high (0.234 kg cm^{-2} TCSA average), considering they were used for a vigorous rootstock such as 'Colt'. Usenik et al. (2006) reported for 'Lapins' sweet cherry trees that production efficiency was affected by the rootstock but not by the training system (Solaxe *vs*. Vogel Spindle). Similarly, Sitarek et al. (2008) showed that 'Lapins' sweet cherry trees trained using the Vogel Central Leader system had a cumulative yield requirement in the third year of 0.06 and 0.360 kg cm^{-2} TCSA for trees on vigorous and dwarfing rootstocks, respectively.

The yield/volume ratio per tree was 82% lower in the pergola system than in the central leader system (Table 6). The high value obtained in the central leader was due to the decrease in canopy volume caused by the branch breakage, which made them more pendulous. A higher yield/volume ratio in more intensive training systems is associated with a more balanced distribution of photoassimilates to the fruits and greater space utilization efficiency.

The leaf area of a tree is closely related to fruit growth and quality, as leaves are the main source of carbohydrates (Robinson et al., 2017). In sweet cherry trees, Whiting (2001) proposed a ratio of 200-300 cm^2 of leaf area per fruit to achieve an optimal balance between vegetative growth and production. However, this ratio can vary between training systems, with trees trained on a traditional central leader having a leaf area of 185 cm^2 to produce a fruit weighing 10 g (equivalent to 0.54 kg m^{-2}), while those trained on a KGB system reached 230 cm^2 (equivalent to 0.44 kg m^{-2}) (Yuri et al., 2021). Similar results were reported in 'Royal Dawn' sweet cherry trees (Blanco et al., 2019). In this study, the pergola system showed twice the efficiency of the KGB in terms of the leaf/fruit ratio, both having high vegetative development. Therefore, central leader remains the best system for converting photoassimilates into fruit, which is confirmed by the fruit dry weight/leaf dry weight ratio, where the central leader was 60% more efficient than the pergola system (Table 7).

Productive efficiency requires controlling vegetative growth in favor of production, which means that each training system must optimize its resources accordingly. Understanding these differences allows producers to adapt their management practices to the specific objectives of the orchard, seeking not only high production volumes but also efficient management of available resources.

Fruit size is one of the main determinants of economic return in sweet cherry production. In this context, differences in fruit size distribution between training systems can have a substantial impact on orchard profitability. Based on prices of 3.32 USD kg^{-1} for category J (26-27.7 mm) and 4.78 USD kg^{-1} for category SJ (28-29.9 mm) (Guangzhou and Shanghai Wholesale Market, China), the higher proportion of larger-sized fruit in the pergola system translated into a 32% increase in income compared with the central leader system, representing a difference of more than 20 000 USD ha^{-1} in favor of the former. Caliber differences between training systems can be attributed to the productive demands of each system, with pergola-trained trees having fewer productive branches but more vigorous ones and a larger leaf area per fruit in relation to the central leader, favoring greater distribution of carbohydrates to the fruits. Similarly, Stone et al. (2022) reported that greater light interception from more open training systems does not necessarily guarantee larger fruit size, as fruit load management plays a more decisive role.

A slight delay in fruit ripening was observed in the pergola system compared to the central leader system. The source/sink relationship can affect not only fruit size but also the ripening process. In this regard, Usenik et al. (2010) showed an increase in fruit size as well as greater sugar accumulation in sweet cherries as the leaf area/fruit ratio increased during the final stage of fruit growth. However, wood carbohydrate reserves may have a more significant influence on fruit quality than the leaf/fruit ratio, as it has been observed that sweet cherries can reach the same size even when their leaf population is significantly reduced (Whiting and Lang, 2004).

In addition, training systems affect the microclimate of the fruit. Studies conducted on grapevine trellises indicate that the horizontal arrangement of the branches reduces the amount of solar radiation reaching the fruit and creates a cooler microclimate around it, which leads to lower anthocyanin synthesis in the fruit, delays sugar accumulation, and results in later ripening (Reynolds and Vanden Heuvel, 2009).

On the other hand, the use of vigorous rootstocks in intensive systems such as those analyzed in the present study could favor plant response and fruit quality in the face of stress events, especially those with high production demands. Previous studies report that high-density training systems that require dwarfing rootstocks to reduce vigor show greater sensitivity to thermal and water stress in the plant, due to the formation of trees with high foliage production and low root volumes, which negatively affects fruit quality if proper canopy and irrigation management is not carried out (Gonçalves et al., 2005).

The pergola system facilitated management tasks by improving fruit accessibility and spatial distribution, thereby reducing labor time and effort. However, further research is needed to optimize management practices and ensure balanced, sustainable long-term production under its high branch renewal.

CONCLUSIONS

This study evaluated the effect of two training systems with permanent wood renewal pruning, central leader and pergola, on the productive, yield efficiency, and fruit quality of ‘Lapins’/'Colt' sweet cherry trees. Trees trained on pergola showed greater light interception than those trained on central leader, mainly due to differences in the number and distribution of their branches. Similarly, the former showed lower rates of transpiration and stomatal conductance, without this affecting CO_2 assimilation.

Although yield per tree did not differ between systems, production per hectare was 20% higher for the pergola than for the central leader, due to its higher planting density. Furthermore, the pergola produced more vigorous branches (≈ 18 mm in diameter), a greater number of fruits per branch, and a larger leaf area per fruit (133 cm^2 fruit^{-1}), compared to the central leader (77 cm^2 fruit^{-1}). The fruits produced in the pergola were larger, with 55% of the fruit over 28 mm in size. This higher proportion of fruit with high commercial value resulted in a 32% increase in economic income, equivalent to more than 20 000 USD ha^{-1} in favor of pergola.

Overall, sweet cherry trees trained on pergola system exhibit superior physiological performance, productivity, and fruit quality compared to the central leader system, likely due to more efficient carbohydrate allocation and improved microenvironmental protection of fruiting structures; however, optimizing fruit load according to branch vigor and refining management practices remain essential to ensure balanced, sustainable long-term production in systems characterized by high renewal of permanent wood.

Author contribution

Conceptualization: J.A.Y. Methodology: J.A.Y., M.P. Formal analysis: A.B., M.P., M.M. Investigation: A.B., M.P., M.M. Writing-original draft: A.B. Writing-review & editing: J.A.Y., M.P., M.M. Funding acquisition: J.A.Y. All co-authors reviewed the final version and approved the manuscript before submission.

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