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"Respuestas Productivas y Fisiológicas del Cerezo (*Prunus avium* L.) Protegido Bajo Mallas"

Tesis para optar al grado de Doctora en Ciencias de la Agronomía

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RESUMEN

El cerezo (*Prunus avium* (L.) L.) es un frutal con alta demanda de sus frutos por parte de los consumidores. Producto de ello se ha registrado en los últimos años un aumento de la superficie con este cultivo a nivel global. Sin embargo, las condiciones meteorológicas inestables producto del cambio climático generan incertidumbre para los agricultores, que ha llevado al cultivo de este frutal en ambientes protegidos. Estos sistemas productivos se basan en el uso de materiales de cobertura tales como plástico y rafia principalmente para prevenir daños en la floración y frutos por eventos de lluvias, heladas y granizadas. Además, en la actualidad se están incorporando mallas para mitigar efectos dañinos de las olas de calor y escasez hídrica. Dependiendo de las características del material empleado, el uso de cobertura altera las condiciones micro-climáticas del huerto, aunque esta situación es sabida, existe escaso conocimiento sobre cómo estas condiciones alteran parámetros productivos y fisiológicos en el cerezo.

La presente tesis doctoral tuvo como objetivo determinar y profundizar en aspectos productivos y fisiológicos que se ven alterados en huertos de cerezo protegidos bajo coberturas, con énfasis en el uso de mallas.

En una primera etapa se realizó una revisión del estado del arte sobre los factores ambientales (luz, temperatura, humedad relativa y viento) involucrados en la producción de cerezos bajo diferentes tipos de cubiertas y su efecto en las respuestas fisiológicas del árbol (intercambio gaseoso de la hoja, relaciones hídricas, desarrollo floral, crecimiento y desarrollo del árbol, y caracteres de calidad de frutos). Como principales conclusiones de esta revisión se determinó que todas las cubiertas utilizadas en cerezo aumentan la proporción de radiación fotosintéticamente activa (PAR) del tipo difusa, disminuyendo el exceso de PAR directa con un resultado positivo en la actividad fotosintética. Sin embargo, esta menor PAR directa genera un desbalance en el crecimiento del árbol, a favor del desarrollo vegetativo en desmedro del reproductivo. En cerezos bajo cubierta también se observa un aumento de la

temperatura que afectaría negativamente el potencial de cuajado de frutos y el rendimiento, pero con impacto positivo en el crecimiento de los frutos. Por otra parte, el uso de cubiertas estaría favoreciendo el estado hídrico del árbol, pero que alteraría el flujo de nutrientes específicos como calcio y a través de ello la firmeza de frutos. Se sugiere que es necesario ajustar las prácticas agronómicas de manejo en huertos de cerezo protegidos de acuerdo a las condiciones micro-climáticas y respuestas fisiológicas particulares que existen bajo las cubiertas.

En una segunda etapa, se investigó el efecto de mallas foto-selectivas de color azul gris (AG) con dos densidades de trama y urdiembre: 4 hilos x 4 hilos por cm^{-1} lineal (AG4x4) y 5 hilos x 5 hilos por cm^{-1} lineal (AG5x5), en un huerto comercial de cerezo de los cultivares Kordia y Regina, establecidos en la localidad de Camarico, Región del Maule, y durante dos temporadas consecutivas. Se evaluó su efecto en las condiciones de luz, intercambio gaseoso de la hoja, desarrollo floral, producción y caracteres de calidad de frutos. Ambas mallas redujeron la densidad de flujo de fotones fotosintéticos (PPFD) en un 24% y 30% para AG4x4 y AG5x5, respectivamente. La eficiencia de uso de la luz, determinada como la relación entre la asimilación neta de CO_2 (A_n) y PPFD se incrementó por el uso de estas mallas en un 73% y 76% para los cultivares Kordia y Regina, respectivamente. En cuanto al desarrollo floral, la malla AG5x5 redujo el número de yemas y primordios florales por yema en 20%, pero con efecto positivo en el tamaño de los frutos, el que aumentó en un 4% y 12% para los cultivares Kordia y Regina respectivamente. Nuestros resultados indican que el uso de malla foto-selectiva AG en huerto de cerezo sería una herramienta útil para optimizar la asimilación neta de CO_2 de la hoja y regular la carga frutal en este cultivo, en tanto su efecto sobre caracteres de calidad de frutos se encuentra fuertemente influenciado por el cultivar y las condiciones ambientales.

Palabra clave:

Cambio climático, fruticultura protegida, materiales de cobertura, producción, fisiología.

SUMMARY

Sweet cherry (*Prunus avium* (L.) L.) fruit is in high demand by consumers. As a result, there has been an increase in the global area under this crop in recent years. However, unstable weather conditions due to climate change have created uncertainty for cherry growers, making it necessary to produce this fruit tree in a protected environment. Cherry tree production in a protected environment is based on the use of covering materials such as plastic and woven with the main objective of preventing damage to the blossom and fruit due to rain, frost, and hailstorms. Other alternatives are currently being incorporated such as nets to mitigate the harmful effects of heat waves and water shortages.

Depending on the characteristics of the material used, the use of coverings alters the microclimatic conditions of the orchard, but there is little knowledge on how these conditions alter the productive and physiological parameters of cherry trees. The aim of this doctoral thesis was to identify and study in depth the productive and physiological aspects that are modified in cherry orchards protected by different types of cover, with particular emphasis on the use of netting.

The first phase encompassed a comprehensive review of the current understanding of environmental factors such as light, temperature, relative humidity and wind involved in the production of cherry trees under different types of cover. This review also examined their effect on the physiological responses of the trees including leaf gas exchange, water relations, flower development, tree growth and development and fruit quality traits.

The main conclusions of this review were that using covers used on cherry trees increases the proportion of diffuse photosynthetically active radiation (PAR) and reduces the excess of direct PAR, which has a positive impact on the photosynthetic activity of the plant. However, this reduction in direct PAR leads to an imbalance in tree growth, promoting vegetative development at the expense of reproductive development. In addition, cherry trees under covers increase air temperature, which

would have a negative effect on fruit set and yield, but a positive effect on fruit growth. On the other hand, the use of covers would benefit the water status of the tree, but would alter the flow of specific nutrients such as calcium and thus fruit firmness. It is suggested that it is necessary to adapt the agronomic management of cherry orchards protected under covering to the specific microclimatic conditions and physiological responses that exist under cover materials.

The second phase involved the effect of photo-selective blue-grey (AG) netting with two weft and warp densities: 4 threads x 4 threads per linear cm⁻¹ (AG4x4) and 5 threads x 5 threads per linear cm⁻¹ (AG5x5), was studied in a commercial cherry orchard of Kordia and Regina cultivars, located in the locality of Camarico, Maule region, during two consecutive seasons. Their effect on light conditions, leaf gas exchange, flower development, yield and fruit quality characteristics was evaluated. Both nets reduced the photosynthetic photon flux density (PPFD) by 24% and 30% for AG4x4 and AG5x5, respectively. Light use efficiency, determined as the ratio of net CO₂ assimilation rate (A_n) to PPFD, was increased by 73% and 76% under netting for the Kordia and Regina cultivars, respectively. In terms of flower development, the AG5x5 net reduced the number of buds and flower primordia per bud by 20%, but had a positive effect on fruit size, which increased by 4% and 12% for the Kordia and Regina cultivars, respectively. Our results indicate that the use of AG photo-selective netting in cherry orchards would be a useful tool to optimize net leaf CO₂ assimilation and regulate fruit load in this fruit crop, while its effect on fruit quality traits is strongly influenced by cultivar and environmental conditions.

Keywords: Climate change, protected fruit growing, cover materials, production, physiology.

I. **CAPÍTULO 1: INTRODUCCIÓN GENERAL**

La producción sostenible de algunas especies frutales, como es el caso del cerezo, cada vez se ve más difícil de alcanzar debido a las condiciones climáticas inestables que afectan al cultivo, y por ende su producción. En Chile, los niveles de radiación y temperaturas elevadas en verano son cada vez más marcados, al igual que inviernos menos fríos dificultando el ciclo reproductivo de este cultivo, sin considerar la inestabilidad en la frecuencia de lluvias, granizos y heladas que ponen en riesgo constantemente la floración y cosecha de frutos.

1.1. Características del cerezo

El cerezo *Prunus avium* (L.) se originó en Asia y el sudeste de Europa, y es popular por su excelente calidad de fruta (Serradilla et al., 2012), cultivándose en aproximadamente 70 países y regiones de todo el mundo (Habib et al., 2017).

Las principales características de la calidad de la cereza son el color, el dulzor, la acidez y la firmeza (Esti et al., 2002). La composición de la cereza depende del cultivar, el clima y el estado de madurez (Mozetič et al., 2006). Una cereza ideal para el consumo tendría un tamaño de fruto óptimo ($\approx 12-15$ g. o 34 mm de diámetro), color intenso (escala 5, Center Technique Interprofessionnel des Fruits et Legumes [CTIFL]), alta firmeza del fruto, concentración mínima de sólidos solubles (≥ 18 ° Brix), pH óptimo del jugo (3.8) y acidez óptima (≥ 8 g / l de ácido málico), con balance óptimo de agridulce (1.5-2 contenido de sólidos solubles) [SSC] / ml NaOH) (Kappel et al., 2012).

Las cerezas son frutos estacionales; apareciendo en el mercado entre finales de primavera y principios de verano, durante el intervalo de frutas frescas no almacenadas. Por lo tanto, son muy apreciadas por los consumidores y, en algunos países incluso se perciben como una fruta de lujo debido a los altos precios que se paga por su consumo (Blando y Oomah, 2019).

Los altos retornos de precios para los productores han estimulado la producción de cerezas en diferentes regiones del mundo, tanto en zonas tradicionales como en

nuevas áreas productivas y a través de la introducción de nuevas variedades. No obstante, aun cuando existe material genético para este propósito, el clima es probablemente la variable más limitante para la expansión productiva de este cultivo en el mundo (Blando y Oomah, 2019).

1.2. Cambio climático

El cambio climático está afectando actualmente la agricultura y a través de eventos meteorológicos extremos como sequías, inundaciones, olas de calor, lluvias fuertes y tormentas de granizo (Boretti y Rosa, 2019; Zanocco et al., 2018), creando de esta manera una serie de estreses bióticos y abióticos en los árboles frutales. Un ejemplo de lo anterior es que el calentamiento global estaría incidiendo en una menor acumulación de frío invernal, obstaculizando de esta manera el adecuado desarrollo del ciclo biológico en especies frutales con altos requerimientos de frío como el caso del cerezo (Luedeling et al., 2013).

En el cerezo la producción se ve influenciada por condiciones ambientales como la acumulación de horas frío invernal, calor primaveral, heladas, granizos, lluvias y olas de calor, cuyas variables inciden directamente en los procesos de floración, cuajado, crecimiento, desarrollo y calidad y condición de los frutos (Blanke et al., 2017). Así por ejemplo, la incidencia de lluvias cerca de la cosecha puede traer consecuencias tales como agrietamiento de frutos (Drahošová et al., 2011; Sekse et al., 2005; Simon, 2006), o menor cuajado de frutos (Barbattini et al., 1983), mientras que altas temperaturas de verano puede inducir la formación de frutos dobles, entre otros problemas productivos (Beppu y Kataoka, 1999; Engin y Ünal, 2008; Johnson et al., 1994).

1.3. Sistemas de cobertura en cerezo

El uso de coberturas protectoras en huertos frutales es cada vez más frecuente y necesario para la protección frente a la inestabilidad climática de los últimos

años. Los sistemas más comúnmente utilizados son de material plástico o rafia (Balkhoven-Baart y Groot, 2005; Meland y Skjervheim, 1998; Simon, 2006), que operan como una protección física resistente al agua (Meland y Skjervheim, 1998), y con la finalidad de protección de frutos del agrietamiento provocado por lluvias previas a la cosecha. Algunas desventajas de los protectores de lluvias plásticos son el alto costo de implementación y la dificultad para regular la alta temperatura y la humedad relativa debajo de estas cubiertas, lo que puede inducir daños en las hojas y frutos y aumentar el riesgo de incidencia de enfermedades o de trastornos fisiológicos en los frutos (Simon, 2006).

Teniendo en cuenta el avance actual del cambio climático, el uso de mallas para prevenir del riesgo de estrés abiótico como el calor, la luz y el viento juega un rol fundamental (Kalcsits et al., 2017). En regiones cálidas, el uso de malla permite proteger a los cultivos del exceso de radiación solar y de las altas temperaturas que causan daños a la fruta, permitiendo al mismo tiempo aumentar la eficiencia del uso del agua y mejorando la adaptación de los árboles y la calidad de la fruta frente a condiciones de alto estrés ambiental (Nicolás et al., 2008).

En fruticultura existen diferentes opciones de mallas, incluidas las mallas antigranizo, de exclusión y foto-selectivas. Estas mallas tienen un impacto diferente en la respuesta y la producción de los árboles frutales según su tipo, el factor de sombra, color y densidad de sus hilos (Manja y Aoun, 2019; Cohen, et al., 2004).

Las mallas foto-selectivas cumplen la función de combinar la protección física con la capacidad de filtro de la radiación solar a través de la modificación de los colores y niveles de sombra (Arthurs et al., 2013; Milenkovic et al., 2012). Estas mallas han sido estudiadas en especies como el manzano (Bastías et al., 2012; Corollaro et al., 2015; Shahak, et al., 2004; Wachsmann et al., 2014), duraznero (Vuković et al., 2016), kiwi (Basile et al., 2012, 2014), arándano (Lobos et al., 2013; Zoratti et al., 2015) y algunas especies frutícolas de hoja persistente tales como mandarina (Wachsmann et al., 2014) y palto (Tinyane et al., 2018).

1.4. Influencia del uso de coberturas en factores micro-ambientales y respuestas fisiológicas

Las cubiertas de plástico o rafia utilizadas para disminuir el riesgo de partiduras de frutos generalmente tienden a aumentar la temperatura y humedad relativa con consecuencias en la calidad de la fruta (Bastías et al., 2017; Bastías y Leyton, 2018; Lang et al., 2011; Simon, 2006). En climas cálidos un aumento de la temperatura debido a una menor ventilación bajo estas cubiertas podría aumentar la demanda hídrica, provocando un estrés en las plantas (Blanke et al., 2017). Por otra parte, la reducción del viento junto con una mayor humedad relativa bajo cubiertas podría ayudar a sostener un mayor estado hídrico de los árboles como consecuencia de una menor demanda atmosférica (Blanco et al., 2021). En cuanto a la intensidad de luz solar, se ha indicado una reducción variable en la disponibilidad de luz bajo cubierta a nivel de huerto, y que oscila de un 15 % en los Países Bajos (Balkhoven-Baart y Groot, 2005), el 25 % en Estados Unidos (Lang et al., 2011) y 40% en Chile (Wallberg y Sagredo, 2014). En cuanto a las respuestas fisiológicas del cerezo bajo cubiertas, se ha observado que la tasa neta de fotosíntesis manifiesta una tendencia a presentar valores más altos bajo cubierta, la cual puede ser atribuida a la protección que brinda el plástico contra el exceso de radiación solar (Blanco et al., 2021a; Sotiropoulos et al., 2014). Sin embargo, otros autores mostraron una menor fotosíntesis neta, transpiración y conductancia estomática en cerezo bajo cubiertas, aunque la eficiencia del uso de la luz de la hoja se ha visto consistentemente incrementada (Zhang et al., 2021). En este mismo sentido, la capacidad de reducción de la luz solar por parte de las cubiertas es relevante como una práctica cultural que se ha utilizado en sistemas de invernaderos y huertos para reducir la carga de energía solar y aumentar la su eficiencia en huertos frutales (Jifon y Syvertsen, 2003), pudiendo mejorar crecimiento de las plantas al reducir el estrés por excesiva intensidad de radiación (Abdel-Ghany y Al-Helal, 2010), o modificar otras condiciones micro ambientales tales como velocidad y temperatura del viento y el aumento de la humedad relativa, disminuyendo con ello la demanda de evapotranspiración, lo que permite que las plantas aumenten

la conductancia estomática y, por lo tanto, la tasa asimilación de CO₂ en comparación con los cultivos que crecen al aire libre (Haijun et al., 2015).

1.5 Hipótesis

El uso de cubiertas protectoras en cerezo modifica las condiciones micro ambientales al interior del huerto protegido, generando respuestas en la planta y en los frutos debido a la modificación de parámetros tales como la luz, temperatura, viento y humedad relativa, impactando de esta manera en procesos fisiológicos del árbol tales como intercambio gaseoso de la hoja, estatus hídrico, crecimiento y desarrollo y caracteres de calidad de frutos.

En lo específico la presente investigación propone que la cobertura de huertos de cerezos con mallas con capacidad selectiva de transmisión de la luz solar impacta positivamente en los procesos fisiológicos y productivos que determinan el potencial de rendimiento y calidad de frutos en cerezos.

1.6. Objetivos

1.6.1. Objetivo general

Determinar aspectos productivos y fisiológicos en huertos de cerezo protegidos bajo diferentes tipos de coberturas, con énfasis en el uso de mallas.

1.6.2. Objetivos específicos

- Realizar una revisión del estado del arte sobre los efectos de coberturas en respuestas fisiológicas y factores ambientales para el cultivo del cerezo.

- Evaluar el efecto de mallas con capacidad selectiva de transmisión de la luz solar sobre indicadores de productivos, tales como rendimiento y calidad de fruta en dos cultivares comerciales de cerezo.
- Determinar el efecto de las mallas sobre indicadores fisiológicos de la planta tales como intercambio gaseoso de la hoja, intercepción y distribución de luz y desarrollo de la yema floral.

1.7. Referencias

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II. CAPÍTULO 2: ENVIRONMENTAL FACTORS AND PHYSIOLOGICAL RESPONSES OF SWEET CHERRY PRODUCTION UNDER PROTECTIVE COVER SYSTEMS: A REVIEW.

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2.1. Abstract

Climate change is increasing sweet cherry (*Prunus avium* (L.) L.) production under cover systems such as high tunnels, rain covers, and nets. The objective of this review is to provide an overview of the environmental factors and physiological responses involved in cherry production under different types of protective covering systems. The most important environmental factors affected by cover systems are photosynthetically active radiation (PAR), temperature, relative humidity, and wind speed, which in turn affect leaf gas exchange, plant water relations, tree growth, flower development, and fruit quality. The use of covering systems has a positive effect on photosynthesis by increasing the amount of diffused PAR, but a negative effect on the reproductive-vegetative tree balance due to lower total PAR availability. Increases in air temperature by cover systems alter differentially flowering and fruit set, impacting positively the ripening time and cell division of the fruits. Plant water status is improved under cover systems, allowing for greater tolerance to water deficit as well as improved potential fruit cell expansion, with an ensuing positive effect on fruit size, but decreasing fruit

firmness due to lower Ca availability fruits. The multiple environmental factors and physiological responses observed in cherry production under cover systems suggest the need to adjust agronomic practices such as pruning, crop load regulation, irrigation, and nutrition according to these specific conditions.

Keywords: Climate change, leaf gas exchange, netting, plastic covers, *Prunus avium*, sunlight, temperature.

2.2. Introduction

Sweet cherry (*Prunus avium* (L.) L.) is a high value fruit, being one of the most important fruits grown in temperate climates. The species is native to the Caucasus, but it is widely cultivated in approximately 70 countries and regions of the world (Habib et al., 2017), including Europe, North and South America, (Iezzoni, 2008), Asia, Africa, and Oceania (Bujdosó and Hrotkó, 2017).

As other fruit crops cultivated in temperate climates, cherry trees require a certain number of chill hours in winter and subsequent heat hours in spring for budding and flowering. In recent years, orchards with new cherry cultivars have been established, including early flowering cultivars with low chill requirements, such as 'Cristobalina', 'Brooks', 'Ruby', 'Somerset', 'Burlat' and 'New Star' (Alburquerque et al., 2008), as well as late flowering cultivars with greater chill requirements, such as 'Bing', 'Garnet', 'Celeste' (Gratacós and Cortés, 2007), 'Regina' (Vercammen and Vanrykel, 2014; Campoy et al., 2019), 'Sweetheart', 'Rubin' (Vercammen and Vanrykel, 2014), 'Emperor Francis', 'Early Burlat', 'Van', and 'Hedelfinger' (Longstroth and Perry, 1996).

Even though advances in breeding programs have allowed the cultivation of cherry in different climatic environments, current climate change conditions are affecting the normal development of this crop at a global level (Measham et al., 2014). In South America fruit growing areas such as Chile, climate conditions impact widely the cherry production by frost and rain events (Rojas et al., 2021). Similarly, in Europe cherry cultivation could be seriously affected by changes in the accumulation of chill hours in winter and heat hours in spring, frequency and intensity of frost, rain and hail

events during flowering and fruit set, sudden rains close to harvest, and high temperatures in summer (Blanke et al., 2017).

Fruit cracking and poor fruit set are the physiological disorders induced by climate with more impact in yield and profitability in cherries. Susceptibility to rain-induced cracking occurs 10 to 25 d before harvest (Simon, 2006), while reduced fruit set is caused by minimum and maximum temperatures in the range of 5 – 16°C, since lower temperature during the flowering results in a lower activity of pollinating bees or reduced viability and germination capacity of pollen granules (Roversi and Ughini, 1996). On the other hand, temperatures over 30°C during flower differentiation generate disorders in the development of ovaries and pistils, influencing double fruit formation (Engin and Ünal, 2008). In addition, more recent studies have indicated that when minimum and maximum temperatures ranged from 25°C to 35°C, and under water stress, negatively affect the net photosynthesis in cherry trees (Beppu et al., 2003).

Protecting trees with covers can prevent damage caused by adverse environmental conditions (Sotiropoulos et al., 2014). In various regions of the world, plastic covers and nets have allowed for maintaining yields in cherry by reducing the risk of rain-induced fruit cracking, fruit damage from birds, and/or tree and fruit damage from hail (Lang, 2014). There are many types of protective covers, including single- or multi-chapel systems, which are structures that cover trees without altering the normal management of the canopy (Janke et al., 2017), as well as plastic tents and high tunnels, which are mainly used in highly productive areas (Lang, 2014). Nets are among the most widely used materials in regions where fruit crops are exposed to heat stress as well as high solar radiation and wind speed (Oliveras-Soto and Bastías, 2018; Salazar-Canales et al., 2021). Plastic and woven covers are mainly used for rain protection. As temperature and relative humidity (RH) can increase under these covers, there is a higher risk of disease incidence, and thus ventilation is required to prevent damage to the leaves and fruit, decreased fruit color, and fruit softening (Simon, 2006; Lang et al., 2011; Bastías et al., 2017; Bastías and Leyton, 2018). Nevertheless, other studies indicate that covers also reduce the need for fungicides during the rainy periods

from flowering to the end of harvest (Børve and Stensvand, 2003). Greenhouse cultivation is a more recent practice in cherry orchards, which allows the creation of more favorable conditions for plant growth by artificially controlling air temperature and RH to extend growing seasons and improve yields (Perrin et al., 2014).

To establish adequate criteria for the agronomic management of cherry trees, it is essential to know and to understand the environmental factors and how these factors affect the physiological responses in the protected-environment cherry production (Lang et al., 2011). The objective of this review is to provide an overview of the environmental factors (light, temperature, RH, and wind speed) and physiological factors (leaf gas exchange, flower development, growth and development of the tree, and fruit quality) involved in cherry production under different types of protective covering systems.

2.3. Environmental factors

2.3.1. Light conditions

Photosynthetically active radiation (PAR) measured as photosynthetically active photon flux density (PPFD) plays a fundamental role in the process of photosynthesis. In cherry trees, the light saturation point of photosynthesis is reached at 900 $\mu\text{mol m}^{-2} \text{s}^{-1}$ PPFD (Zhang et al., 2021). Depending on climatic conditions, lower PPFD intensity has been reported in covered orchards, with reductions of 15% (Balkhoven-Baart and Groot, 2005), 25% (Lang et al., 2011) and 40% (Wallberg and Sagredo, 2014). Furthermore, the use of protective covering reduced light intensity by 40% and light distribution within the canopy by 50%, reaching 6% in the lower parts of the tree canopies, which is the critical level for the proper development of processes such as floral induction (Mika et al., 2019). The exposure time of the materials also influences photosynthetic light availability. Lang et al. (2011) showed that PPFD was reduced by 25% in the third year of the use of polyethylene, indicating that leaves exposed to filtered sunlight would receive enough light for photosynthetic activity. However, leaves

inside the canopy presented lower levels of light, and thus additional practices such as strategic pruning or the use of reflective orchard floor materials are required to maintain good light penetration through the canopy (Lang et al., 2011). In this sense, it is important to consider that the amount and composition of light inside the canopy change due to the effect of the optical properties of reflectance, absorbance and transmittance of the leaves (Baldini et al., 1997). These characteristics can be regulated by the type of material of the protective cover since specific light composition does not only affect photosynthesis and stomatal conductance, but also plant morphogenesis, pigment synthesis, insect activity, and other aspects (Lang, 2014). The color of nets can also alter aspects such as fruit growth or leaf stomatal conductance as observed in other fruit crops such as apples. Changes in light composition when using blue net (400-700 nm) compared to red net (600-700 nm) have been associated with higher fruit growth rates and stomatal opening of the leaves (Bastías et al., 2012; 2021). In tunnel cherry production, when incident light was reduced by up to 54% PPFD, UV-A (320-390 nm) and UV-B (280-320 nm) light levels were reduced by 22% and 2%, respectively (Schmitz-Eiberger and Blanke, 2012). Furthermore, there is evidence that changes in the UV light spectrum by polyethylene covers influences photosynthesis and the flight of pollinators, such as bees, since they have greater visibility and ability to detect floral organs in this UV light spectrum (Lang, 2014). Similarly, these variations in UV light levels also affect anthocyanin biosynthesis in the epidermis. This is relevant in yellow-fleshed cherry cultivars such as 'Sato Nishiki', 'Rainier' and 'Early Robin' because the red color of the fruits diminishes under covers with reduced UV light transmission (Mulabagal et al., 2009).

Bastías and Leyton (2018) showed that photosynthetic light transmission under cover changes on sunny and cloudy days, decreasing by 58% (due to their shading effect) and 36%, respectively (Figure 1). Differences in photosynthetic light transmission are also found between cover materials. On a sunny day, plastic can transmit about 7% more photosynthetic light than raffia; however, both materials roughly transmit the same amount of light on a cloudy day (Figure 1). This indicates that the use of protective covers significantly reduces the amount of light for

photosynthesis, its effect being more marked on sunny days ('shading effect') rather than cloudy days. Plastic covers can provide greater photosynthetic light availability than raffia covers, and thus it is more advisable to use materials that ensure a greater transmission capacity in this light component (Bastías and Leyton, 2018).

2.3.2. Temperature

In recent decades, global climate change has had impacts on temperature patterns, resulting not only in hotter and drier summers but also warmer winters, to which crops need to adapt (Kaufmann and Blanke, 2017a; 2017b). It has been reported that sustained high temperatures (35-40 °C) as a result of high solar radiation can impair key physiological processes for fruit tree cultivation, such as cell division, leaf expansion and reproductive development (Flaishman et al., 2015), which has also been observed in covered crops. There is evidence that when minimum temperatures under high tunnel exceeds in 2°C to the open field conditions can accelerate cell division and expansion during fruit development (Retamal-Salgado et al., 2015). This is particularly important in cherry crop because different growth and developmental stages, such as bud recession, flowering, and fruit growth, are subject to strict temperature control or can be seriously affected by extreme temperatures (Wenden et al., 2017). In fact, sustained low temperatures below a certain threshold result in continuous but reduced shoot growth, while a marked drop in temperature can induce an immediate cessation of growth (Sønsteby and Heide, 2019).

Plastic covers allow solar radiation transmittance but prevent or limit convective and radiative heat transfer to the outside, thus retaining energy and accumulating heat (Jett, 2017). However, this principle does not always ensure the control of a marked drop in temperature. In fact, a single-layer plastic cover does not provide complete protection from phenomena such as frost because radiant energy is transmitted relatively quickly, resulting in inefficient heat retention in the orchard and no additional heat. In this way, night temperatures inside polyethylene high tunnels equilibrate relatively quickly with that outside, even dropping below the freezing point, with an

increased risk of frost under the tunnel (Dekova and Blanke, 2007). However, a study by Janke et al. (2017) showed that double-layer plastic cover increased air temperature by an average of 12 °C in summer and 7.8 °C in winter, while the use of polyethylene row covers inside the high tunnel further moderated temperature fluctuation, increasing freeze protection. Furthermore, Vávra et al. (2019) found that covered cherry orchards increased the temperature by approximately 1-2 °C, helping reduce frost damage during flowering.

Considering that rain protection is required until harvest and that flower initiation and differentiation coincides with fruit ripening (Guimond et al., 1998), high temperatures during this period could affect the formation of flowers and even the following year's yield since an excessive rise in temperature in protected environment cherry cultivation could alter flowering time, causing sterility of the embryo sac (Sønsteby and Heide, 2019), and thus resulting in reduced fruit set and yield. Temperature can also alter fruit growth and development in cover systems. If temperatures are too low, fruit ripening is delayed; if temperatures exceed 28 °C for 2 h during the first stage of fruit growth, the fruit drop rate can reach as high as 50%-60%; and if the temperature exceeds 30 °C, fruit drop could exceed 80% (Zhang et al., 2018b).

Poor fruit set and double fruit formation are the most serious problems affecting cherry production due to temperature increase, which has accelerated due to global warming (Imrak et al., 2014). However, the occurrence of double fruit has rarely been observed in cherry cultivation under covering systems such as plastic greenhouses, which are used to anticipate harvest dates, even in warm regions. This occurs because the use of protective covers results in earlier flower differentiation, preventing double fruits due to high temperatures during the summer (Beppu et al., 2001). In fact, these systems have been used to reduce the incidence of double fruits. In this sense, Imrak et al. (2014) reported that the use of green netting with 55% light transmission reduced air temperature between 1.9 and 3.1 °C diminishing the pistil or double fruit formation by 60% and 28%, respectively. Furthermore, covers such as nets reduce incident radiation during bud differentiation and may reduce maximum air temperatures below

thresholds for abnormal pistil development (Beppu and Kataoka, 2000; Whiting and Martin, 2008; Imrak et al., 2014). The same effect can be achieved with the use of plastic and raffia covers, with reductions of 3-4 °C in fruit temperature due to lower incident solar radiation (Bastías and Leyton, 2018).

In greenhouse cherry cultivation, Zhang et al. (2018b) determined that the optimal temperature ranges were 5-18 °C for budding, 17-19 °C for flowering, and 22-25 °C during fruit development for cultivars 'Red Lamp', 'Tieton', 'Summit', 'Van', 'Lapins' and 'Santina'. In the same experiment was also determined that, compared to the reduction of the photoperiod by darkening with thick mats, the accumulation of cold was more effective in terms of fruit set and yield (Zhang et al., 2018b).

Another important aspect to consider when using protective orchard covering systems is the effect of temperature on good pollination and fruit set. A study conducted by Zhang et al. (2018a) showed that pollen hydration and germination were poor under low temperatures, while ovule viability decreased with increasing temperature. Highly productive cultivars such as 'Rainier' and 'Sweetheart' were more tolerant to warmer temperatures than 'Tieton' and 'Benton' (low productivity cultivars), suggesting that warm temperatures, which accelerate ovule senescence, are the main factor in the low productivity of some cherry cultivars. Likewise, temperature could affect the chemical characteristics of the fruit. In this sense, an increase in the content of phenolic compounds was observed in cherries grown under cover, being attributed to extremely high temperatures, particularly on days of intense solar radiation, limited air circulation, and stress associated with the plant (Schmitz-Eiberger and Blanke, 2012).

Avoiding overheating is a key issue in protective covering systems. The cover system commonly used in cherry orchard is the roof type which allows good ventilation thanks to the slope of roof and the spacing between rows (Børve et al., 2003). In high tunnel systems, the ventilation implies a high economic cost due to the fact that side covers need to be removed or layers of polyethylene need to be rolled when it is not raining, requiring a high amount of labor (Meland et al., 2017).

2.3.3. Relative humidity

Plastic covers and high tunnels are among the most popular covering systems in highly productive areas. They do not only modify the orchard environment but also RH, which plays an important role in certain development stages of cherries (Lang, 2014). During flowering, RH should be maintained in the range of 50% to 70% under controlled environments. If humidity is higher, pollen becomes “sticky”, while it dries and loses viability at very low humidity levels (Zhang et al., 2018b). The literature has described that high tunnels increase both RH and air temperature (Lang et al., 2016; Blanco et al., 2019b), affecting flowering and fruiting, and resulting in a negative impact on yield and fruit quality (Lang, 2014; Meland et al., 2017; Blanco et al., 2021a). Both temperature and RH determine the values of vapor pressure deficit that are reached under a protective covering, which plays an important role in leaf stomatal conductance (g_s), and thus in plant transpiration rate and photosynthesis (Righi et al., 2012). An increase in g_s of ‘Prime Giant’ cherry trees was observed under high RH and low vapor pressure deficit when the soil was in the field capacity (Blanco et al., 2018). In this sense, it has been reported that RH reached a maximum and minimum mean value that were 5% and 16% higher in high tunnels compared to open field conditions, respectively, with a slight decrease in vapor pressure deficit inside the tunnels (Blanco et al., 2021b). Furthermore, RH reached a lower maximum and minimum mean values in ran covers compared to values recorded under open field conditions (Bastías et al., 2017).

The RH is related to lower Ca concentration in cherries grown under high tunnel production systems because trees are exposed to higher RH and lower vapor pressure deficit, which may influence Ca absorption and distribution during fruit development (Blanco et al., 2021a), since the Ca presents lower mobility at phloem level and therefore is mainly transported to plant organs via xylem tissue and by transpiration driving force. Furthermore, this occurs due to a lower fruit transpiration rate (Winkler et al., 2020), and an increase in the vegetative growth of shoots rather than fruits (Blanco et al., 2021a).

For controlled greenhouse conditions, the optimum ranges of RH for proper budding, flowering, and cherry fruit development are 60%-80%, 50%-70%, and 50%-60%, respectively (Zhang et al., 2018b). An increase of 10% to 15% in RH can induce flower and fruit drop under rain covers due to excess water condensation, resulting in disease appearance (Blanke and Balmer, 2008). In addition, humidity control during fruit ripening is key to preventing fruit cracking. If RH increases above 75%, frequency of microcracks on the fruit surface increases exponentially (Knoche and Peschel, 2006). Conversely, Zhang et al. (2018b) showed that maintaining RH at values between 50% and 60% during mesocarp expansion effectively reduces the formation of cracks.

2.3.4. Wind speed

Wind is another factor that affects cherry production. In fact, the use of protective covers is essential in regions where wind limits production, affecting crop photosynthesis as well as respiration and transpiration rates (Girona et al., 2012). In this sense, Lang (2014) reported a reduction between 5 and 20 km h⁻¹ in wind speed in a high tunnel system. Reduced wind speed and increased RH under protective covering can cause negative effects on crops (Castellano et al., 2008), but positive aspects such as reduced evapotranspiration and a more efficient C acquisition have also been identified (Lang et al., 2016). Furthermore, reduced damage by wind results in lower bruising incidence and fruit rotting in orchards grown under covers (Lang, 2014). It should be noted that the type of covering system influences both wind speed and air circulation. Differences in wind speed between types of covering systems have been observed (Arthurs et al., 2013), particularly considering that ventilation allows reducing wind intensity, helping air move with less resistance under the covering (Blanke et al., 2017).

The extent to which protective covering systems influence light, temperature, RH, and wind depends on the type of covering, location, and management of the system by cherry growers (Table 1). In this sense, even when the use of rain covers is preferred because it is economically more convenient than uncovered orchards (Simon, 2006), it

is important to evaluate their potential benefits and limitations for cherry production in order to determine the cost-benefit ratio.

2.4. Physiological responses

2.4.1. Leaf gas Exchange

Maximum net CO₂ assimilation (A_n) of most C₃ species is saturated with a relatively low amount of photosynthetically active radiation (PAR) (600-900 $\mu\text{mol m}^2 \text{s}^{-1}$ PPFD, representing 30%-40% of total sunlight (1500-2000 $\mu\text{mol m}^2 \text{s}^{-1}$ PPFD). Temperature is one of the factors that can influence A_n ; in many deciduous trees, a reduction in A_n due to temperature increase occurs because of an increased respiration rate (Lakso, 1994). Beppu et al. (2003) showed that A_n decreased when cherry trees grown under low temperatures were subjected to temperatures above 25 °C, while trees grown at high temperatures reached maximum A_n at 30 °C, decreasing to a smaller extent even up to 35 °C, which demonstrates that there is temperature acclimatization of the photosynthesis of cherry tree leaves. This effect of temperature on leaf gas exchange can be exacerbated by conditions of low soil moisture in summer, decreasing A_n , transpiration rate (E) and g_s , and resulting in a decrease in carbohydrate accumulation (Beppu et al., 2003).

The use of protective covers can differentially alter leaf gas exchange depending on the material used. Bastías et al. (2011; 2021) showed that, regardless of PAR intensity, the use of blue netting resulted in an increase in A_n , E and leaves in apple (*Malus domestica* (Suckow) Borkh.) compared to the use of red netting, affecting photosynthetic capacity due to changes in the amount and quality of light. On the other hand, the use of low-density plastic covers in blueberries (*Vaccinium corymbosum* L.) grown in a high tunnel system increased g_s values compared to those grown under open field conditions, which can be attributed to a greater availability of diffuse PAR under cover (Retamal-Salgado et al., 2015). In general, even though polyethylene films used in greenhouses or tunnels can reduce total PAR transmission they increase the

amount of diffuse PAR, which is beneficial for photosynthesis and crop productivity (Li et al., 2014).

In cherry, there are differences in the photosynthetic adaptation to low light conditions (Wang and Hu., 2014). A recent study conducted by Zhang et al. (2021) revealed that using the plastic covers with ability of 55% of PAR transmission resulted in decreases of 43% and 45% in A_n in 'Tieton' and 'Brooks' cherry cultivars, respectively, due to insufficient light under cover. On the other hand, it has been reported that using plastic cover with ability of 85 – 87% of PAR transmission increased A_n in 'Santina' and 'Van' cultivars (Sotiropoulos et al., 2014; Blanco et al., 2021b), demonstrating that photosynthetic responses of tree cherry under cover systems is widely influenced by the characteristics of cover materials and cultivars.

2.4.2. Water relations

There are different studies on water relations focused on irrigation strategies aimed at improving water productivity without reducing crop yield and quality (Blanco et al., 2019a). These studies and strategies should be adjusted in orchards under covers since protected environmental conditions tend to reduce water evaporation from the soil, resulting in greater availability of water for irrigation (Janke et al., 2017). When transpiration demand is high under open field conditions without covering, in dwarfing rootstock there is greater hydraulic resistance to supply water to the leaves, leading to decreases in plant water potential and g_s . Blanco et al. (2021b) with 'Santina' cherry trees on 'Colt' (*P. avium* × *P. pseudocerasus*) rootstock showed that minimum stem water potential recorded in trees grown in high tunnels reached -0.83 MPa., while uncovered trees recorded a value of -1.15 MPa. Furthermore, water potential of fruit depends to a large extent on stem water potential (Blanco et al., 2019c), while it is related to environmental variables such as vapor pressure deficit (Measham et al., 2014; Blanco et al., 2018). In this sense, it has been reported that high tunnel cultivation improves plant water status by reducing vapor pressure deficit and losses due to water evaporation, increasing midday stem water potential. This would lead to an increase

in the water potential and turgor of the fruit, promoting higher growth rates (Blanco et al., 2021b).

2.4.3. Flower development

The use of netting allows reducing incident solar radiation during flower differentiation, which would mitigate the negative effect of high summer temperatures, e.g., abnormal development of pistils and fruits (Beppu and Kataoka, 2000; Whiting and Martin, 2008; Imrak et al., 2014). Tunnel closure during flower development increases air temperature during the spring (Blanke et al., 2017), which can induce abnormal late flowering and poor fruit set; furthermore, heat stress during flowering. It has been estimated that when air temperature exceed 1 to 3 °C in comparison to normal conditions, can reduce fruit set because temperature increase promotes accelerated growth of the pollen tube, a reduced number of pollen tubes that grow in the style, ovule degeneration and decreased stigmatic receptivity (Hedhly et al., 2007), demonstrating the importance of ventilation practices in cherry production under cover systems, especially during spring with warm conditions or the use cover materials with more ventilation ability such as netting systems. In addition, have been indicated that high temperatures of early summer can lead to the suppression of flower initiation in cherry production under covering (Sønsteby and Heide, 2019), while the increase in temperature at the end of bud breaking allows advancing the flowering date, resulting in a positive impact on advance in harvest date and better prices in the market, therefore a positive impact in the profitability without increase in the costs of fruit production (Dekova and Blanke, 2007). In this sense, to balance the negative and positive effects of temperature increase, it is advisable to grow cultivars with abundant flower buds and high and stable yield, such as 'Summit' and 'Lapins' (Zhang et al., 2018b).

2.4.4. Tree growth and development

It has been described that winter dormancy in cherry trees is controlled by the interaction of photoperiod and temperature (Heide, 2008). Covers with an impact on light quality, such as colored nets, alter the amount of light in the blue, red, and far-red spectra, affecting shoot growth and bud break patterns, mediated by the interaction of photoreceptors as phytochromes and cryptochromes (Bastías and Corelli-Grappadelli, 2012). Limited sunlight conditions under protective covering favor shoot growth over fruit development, with an impact on the balance of vegetative and reproductive growth of the tree. In this case, covers that reduce the amount of red light vs. red-far light promote greater shoot development, while those that increase this proportion allow a more balanced control of shoot growth, positively influencing fruit growth (Bastías et al., 2012).

Lang et al. (2011) demonstrated that high tunnel cultivation of sweet cherry allowed for greater growth and development of trees, resulting in more rapid filling of allotted space with increases of 24% and 20% in tree height and leaf size, respectively. Similar results were found in previous studies on cherry trees grown under cover, showing more vigorous growth (Blanke and Balmer, 2008), or increased crown volume and growth of new shoots (Rubauskis et al., 2013) compared to uncovered trees. However, more recent studies have described that there is no detectable difference in vegetative growth under covers (Blanco et al., 2019b). Even though the greater increase in growth and development of trees under covers can be mainly attributed to light conditions (Bastías and Corelli-Grappadelli, 2012; Bastías et al., 2012), this could also be regulated by temperature. Lang (2014) demonstrated that high tunnel covers increased growing degree day (GDD) by 10%. This agrees with Retamal-Salgado et al. (2015) and Sønsteby and Heide (2019), who found that shoot growth increases with the increase in exposure time to high temperatures in the greenhouse, resulting from air temperature increase. It should be noted that excessive vegetative growth of cherry trees grown in high tunnels could negatively affect light interception and distribution within the canopy, reducing fruit quality and flower differentiation for the following season (Ayala and Lang, 2017). In addition to what is mentioned above; during flower

development the air temperature increases, which can induce abnormal late flowering and poor fruit set; in addition, heat stress during flowering.

2.4.5. Fruit quality

The use of protective covers increases fruit size, which is attributed to the effect of light conditions on the balance between shoot and fruit growth (Bastías et al., 2012), or to the temperature increase during flowering and fruit set, which promotes higher cell division during the first growth stage (Retamal-Salgado et al., 2015; Bastías and Leyton, 2018). Lang et al. (2011) indicated that fruit weight in 'Rainier' cherry trees grown in tunnels was higher compared to non-covered trees. This increase in fruit size due to the effect of covers has been reported in different studies on 'Lapins' (Wallberg and Sagredo, 2014); 'Samba', 'Bellise' and 'Rita' (Overbeck et al., 2017); 'Burlat', 'Samba' and 'Prime Giant' (Schmitz-Eiberger and Blanke, 2012); 'Ulster' (Cline et al., 1995); and 'Royal Down' and 'Santina' (Bastías and Leyton, 2018), these results would be indicating that reducing in the fruit quantity due to lower fruit set under covers, as was mentioned above, would be resulting in better fruit quality in terms of fruit size.

Regarding color development, the results are contradictory. There are studies that report low color values in cherries grown under covers under climate conditions with lower sunlight availability such as Norway, Germany and southern of Chile (Børve et al., 2003; Dekova and Blanke, 2007; Wallberg and Sagredo, 2014), while other studies report higher values of fruit colors in cherry orchards cultivated under climate conditions with more sunlight availability such as Greece and central-northern of Chile (Kafkaletou et al., 2015; Bastías et al., 2017). It should be noted that covers have an important impact on fruit color, particularly in bicolor cherries such as 'Rainier' (Lang, 2009).

Regarding fruit firmness, there is evidence that this parameter is not affected in cherry cultivation under covers in warm climate when were only installed during the critical periods of rain-cracking (Kafkaletou et al., 2015; Mika et al., 2019). However, several studies have reported that when protective covers are installed in cherry orchards for the whole period and from flowering to harvest, fruits tend to be softer

(Dekova and Blanke, 2007; Wallberg and Sagredo, 2014; Bastías and Leyton, 2018). Similarly, Meland et al. (2017) reported that fruit from trees covered from the straw-yellow fruit stage to harvest was firmer than fruit covered from flowering to harvest. In addition, the presence of firmer fruits under cover has been reported only in early stages of harvest of cherries grown in countries in which the weather present lower or moderate temperature conditions such as Norway and Germany (Cline et al., 1995; Dekova and Blanke, 2007; Schmitz-Eiberger and Blanke, 2012). Finally, Blanco et al. (2021a) described lower firmness in ‘Santina’ sweet cherries under plastic covers, which is associated with lower Ca concentrations in the fruit, probably induced by the high tunnel microclimate (high RH) that reduces fruit transpiration rate (Winkler et al., 2020) and increases vegetative growth, leading to Ca imbalances in the fruit.

Regarding sugar content, higher levels of glucose, fructose and sorbitol have been reported in cherries grown under cover (Usenik et al., 2009), with higher levels of total soluble solids (Børve et al., 2003; Usenik et al., 2009; Rubauskis et al., 2013; Wallberg and Sagredo, 2014; Meland et al., 2017). However, Suran et al. (2019) found a lower content of soluble solids in cherry cultivation under cover, while other studies have reported adequate total soluble solids and titratable acidity relationships (Schmitz-Eiberger and Blanke, 2012; Kafkaletou et al., 2015; Zhang et al., 2018b). Furthermore, the covering system could also have an influence on sugar content, thus fruit from trees covered with umbrella-type cover recorded a lower content of soluble solids compared to the fruit from trees under sloped-roof covering (Børve et al., 2003).

In summary, the effect of covers on fruit quality parameters differs depending on the type of cover, location, and management of the system. This information is a key tool to support the decision making by cherry growers (Table 2).

2.5. Conclusions

The use of protective covers is an effective strategy for the control abiotic stress in cherry trees, particularly rain and other climate hazards. However, covers alter environmental conditions of light, temperature, relative humidity, and wind, affecting the

physiological responses of the tree, depending on climate conditions and characteristics of cover materials. Protective covers increase the amount of diffused PAR, benefiting the photosynthetic activity of cherry trees due to protection from excessive direct radiation, but generating an imbalance between vegetative and reproductive growth. This occurs because covering systems decrease the total amount of available light to the plant, negatively affecting light distribution in the canopy. Excessive increase in temperature under covers during flowering and flower set can negatively affect crop yield, while it can positively affect cell division, also anticipating harvest date by accelerating fruit ripening. Cherry trees under cover have a better water status compared to uncovered trees, showing better tolerance to water deficit and improved fruit turgor potential, with positive impacts on fruit size. Regarding fruit quality parameters, covers increase fruit size due to their positive effect on cell division (temperature) and expansion (hydric status), but they decrease fruit firmness, apparently due to the lower availability of Ca in the fruits. Increasing of fruit size by covers could also to be related to reduction of fruit load and regulated by the temperature conditions during the flowering and fruit set. The effect of covering systems on color and sugar content has not been fully determined yet. The multiple environmental factors and physiological responses observed in cherry production suggest the need to adjust agronomic practices such as pruning, tree management, load regulation, irrigation, and nutrition according to the specific conditions for each protective covering system.

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Table 1. Influence of different protective covering systems on environmental conditions in sweet cherry (*Prunus avium* (L.) L.)

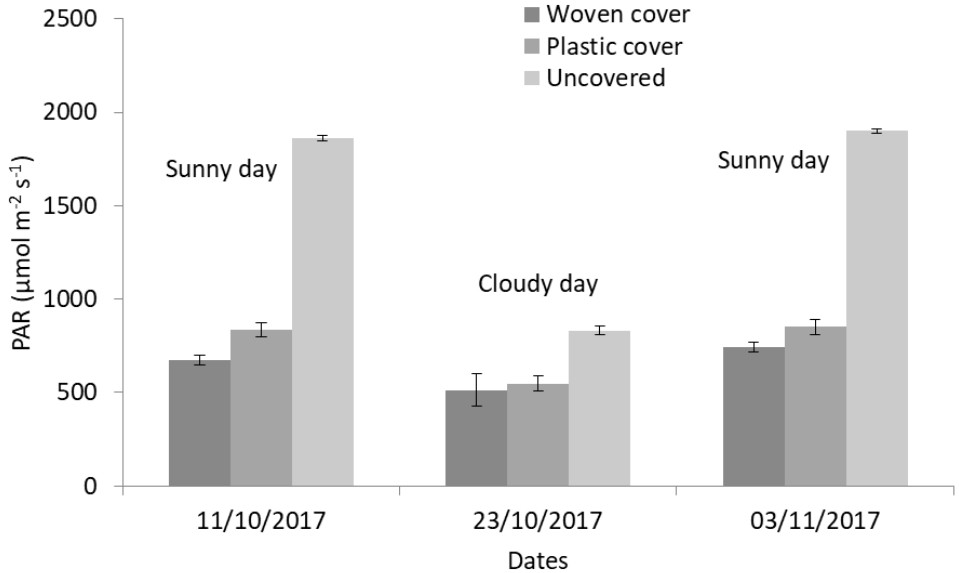
Variable	Cover system	Response	Reference
Temperature	Rain protective shelter	Increased	Børve et al., 2003; Børve and Stensvand, 2003; Simon, 2006; Schmitz-Eiberger and Blanke, 2012
Temperature	Woven shade	Decreased	Beppu and Kataoka, 2000
Temperature	Green plastic nets	Decreased	Imrak et al., 2014
Temperature	Hight tunnel	Increased	Blanke and Balmer, 2008; Blanco et al., 2019a; 2021a; 2021b
Temperature	Greenhouse	controlled	Zhang et al., 2017
PAR	Tunnel	Decreased (15%-40%)	Balkhoven-Baart and Groot, 2005; Blanke and Balmer, 2008; Lang et al., 2011; Lang, 2014; Overbeck et al., 2017; Mika et al., 2019
PAR	Poly tunnel	Decreased (up to 54%)	Schmitz-Eiberger and Blanke, 2012
PAR	Hygrove Poly tunnel	Decreased (16 to 25%)	Overbeck et al., 2017
PAR	Shelter plastic cover	Decreased (up to 58%)	Overbeck et al., 2018
PAR	Gabled (Vöen™) crop covers	Decreased (40%)	Wallberg and Sagredo, 2014
RH	Hight tunnel	Increased	Blanke and Balmer, 2008; Blanco et al., 2019b
RH	Umbrella type covers	Increased	Børve et al., 2003

PAR: Photosynthetically active radiation; RH: relative humidit

Table 2. Influence of different cover materials on sweet cherry quality parameters (*Prunus avium* (L.) L.)

Variable	Material	Response	References
Firmness	Plastic cover	Higher	Cline et al., 1995; Meland et al., 2017
Firmness	Plastic cover	Lower	Dekova and Blanke, 2007; Blanke and Balmer, 2008; Maria et al., 2008; Lang, 2014; Wallberg and Sagredo, 2014; Bastías et al., 2017; Meland et al., 2017; Bastías and Leyton, 2018; Blanco et al., 2019b; Suran et al., 2019; Blanco et al., 2021a
Firmness	Plastic cover	Without difference	Schmitz-Eiberger and Blanke, 2012; Kafkaletou et al., 2015; Mika et al., 2019
Firmness	Woven cover	Decreased	Maria et al., 2008
Color	Plastic cover	Increased	Cline et al., 1995; Dekova and Blanke, 2007; Schmitz-Eiberger and Blanke, 2012; Bastías et al., 2017
Color	Plastic cover	Decreased	Børve et al., 2003; Simon, 2006; Dekova and Blanke, 2007; Mulabagal et al., 2009; Wallberg and Sagredo, 2014; Mika et al., 2019
Color	Plastic cover	Without difference	Blanco et al., 2021b
Soluble solids	Plastic cover	Lower	Børve et al., 2003; Schmitz-Eiberger and Blanke, 2012; Kafkaletou et al., 2015; Zhang et al., 2018b; Blanco et al., 2019a
Soluble solids	Plastic cover	Higher	Børve et al., 2003; Usenik et al., 2009; Rubauskis et al., 2013; Wallberg and Sagredo, 2014; Bastías et al., 2017; Meland et al., 2017; Bastías and Leyton, 2018
Soluble solids	Plastic cover	Without difference	Overbeck et al., 2017; Blanco et al., 2021b
Size	Plastic cover	Increased	Cline et al., 1995; Schmitz-Eiberger and Blanke, 2012; Rubauskis et al., 2013; Wallberg and Sagredo, 2014; Overbeck et al., 2017; Blanco et al., 2019a
Size	Plastic cover	Decreased	Blanke and Balmer, 2008
Size	Plastic cover	Without difference	Meland et al., 2017
Weight	Plastic cover	Without difference	Børve et al., 2008; Usenik et al., 2009; Sotiropoulos et al., 2014
Weight	Plastic cover	Higher	Balkhoven-Baart and Groot, 2005

Figure 1. Photosynthetically active radiation (PAR) transmission in cherry orchards covered under woven, plastic and without cover (control) in Chile (adapted from Bastías and Leyton, 2018).



Each point represents the mean \pm standard error.

III. CAPÍTULO 3: PHOTO-SELECTIVE NETTING IMPROVES LEAF-LEVEL LIGHT USE EFFICIENCY, REDUCES FLOWER DEVELOPMENT, AND ALTERS FRUIT QUALITY TRAITS IN ‘KORDIA’ AND ‘REGINA’ SWEET CHERRY TREES

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3.1. Abstract

Plastic or woven rain covers have been widely evaluated for preventing rain-induced damage in sweet cherry, but the recent use of netting to prevent damage from heat waves has been little explored. There is scarce information about the impact of netting on cherry crop physiology and production. The objective of this study was to evaluate the effect of blue-gray (BG) photo-selective nets of two different thread densities on light conditions, leaf gas exchange, flower development, yield, and fruit quality in ‘Regina’ and ‘Kordia’ cherry orchards. The experiment was conducted in two

consecutive seasons, using the following protection treatments, BG4x4 (4 thread cm⁻¹) and BG 5x5 (5 thread cm⁻¹). A control treatment consisting of non-covered trees was also included. Both BG4x4 and BG5x5 netting reduced the photosynthetic photon flux density (PPFD) by 24% and 30%, respectively, compared to the control. In addition, both treatments significantly increased ($p < 0.05$) light use efficiency measured as a ratio of net photosynthesis rate (A_n) and incident PPFD, with respective increases of 73% and 76% in 'Kordia', and 15 % and 57% in 'Regina'. In both cultivars, the use of BG5x5 netting reduced the number of flower buds or flower primordia per bud by about 20% compared to the control, but with significant increases of 4% and 12% in fruit size for 'Kordia' and 'Regina', respectively. The use of nets did not affect the quality of the fruit, it even improved the size. The results indicate that BG netting is a useful tool to optimize net CO₂ assimilation and crop load regulation by managing available sunlight in cherry orchards. Its impact on fruit quality traits should be validated according to cultivar and cultivation site.

Keywords: Protected fruit growing, two-colored nets, leaf gas exchange, flower induction, fruit size, *Prunus avium* (L). L.

3.2. Introduction

Altered weather patterns associated with climate change have affected sweet cherry (*Prunus avium* (L).L.) production, resulting in damage to flowering due to rain and frost, development of double fruits due to extreme temperatures, defoliation, and post-harvest water stress (Blanco et al., 2019). Globally, the use of protection systems is recognized as an effective technology to prevent crop damage. In sweet cherry trees, the used of woven or plastic covers has gained great popularity, providing protection from flowering to the end of the harvest, and thus preventing rain- or frost-induced damage during flowering as well as fruit cracking in stages close to the harvest (Børve & Stensvand, 2003). Similarly, high tunnels and roof covers, which exert greater control

of microclimatic temperature conditions, have shown positive effects on cherry production by enhancing growth, advancing harvest date, and increasing yields (Lang, 2014).

Netting is also an effective tool to protect orchards. In cherry, it has been recently introduced to prevent disorders such as double fruits due to high temperatures (Bastías et al., 2023), the adverse effects of water scarcity (Stone et al., 2022), and rain-induced fruit cracking (Gonçalves et al., 2023). Unlike woven and plastic covers, nets are made of a porous, non-waterproof material with different radiometric, mechanical and air permeability properties, thus preventing damage from excessive solar radiation and high temperature, wind, hailstorms, and attacks by insects or bird (Castellano et al., 2008).

Depending on the thread density and color, nets can significantly alter the amount and quality of solar radiation, thus changing the physiological and productive responses of crops (Bastías and Boini, 2022). In this sense, a study conducted by Blanke (2007) with monofilament nets demonstrated that white nets (3 x 9 mm), gray nets (2.8 x 6.9 mm) and black nets (2.5 x 6.5 mm) reduced photosynthetically active radiation (PAR) by 7%, 13%, and 18%, respectively. Colored nets (blue, red) have effects on the spectral transmission of sunlight. White, grey, or black nets do not alter the spectral transmission of light at different wavelengths; red nets reduce light transmission in the blue spectrum (400-500 nm) and increase it in the red (600-700 nm) and far-red (700-800 nm) spectrum; and blue nets alter light transmission in the opposite way (Bastías and Boini, 2022).

The changes caused by netting in quantity and quality of solar radiation affect leaf gas exchange in fruit species, with different responses depending on the type of net, species, and climatic conditions. In apples (*Malus domestica* Borkh.), black netting at 20% shade reduced net CO₂ assimilation (A_n) and stomatal conductance (g_s) by 14% and 21%, respectively (Gindaba & Wand, 2007), while pearl-gray netting at 22% shade increased A_n and g_s by 50% (Bastías et al., 2021a). Blue and red nets at 40% shade with the same density triggered different responses in apple; blue nets increased g_s by

21% compared to red nets, which was attributed to the stimulation of a greater leaf stomatal opening in the presence of blue light (Bastías et al., 2021b). In blueberry (*Vaccinium corymbosum* L.), A_n increased depending on the PAR transmitted under the nets, with the highest A_n value recorded up to 50 - 60% of PAR and the lowest value under black netting at 75 % shade (Lobos et al., 2012).

The literature has also reported on the effects of color netting on the reproductive and vegetative responses of plants. In kiwi plants (*Actinidia deliciosa* (A. Chev.)), the use of blue, gray, red and white anti-hail nets decreased fertility and yield (Basile et al., 2008). In addition, red and gray nets increased vegetative growth, while blue nets resulted in a reduction (Basile et al., 2014). In blueberry, a reduction between 41 and 53% of PAR with the use of colored nets resulted in negative effects on the number of flower buds, but it did not affect yield (Lobos et al., 2013).

Netting can also affect fruit quality traits to different extents depending on the fruit species. In apple trees, blue and gray nets increased fruit size by 15 - 20% (R. M. Bastías et al., 2012). In pear (*Pyrus communis* L.) trees, fruit size increased by 95% (Shahak et al., 2008). In table grapes (*Vitis vinifera* L.), the use of this protective system increased berry weight in 30% (Shahak et al., 2008). In peach (*Prunus persica* (L.) Batsch.), netting resulted in a 9% increase in fruit size, but a 30% decrease in fruit firmness (Vuković et al., 2017). In blueberries, fruit size was not affected, but firmness was up to 20% greater under netting depending on the cultivar and climatic conditions (Matamala et al., 2023).

Several studies have reported on the effect of netting on the physiology and production of different fruit species. However, there is limited information regarding the effect of this technology on cherry orchards because studies on this species have mainly focused on the effects of woven and plastic covers (Salvadores and Bastías, 2023). In order to cope with the challenges of the current climate change scenario, blue-gray photo-selective nets have been recently developed to control the damage associated with high temperatures and excessive solar radiation in fruit crops, such as apple trees (Bastías and Boini, 2023). The present work details a field experiment

design to address the following question: Can specific light conditions under these photo-selective nets alter the physiology, production and fruit quality in cherry trees. Therefore, the objective of this study was to evaluate the effect of blue-gray photo-selective nets with two different thread densities on the quantity and quality of sunlight, leaf gas exchange, flower development, yield, and fruit quality in 'Regina' and 'Kordia' cherry orchards.

3.3. Materials and Methods

3.3.1. Plant material and experimental design

The trial was carried out during two consecutive seasons (2018/2019 and 2019/2020) in a 6-year-old commercial cherry orchard located in Camarico, Talca Province, Río Claro District, Maule Region, Chile (35°14'09.1"S; 71°14'28.5" W). The study site is characterized by a cold temperate climate with dry and hot summers and humid winters. Rainfall is mainly concentrated in autumn and winter (Del Pozo and Del Canto, 1999), with an annual average of 1012 mm. The highest temperatures are recorded in January, with an average of 29.1°C, and the lowest temperatures are recorded in July, with an average of 12.1°C (DGA, 2023). The orchard was established in a planting frame of 4.5 x 2.5 m, with an east–west orientation. The trial was established in 'Regina' and 'Kordia' cultivars grafted on Maxma 14 rootstock. The orchard was irrigated using a sprinkler system with a flow rate of 4 L h⁻¹. The trees were trained on a central axis system, with lateral branches of lower vigor than those of the central axis.

From full bloom (second and first week of September for the 2018/2019 and 2019/2020 seasons, respectively) until leaf fall (beginning of May for both seasons), the trees were covered with blue-gray (BG) monofilament nets (Delsantek S.A., Chile), at warp and weft densities of 4 threads per cm (BG4x4) and 5 threads per cm (BG5x5) (Fig. 1). Non-covered trees were used as control.

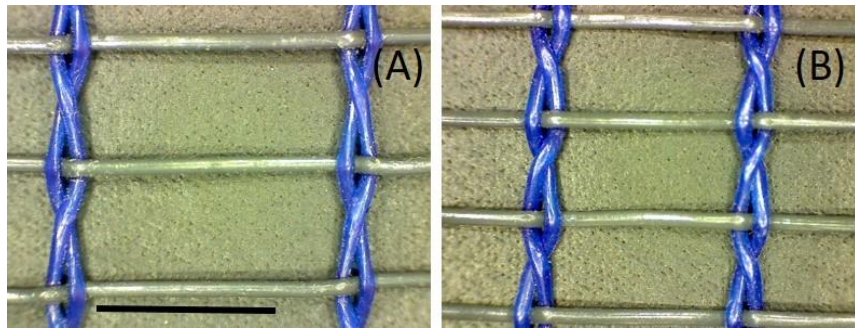


Fig.2. Details of blue-gray monofilament net at warp and weft densities of 4 threads per cm (BG4x4) and 5 threads per cm (BG5x5) used to covers the cherry orchard experiment. Black bar = 5 mm.

The nets were placed in a roof-type system at a height of 4.5 meters from the ground and covering plots of six rows of trees and 742.5 m². The experiment was conducted using a completely randomized block design with three replicates and two trees as experimental unit (Fig. 2).



Fig. 3. Experimental plot under blue-gray netting at 4x4 (BG4x4) and 5x5 (BG5x5) thread densities, compared with a non-covered control (C) in a commercial sweet cherry orchard arranged in three blocks (B I, B II and B III).

3.3.2 *Light conditions*

A sample of each type of 1 x 1 m BG4x4 and BG5x5 net was placed at a height of approximately 1.5 m in order to determine the spectral transmission of light at a wavelength range of 350 - 1700 nm. Measurements were made at full sun at noon, using a dual UV-VIS-IR spectrum radiometer BLUE-Wave and DWARF-Star models, which were connected to a CR2 cosine receptor (StellarNet INC., Tampa FL, USA), and following the methodology used by Olivares-Soto et al. (2020). After the harvest, the photosynthetically active photon flux density (PPFD, $\mu\text{mol m}^{-2} \text{s}^{-1}$) was measured above and below the tree canopy using an AccuPAR LP-80 ceptometer (Decagon Devices, USA). To determine PPFDD below the canopy, the ceptometer rod was passed at ground level and above wooden slats graduated every 40 cm, from the midpoint of a row to the midpoint of the following row. The measurements were made 2 hours before solar noon (9:00 – 10:00 AM), at solar noon (12:00 – 1:00 PM) and 2 hours after solar noon (3:00 – 4:00 PM). The data collected was used to determine the amount of PPFDD transmitted under the nets. Light interception (%) and the amount of transmitted light (%) by the tree were estimated according to the methodology proposed by Wünsche et al. (1995).

3.3.3. *Leaf gas exchange*

Before harvest (3 and 12 days before harvest for 'Kordia' and 'Regina' for the 2019/20 and 2018/19 seasons, respectively), measurements of PPFDD ($\mu\text{mol m}^{-2} \text{s}^{-1}$), net CO₂ assimilation rate (A_n , $\mu\text{mol m}^{-2} \text{s}^{-1}$), stomatal conductance (g_s , $\text{mmol m}^{-2} \text{s}^{-1}$) and leaf transpiration rate (E , $\text{mmol m}^{-2} \text{s}^{-1}$) were made using a TARGAS 1 equipment (PP System International, Inc., Massachusetts, USA). Based on the obtained data, photosynthetic light use efficiency (LUE, A_n/PPFD), water use efficiency (WUE, A_n/E), and intrinsic water use efficiency (IWUE, A_n/g_s) were determined as proposed by Kong et al., (2017) and Bastías et al., (2021a). All measurements were made in full sun on one leaf per tree and at two time points (morning and afternoon) from 09:30 to 11: 00

a.m. and from 3:00 p.m. to 4:30 p.m. The sampled leaves were mature and fully exposed from the middle zone of one-year shoots.

3.3.4. *Flower development and yield*

During the bud dormancy period (183 and 161 days before harvest for 'Kordia' and 'Regina for the 2018/2019 and 2019/2020 seasons, respectively), 5 two-year-old spurs and 5 one-year-old shoots were collected per tree. The buds from each spur and shoot were dissected transversely using a scalpel. Subsequently, the lower part of the bud was carefully opened until the flower primordia (FP) were visible. The total number of PF per spur (S) or annual shoot (OS) was determined by observation under a stereoscopic at a 10X (Model SZ61, Olympus, Kyoto, Japan), which was connected to a KL 1600 LED camera (SCHOTT, Mainz, Germany). At harvest, the total number of fruits per tree was weighed using a precision scale model PCE-PCS 30 (PCE Instruments, Santiago, Chile) and yield was expressed as kg per tree.

3.3.5. *Fruit quality*

Thirty fruits were randomly collected from each tree and the following parameters were determined: firmness and fruit diameter (mm) using a Firmtech 2 equipment (Bioworks Inc., Kansas, USA); pedicel detachment force (kg) using a dynamometer model FGV-5XY (Shimpo, Massachusetts, USA); soluble solids (°Brix) using a digital refractometer model HI 96801 (Hanna Instruments, Woonsocket, Rhode Island, USA); and acidity (%) using a digital refractometer model PAL BX 1 ACID F5 (Atago, Tokyo, Japan). Fruit color was measured using a CTIFL scale (Centre Technique Interprofessionnel des fruits et légumes).

3.4 *Data analysis*

Data were analyzed using an analysis of variance (ANOVA). Prior to this, assumptions of normality and homogeneity of variances were evaluated. Mean separations were performed using the LSD Fisher test ($\alpha = 0.05$). For non-normally distributed data, a Friedman's test was performed. All analyzes were carried out using the Infostat statistical software (Balzarini et al., 2008).

3.5. Results

3.5.1. Light conditions

The spectral sunlight transmission analysis allowed determining that BG4x4 and BG5x5 nets transmitted 38% and 29% of the incident UV radiation (350-400nm), respectively. Regarding photosynthetically active radiation, PAR (400-700nm), transmission reached 65% and 60% for BG4x4 and BG5x5, respectively (Fig. 3). Solar radiation in the near-infrared spectrum (NIR, 800-1100nm) transmitted under the protection systems was 64% and 61% for BG4x4 and BG5x5 netting, respectively. In the case of shortwave infrared (SWIR, 1100 – 1700 nm), BG4x4 and BG5x5 nets transmit 92 and 91% of the incident radiation for that wavelength, respectively (Fig. 4). The BG4x4 netting has higher transmission, mainly of UV and PAR radiation, compared to the BG5x5 netting.

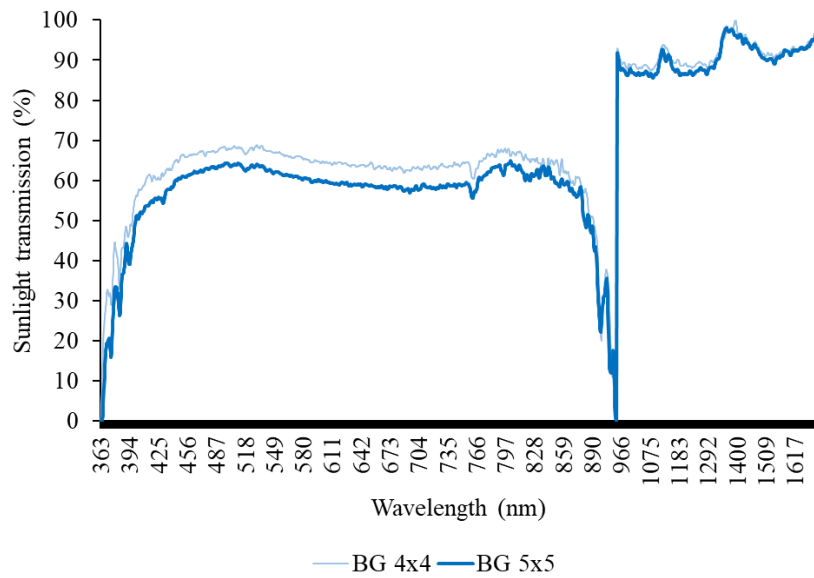


Fig. 4. Spectral sunlight transmission of blue-gray netting at 4x4 (BG4x4), and 5x5 (BG5x5) thread densities.

The blue-gray nets significantly affected the transmission of PPFD measured above the tree canopy for both ‘Regina’ and ‘Kordia’ in the 2018/2019 and 2019/2020 seasons. For ‘Kordia’, BG4x4 and BG5x5 nets significantly reduced PPFD transmission by an average of 23% and 33% considering both seasons, respectively. For ‘Regina’, this reduction was 25% and 30%, respectively. In the 2018/2019 season, ‘Kordia’ recorded a significant increase in light transmission in the BG4x4 netting treatment compared to the control (non-covered trees) and the BG5x5 netting (Table 3). The light interception was not significantly affected by the protection systems evaluated.

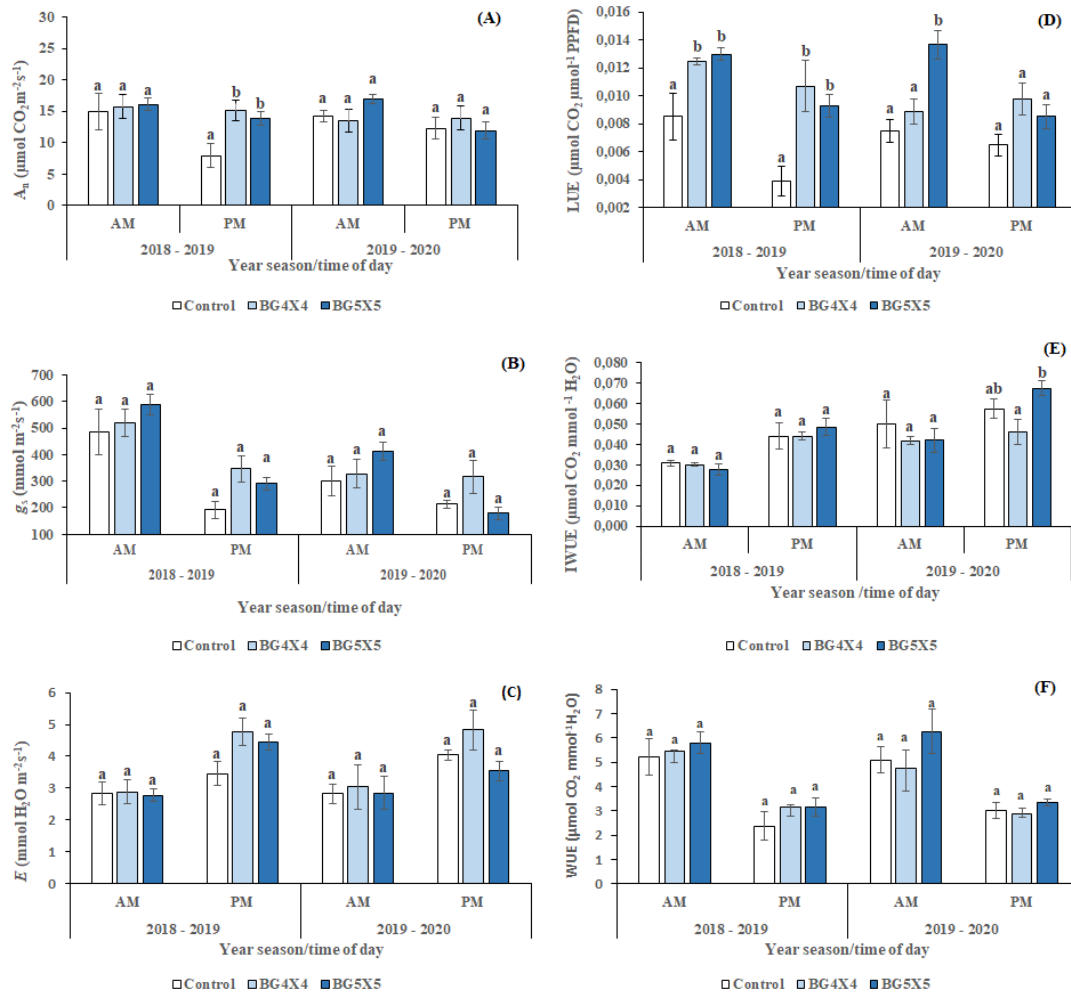
Table 3. Photosynthetic photon flux densities (PPFD) of blue-gray netting at 4x4 (BG4x4), and 5x5 (BG5x5) thread densities, compared with full sunlight (control). **: highly significant and non-significant at $P < 0.005$. Different letters within columns denote significant differences by LSD test.

PPFD light Transmission	'Kordia'				'Regina'			
	Control	BG4x4	BG5x5	<i>P-value</i>	Control	BG4x4	BG5x5	<i>P-value</i>
2018/2019 season								
PPFD above canopy ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	1800.54 c	1373.80 b	1191.52 a	$< 0.0001^{**}$	1820.34 c	1364.42 b	1269.37 a	$< 0.0001^{**}$
PPFD transmission (%)	29.06 a	33.2 c	29.9 ab	0.0037^{**}	47.03 a	47.0 a	44.8 a	0.3848^{ns}
PPFD interception (%)	70.9 a	66.8 a	70.1 a	0.7655^{ns}	52.7 a	53.0 a	55.2 a	0.8069^{ns}
2019-2020 season								
PPFD above canopy ($\mu\text{mol m}^{-2}\text{s}^{-1}$)	1959.21 c	1507.68 b	1343.11 a	$< 0.0001^{**}$	1987.55 c	1508.97 b	1393.83 a	$< 0.0001^{**}$
PPFD transmission (%)	30.1 a	33.1 a	30.0 a	0.7487^{ns}	46.4 a	48.4 a	42.7 a	0.1651^{ns}
PPFD interception (%)	69.9 a	66.9 a	70.0 a	0.8579^{ns}	53.6 a	51.6 a	57.3 a	0.4005^{ns}

3..5.2. Leaf gas exchange

For 'Kordia', the use of the BG4x4 and BG5x5 nets did not significantly affect g_s , E or WUE of leaf in any of the evaluated seasons or periods (Fig. 5 B – C y F), but it had a significant effect on A_n , LUE and IWUE (Fig. 5 A, D – E). During the 2018/2019 season, BG4x4 and BG5x5 netting increased A_n for the PM period by 89.8% and 73.8%, respectively (Fig. 5A). In the 2018/2019 season, BG4x4 netting increased LUE by 47% in the AM period and by 174% in the PM period (Fig. 5D). In the same season, the BG5x5 netting treatment recorded increases of 53% and 138% in LUE for the AM and PM periods, respectively (Fig. 5D). In the 2019/2020 season, the BG5x5 netting treatment increased LUE by 83% for the AM period compared to the non-covered trees (control), showing no significant differences in the PM period (Fig. 5D). Additionally,

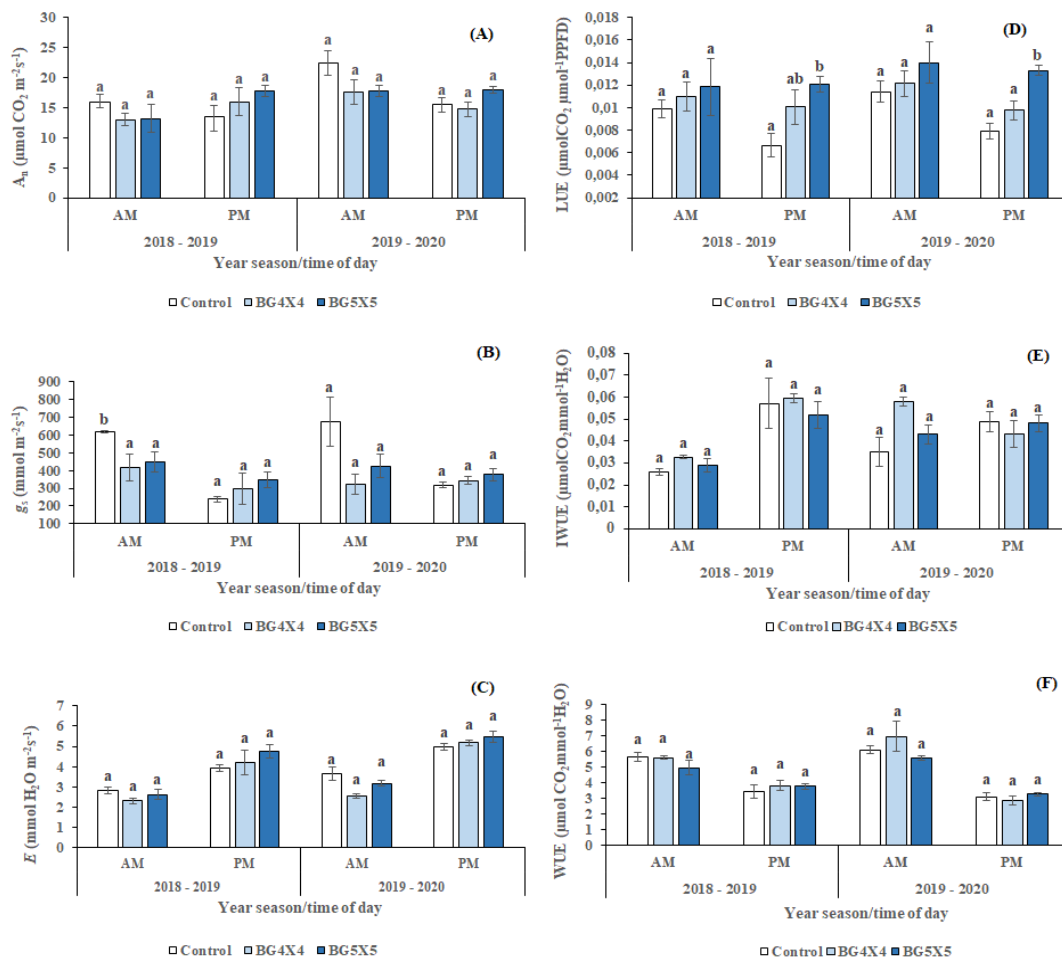
IWUE was 17% higher in the BG5x5 netting treatment compared to the BG4x4 treatment during the PM period in the 2019/2020 season, but IWUE did not differ from that recorded in the non-covered trees (Fig. 5E). Both seasons are compared for each cultivar with their measurements in two periods of the day AM and PM.



Different letters denote significant differences by LSD test. The significance level was determined at the 5%.

Fig. 5. Influence of blue-gray netting at 4x4 (BG4x4) and 5x5 (BG5x5) thread densities, compared with full sunlight (control) on (A) net photosynthesis rate (A_n), (B) stomatal conductance (g_s), (C) transpiration rate (E), (D) photosynthetic light use efficiency (LUE), (E) intrinsic water use efficiency (IWUE), and (F) water use efficiency (WUE) in 'Kordia' sweet cherry leaves.

For 'Regina', the use of BG4x4 and BG5x5 nets did not significantly affect leaf A_n , IWUE, E or WUE in any season or time period (Fig. 6 (A), (E), (C) and (F)). However, the protection systems resulted in significant increases in LUE in both 'Regina' and 'Kordia' (Fig. 6D). The LUE recorded under BG5x5 nets and during the PM period was 68% and 82% higher than the control for the 2018/2019 and 2019/2020 seasons, respectively. It is important to note that the use of the BG4x4 and BG5x5 netting significantly decreased in this cultivar, while g_s decreased during the AM period by 32% and 27%, respectively, compared to the non-covered trees (Fig. 6B).



Different letters denote significant differences by LSD test. The significance level was determined at the 5%.

Fig. 6. Influence of blue -gray netting at 4x4 (BG 4x4) and 5x5 (BG5x5) thread densities, compared with full sunlight (control) on (A) net photosynthesis rate (A_n), (B) stomatal conductance (g_s), (C) transpiration rate (E), (D) photosynthetic light energy use efficiency (LUE), (E) intrinsic water use efficient (IWUE), and (F) water use efficiency (WUE) in 'Regina' sweet cherry leaves.

3.5.3. Flower development and yield

For 'Kordia', BG5x5 netting significantly affected flower development in terms of number of flower buds and number of flower primordia (Table 4). In both seasons, BG5x5 netting resulted in a reduction of 21% and 24% in the number of flower buds and flower primordia per one-year-old shoot, respectively, compared to the non-covered trees. Similarly, the number of spur buds was negatively affected by BG5x5 netting during 2018/2019 season, with an average decrease of 18% compared to the non-covered trees (Table 4). On the contrary, the 4x4 BG netting did not negatively affect flower development in terms of spur flower buds and shoot buds of this cultivar in any of the seasons. In addition, it should be noted that no significant effects of any of the netting systems was observed on 'Kordia' fruit yield (Table 4).

Table 4. Influence of blue-gray (BG) netting at 4x4 (BG4x4) and 5x5 (BG5x5) thread densities, compared with full sunlight (control) on spur flower bud (FB S⁻¹), one-year-old shoot bud (FB OS⁻¹), spur flower primordium (FP S⁻¹), one-year old shoot primordium (FP OS⁻¹), and yield (kg tree⁻¹) in on 'Kordia' sweet cherry trees. **: ns: highly significantly and non-significantly at $P < 0.005$. Different letters within columns denote significant differences by Friedman's test.

Treatments	FB S ⁻¹ (N°)	FB OS ⁻¹ (N°)	FP S ⁻¹ (N°)	FP OS ⁻¹ (N°)	Yield (kg/tree)
Season					
2018/2019					
Control	7.0 a	8.8 b	18.4 a	22.0 b	25.44 a
BG4x4	6.5 a	8.0 b	16.9 a	18.8 b	22.96 a
BG5x5	6.5 a	6.7 a	17.0 a	15.9 a	27.28 a
<i>P</i> -value	0.3616	0.0007**	0.3673	0.0028**	0.2626 ^{ns}
2019/2020					
Control	7.2 b	6.2 b	18.7 a	20.4 b	19.79 a
BG4x4	7.3 b	5.5 ab	15.1 a	22.6 b	20.34 a
BG5x5	5.9 a	5.1 a	15.7 a	16.5 a	18.01 a
<i>P</i> -value	0.015**	0.0216**	0.139 ^{ns}	0.0019**	0.7443 ^{ns}

For 'Regina', BG4x4 netting significantly reduced the number of spur flower primordia in the 2018/2019 season, being 16% lower than the control (Table 5). In the 2019/2020 season, BG4x4 netting decreased the number of spur flower buds by 17%, while BG5x5 netting decreased the number of spur flower primordia by 21% compared to the control (Table 5). In the same season and cultivar, the BG4x4 and BG5x5 netting treatments decreased fruit yield by 26% and 47%, respectively (Table 5).

Table 5. Influence of blue-gray (BG) netting at 4x4 (BG4x4) and 5x5 (BG5x5) thread densities, compared with full sunlight (control) on spur flower bud (FB S⁻¹), one-year-old shoot bud (FB OS⁻¹), spur flower primordium (FP S⁻¹), one-year old shoot primordium (FP OS⁻¹), and yield (Kg tree⁻¹) in 'Regina' sweet cherry trees. **: ns: highly significant and non-significant at $P < 0.005$. Different letters within columns denote significant differences Friedman test.

Treatments	FB S ⁻¹ (N°)	FB OS ⁻¹ (N°)	FP S ⁻¹ (N°)	FP OS ⁻¹ (N°)	Yield (kg/tree)
2018/2019 season					
Control	6.0 a	6.2 a	16.2 b	14.4 a	18.0 a
BG4x4	5.5 a	6.3 a	13.6 a	14.0 a	14.2 a
BG5x5	6.0 a	5.8 a	14.9 ab	13.3 a	16.6 a
<i>P</i> -value	0.19 ^{ns}	0.7003	0.0255 ^{**}	0.9757 ^{ns}	0.3397 ^{ns}
2019/2020 season					
Control	6.3 c	6.8 a	21.0 b	23.0 a	29.0 c
BG4x4	5.2 a	6.3 a	17.8 ab	21.7 a	21.4 b
BG5x5	5.4 ab	6.9 a	16.6 a	22.5 a	15.5 a
<i>P</i> -value	0.0297 ^{**}	0.2125 ^{ns}	0.043 ^{**}	0.2088 ^{ns}	0.0004 ^{**}

3.5.4. Fruit quality

BG4x4 and BG5x5 netting significantly decreased 'Kordia' fruit firmness in both seasons, with average reductions of 7% and 14% with respect to the control,

respectively (Table 6). However, fruit size increased by 4% under BG5x5 netting in the 2019/2020 season, and by 3% under BG4x4 netting in the 2018/2019 season. Additionally, BG4x4 netting significantly reduced fruit color by an average of 6% in both seasons (Table 6). Soluble solids content or fruit acidity were not affected by the netting treatments in this cultivar.

Table 6. Influence of blue-gray (BG) netting at 4x4 (BG4x4) and 5x5 (BG5x5) thread densities, compared with full sunlight (control) on fruit quality parameters in 'Kordia' sweet cherry orchard. Different letters denote significant differences by LSD test. The significance level was determined at the 5%.

Treatments	Fruit firmness (g mm ⁻¹)	Fruit color CTIFL	Fruit size (mm)	Soluble Solids ° Brix	Acid Content (%)
Season					
2018/2019					
Control	345.65 c	5.81 b	25.70 a	18.10 a	1.14 a
BG4x4	321.09 b	5.44 a	26.36 b	17.27 a	0.88 a
BG5x5	293.98 a	5.86 b	26.02 ab	15.80 a	0.92 a
P values	< 0.0001**	<0.0001**	0.0079**	0.2723 ^{ns}	0.5939 ^{ns}
Season					
2019/2020					
Control	362.37 c	5.80 b	27.48 b	20.70 a	1.05 a
BG4x4	337.49 b	5.43 a	27.05 a	18.42 a	0.85 a
BG5x5	317.28 a	5.85 b	28.52 c	18.10 a	0.92 a
P values	< 0.0001**	<0.0001**	<0.0001**	0.1319 ^{ns}	0.2238 ^{ns}

For 'Regina', BG5x5 netting significantly increased fruit firmness by 4.6% in the 2018/2019 season. However, the netting treatments showed no significant effects on fruit firmness in the following season (Table 7). In addition, the nets had a significant effect on fruit color, with a 5% decrease in the 2018/2019 season. Conversely, increases of 8.4% and 14% in fruit color were recorded in the 2019/2020 season under BG4x4 and BG5x5 netting, respectively (Table 7). Regarding fruit size, BG5x5 netting

resulted in a significant increase of 12% in the 2019/2020 season compared to the non-covered trees. In the same season, BG5x5 netting significantly increased the soluble solids content by an average of 12.6% compared to the control. Both netting treatments reduced acidity by an average of 6% compared to the control, but this effect was observed only during the 2018/2019 season (Table 7).

Table 7. Influence of blue-gray (BG) netting at 4x4 (BG4x4) and 5x5 (BG5x5) thread densities, compared with full sunlight (control) on fruit quality parameters in ‘Regina’ sweet cherry orchard. Different letters denote significant differences by LSD test. The significance level was determined at the 5%. *, **, ns: highly significant and non-significant at $P < 0.005$. Different letters within columns denote significant differences by LSD test.

Treatments	Firmness (g mm ⁻¹)	Color CTIFL	Size (mm)	Soluble Solid ° Brix	Acid Content (%)
Season					
2018/2019					
Control	302.08 a	5.16 b	27.85 a	19.02 a	0.98 a
BG4x4	304.18 a	4.88 a	27.82 a	18.80 a	0.92 b
BG5x5	315.98 b	5.19 b	28.11 a	17.85 a	0.92 b
<i>P values</i>	0.0294**	0.0002**	0.1684 ^{ns}	0.2301 ^{ns}	0.051*
Season					
2019/2020					
Control	361.84 a	4.79 a	26.53 a	17.37 a	0.55 a
BG4x4	360.18 a	5.19 b	26.81 a	18.23 ab	0.54 a
BG5x5	351.42 a	5.46 c	29.70 b	19.55 b	0.58 a
<i>P values</i>	0.136 ^{ns}	<0.0001**	<0.0001**	0.0472*	0.5274 ^{ns}

3.6. Discussion

3.6.1. Photo-selective netting improves the photosynthetic light use efficiency in cherry leaves

Sunlight is the main environmental factor determining yield and fruit quality in fruit trees, since PPFD plays a key role in photosynthesis and carbohydrate partitioning (Corelli-Grappadelli et al., 2017). Several authors have reported that the reduction in PPFD by the use of netting impacts A_n in different ways (Bastías et al., 2021; Salazar-Canales et al., 2021). In cherry trees, the light saturation point of photosynthesis is reached at $900 \mu\text{mol m}^{-2} \text{s}^{-1}$ PPFD (Zhang et al., 2021). In the present study, PPFD availability decreased by about 24% under BG4x4 netting and close to 32% under BG5x5 netting, corresponding to approximate values of 1450 and $1300 \mu\text{mol m}^{-2}\text{s}^{-1}$ PPFD, respectively. This indicates that PPFD values under both protection systems were higher than the maximum light saturation levels for cherry trees (Zhang et al., 2021), and thus the decrease in light availability under netting had no negative effects on photosynthesis. This is further corroborated by the fact that the netting treatments showed no negative impact on leaf A_n in both 'Regina' and 'Kordia'. In the latter cultivar, A_n reached significantly higher values in BG4x4 and BG5x5 netting in the PM period for the 2018/2019 season (Fig. 5A), which aligns with the findings of Bastías et al. (2012) using of blue netting in apples. Other studies on the same species have recorded a reduction in A_n with the use of black and green-black nets, which highlights the importance of net color in influencing net in leaf photosynthetic capacity (Gindaba & Wand, 2005; Solomakhin & Blanke, 2008).

Previous studies carried out on European hazel (*Corylus avellana* L.) revealed that the use of blue-gray photo-selective nets reduced PPFD by 24% but increased the proportion of diffuse PPFD by 47% (Salazar-Canales et al., 2021). In this context, it has been demonstrated that the effect of net color on the higher proportion of diffuse light enhances leaf-level LUE (i.e. the ratio between A_n and incident PPFD), as observed in species such as paprika (*Capsicum annuum* L.). In this case, higher LUE values were obtained with the use of pearl-colored netting compared to black netting, which is related to the high light dispersion capacity provided by the former in the photosynthetically active light spectrum (Kong et al., 2017). In our research, BG4x4 and BG5x5 nets significantly increased LUE in both cherry cultivars and seasons (Fig. 5D, 6D). This was particularly evident during the PM period, i.e. when the levels of radiation

and temperature are higher or more stressful for the plant. This finding agrees with previous reports that observed higher LUE values when leaves were exposed to high temperatures and excessive solar radiation in apple trees grown under blue photo-selective nets compared to the uncovered trees (Mupambi et al., 2018).

In the present study, UV light was altered by the use of blue-gray nets, with reduction of 60 and 70% under the BG4x4 and BG5x5 treatments, respectively (Fig. 4). Increased LUE has been associated with the reduction in UV radiation under netting by two mechanisms. One is that less UV light would reduce the probability of photoinhibition in leaves, as the UV spectrum would induce a greater inhibitory effect on photosynthesis compared to other components of sunlight (Kong et al., 2017). The other mechanism would involve the development of leaves with a lower palisade and cuticle thickness. The increase in thickness of these cell layers has been related to a defense mechanism of the leaf against high levels of UV radiation. Given that netting reduces UV radiation, the cell layers of the leaves would be less developed, resulting in more efficient light transmission to the inner part of the leaf and thus greater CO₂ assimilation (Kong et al., 2017).

Another factor that could explain the greater LUE in cherry leaves under netting is the variation in the light spectrum or light color. In this regard, a previous study conducted by Bastías et al. (2021) revealed that leaves grown under blue- and red-colored netting develop as shade leaves, limiting their photosynthetic capacity due to a reduced palisade-cell development and lower stomatal density; however, these morphological changes did not affect their performance in the A_n rate. This could explain the greater LUE found in leaves of 'Kordia' and 'Regina' cherry trees grown under BG5x5 and BG4x4 netting (Figs. 5D and 6D). Additionally, net color may influence the g_s of the leaves. It has been described that the wavelength of blue light is more effective than red light in promoting the opening of the stomata and preventing their closing (Bastías et al., 2021). In the present study, even though nets with a blue color component were used, g_s did not show significant increases in any of the seasons, type of net or cherry cultivar evaluated (Fig. 5B and 6B). Therefore, the positive effect

on LUE could not be attributed to the effect of the light color component on the g_s . Other studies have reported the importance of blue light in improving chlorophyll and other pigments of the light harvesting complex (LHC-II) and, under conditions of shade or low level of PPFD, enhancing the photosynthetic capacity of the leaf, which is mediated by plant-specific photoreceptors called phototropins (Mathur et al., 2018). The present work measured PS-II efficiency in leaves under netting (data not shown), but no significant effects were observed. As pigments were not studied, the increase in LUE under nets could not be attributed to these biochemical factors, thus constituting a subject for future research.

3.6.2. Reduction of light availability under photo-selective netting harms flower induction, but improves fruit size in cherry trees

It has been described that the reduction in light availability affects the reproductive stage of the fruit tree because it has a direct effect on the induction and differentiation of flower buds (Corelli-Grappadelli, 2003). In the present study, the use of photo-selective netting significantly reduced the number of flower buds and flower primordia per bud in both cultivars (Tables 2 and 3), which agrees with previous reports in blueberry (*Vaccinium corymbosum* L.) (Lobos et al., 2012) and kiwi (Basile et al., 2008). In our trial, the period in which the nets were installed (flowering to leaf fall) coincided with the period of flower bud induction occurring late in the spring (Villar et al., 2020). A higher reduction in flower buds was observed under BG5x5 netting in both cultivars and to a lower extent in BG4x4 netting only in 'Regina' (Tables 4 and 5). Therefore, these results demonstrate that flower development in cherry trees would be partially limited by netting that reduces light transmission by 25%, but much more significantly limited by a 30% reduction (Table 3).

The reduction in light availability under netting also affected flower development in the two evaluated cherry cultivars. This can be explained by the fact that light conditions inside the canopy may be limiting for adequate flower development, being

accentuated by the use of the netting systems. In this regard, Scofield et al. (2020) have described that light interception in adult cherry trees, which exhibit greater leaf development, is higher than in young cherry trees with lower flower development, doubling the percentage of intercepted light. However, light transmitted to the inner canopy in adult orchards is low, with values close to 7% compared to the 56% transmission in younger cherry trees (Scofield et al., 2020). In the present study, light transmission below the canopy reached values close to 30% in 'Kordia' and 46% in 'Regina' in both seasons (Table 1). These values measured below the canopy would be lower than those in younger trees, which have a greater light transmission capacity (Scofield et al., 2020). This suggests that protected cultivation under photo-selective nets requires canopy management, including pruning and training technique, to allow for a better penetration of light into the innermost parts of the tree and ensure greater flower development in that area of the orchard.

The reduction in light availability under netting led to a decreased flower development, reaching a maximum reduction of approximately 20% for both cultivars, especially with BG5x5 (Tables 4 and 5). In cherry trees, the use of manual or chemical thinning techniques to reduce the amount of flowers has been proposed as a method to control fruit load, thereby enhancing quality traits such as fruit size, which positively affects the market price for growers (Whiting & Ophardt, 2005). One of the chemical alternatives is the use of the growth regulator gibberellic acid (GA_3), when applied at a concentration of 50 mg L⁻¹ and 100 mg L⁻¹ during the flower bud induction stage reduced the number of flowers by 27% and 38%, respectively, improve fruit size by 2% and 3% (Lenahan et al., 2006).

A reduction of 20% in flower development observed with the use of BG5x5 netting resulted in an increase in fruit size by 4% and 12% in 'Kordia' and 'Regina', respectively (Tables 4 and 5). This suggests that the use of photo-selective netting could be an effective non-chemical tool for controlling the number of flowers and managing fruit load in cherry trees, particularly in combinations of cultivars and rootstocks that exceed optimum fruit load. This approach could reduce production

costs and the use of agrochemicals, thereby offering a more economically and environmentally sustainable alternative for cherry production under the current climate change scenario.

3.6.3. Photo-selective netting differentially affect the fruit firmness, color, sugar and acidity.

The effect of the photo-selective netting on fruit firmness differed depending on the cherry cultivar, with a reduction observed in 'Kordia' but no negative effects on 'Regina' (Tables 6 and 7). To the best of the authors' knowledge, this is the first report on the effect of this type of blue-gray photo-selective netting on fruit firmness in cherries. In contrast, the effect of waterproof woven or plastic covers on fruit firmness has been extensively documented (Bastías and Leyton, 2018; Blanco et al., 2019; Blanco et al., 2020). In blueberries, Matamala et al. (2023) evaluated the effects of rain cover and netting materials, finding significantly firmer fruits under netting, with differences attributed to with UV light exposure. The cuticle provides protection against excessive sunlight, resulting in fruits exposed to higher UV radiation developing thicker cuticle as a defense mechanism. In the present study, BG4x4 and BG5x5 netting reduced UV light transmission by 60% and 70%, respectively (Fig.3), indicating that the changes in fruit firmness observed in 'Kordia' could be associated with UV light exposure. This aligns with the findings of Bastías and Boini (2023) in apple trees, where as the fruits grown under netting with a 15% decrease in light transmission were firmer than those grown under netting with 55% shade. However, the reduction in light transmission does not explain the results observed in 'Regina', suggesting that the response of fruit firmness to light conditions under netting is cultivar dependent and involves anatomical aspects, such as differences in cuticle and epidermis thickness, as well as internal cell development of the fruits, as recently was reported in blueberries and apples (Bastías and Boini, 2023; Matamala et al., 2023).

Regarding fruit color, BG4x4 netting reduced color intensity in both 'Kordia' and 'Regina', while BG5x5 netting maintained or increased this parameter. The decrease

in color observed with BG4x4 netting can be attributed to the reduction in light intensity, specifically in UV light as it is involved in the synthesis of anthocyanins (Pino et al., 2023). Given that the reduction in UV radiation was greater with BG5x5 netting, a greater reduction in fruit color development was expected; however, this did not occur. This can be explained by the reduction in flower buds under netting, leading to a greater supply of carbohydrates through the regulation of fruit load, which is essential for the synthesis of anthocyanins and color development in fruits (Serra et al., 2016).

With respect to soluble solids content and acidity, netting showed effects only in 'Regina' and in one of the evaluated seasons. Recent studies have reported varied values of sugars as well as adequate levels of soluble solids and titratable acidity, indicating that the effect of protection systems on quality parameters varies depending on the type of cover, location, and management of the cover used (Salvadores and Bastías, 2023). Therefore, it is important to understand the interactions between crop environment, cultivar, and protection systems.

3.7. Conclusions

The use of blue-gray photo-selective netting decreased photosynthetic light availability by 25% and 30%, but this did not affect net photosynthesis rate. In fact, photosynthetic light efficiency improved in the leaves of both cherry cultivars under protected cultivation. From an eco-physiological perspective, these results demonstrate that the leaves of cherry trees grown under netting make more efficient use of sunlight in the process of net CO₂ assimilation. This is likely influenced by factors such as net color, the effect of netting on a higher proportion of diffuse light and leaf anatomical and biochemical traits, which require to be further exploration.

Changes in light availability resulting from variations in thread density of the nets significantly reduced flower development, but with only a partial reduction and a positive impact on the increase in fruit size. This suggests that the use of photo-selective netting could be a useful non-chemical tool to regulate crop load in cherry orchards.

The effect of netting on fruit quality parameters such as firmness, color, and soluble solids content depend on the cultivar and climatic conditions. Therefore, it is difficult to predict with certainty how netting systems would impact these parameters in other latitudes and cultivars. More in-depth studies are required to evaluate the behavior of these types of nets in different cultivars and environmental conditions to determine their impact on fruit quality.

3.8. CRediT authorship contribution statement

Yessica Salvadores: Writing — original draft, Methodology, Data curation, Formal analysis. **Richard M. Bastías:** Writing – review & editing, Supervision, Project administration, Resources, Funding acquisition, Conceptualization, Investigation, Formal analysis, Visualization. **María Dolores López:** Writing – review & editing. **Karen Sagredo:** Writing – review & editing.

3.9. Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

4.0. Data availability statement

The data presented in this study are available in the article.

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IV. CONCLUSIONES GENERALES

El uso de cubiertas de plástico o rafia para la protección del cerezo frente a condiciones climáticas, principalmente lluvias cercanas a cosecha, sigue siendo el método más efectivo para el control de partidura. Sin embargo, bajo esta condición de huerto protegido se generan una serie de modificaciones en factores ambientales tales como en la intensidad y calidad de la luz solar, temperatura, humedad relativa y velocidad del viento, lo cual genera respuestas tanto positivas como negativas debido cambios en procesos fisiológicos de la planta, tales como intercambio gaseoso de la hoja, estatus hídrico, crecimiento y desarrollo reproductivo y vegetativo, y caracteres de calidad de los frutos, que ameritan un ajuste en el manejo agronómico de este cultivo bajo esta condición particular de cultivo protegido.

La producción de cerezo bajo malla, es una alternativa de protección poco explorada en este cultivo. Los hallazgos encontrados a partir de esta investigación doctoral, plantean que el uso de malla azul-gris se presenta como una alternativa interesante para huertos comerciales de cerezo, ya que estarían mejorando la eficiencia del uso de la luz solar por parte del cultivo y tendrían un efecto regulador de carga frutal al permitir controlar el desarrollo de yemas florales con impacto positivo en un mayor tamaño de frutos, lo que podría ser útil como método de raleo “no químico” para huertos de cerezos que se cultivan bajo malla. Finalmente, los resultados de esta investigación sugieren que el impacto de las mallas en los caracteres de calidad de frutos va a depender del cultivar y de las condiciones ambientales (temporada, localidad).