



Universidad de Concepción  
Dirección de Postgrado  
Facultad de Agronomía Programa de Magister en Ciencias Agronómicas

**MALLAS FOTO-SELECTIVAS AFECTAN DIFERENCIALMENTE LAS  
CONDICIONES MICRO CLIMÁTICAS, COMPONENTES DE  
RENDIMIENTO Y CARACTERÍSTICAS FISIOLÓGICAS DE LA HOJA  
EN AVELLANO EUROPEO (*CORYLUS AVELLANA L.*)**

Tesis para optar al grado de Magíster en Ciencias Agronómicas  
Mención Producción y Protección Vegetal

FELIPE IGNACIO SALAZAR CANALES  
CHILLÁN-CHILE  
2020

Profesor Guía: Richard Bastías Ibarra  
Dpto. de Producción Vegetal, Facultad de Agronomía  
Universidad de Concepción

Esta tesis ha sido realizada en el Departamento de Producción Vegetal de la Facultad de Agronomía, Universidad de Concepción.

Profesor guía:

Richard Bastías Ibarra  
Ing. Agrónomo, Mg. Hort. Ph.D.

---

Profesor Guía  
Facultad de Agronomía  
Universidad de Concepción

Comisión evaluadora:

Arturo Calderón Orellana  
Ing. Agrónomo, Ph.D.

---

Evaluador Interno  
Facultad de Agronomía  
Universidad de Concepción

Rosemarie Wilckens Engelbreit  
Lic. en Biología, Dr. rer. nat.

---

Evaluadora Interna  
Facultad de Agronomía  
Universidad de Concepción

Macarena Gerding González  
Ing. Agrónomo, Ph.D.

---

Directora Programa  
Facultad de Agronomía  
Universidad de Concepción

## AGRADECIMIENTOS

Esta investigación fue realizada gracias al financiamiento del Programa Tecnológico CORFO CÓDIGO 16PTECF5-66647 “CENTRO PARA LA INVESTIGACIÓN E INNOVACIÓN EN FRUTICULTURA PARA LA ZONA SUR - Proyecto Sostenibilidad y uso eficiente de recursos en la producción de avellano europeo (*Corylus avellana* L.) en la zona centro sur de Chile”.

Quisiera manifestar mis más sinceros agradecimientos a mi Profesor Guía, Dr. Richard Bastías Ibarra, por su orientación y constante apoyo durante el desarrollo de esta investigación.

De igual manera, agradecer a los docentes del Departamento de Producción Vegetal Dra. Rosemarie Wilckens Engelbreit y Dr. Arturo Calderón Orellana por su colaboración en las evaluaciones de laboratorio y terreno.

Un especial agradecimiento a los profesionales y colegas del Laboratorio de Fruticultura de la Universidad de Concepción, Esteban González, Gustavo Soto, Ignacio Urra y Nicol Romero por todo su apoyo en las evaluaciones de terreno y laboratorio.

También agradecer a la profesional Caterin Candía de Agrícola y Forestal Santa Elena por el apoyo técnico en la mantención de los ensayos de campo.

Finalmente, pero no menos importante, agradecer a mi familia por el apoyo y comprensión en esta etapa de mi vida, en forma muy especial a mi madre Ximena Canales quien fue un pilar fundamental para que este proyecto llegara a buen término.

## TABLA DE CONTENIDOS

	<b>Página</b>
Resumen	vii
Summary	ix
<b>Capítulo 1.</b> Introducción general	1
Hipótesis	5
Objetivo general	5
Objetivos específicos	5
Referencias	6
<b>Capítulo 2.</b> Photo-selective nets differentially affect microclimatic conditions, yield components and leaf physiological characteristics in hazelnut ( <i>Corylus avellana</i> L.)	9
Abstract	10
Introduction	11
Materials and Methods	14
Results	19
Discussion	23
Conclusions	31
Acknowledgements	32
Literature cited	32

## ÍNDICE DE TABLAS Y FIGURAS

		<b>Página</b>
Table 1	The light properties estimated under Black (B), Blue-gray (BG) and Pearl-gray (PG) colored nets in comparison to uncovered trees (Control).	38
Table 2	Fruit yield components estimated under Black (B), Blue-gray (BG) and Pearl-gray (PG) colored nets in comparison to uncovered trees (Control) during three consecutive year seasons in hazelnut orchard.	39
Table 3	Leaf physiological characteristics estimated under Black (B), Blue-gray (BG) and Pearl-gray (PG) colored nets in comparison to uncovered trees (Control) for controlled and ambient light conditions in hazelnut orchard.	40
Table 4	Regression coefficient for the relationship between leaf photosynthesis rate and leaf stomatal conductance as affected by Black (B), Blue-gray (BG) and Pearl-gray (PG) colored nets in comparison to uncovered trees (Control) for controlled and ambient light conditions.	41
Figure 1	Experimental plot with Blue-gray (BG), Pearl-gray (PG) and Black (B) colored nets compared to uncovered control (C) trees in a hazelnut orchard.	42
Figure 2	Daily pattern of global solar radiation and air temperature as affected by Black (B), Blue-gray (BG) and Pearl-gray (PG) colored nets in comparison to uncovered trees (Control) during 2018-2019 (A and C) and 2019-2020 (B and D) year seasons in a hazelnut orchard.	43
Figure 3	Daily pattern of relative humidity and vapour pressure deficit as affected by Black (B), Blue-gray (BG) and Pearl-gray (PG) colored nets in comparison to uncovered trees (Control) during 2018-2019 (A and C) and 2019-2020 (B and D) year seasons in a hazelnut orchard.	44
Figure 4	Cumulative fruit yield as affected by Black (B), Blue-gray (BG) and Pearl-gray (PG) colored nets in comparison to uncovered trees (Control) in a hazelnut orchard.	45

Figure 5	Variation on fruit yield per harvest time as affected by Black (B), Blue-gray (BG) and Pearl-gray (PG) colored nets in comparison to uncovered trees (Control) in a hazelnut orchard during 2017-2018 (A), 2018-2019 (B) and 2019-2020 (C) year seasons.	46
Figure 6	Relationship between photosynthesis rate ( $A_n$ ) and stomatal conductance ( $g_s$ ) in hazelnut leaves as affected by uncovered (A), Black (B), Blue-gray (C) and Pearl-gray (D) net systems. Leaf gas exchange measurements were carried out under controlled light conditions.	47
Figure 7	Relationship between photosynthesis rate ( $A_n$ ) and stomatal conductance ( $g_s$ ) in hazelnut leaves as affected by uncovered (A), Black (B), Blue-gray (C) and Pearl-gray (D) net systems. Leaf gas exchange measurements were carried out under ambient light conditions.	48
Figure 8	Variation on leaf PPFD incident (A), leaf UV incident (B), leaf temperature (C) and leaf Fv/Fm (D) as affected by Black (B), Blue-gray (BG) and Pearl-gray (PG) colored nets in comparison to uncovered trees (Control) in hazelnut orchard.	49

MALLAS FOTO-SELECTIVAS AFECTAN DIFERENCIALMENTE LAS CONDICIONES MICRO CLIMÁTICAS, COMPONENTES DE RENDIMIENTO Y CARACTERÍSTICAS FISIOLÓGICAS DE LA HOJA EN AVELLANO EUROPEO (*CORYLUS AVELLANA* L.)

PHOTO-SELECTIVE NETS DIFFERENTIALLY AFFECT MICROCLIMATIC CONDITIONS, YIELD COMPONENTS AND LEAF PHYSIOLOGICAL CHARACTERISTICS IN HAZELNUT (*CORYLUS AVELLANA* L.)

## **RESUMEN**

Las mallas foto-selectivas han sido usadas como una herramienta para reducir el estrés ambiental y mejorar rendimientos en cultivos hortofrutícolas, pero no hay conocimiento acerca de respuestas del avellano europeo bajo estas mallas. El objetivo de esta investigación fue estudiar la influencia de mallas foto-selectivas sobre el microclima, rendimiento y características fisiológicas de la hoja en avellano europeo. Durante tres temporadas consecutivas, un huerto de avellano europeo 'Tonda di Giffoni' fue cubierto con mallas de colores Negra (N), Azul-gris (AG) y Perla-gris (PG) tejidas con una densidad estándar de 4 hilos en la urdiembre y trama por  $\text{cm}^{-1}$ , respectivamente. Como control se dejaron árboles sin cobertura. Se evaluó el efecto de las mallas sobre las condiciones micro climáticas (intensidad y composición de la radiación solar,

temperatura del aire, humedad relativa y déficit de presión de vapor, VPD), los componentes del rendimiento (rendimiento acumulado; rendimiento por fecha de cosecha; peso de fruto, FW y peso de semilla, SW) y las características fisiológicas de la hoja (tasa neta de la fotosíntesis,  $A_n$ ; conductancia estomática,  $g_s$ ; peso específico de la hoja, SWL y densidad estomática, SD). La malla PG produjo el mayor incremento en la radiación solar difusa (47%) y global (5%) en comparación a las mallas AG y N. El VPD disminuyó un 12% bajo malla N, pero solo un 5% bajo mallas PG y AG. La malla PG incrementó significativamente el rendimiento acumulado, FW y SW y en un 12%, 13% y 6%, respectivamente comparado al Control. Las mallas N y AG redujeron la SD entre un 8 - 30% y el L SWL entre 15 - 20%, respectivamente. La malla PG no alteró ni la SD ni tampoco el SWL. Se encontró una relación significativa entre  $A_n$  y  $g_s$  bajo todas las mallas, pero no para el Control. Esta relación entre  $A_n$  y  $g_s$  fue significativamente positiva para la malla PG y negativa para la malla AG. Las mallas foto-selectivas son una interesante herramienta de base fisiológica que permite mejorar el rendimiento en huertos de avellano europeo bajo condiciones climáticas extremas. La malla PG es la alternativa más prometedora para este cultivo frutícola.



## SUMMARY

Photo-selective colored nets have been used as a tool to reduce climatic stress and improve yields in horticultural crops, but there is no knowledge regarding responses of hazelnut crop under these nets. The objective of this research was to study the influence of photo-selective nets on microclimate, yield and leaf physiological characteristics in hazelnut. During three consecutive seasons, a hazelnut orchard 'Tonda di Giffoni' was covered with Black (B), Blue-gray (BG) and Pearl-gray (PG) colored nets with a standard density of 4 warp and weft threads  $\text{cm}^{-1}$ . Uncovered trees were left as control. Microclimatic conditions (solar radiation intensity and composition, air temperature, relative humidity and vapor pressure deficit, VPD), yield components (accumulated yield; yield by harvest date; fruit weight, FW and seed weight, SW) and leaf physiological characteristics (net photosynthesis rate,  $A_n$ ; stomatal conductance,  $g_s$ ; specific leaf weight, SLW and stomatal density, SD) were evaluated. PG netting had the greatest increase in diffuse (47%) and global (5%) solar radiation compared to BG and B nettings. VPD decreased by 12% under B netting, but only 5% under PG and BG netting. PG nets significantly increased accumulated yield, FW and SW by 12%, 13% and 6% compared to the control, respectively. B and BG nets reduced SD by 8 and 30% and SLW by 15 and 20%, respectively. PG netting did not alter either SD or SLW. A significant relationship between  $A_n$  and  $g_s$  was found under all nets, but not for the control. This relationship between  $A_n$  and  $g_s$

was significantly positive for PG netting and negative for BG netting. Photo-selective netting is an interesting physiology-based tool allowing for yield improvement in hazelnut orchards under extreme climate conditions. PG netting is the most promising alternative for this fruit crop.

## **CAPÍTULO 1**

### **INTRODUCCIÓN GENERAL**

La luz solar es el principal factor ambiental que determina la productividad en huertos frutales. Numerosos trabajos han demostrado que el rendimiento de fruta en diferentes especies frutales se incrementa en la medida que aumenta la intercepción y distribución de la luz dentro del dosel de la planta (Wünsche y Lakso, 2000; Corelli-Grappadelli, et al., 2017). Esta relación entre luz y rendimiento en frutales se explica por el efecto directo de la luz sobre los procesos de la fotosíntesis en las hojas y la partición de asimilados hacia el crecimiento y desarrollo de órganos reproductivos como flores y frutos (Zhang et al., 2018). La reducción de la intensidad de la luz afecta más negativamente a la fase reproductiva que a la fase vegetativa, ya que influye directamente en la inducción y la diferenciación de yemas florales, así como también en el tamaño, el color y la calidad organoléptica del fruto (Corelli-Grappadelli, 2003). Se ha demostrado que el desarrollo floral puede verse afectado entre un 13 y 30% cuando se disminuye la intensidad de la luz por efecto de la excesiva sombra en especies como el manzano (*Malus domestica* Borkh.) (Solomakhin y Blanke, 2008). En olivo (*Olea europaea* L.) se observó que a mayor intercepción de luz, mayor era el aumento del peso seco y el contenido de aceite del fruto (Benelli et al., 2014). Para el caso del avellano europeo (*Corylus avellana* L.), la falta de luz afectó negativamente los componentes del

rendimiento, tales como peso de fruta y densidad de flores. En este caso, cuando se redujo la disponibilidad de luz en un 50% se observó una disminución similar en el peso de frutos por planta y de 40% y 15% en la densidad de flores masculinas y femeninas, respectivamente (Hampson et al., 1996). Además, en esta misma investigación se estableció que una reducción en la disponibilidad de luz a través del sombreamiento afectó negativamente aspectos fotosintéticos de la hoja, tales como densidad estomática, peso específico de hoja y asimilación neta de CO<sub>2</sub> (Hampson et al., 1996).

Aun cuando en plantas existe un aumento lineal de la asimilación de CO<sub>2</sub> en la medida que se incrementa la intensidad de radiación fotosintéticamente activa, esta relación no es lineal con la respuesta en los procesos bioquímicos de la fotosíntesis. La relación no lineal se debe a que con un incremento en la intensidad lumínica se produce una saturación del proceso de la fotosíntesis de la hoja. En este punto la tasa de absorción de fotones excede la tasa de transporte de electrones desde el fotosistema II (PS-II) al fotosistema I (PS-I), lo que conlleva a un daño del aparato fotosintético y fotoinhibición (Jifon y Syvertsen, 2001). En especies frutales de clima templado frío se ha determinado que el punto de saturación lumínica de la fotosíntesis es en torno al 50% de la cantidad de luz fotosintética incidente (Corelli-Grappadelli y Lakso, 2007). Se ha demostrado que reducir moderadamente la intensidad de la luz tiene efectos positivos en mitigar la fotoinhibición de las hojas y mejorar su intercambio gaseoso (Jifon y Syvertsen, 2003; Hepaksoy y Dayioglu, 2016).

Ello también ha sido recientemente documentado en avellano europeo. En un experimento realizado en esta especie se demostró que solo las plantas protegidas del exceso de luz solar son capaces de recuperar su capacidad de fotosíntesis cuando fueron sometidas a corte y posterior reposición del riego (Luciani et al., 2020).

En los últimos años se ha promovido el uso de mallas de color foto-selectivas como técnica para mitigar los efectos de la excesiva radiación solar en frutales (Shahak et al., 2014). Estas mallas contienen diversos pigmentos que permiten que filtren longitudes de onda solares específicas según las respuestas fisiológicas deseadas en la planta y, a la misma vez, dispersando la luz y asegurando que ésta penetre en forma más eficiente al interior del dosel (Zoratti et al., 2015). Dependiendo del color de los hilos, las mallas foto-selectivas pueden reducir el estrés por radiación solar en árboles frutales, mejorando el potencial de rendimiento en la mayoría de las especies estudiadas (Shahak et al., 2014). En kiwi (*Actinidia deliciosa* (A. Chev.)) el uso de mallas de colores afectó de manera distinta el tamaño de los frutos y su calidad, en donde las mallas blancas y rojas promovieron una mayor acumulación de materia seca en la fruta, lo que se tradujo en una alta concentración de sólidos solubles. En cambio, el uso de mallas de color azul y gris produjo el efecto opuesto en esta especie (Basile et al., 2012). En arándano (*Vaccinium corymbosum* L.) se determinó que el uso de mallas de colores foto-selectivas no afectan el rendimiento. Sin embargo, el exceso de

sombreado con estas mallas afectó negativamente el contenido de sólidos solubles en los frutos y la cantidad de yemas florales en la planta (Lobos et al., 2013). En manzano el uso de malla de color perla incrementó en un 30% el rendimiento por árbol, debido a su efecto en el aumento del tamaño de los frutos (Shahak et al., 2008). Posteriormente, en la misma especie se observó un resultado similar usando malla de color azul, donde esta malla permitió que los frutos aumentaran el diámetro en un 45% (Bastías et al., 2012).

Desde el punto de vista fisiológico la influencia del color de la malla ha sido también estudiada con resultados contrastantes, dependiendo de la especie. En pomelo (*Citrus paradisi* L.) y naranjo (*Citrus sinensis* L.) el uso de malla negra disminuyó la intensidad de la luz solar, mejorando la conductancia estomática y la fotosíntesis entre un 50 y 30% (Jifon y Syvertsen, 2001). En un estudio más reciente se comprobó que el uso de malla foto-selectiva de color azul mejoró la eficiencia del uso de la luz y redujo el grado de fotoinhibición a nivel de las hojas, cuando fue empleada en un ambiente climático árido y con excesiva radiación solar (Mupambi et al., 2018).

Si bien es cierto que, existen antecedentes sobre el efecto del uso de mallas foto-selectivas sobre diversas especies frutales, no existe información sobre la influencia que podrían tener estas mallas en una especie como el avellano europeo. La presente investigación postula que la cobertura de plantas de avellano europeo con mallas foto-selectivas permite modular diferencialmente (dependiendo del color de la malla) el ambiente, el rendimiento y la fisiología de

este cultivo bajo condiciones de campo. El objetivo de este trabajo fue evaluar el efecto de mallas de colores foto-selectivas sobre las condiciones micro climáticas, los componentes de rendimiento de la planta y las características fisiológicas de la hoja en avellano europeo.

## **HIPOTESIS**

La cobertura de plantas de avellano europeo con mallas foto-selectivas permite modular diferencialmente (dependiendo del color de la malla) el ambiente, el rendimiento y la fisiología del este cultivo bajo condiciones de campo.

## **OBJETIVO GENERAL**

Evaluar el efecto de mallas de colores foto-selectivas sobre las respuestas productivas y fisiológicas en plantas de avellano europeo, bajo condiciones de huerto.

## **OBJETIVOS ESPECÍFICOS**

- Determinar la influencia del uso de mallas de colores foto-selectivas en las condiciones micro climáticas del huerto.
- Cuantificar el efecto de las mallas sobre los componentes de rendimiento del cultivo.
- Identificar cuales características fisiológicas de hojas del avellano europeo podrían alterarse por el uso de estas mallas.

## REFERENCIAS

- Basile B, Giaccone M, Cirillo C, Ritieni A, Graziani G, Shahak Y, Forlani M (2012) Photo-selective hail nets affect fruit size and quality in Hayward kiwifruit. *Sci Hort* 141:91-97. <https://doi.org/10.1016/j.scienta.2012.04.022>
- Bastías RM, Manfrini L, Corelli-Grappadelli L (2012) Exploring the potential use of photo-selective nets for fruit growth regulation in apple. *Chil J Agric Res* 72:224-231. <http://dx.doi.org/10.4067/S0718-58392012000200010>
- Benelli G, Caruso G, Giunti G, Cuzzola A, Saba A, Raffaelli A, Gucci R (2014) Changes in olive oil volatile organic compounds induced by water status and light environment in canopies of *Olea europaea* L. trees. *J Sci Food Agric* 95: 2473-2481. <http://dx.doi.org/10.1002/jsfa.6977>
- Corelli-Grappadelli L, Lopez G, Manfrini L, Zibord M, Morandi B, Bastias R, Losciale P (2017) Conditioning the orchard light environment for greater efficiency and sustainability. *Acta Hort* 1177:73-78. <https://doi.org/10.17660/ActaHortic.2017.1177.7>
- Corelli-Grappadelli L, Lakso AN (2007) Is maximizing orchard light interception always the best choice?. *Acta Hort* 732:507-518. <https://doi.org/10.17660/ActaHortic.2007.732.77>
- Corelli-Grappadelli, L. (2003) Light Relations. In: *Apples: Botany, Production and Uses*. D.C. Ferree and I.J. Warrington Eds. CAB International: Wallingford, UK, pp. 195 – 216.
- Hampson CR, Azarenko AN, Potter JR (1996) Photosynthetic rate, flowering and yield component alteration in hazelnut in response to different light



environments. J Am Soc Hortic Sci 121:1103–1111.  
<https://doi.org/10.21273/JASHS.121.6.1103>

Hepaksoy S, Dayioğlu A (2016) Fruit quality and sunburn of apple cv. Early Red One under shading nets. 27<sup>th</sup> International Scientific-Expert Congress of Agriculture and Food Industry, Bursa, Turkey. Ziraat Fakültesi Dergisi, Uludağ Üniversitesi 30:642-646.

Jifon JL, Syvertsen JP (2003) Moderate shade can increase net gas exchange and reduce photoinhibition in citrus leaves. Tree Physiol 23:119–127.  
<https://doi.org/10.1093/treephys/23.2.119>

Jifon JL, Syvertsen JP (2001) Effects of moderate shade on citrus leaf gas exchange, fruit yield, and quality. Proc Fl State Hort Soc 114:177–181.  
<https://doi.org/10.1093/treephys/23.2.119>

Lobos GA, Retamales JB, Hancock JF, Flore JA, Romero-Bravo S, Del Pozo A (2013) Productivity and fruit quality of *Vaccinium corymbosum* cv. Elliott under photo-selective shading nets. Sci Hortic 153:143-149.  
<https://doi.org/10.1016/j.scienta.2013.02.012>

Luciani E, Palliotti A, Frioni T, Tombesi S, Villa F, Zadra C, Farinelli D (2020) Kaolin treatments on Tonda Giffoni hazelnut (*Corylus avellana* L.) for the control of heat stress damages. Sci Hortic 263:109097.  
<https://doi.org/10.1016/j.scienta.2019.109097>

Mupambi G, Musacchi S, Serra S, Kalcsits LA (2018) Protective netting improves leaf-level photosynthetic light use efficiency in ‘Honeycrisp’ apple under heat

stress. HortScience 53:1416–1422. <https://doi.org/10.21273/HORTSCI113096-18>

Shahak Y (2014) Photosensitive netting: an overview of the concept, research and development and practical implementation in agriculture. Acta Horti 1015:155–162. <https://doi.org/10.17660/ActaHort.2014.1015.17>.

Shahak Y, Ratner K, Giller YE, Zur N, Or E, Gussakovsky EE, Greenblat-Avron Y (2008) Improving solar energy utilization, productivity and fruit quality in orchards and vineyards by photosensitive netting. Acta Horti 772:65–72. <https://doi.org/10.17660/actahort.2008.772.7>

Solomakhin A, Blanke MM (2008) Coloured hailnets alter light transmission, spectra and phytochrome, as well as vegetative growth, leaf chlorophyll and photosynthesis and reduce flower induction of apple. Plant Growth Regul 56:211–218. <http://dx.doi.org/10.1007/s10725-008-9302-7>

Wünsche JN, Lakso AN (2000) Apple tree physiology: Implications for orchard and tree management. Comp fruit tree 33:82-88.

Zhang BB, Xu, JL, Zhou M, Yan DH, Ma RJ (2018) Effect of light quality on leaf photosynthetic characteristics and fruit quality of peach (*Prunus persica* L. Batch). Photosynthetica 56:1113–1122 <https://doi.org/10.1007/s11099-018-0820-x>

Zoratti L, Jaakola L, Häggman H, Giongo L (2015) Modification of sunlight radiation through colored photo-selective nets affects anthocyanin profile in *Vaccinium* spp. Berries. PLoS ONE 10:e0135935. <http://dx.doi.org/10.1371/journal.pone.0135935>

**CAPÍTULO 2: ARTÍCULO SE ENVIARÁ A LA REVISTA HORTICULTURE,  
ENVIRONMENT, AND BIOTECHNOLOGY (HEB)**

**PHOTO-SELECTIVE NETS DIFFERENTIALLY AFFECT MICROCLIMATIC  
CONDITIONS, YIELD COMPONENTS AND LEAF PHYSIOLOGICAL  
CHARACTERISTICS IN HAZELNUT (*CORYLUS AVELLANA* L.)**

**Felipe Salazar-Canales<sup>1</sup>, Richard M. Bastías<sup>1\*</sup>, Arturo Calderón-Orellana<sup>1</sup>,  
Rosemarie Wilckens<sup>1</sup>, Esteban González<sup>1</sup>**

<sup>1</sup>Universidad de Concepción, Facultad de Agronomía, Av. Vicente Méndez 595,  
Chillán, Chile.

\*Corresponding author ([ribastias@udec.cl](mailto:ribastias@udec.cl)).

## **Abstract**

Photo-selective colored nets have been used as a tool to reduce climatic stress and improve yields in horticultural crops, but there is no knowledge regarding responses of hazelnut crop under these nets. The objective of this research was to study the influence of photo-selective nets on microclimate, yield and leaf physiological characteristics in hazelnut. During three consecutive seasons, a hazelnut orchard 'Tonda di Giffoni' was covered with Black (B), Blue-gray (BG) and Pearl-gray (PG) colored nets with a standard density of 4 warp and weft threads cm<sup>-1</sup>. Uncovered trees were left as control. Microclimatic conditions (solar radiation intensity and composition, air temperature, relative humidity and vapor pressure deficit, VPD), yield components (accumulated yield; yield by harvest date; fruit weight, FW and seed weight, SW) and leaf physiological characteristics (net photosynthesis rate,  $A_n$ ; stomatal conductance,  $g_s$ ; specific leaf weight, SLW and stomatal density, SD) were evaluated. PG netting had the greatest increase in diffuse (47%) and global (5%) solar radiation compared to BG and B nettings. VPD decreased by 12% under B netting, but only 5% under PG and BG netting. PG nets significantly increased accumulated yield, FW and SW by 12%, 13% and 6% compared to the control, respectively. B and BG nets reduced SD by 8 and 30% and SLW by 15 and 20%, respectively. PG netting did not alter either SD or SLW. A significant relationship between  $A_n$  and  $g_s$  was found under all nets, but not for the control. This relationship between  $A_n$  and  $g_s$  was significantly positive for PG netting and negative for BG netting. Photo-

selective netting is an interesting physiology-based tool allowing for yield improvement in hazelnut orchards under extreme climate conditions. PG netting is the most promising alternative for this fruit crop.

**Key words:** Colored nets · fruit yield · leaf morphology · leaf gas exchange

## **1. Introduction**

Sunlight is the main environmental factor that affects crop yield in fruit orchards. Several studies have described that fruit yield in different fruit tree species increases as light interception and distribution within the tree canopy increases (Wünsche and Lakso, 2000; Corelli-Grappadelli et al., 2017). In fact, the relationship between light and yield in fruit trees is explained by the direct effect of light on the processes of photosynthesis and assimilate partitioning as related to plant growth and development of reproductive organs such as flowers and fruits (Zhang et al., 2018). Reductions in light intensity affect more negatively the reproductive than the vegetative phase because light has a direct effect on flower bud induction and differentiation, as well as size and organoleptic fruit characteristics (Corelli-Grappadelli, 2003).

On the other hand, an excess of light can adversely affect fruit production in temperate fruit trees. In this sense, it has been determined that light saturation point of photosynthesis is around 50% of the amount of incident photosynthetic light (Corelli-Grappadelli and Lakso, 2007). At this point, the rate of photon absorption exceeds that of electron transport rate from PS-II to PS-I, leading to

damage of the PSII photosynthetic apparatus and photoinhibition due to the stress caused by high light (Jifon and Syvertsen, 2001).

With respect to hazelnut (*Corylus avellana* L.), there is evidence that the lack of light negatively affects yield components, such as fruit weight and flower density. For example, a study conducted by Hampson et al. (1996) showed that a 50% reduction in light availability resulted in reduced fruit weight and a decrease of 40% and 15% in male and female flower production, respectively. In addition, the authors also determined that a reduction in light availability through shading negatively affected leaf photosynthetic aspects, such as stomatal density, specific leaf weight and net CO<sub>2</sub> assimilation (Hampson et al., 1996). More recent studies have shown that, under water stress conditions, only plants protected from excess sunlight are capable of recovering the photosynthetic activity of their leaves, as observed in a study that compared plants treated and not treated with a kaolin clay based 'sunscreen' product (Luciani et al., 2020).

The use of photo-selective colored netting has also been promoted in the last few years to protect the horticultural crops from environmental stresses, improving productivity and fruit quality through sunlight management (Shahak et al., 2014). Depending on their color of threads, photo-selective nets filtering specific solar wavelengths based on the physiological responses desired in the plant while scattering light in order to ensure sunlight reaches the inner canopy more efficiently (Zoratti et al., 2015). In kiwi (*Actinidia deliciosa* L.), the use of

photo-selective nets affected fruit size and quality differently. White and red netting induced a high accumulation of dry matter in the fruit, which resulted in a high concentration of soluble solids, while blue and gray netting showed opposite results (Basile et al., 2012). In blueberry (*Vaccinium corymbosum* L.), it was determined that the use of photo-selective colored netting does not affect fruit yield. However, excess shading with these nets negatively affected the content of soluble solids in fruits and the amount of flower buds (Lobos et al., 2013). In apple (*Malus domestica* Borkh.), the use of pearl netting increased yield by 30% per tree, which was explained by the increase in fruit size (Shahak et al., 2008). Similar results were observed in a study conducted by Bastías et al. (2012) using blue netting in the same species, recording an increase in fruit diameter by 40-45%.

From a physiological point of view, the influence of colored shade netting has varied between fruit species. In grapefruit (*Citrus paradisi* L.) and orange (*Citrus sinensis* L.), the use of black netting reduced the transmittance of photosynthetically active radiation (PAR) by 60%, resulting in improved stomatal conductance and photosynthesis between 50 and 30% (Jifon and Syvertsen, 2001). A more recent study developed in apple confirmed that the use of photo-selective blue net improved leaf photosynthetic efficiency, and in turn reducing symptoms of photoinhibition in an arid environment with excessive solar radiation (Mupambi et al., 2018). Although photo-selective colored nets have been evaluated in different fruit crops, to our knowledge, there is no published

research on the effect of photo-selective colored netting on hazelnut. The present study proposes that, depending on the color of the net, photo-selective netting differentially affects productive and physiological responses in hazelnut trees. The objective of this research work was to evaluate the effect of photo-selective colored nets on microclimatic conditions, tree yield components and leaf physiological characteristics in a commercial hazelnut orchard.

## **2. Materials and methods**

### *2.1. Plant material and experimental design*

The trial was carried out in a commercial hazelnut (*Corylus avellana* L.) orchard cv. Tonda di Giffoni, located in Camarico (Maule Region, Chile; 35°14' S, 71°22' O), during the 2017-2018, 2018- 2019 and 2019-2020 seasons. The area has a cold temperate climate with dry and hot summers and humid winters with rainfall mainly concentrated in the autumn and winter seasons (INIA, 2019). The experiment was established on 10-year-old trees, trained as a central axis system, planted 5 x 4 m apart, with a density of 500 trees per ha<sup>-1</sup> and east-west row oriented. The trees were irrigated using a drip irrigation system with two drip lines per tree; drippers were placed at a distance of 0.5 m, and with a flow rate of 2.4 liters per hour. The treatments consisted of using mono-filament photo-selective nets of the following colors: Black (B), Blue-gray (BG) and Pearl-gray (PG) (Delsantek S.A., Chile), and with a standard weft and warp density of 4 threads cm<sup>-1</sup>. A control treatment, consisting of uncovered trees, was also included. The nets were installed once leaf emergence occurred



(October 27, 2017) at a height of 5 m above the ground and remained extended throughout the whole phenological period of the crop. The experiment was established in a completely randomized block design with three replicates; each type of net was randomly assigned to each block consisting of plots of 480 m<sup>2</sup>, with 5 rows of 6 trees per plot (Figure 1).

## 2.2. *Microclimatic conditions*

Colored net samples 1x1 m were used to determine total (PPFD,  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) and diffuse (PPFD<sub>difusse</sub>,  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) light transmission prior to net installation. Diffuse PPFD was determined according to the methodology described by Umanzor et al. (2017) using a LI-191SA quantum sensor connected to a LI-1400 datalogger (LICOR, Lincoln, NE, USA). To obtain PPFD<sub>difusse</sub> values, the quantum sensor was placed under the shadow projected by a black rubber sphere of 32.5 cm in diameter placed at a distance of 15 cm from the sensor.

A WatchDog 2900ET weather station (Spectrum technologies, Inc., Illinois, USA) was installed in the center of each treatment and 1.2 m above the ground on a clear summer day in the 2018-2019 and 2019-2020 seasons. The meteorological stations were programmed to record data of global solar radiation ( $\text{W m}^{-2}$ ), air temperature ( $^{\circ}\text{C}$ ), and relative air humidity (%) with 15-minute intervals between 11:30 am and 4:30 pm. For the measurement of global solar radiation, the meteorological station was equipped with a LIGHTSCOUT pyranometer that measures solar energy between 300 to 1100 nm (Spectrum technologies, Inc., Illinois, USA). The data of temperature and

relative humidity obtained were used to calculate the air vapor pressure deficit (VPD, kPa) using the following relationship:

$$(1) \quad \text{VPD} = e_s (1 - \text{RH}/100),$$

where RH is air relative humidity and  $e_s$  corresponds to the saturation pressure of the water vapor, which was estimated according to the following equation (Landsberg and Sands, 2011):

$$(2) \quad e_s = 0.611 \exp (17.2 * T_a) / (T_a + 237.5)$$

where  $T_a$  corresponds to air temperature ( $^{\circ}\text{C}$ ).

### 2.3. *Tree yield components*

Fruit yield was assessed for three consecutive seasons: 2017-2018, 2018-2019 and 2019-2020. Hazelnuts were harvested when the trees dropped 20% of the fruit. The fruit was harvested at intervals of approximately 10 days, and immediately weighed on a platform scale model PCE-PCS 30 (PCE Instruments, Santiago, Chile). For each harvest, a sample consisting of 20 randomly selected fruits per tree was taken. Seed filling was calculated based on the relationship between the weight of seed and the weight of fruit with shell, using a digital tabletop scale, model A6702231 (Veto, Santiago, Chile), with an accuracy of 0.001 g. In addition, the equatorial diameter of the hazelnuts was measured using a VWR digital caliper (Radnor, Pennsylvania, USA) with an accuracy of 0.01 mm.

#### 2.4. *Leaf physiological characteristics*

During midday-January of the 2018-2019 and 2019-2020 seasons, a sample consisting of one and two sun-exposed leaves per tree, was taken and the following parameters were measured: net photosynthesis rate ( $A_n$ ,  $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ), stomatal conductance ( $g_s$ ,  $\text{mmol m}^{-2} \text{ s}^{-1}$ ), transpiration rate ( $E$ ,  $\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$ ) and intercellular  $\text{CO}_2$  concentration ( $C_i$ ,  $\mu\text{mol mol}^{-1}$ ). Measurements were carried out under artificial light of  $1200 \mu\text{mol m}^{-2} \text{ s}^{-1}$  of PPFD provided by a white LED lamp and under full sunlight using a TARGAS-1 infrared gas analyzer (PP Systems, Amesbury, USA). Simultaneous measurements of chlorophyll fluorescence were performed using a portable fluorometer, model OS-30p (Opti-Sciences, New Hampshire, USA). For this, maximum ( $F_m$ ) and minimum ( $F_o$ ) fluorescence were determined after dark adaptation for 30 minutes (Reyes-Díaz et al., 2009), using leaf clips with a mobile obturation plate. The maximum photochemical efficiency of PS-II ( $F_v/F_m$ ) was estimated using the relationship  $F_v/F_m = (F_m - F_o) / F_m$  proposed by Maxwell and Johnson (2000). In addition, the leaf temperature ( $^{\circ}\text{C}$ ) was quantified through infrared radiometer SI-111-SS (Apogee Instruments Inc., Logan, UT, USA). PPFD incident on the leaf ( $\mu\text{mol m}^{-2} \text{ s}^{-1}$ ) was measured by a quantum sensor MQ-200 (Apogee Instruments Inc., Logan, UT, USA), whereas UV radiation incident on the leaf ( $\text{W m}^{-2}$ ) was measured through a MU-250 sensor (Apogee Instruments Inc., Logan, UT, USA). All leaf measurements were carried out between 10:00

am to 14:00 pm; i.e. when the maximal leaf stomatal conductance has been described in hazelnut (Özmen, 2016).

Once measurements of leaf gas exchange under controlled light were completed, eight leaves were randomly selected from two trees per plot and block. The sample was stored and transported in refrigeration using a 4.5 L cooler Eskimo (Pinnacle, Maharashtra, India) for subsequent morphological analysis. Trichomes were removed from the underside zone of four leaves using adhesive tape. The interveinal area of two lower portions of each leaf was then painted with clear nail polish and let to dry. Then the film was removed and placed on a slide with distilled water and examined under a binocular microscope at 40X magnification, model XSZ-107BN (Arquimed, Santiago, Chile). Subsequently, the number of stomata per observation field was counted and stomatal density (SD) was calculated in  $n^{\circ} \text{ mm}^{-2}$ . In the four remaining leaves, a circular tissue sample of 11 mm in diameter was taken using a hole punch from the same area of the leaf. Then the discs were dried in a D-6450 Hanau oven (Heraeus Instruments, Germany) at a temperature of 65 °C until reaching a constant weight and through a digital analytical balance 1602-MP8-1 (Sartorius, Göttingen, Germany) and specific leaf weight (SLW) was estimated in  $\text{mg cm}^{-2}$ .

### 2.5. *Plant water status*

Stem water potential was measured at midday (12:00-3:00 pm) using a pressure chamber (PMS Instruments, Washington, USA). One shaded leaf per tree was covered with aluminized bags 40 minutes before measuring stem water potential (McCutchan and Shackel, 1992).

### 2.6. *Statistical analysis*

Data were subjected to an analysis of normality and homoscedasticity of the residuals in order to meet the assumptions of the analysis of variance (ANOVA). The data that met the assumptions of the analysis were then subjected to an ANOVA at a significance level equal to  $P < 0.05$  and  $0.01$ . Mean separation was conducted using the LSD test at a confidence level of 95%. A linear regression analysis was performed to determine the relationships between  $A_n$  and  $g_s$  at a significance level equal to  $P < 0.05$  and  $0.01$ . The statistical analysis was carried out using INFOSTAT software (Balzarini et al., 2008).

## **3. Results**

### 3.1 *Microclimatic conditions*

The analysis of the light properties of the colored net materials under study showed that BG netting resulted in a significant decrease ( $P < 0.0001$ ) of 24% in total PPFD compared to the control (uncovered trees), while B and PG netting resulted in decreases of 21% and 19%, respectively (Table 1). The diffuse PPFD proportion under BG and PG nets increased significantly ( $P < 0.0001$ ) by 47% and 12% compared to the Control, respectively (Table 1).

The B netting reduced the amount of global solar radiation (300 - 1100 nm) available by 25% under field conditions in both seasons (2018-2019 and 2019-2020), while BG and PG netting resulted in reductions of 20 and 17%, respectively (Fig. 2 a, b). Air temperature under B netting was on average 1.3 °C lower than that recorded under no netting (control) for both seasons, while the value recorded with BG and PG netting was 0.6 °C lower. The decrease in air temperature reached 5% for B netting and 2% for PG and BG netting compared to the Control (Fig. 2 c, d). For both seasons, relative humidity decreased on average 3% under B netting, and 1% and 0.1% under PG and BG netting, respectively (Fig. 3 a, b). Air vapor pressure deficit (VPD) under B netting was on average 0.3 kPa lower compared to the Control, and 0.1 kPa lower under BG and PG netting. The decrease in VPD reached 12% for B netting and 5% for PG and BG netting (Fig. 3 c, d).

### 3.2 *Tree yield components*

During three consecutive growing seasons (2017-2018, 2018-2019 and 2019-2020), PG netting resulted in a greater and significant ( $P = 0.0275$ ) increase in fruit yield per tree when compared to yield levels recorded with the other colored nets and Control (Fig. 4). In this sense, the accumulated yield observed under PG netting was 12% and 20% higher than the Control and BG netting, respectively. The B netting did not significantly affect fruit yield compared to the Control and other colored nets (Fig. 4). In terms of commercial fruit yield, average values for fruit weight, fruit diameter and seed weight for the three

consecutive seasons were 13%, 30% and 6% higher under PG netting compared to average values recorded with Control, B and BG netting (Table 2). These differences were statistically significant for the 2018-2019 ( $P < 0.0001$ , = 0.0003 and 0.0009, respectively) and 2019-2020 ( $P = 0.0017$ , 0.0004 and 0.0039, respectively) year seasons (Table 2). On the other hand, the B, BG and PG netting affected the distribution of fruit yield by harvest date (Fig. 5). Harvest yield during the first harvest date was 5%, 13% and 19% higher than that recorded under no netting (Control) for the 2017-2018, 2018-2019 and 2019-2020 seasons, respectively (Fig. 5 a, b, c), with a statistically significant difference ( $P = 0.0125$  and 0.0198, respectively) for the last two seasons (Fig. 5 b, c).

### 3.3 Leaf physiological characteristics and plant water status

Netting did not significantly affect any of the measured leaf gas exchange variables under both ambient and artificial light. Similarly, there was no effect of netting on the photochemical efficiency of photosystem II ( $F_v/F_m$ ) and midday stem water potential (Table 3). However, netting significantly affected the morphological characteristics of stomatal density and leaf specific weight ( $P = 0.0001$  and 0.0004, respectively). B and BG netting decreased SD by 8% and 31% compared to Control, and it also resulted in decreases of 20% and 15% in SLW, respectively. Neither stomatal density nor specific leaf weight were significantly affected by PG netting (Table 3). PPFD incident on the leaves decreased by 25% ( $P = < 0.0001$ ) under all netting treatments (Table 3).

Measurements under both controlled and ambient light conditions showed a statistically significant relationship between  $A_n$  and  $g_s$  in leaves grown under colored nets, but not in those grown in uncovered conditions (Table 4). For both conditions (artificial and natural light) and in all colored netting, the variation in the  $A_n$  of the leaves was explained in over 90% ( $P < 0.0001$  and  $< 0.0005$ ) by the effect of the variation in  $g_s$  (Table 4). In controlled light conditions measurements, the relationship between  $A_n$  and  $g_s$  under PG netting presented a positive polynomial curve pattern ( $B_2 = 0.000079$ ) (Table 5; Fig. 6 d). Under BG and B netting this relationship showed a negative ( $B_2 = -0.000067$  and  $-0.000096$ , respectively) polynomial curve pattern (Table 4, Fig. 6 a, b). Under ambient light conditions, the relationship between  $A_n$  and  $g_s$  presented a positive polynomial curve pattern for PG and B netting ( $B_2 = 0.00051$  and  $0.00043$ , respectively) (Table 4; Fig. 7 b, d). Similar to measurements carried out in controlled light conditions, BG netting had a negative polynomial curve with a statistically significant difference in the slope ( $P = -0.0013$  and  $-0.0059$ ) (Table 4; Fig. 7 a, c).

The amount of PPFD and UV light incident on the leaf was significantly reduced ( $P < 0.001$ ) and by a proportion of 25 -27% due to the effect of all colored netting (Fig. 8, a, b). During the morning, the leaf temperature was significantly ( $P = 0.014$ ) lower under all colored netting when was compared with Control (Fig. 8, c). At solar noon, PG and B netting significantly ( $p < 0.0125$ ) decreased the leaf temperature compared to the control, while BG netting did not reduce



significantly the leaf temperature (Fig. 8, c). Under BG and Control the leaf temperature reached values above 35°C, whereas under B and PG netting the leaf temperature was reduced up to 5°C (Fig. 8, c). The leaf photochemical efficiency of PS-II, measured as  $F_v/F_m$ , did not differ among netting treatments (Fig. 8, d).

#### **4. Discussion**

Even though thread density was the same for all types of nets, PG and BG netting presented higher values of global solar radiation transmission compared to B netting. This would indicate that these differences in radiation transmission are due to net color. Numerous studies on colored nets have shown that the color of the net differently affects light availability. Basile et al. (2012) found that Blue and Gray nets decreased sunlight by 27%, while Red netting resulted in a reduction of 20%. A study conducted by Solomakhin and Blanke (2008) reported that the use darker nets (Green-black and Red-black) reduced light transmission by 18-23%, while lighter nets (Red-white and White) resulted in a 10-14% reduction. Abdel-Ghany and Al-Helal (2010) observed that nets of lighter or brighter colored threads increase the amount of light availability due to a greater proportion of diffuse radiation. In the present study, PG netting presented the highest global solar radiation transmission values (Fig. 2 a, b), which is consistent with the greater amount of diffuse light that this material provides compared to the other colored netting (Table 1).

On the other hand, the differential effect of colored nets on air temperature and relative humidity can also be explained by differences in global solar radiation transmission (Solomakhin and Blanke, 2010). Abdel-Ghany et al. (2015) indicated that dark-colored nets presented a greater absorption of solar radiation throughout the day. This would explain why B netting (in the present study) decreased air temperature to a greater extent, when compared to PG and BG netting. In this sense, Baille et al. (2001) described that the variation of solar radiation measured under nets resulted in indirect changes of other microclimatic variables such as relative humidity and VPD, which would explain the lower relative humidity and higher VPD values found under PG and BG netting.

The use of PG netting resulted in the highest cumulative fruit yield, equivalent to an estimated increase of 1.5 t ha<sup>-1</sup> during three consecutive seasons. The positive effect on yield can be explained by the higher amount of diffuse radiation that this type of netting provides, resulting in greater light availability for the plant. These results agree with previous studies in which shade nets with a greater capacity to increase diffuse light significantly increased fruit yield in other horticultural crops due to an increased plant photosynthetic capacity (Hemming et al., 2008). In addition, PG netting significantly increased fruit weight, fruit diameter and seed weight (Table 2). These findings coincide with those reported by Dueck et al. (2012) in tomato as the plants grown under a

higher amount of diffuse light produced higher fruit weight compared to those grown under direct light.

Reduced VDP could also explain the effect of PG netting on the larger fruit and seed size found in this study. Larger fruit size was observed in apples associated with a reduction in VPD conditions that increased the supply of carbohydrate for fruit growth (Bastías et al., 2012). However, the reduction in VPD under PG was lower than the other colored nets (Fig. 3 c, d), and therefore would only partially explain these results. It is important to note that fruit size is the result of balance between inflow and outflow of water and assimilate during fruit growth. In this sense, each fruit crop has a particular growth behavior under VDP conditions and is regulated by the balance between skin transpiration and assimilate transport through the phloem (Morandi et al., 2012). Hazelnut fruit size is determined by the potential development of the ovary, ovule and embryo, whose growth rate ultimately determines fruit weight, seed weight, and yield, where the transpiration and phloem activity could be play an important role on nutrient and assimilate transport for adequate fruit growth (Beyhan and Marangoz, 2007). Even though reductions in VPD have been associated with higher fruit size at harvest (Bastías et al., 2012), the relationship between VPD and fruit size was not consistent in the present study. For instance, in the second season, fruits from plants under PG nets were significantly larger than those from the other treatments. However, air VPD during the second season showed smaller variability among treatments than during the third season. In

fact, in the third season, fruits from plants under open field conditions showed both the highest VPD and fruit size. Therefore, it seems that differences in other microclimate parameters, such as air temperature and solar radiation might have had a greater impact on fruit size than air VPD.

On the other hand, it was found that all colored nets produced higher fruit drop for the first harvest dates compared to the control. Early fruit drop has been related to hormonal changes that trigger abscission during ripening. This involves the hormonal interaction between indole-3-acetic acid (IAA) and ethylene, which plays an important role in the abscission process, allowing the fruit to be picked before harvest (Li and Yuan, 2008). Although there is little information about how environmental conditions influence fruit abscission, it has been established that a decrease in both light intensity and duration (photoperiod) stimulates abscission of organs such as leaves and fruits due to changes in hormonal signals that promote senescence (Arseneault and Cline, 2016). The fact that the colored nets used in our study reduced the amount of sunlight available to the plant (Fig. 2 a, b) would explain why hazelnuts grown under cover dropped earlier compared to those of the control treatment. This effect of netting on early fruit drop could provide additional benefits for hazelnut production under shade netting by improving mechanized harvesting efficiency, reducing the risk of diseases and improving the drying efficiency of fruits in areas where harvest delay coincides with rainy weather conditions and high relative humidity (Yildiz and Tekgüler, 2014).

In terms of characteristics of the leaf, the reduction in light availability under PG netting (the cover with the best performance in the present study) did not alter the anatomical characteristics of the leaf such as SLW and SD. This finding does not agree with previous studies that have reported a negative effect of netting or shading on the reduction in SLW and SD (Hampson et al., 1996; Gregoriou et al., 2007; Solomakhin and Blanke, 2010). However, leaves from trees grown under BG and B nets presented a lower SD and SLW compared to those from trees grown in full sun (Table 4). This is probably due to the lower light availability observed under these nets compared to PG netting (Table 1; Fig. 2), confirming that hazelnut leaves have high plasticity in terms of morphological changes associated with subtle alterations in sunlight availability (Hampson et al., 1996). The differences in leaf morphology observed among colored nets were not reflected in direct modifications on gas exchange variables such as photosynthesis and leaf stomatal conductance. This could be due to a number of different reasons. In our study, photosynthesis was measured in leaves exposed to full sun, i.e. mostly exposed to direct light and not diffuse. It has been described that unexposed leaves present the highest exposure to diffuse light, and consequently have a different photosynthetic light-response curve (Li and Yang, 2015). This could explain why the use of PG netting had no significant effect on leaf net photosynthesis, suggesting photosynthesis measurements in the entire plant canopy as including both exposed and non-exposed could allow for a more precise determination of the

effect of colored nets on photosynthesis (Li and Yang, 2015). In addition, PPFD measured at the leaf level was greater than  $1,300 \mu\text{mol m}^{-2} \text{s}^{-1}$  in all colored nets, which is higher than the light saturation point of photosynthesis for hazelnut (equivalent to  $1,000 \mu\text{mol m}^{-2} \text{s}^{-1}$ ) (Hampson et al., 1996). These arguments would explain why a reduction in SLW by B and BG netting was not reflected at lower photosynthesis capacity rate. Similarly, the lower SD found with BG netting did not result in a reduction in  $g_s$ , which may be attributable to the blue color of the net as it contributes to a higher amount of light in the blue spectrum (data not shown). There is evidence that indicates that blue light stimulates stomatal opening in plants by activation of plasma membrane H(+)-ATPase, hyperpolarizing it through acidification and increasing the negative internal electrical potential. This drives  $\text{K}^+$  absorption, in turn increasing the turgor potential of the guardian cells of the stoma, and consequently their opening (Shimazaki et al., 2007). This explains why a reduction in the number of stomata under BG netting did not have an effect on reduced leaf  $g_s$ .

Although no differences were found in terms of absolute values of leaf gas exchanges among colored nets, the linear regression analysis showed a close and significant relationship between  $A_n$  and  $g_s$  for all leaves grown under colored nets, but not in the control (Table 5; Fig. 6 and 7). This indicates that the variation of  $A_n$  in uncovered leaves would be explained by a non-stomatal or biochemical mechanism, associated with the effect of excess radiation and high temperature on the inhibition of PS-II or Rubisco activity (Farquhar and

Sharkey, 1982). According to the results, leaf temperature under no netting was 5 °C higher than that recorded under colored nets, reaching values close to 40 °C, but without negative effects on the photochemical activity of PS-II when was measured by the  $F_v/F_m$  ratio (Fig. 8). These results are consistent with previous studies in which the variation of photosynthesis in uncovered trees exposed to higher PPFD levels and high temperatures was limited by other non-stomatal factors (Medina et al., 2002; Jifon and Syvertsen, 2003), rather than the inhibition of electron transport or PS-II activity. In fact, an inactivation of Rubisco capacity due to temperatures over 35 °C would probably account for the variation of photosynthesis (Zhang et al., 2001).

The relationship between  $A_n$  and  $g_s$  under BG netting (negative hyperbola) was very different from that of PG netting (positive hyperbola) (Fig. 6c, d; Fig. 7c, d). According to Farquhar and Sharkey (1982), this would indicate that an increase in stomatal conductance does not produce photosynthetic saturation in the leaves grown under PG netting; conversely, photosynthesis is saturated with increases in stomatal conductance in leaves from trees grown under BG netting. It has been described that saturation of photosynthesis from increased stomatal conductance could be explained by non-stomatal limitations associated with a decrease in Rubisco activity or electron transport rate (Zhang et al., 2001). As mentioned before, the leaves under BG netting presented a lower SLW. Reduction of SLW result from less chlorophyll palisade thickness development limiting leaf photosynthetic capacity under lower light availability

(Gregoriou et al., 2007), which would explain the differences in non-stomatal limitation with respect to PG netting. In addition, leaf temperature measured at noon under BG netting was similar to that under no netting, reaching values higher than 35°C, which represents a greater limitation of photosynthesis by non-stomatal factors such as inhibition of Rubisco activity (Zhang et al., 2001). On the other hand, Massonet et al. (2007) have indicated that leaves with a linear relationship between  $A_n$  and  $g_s$  are more water-conserving than those with a curvilinear relationship. In the present study, leaves under PG conditions showed that small reductions in  $g_s$  were associated with larger drops in  $A_n$  than those under the conditions of the remaining treatments. This suggests that, under water stress, a hazelnut orchard covered with PG netting may exhibit a different relationship between stomatal conductance and net photosynthesis than when covered with B and BG netting. It is worth mentioning that the midday stem water potentials measured in our study were in the range defined for well-irrigated conditions (between -0.8 and -0.6 MPa) (Ortega-Farias et al., 2020). The authors described negative effects on yield and photosynthesis with midday stem water potential values lower than -1.3 MPa. This may demonstrate that, in situations of adequate water supply, the microclimatic conditions that are generated under PG netting allow the development of leaves with a more positive relationship between  $A_n$  and  $g_s$ . This would also explain why this colored netting resulted in higher fruit yield in hazelnut.



## **5. Conclusions**

In conclusion, depending on color of net, photo-selective nets differently affect microclimatic conditions with an ensuing impact on yield in hazelnut orchards. PG netting is the most promising alternative to maximize the yield in hazelnut under climate conditions where excessive solar radiation and high temperature could be limiting the growth and development of hazelnut trees. Permanent covering of hazelnut orchard with PG netting provides a better modulation of leaf traits to maximize photosynthesis and thus constitutes an interesting tool to optimize the hazelnut tree physiological potential through sunlight management. In addition, the use of netting could be a tool to anticipate harvest date, which could provide additional benefits in hazelnuts orchards under PG photo-selective netting.

### **Author contribution statement**

#### **Affiliations**

Universidad de Concepción, Facultad de Agronomía, Av. Vicente Méndez 595, Chillán, Chile.

Felipe Salazar Canales, Richard M. Bastías, Arturo Calderón-Orellana, Rosemarie Wilckens, Esteban González.

#### **Contributions**

FSC: Data collection and analysis, drafting the article. RMB: Mentoring in the conception and design of the research work, critical revision of the article. ACO:

Supporting with plant water status analysis. RW: Supporting with leaf morphological analysis. EG: Technical assistance with field trials.

### **Acknowledgements**

We gratefully acknowledge the Production Development Corporation (CORFO) of Chile for funding this research through the Technological Program n° 16PTECF5-66647 “Center for Research and Innovation in Fruit Growing for the South Zone”.

### **Compliance with ethical standards**

The authors declare that they have no conflict of interest. This article does not contain any studies involving human or animal participants performed by any of the authors.

### **Literature Cited**

Abdel-Ghany AM, Al-Helal IM (2010) Characterization of solar radiation transmission through plastic shading nets. *Sol Energy Mater Sol Cells* 94:1371–1378. <https://doi.org/10.1016/j.solmat.2010.04.005>

Abdel-Ghany AM, Al-Helal IM, Shady MR, Ibrahim AA (2015) Convective heat transfer coefficients between horizontal plastic shading nets and air. *Energy Buildings* 93:119-125. <https://doi.org/10.1016/j.enbuild.2015.02.010>

Arseneault MH, Cline JA (2016) A review of apple preharvest fruit drop and practices for horticultural management. *Sci Hortic* 211:40-52. <https://doi.org/10.1016/j.scienta.2016.08.002>

Baille A, Kittas C, Katsoulas N (2001) Influence of whitening on greenhouse microclimate and crop energy partitioning. *Agric Forest Meteor* 107:293–306. [https://doi.org/10.1016/s0168-1923\(01\)00216-7](https://doi.org/10.1016/s0168-1923(01)00216-7)

Balzarini MG, González L, Tablada M, Casanoves F, Di Rienzo JA, Robledo CW (2008) *InfoStat: statistical software*. Brujas, Córdoba, Argentina, 2008; pp. 329.

Basile B, Giaccone M, Cirillo C, Ritieni A, Graziani G, Shahak Y, Forlani M (2012) Photo-selective hail nets affect fruit size and quality in Hayward kiwifruit. *Sci Hortic* 141:91-97. <https://doi.org/10.1016/j.scienta.2012.04.022>

Bastías RM, Manfrini L, Corelli-Grappadelli L (2012) Exploring the potential use of photo-selective nets for fruit growth regulation in apple. *Chil J Agric Res* 72: 224-231. <http://dx.doi.org/10.4067/S0718-58392012000200010>

Beyhan N, Marangoz D (2007) An investigation of the relationship between reproductive growth and yield loss in hazelnut. *Sci Hortic* 113:208–215. <https://doi.org/10.1016/j.scienta.2007.02.007>

Corelli-Grappadelli L, Lopez G, Manfrini L, Zibord M, Morandi B, Bastias R, Losciale P (2017) Conditioning the orchard light environment for greater efficiency and sustainability. *Acta Hortic* 1177:73-78. <https://doi.org/10.17660/ActaHortic.2017.1177.7>

Corelli-Grappadelli L, Lakso AN (2007) Is maximizing orchard light interception always the best choice?. *Acta Hortic* 732:507-518. <https://doi.org/10.17660/ActaHortic.2007.732.77>

Corelli-Grappadelli, L. (2003) Light Relations. In Apples: Botany, Production and Uses. D.C. Ferree and I.J. Warrington Eds. CAB International: Wallingford, UK, pp. 195 – 216.

Dueck T, Janse J, Li T, Kempkes F, Eveleens B (2012) Influence of diffuse glass on the growth and production of tomato. *Acta Hort* 956:75-82. <https://doi.org/10.17660/ActaHortic.2012.956.6>

Farquhar GD, Sharkey TD. (1982) Stomatal conductance and photosynthesis. *A Rev Plant Physiol* 33:317-345.

Gregoriou K, Pontikis K, Vemmos S (2007) Effects of reduced irradiance on leaf morphology, photosynthetic capacity, and fruit yield in olive (*Olea europaea* L.) *Photosynthetica* 45:172-181. <https://doi.org/10.1007/s11099-007-0029-x>

Hampson CR, Azarenko AN, Potter JR (1996) Photosynthetic rate, flowering and yield component alteration in hazelnut in response to different light environments. *J Am Soc Hortic Sci* 121:1103–1111. <https://doi.org/10.21273/JASHS.121.6.1103>

Hemming S, Dueck T, Janse J, Van Noort F (2008) The effect of diffuse light on crops. *Acta Hort* 801:1293-1300.

Jifon JL, Syvertsen JP (2003) Moderate shade can increase net gas exchange and reduce photoinhibition in citrus leaves. *Tree Physiol* 23:119–127. <https://doi.org/10.1093/treephys/23.2.119>

Jifon JL, Syvertsen JP (2001) Effects of moderate shade on citrus leaf gas exchange, fruit yield, and quality. *Proc Fl State Hort Soc* 114: 177–181. <https://doi.org/10.1093/treephys/23.2.119>

Landsberg JJ, Sands P (2011) Physiological Ecology of Forest Production: Principles, Processes and Models. Academic Press (Elsevier), London, pp 352.

Li T, Yang Q (2015) Advantages of diffuse light for horticultural production and perspectives for further research. *Front Plant Sci* 6:704. <https://doi.org/10.3389/fpls.2015.00704>

Li J, Yuan R (2008) NAA and ethylene regulate expression of genes related to ethylene biosynthesis, perception, and cell wall degradation during fruit abscission and ripening in 'Delicious' apples. *J Plant Growth Reg* 27:283–295. [10.1007/s00344-008-9055-6](https://doi.org/10.1007/s00344-008-9055-6)

Lobos GA, Retamales JB, Hancock JF, Flore JA, Romero-Bravo S, Del Pozo A (2013) Productivity and fruit quality of *Vaccinium corymbosum* cv. Elliott under photo-selective shading nets. *Sci Hortic* 153:143-149. <https://doi.org/10.1016/j.scienta.2013.02.012>

Luciani E, Palliotti A, Frioni T, Tombesi S, Villa F, Zadra C, Farinelli D (2020) Kaolin treatments on Tonda Giffoni hazelnut (*Corylus avellana* L.) for the control of heat stress damages. *Sci Hortic* 263:109097. <https://doi.org/10.1016/j.scienta.2019.109097>

Maxwell K, Johnson GN (2000) Chlorophyll fluorescence – a practical guide. *J Exp Bot* 51:659-668. <https://doi.org/10.1093/jexbot/51.345.659>

Massonet C, Costes E, Rambal S, Dreyer E, Regnard JL (2007) Stomatal regulation of photosynthesis in apple leaves: Evidence for different water-use

strategies between two cultivars. *Ann Bot* 100:1347–1356.  
<https://doi.org/10.1093/aob/mcm222>

McCutchan H, Shackel KA (1992) Stem-water potential as a sensitive indicator of water stress in prune trees (*Prunus domestica* L. cv. French). *J Amer Soc Hortic Sci* 117:607-611. <https://doi.org/10.21273/JASHS.117.4.607>

Medina CL, Souza RP, Machado EC, Ribeiro RV, Silva JAB (2002) Photosynthetic response of citrus grown under reflective aluminized polypropylene shading nets. *Sci Hortic* 96:115-125. [https://doi.org/10.1016/S0304-4238\(02\)00085-7](https://doi.org/10.1016/S0304-4238(02)00085-7)

Morandi B, Zibordi M, Losciale P, Manfrini L, Bastías, R.M, Corelli-Grappadelli L (2012) Apple and Peach: A different role for fruit transpiration? *Acta Hortic* 932: 213 – 218.

Mupambi G, Musacchi S, Serra S, Kalcsits LA (2018) Protective netting improves leaf-level photosynthetic light use efficiency in ‘Honeycrisp’ apple under heat stress. *HortScience* 53:1416–1422. <https://doi.org/10.21273/HORTSCI113096-18>

Ortega-Farias S, Villalobos-Soublett E, Riveros-Burgos C, Zúñiga M, Ahumada-Orellana LE (2020) Effect of irrigation cut-off strategies on yield, water productivity and gas exchange in a drip-irrigated hazelnut (*Corylus avellana* L. cv. Tonda di Giffoni) orchard under semiarid conditions. *A Water Manag* 238:106173. <https://doi.org/10.1016/j.agwat.2020.106173>

Özmer S (2016) Quantification of leaf water potential, stomatal conductance and photosynthetically active radiation in rainfed hazelnut *Erw-Obst* 58:273–280.

Paradiso R, Marcelis LFM (2012). The effect of irradiating adaxial or abaxial side on photosynthesis of rose leaves. *Acta Hort* 956, 157–163. <https://doi.org/10.17660/ActaHortic.2012.956.15>

Reyes-Díaz M, Alberdi M, Mora ML (2009) Short-term aluminum stress differentially affects the photochemical efficiency of photosystem II in highbush blueberry genotypes. *J Amer Soc Hort Sci* 134:14–21. <https://doi.org/10.21273/JASHS.134.1.14>

Shahak Y (2014) Photosensitive netting: an overview of the concept, research and development and practical implementation in agriculture. *Acta Hort* 1015:155–162. <https://doi.org/10.17660/ActaHortic.2014.1015.17>.

Shahak Y, Ratner K, Giller YE, Zur N, Or E, Gussakovsky EE, Greenblat-Avron Y (2008) Improving solar energy utilization, productivity and fruit quality in orchards and vineyards by photosensitive netting. *Acta Hort* 772:65–72. <https://doi.org/10.17660/actahortic.2008.772.7>

Shimazaki KI, Doi M, Assmann SM, Kinoshita T (2007) Light regulation of stomatal movement. *Ann Rev Plant Biol* 58:219–47. <https://doi.org/10.1146/annurev.arplant.57.032905.105434>

Solomakhin A, Blanke MM (2010) The microclimate under coloured hailnets affects leaf and fruit temperature, leaf anatomy, vegetative and reproductive growth as well as fruit colouration in apple. *Ann Appl Biol* 156: 121–136. <https://doi.org/10.1111/j.1744-7348.2009.00372.x>

Solomakhin A, Blanke MM (2008) Coloured hailnets alter light transmission, spectra and phytochrome, as well as vegetative growth, leaf chlorophyll and

photosynthesis and reduce flower induction of apple. *Plant Growth Regul* 56:211–218. <http://dx.doi.org/10.1007/s10725-008-9302-7>

Umanzor C, Bastías RM, Wilckens R, Quezada C (2017) Influence of using of pearl and red nets on micro-climate conditions, fruit sun damage and fruit color development in ‘Gala’ and ‘Fuji’ apple orchards. *Rev Bras Frutic* 39:930–943. <https://doi.org/10.1590/0100-29452017930>

Wünsche JN, Lakso AN (2000) Apple tree physiology: Implications for orchard and tree management. *Comp Fruit Tree* 33:82-88.

Yildiz T, Tekgüler A (2014) The effects of different maturity times of fruit ripening and limb connection heights on the percentages of fruit removal in mechanical harvesting of hazelnut (cv. Yomra) *J Agric Sci* 20: 38 – 47.

Zhang BB, Xu, JL, Zhou M, Yan DH, Ma RJ (2018) Effect of light quality on leaf photosynthetic characteristics and fruit quality of peach (*Prunus persica* L. Batch). *Photosynthetica* 56:1113–1122 <https://doi.org/10.1007/s11099-018-0820-x>

Zhang S, Li Q, Ma K, Chen L (2001) Temperature-dependent gas exchange and stomatal/non-stomatal limitation to CO<sub>2</sub> assimilation of *Quercus liaotungensis* under midday high irradiance. *Photosynthetica* 39:383-388. <https://doi.org/10.1023/A:1015130326683>

Zoratti L, Jaakola L, Häggman H, Giongo L (2015) Modification of sunlight radiation through colored photo-selective nets affects anthocyanin profile in *Vaccinium* spp. *Berries. PLoS ONE* 10:e0135935. <http://dx.doi.org/10.1371/journal.pone.0135935>



Table 1. Light properties estimated under Black (B), Blue-gray (BG) and Pearl-gray (PG) colored nets in comparison to uncovered trees (Control). PPFD: Photosynthetic photon flux density. \*, \*\*, ns: Significantly, highly significantly and non-significantly at  $P < 0.05$  and  $0.01$ , respectively.

Net System	Light properties	
	PPFD <sub>total</sub> ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ )	PPFD <sub>diffuse</sub> (%)
Control	2011.8 a	10.3 c
B	1591.2 b	10.8 bc
BG	1537.6 c	11.5 b
PG	1619.2 b	15.1 a
<i>P-value</i>	<0.0001**	<0.0001**

Fuente: Elaboración propia

Table 2. Fruit yield components estimated under Black (B), Blue-gray (BG) and Pearl-gray (PG) colored nets in comparison to uncovered trees (Control) during three consecutive year seasons in hazelnut orchard. \*, \*\*, ns: Significantly, highly significantly and non-significantly at  $P < 0.05$  and  $0.01$ , respectively.

Net System	Nut weight (g)	Nut diameter (mm)	Kernel weight (g)	Kernel ratio (%)
2017-2018 Year season				
Control	3.05 a	20.6 a	1.40 a	45.8 a
B	3.14 a	20.6 a	1.44 a	45.9 a
BG	3.11 a	20.7 a	1.45 a	46.9 a
PG	3.26 a	21.0 a	1.49 a	45.7 a
<i>P-value</i>	0.4484 <sup>ns</sup>	0.1404 <sup>ns</sup>	0.1203 <sup>ns</sup>	0.1162 <sup>ns</sup>
2018-2019 Year season				
Control	3.11 b	20.8 b	1.50 b	48.4 a
B	3.14 b	20.7 b	1.52 b	48.7 a
BG	3.18 b	20.8 b	1.55 b	48.8 a
PG	3.37 a	21.2 a	1.61 a	48.0 b
<i>P-value</i>	<0.0001 <sup>**</sup>	0.0003 <sup>**</sup>	0.0009 <sup>**</sup>	0.0082 <sup>**</sup>
2019-2020 Year season				
Uncovered	3.24 a	21.0 a	1.51 a	46.6 a
B	3.12 b	20.5 b	1.45 b	46.6 a
BG	3.11 b	20.6 b	1.45 b	46.6 a
PG	3.31 a	21.2 a	1.54 a	46.4 a
<i>P-value</i>	0.0017 <sup>**</sup>	0.0004 <sup>**</sup>	0.0039 <sup>**</sup>	0.8313 <sup>ns</sup>

Fuente: Elaboración propia

Table 3. Leaf physiological characteristics estimated under Black (B), Blue-gray (BG) and Pearl-gray (PG) colored nets in comparison to uncovered trees (Control) for controlled and ambient light conditions in hazelnut. Net photosynthesis rate ( $A_n$ ), stomatal conductance ( $g_s$ ), transpiration rate ( $E$ ), leaf intercellular CO<sub>2</sub> concentration ( $C_i$ ), instantaneous carboxylation efficiency ( $A/C_i$ ), maximum photochemical efficiency of photosystem II ( $F_v/F_m$ ), stem water potential (SWP), stomata density (SD) and specific leaf weight (SLW). \*, \*\*, ns: Significantly, highly significantly and non-significantly at  $P < 0.05$  and  $0.01$ , respectively.

Leaf parameters	Net System				<i>P</i> -value
	Control	B	BG	PG	
Controlled light conditions					
$A_n$ ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ )	9.6 a	7.7 a	8.2 a	10.4 a	0.3253 <sup>ns</sup>
$g_s$ ( $\text{mmol m}^{-2} \text{ s}^{-1}$ )	179.2 a	137.9 a	156.3 a	192.4 a	0.4180 <sup>ns</sup>
$E$ ( $\text{mmol H}_2\text{O m}^{-2} \cdot \text{s}^{-1}$ )	1.7 a	1.4 a	1.6 a	1.7 a	0.6034 <sup>ns</sup>
$C_i$ ( $\mu\text{mol mol}^{-1}$ )	275.8 a	285.2 a	286.9 a	271.9 a	0.4180 <sup>ns</sup>
$A/C_i$	0.02 a	0.02 a	0.02 a	0.02 a	0.4008 <sup>ns</sup>
$F_v/F_m$	0.78 a	0.78 a	0.78 a	0.78 a	0.5156 <sup>ns</sup>
SWP (-Mpa)	0.61 a	0.60 a	0.61 a	0.63 a	0.8574 <sup>ns</sup>
SD ( $\text{n}^\circ \text{ mm}^{-2}$ )	217.9 a	200.0 a	150.4 b	211.3 a	<0.0001 <sup>**</sup>
SLW ( $\text{mg cm}^{-2}$ )	5.9 a	4.7 c	5.0 bc	5.6 ab	0.0004 <sup>**</sup>
Ambient light conditions					
PPFD ( $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ )	1855,8 a	1378,5 b	1390,2 b	1387,2 b	<0,0001 <sup>**</sup>
$A_n$ ( $\mu\text{mol CO}_2 \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ )	4,8 a	4,9 a	5,2 a	6,3 a	0,4570 <sup>ns</sup>
$g_s$ ( $\text{mmol m}^{-2} \text{ s}^{-1}$ )	86,3 a	98,2 a	100,3 a	108,8 a	0,7680 <sup>ns</sup>
$E$ ( $\text{mmol H}_2\text{O m}^{-2} \cdot \text{s}^{-1}$ )	1,8 a	2,0 a	2,0 a	2,1 a	0,9475 <sup>ns</sup>
$C_i$ ( $\mu\text{mol} \cdot \text{mol}^{-1}$ )	298,2 a	304,0 a	301,3 a	284,2 a	0,4223 <sup>ns</sup>
$A/C_i$	0.01 a	0.01 a	0.01 a	0.02 a	0,0947 <sup>ns</sup>
$F_v/F_m$	0,74 a	0,75 a	0,75 a	0,73 a	0,6772 <sup>ns</sup>
SWP (-Mpa)	0,89 a	0,86 a	0,84 a	0,83 a	0,8553 <sup>ns</sup>

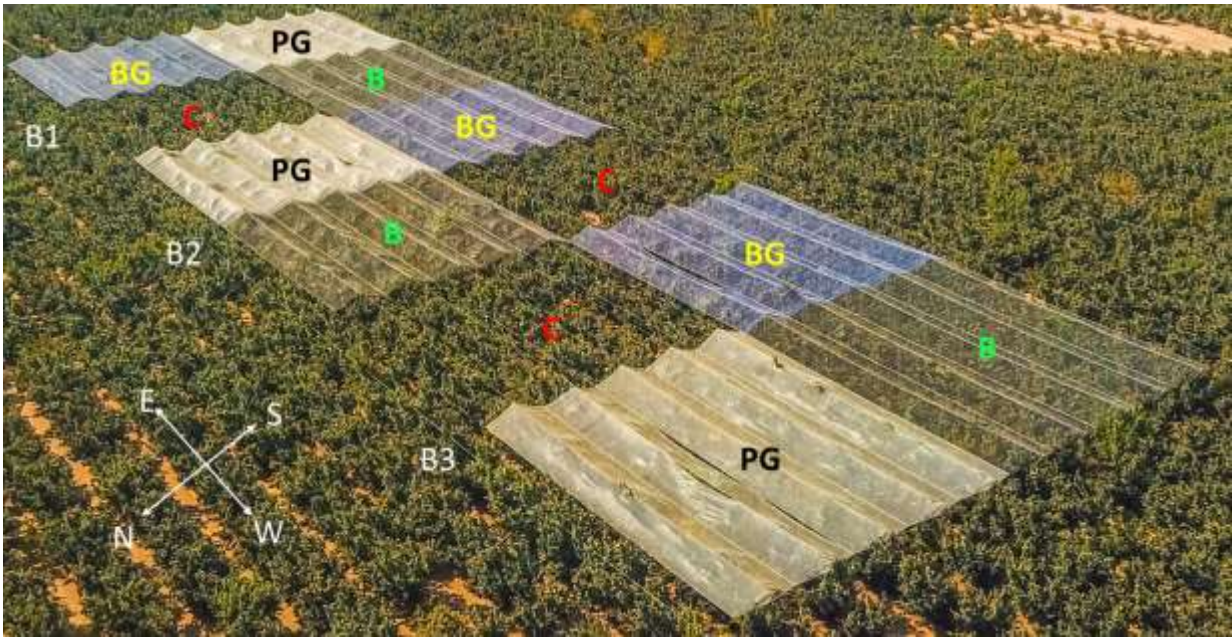
Fuente: Elaboración propia

Table 4. Regression coefficient for the relationship between leaf photosynthesis rate and leaf stomatal conductance as affected by Black (B), Blue-gray (BG) and Pearl-gray (PG) colored nets in comparison to uncovered trees (Control) for controlled and ambient light conditions. Regression equation is  $Y = \beta_0 + \beta_1 X + \beta_2 X^2$  \*; \*\*, ns: Significantly, highly significantly and non-significantly at  $P < 0.05$  and 0.01, respectively.

Regression coefficients	Net System			
	Control	B	BG	PG
	Controlled light conditions			
$\beta_0$	2.01 <sup>ns</sup>	-1.00 <sup>ns</sup>	-0.87 <sup>ns</sup>	4.32*
$\beta_1$	0.06 <sup>ns</sup>	0.08*	0.07*	0.01 <sup>ns</sup>
$\beta_2$	-0.000058 <sup>ns</sup>	-0.000096 <sup>ns</sup>	-0.000067 <sup>ns</sup>	0.000079 <sup>ns</sup>
R <sup>2</sup>	0.47 <sup>ns</sup>	0.91**	0.94**	0.93**
	Ambient light conditions			
$\beta_0$	-12.78 <sup>ns</sup>	5.23 <sup>ns</sup>	-3.89**	7.54*
$\beta_1$	0.34 <sup>ns</sup>	-0.05 <sup>ns</sup>	0.16**	-0.07 <sup>ns</sup>
$\beta_2$	-0.0013 <sup>ns</sup>	0.00043 <sup>ns</sup>	-0.00059**	0.00051 <sup>ns</sup>
R <sup>2</sup>	0.85 <sup>ns</sup>	0.90*	1.00**	0.95*

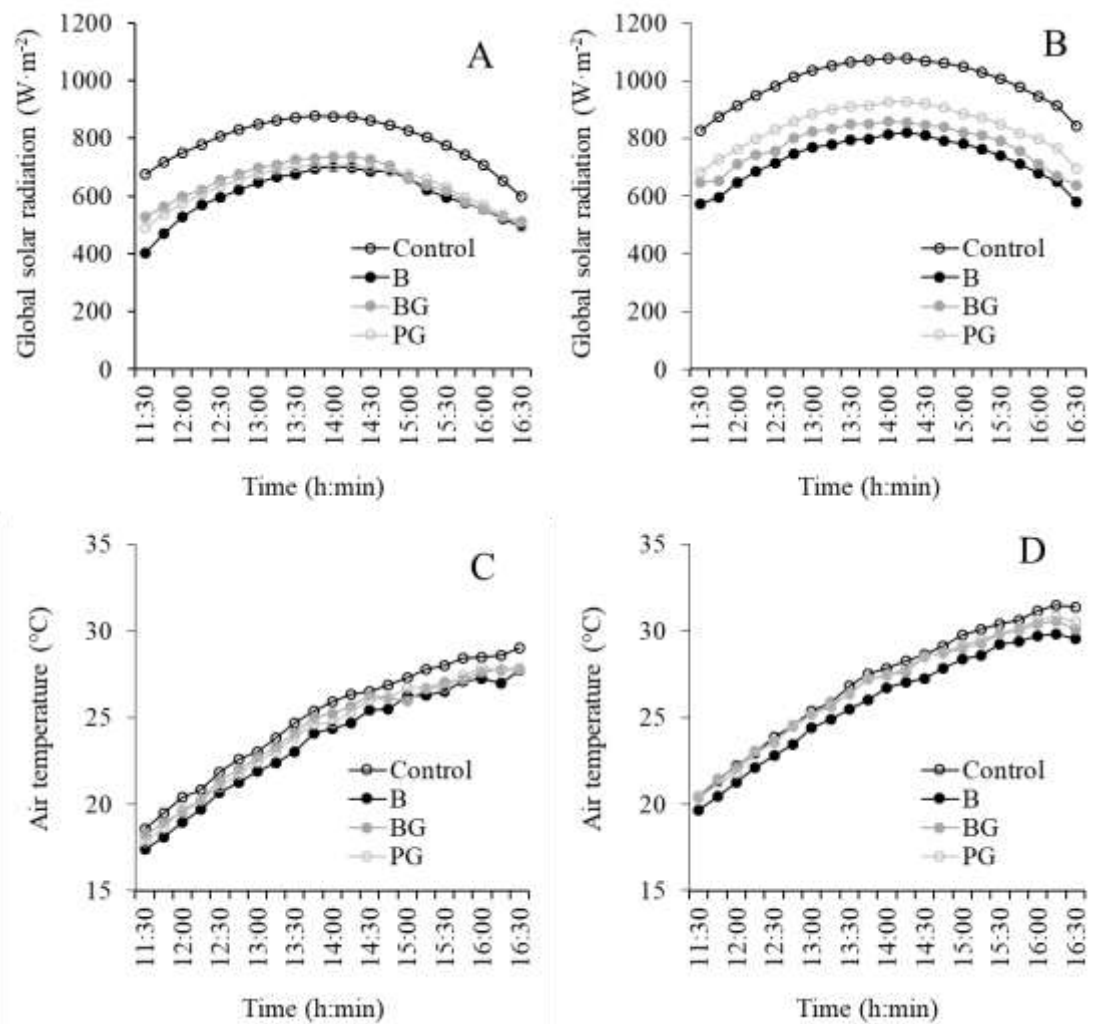
Fuente: Elaboración propia.

Figure 1. Experimental plot with Blue-gray (BG), Pearl-gray (PG) and Black (B) colored nets, compared to uncovered control trees (C) in commercial hazelnut orchard.



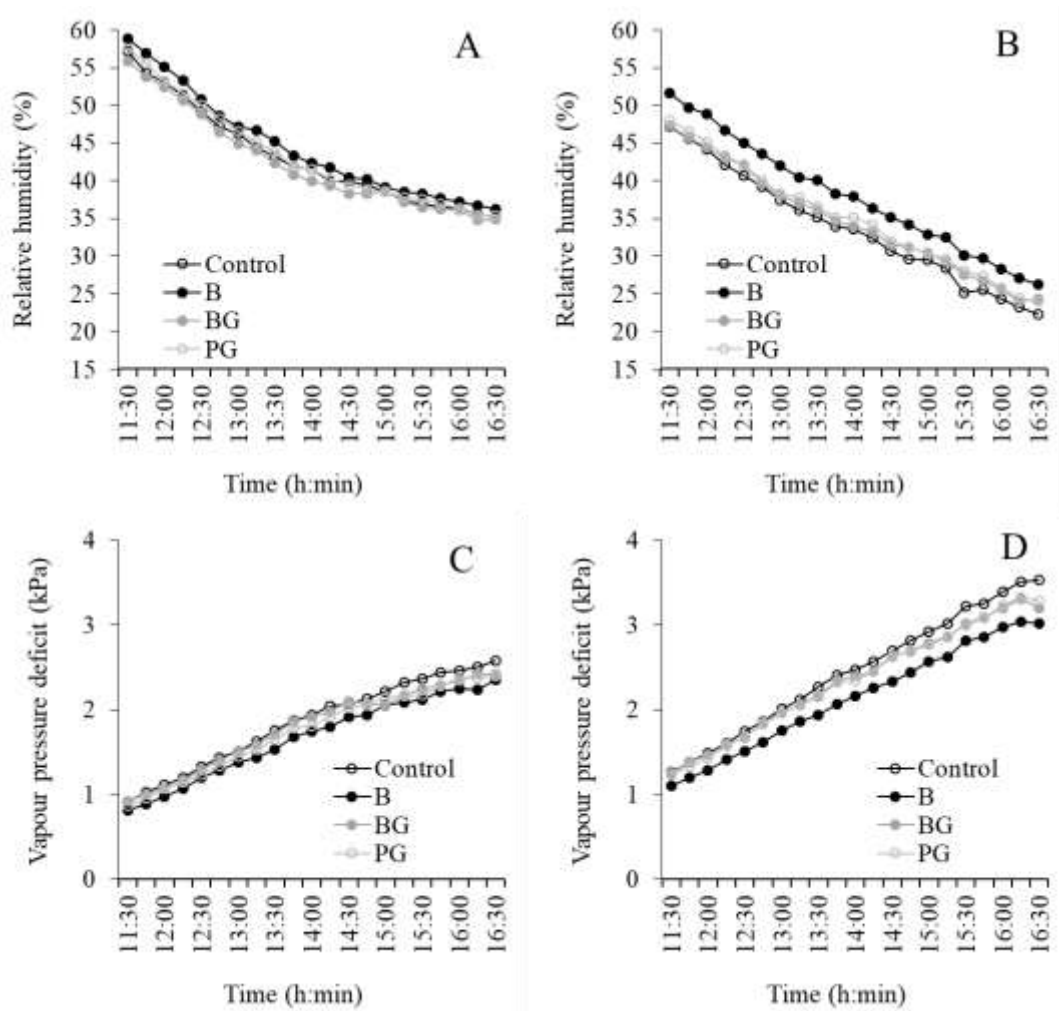
Fuente: Elaboración propia.

Figure 2. Daily pattern of global solar radiation (A and B) and air temperature (C and D) as affected by Black (B), Blue-gray (BG) and Pearl-gray (PG) colored nets in comparison to uncovered trees (Control) during 2018-2019 (A and C) and 2019-2020 (B and D) year seasons in a hazelnut orchard.



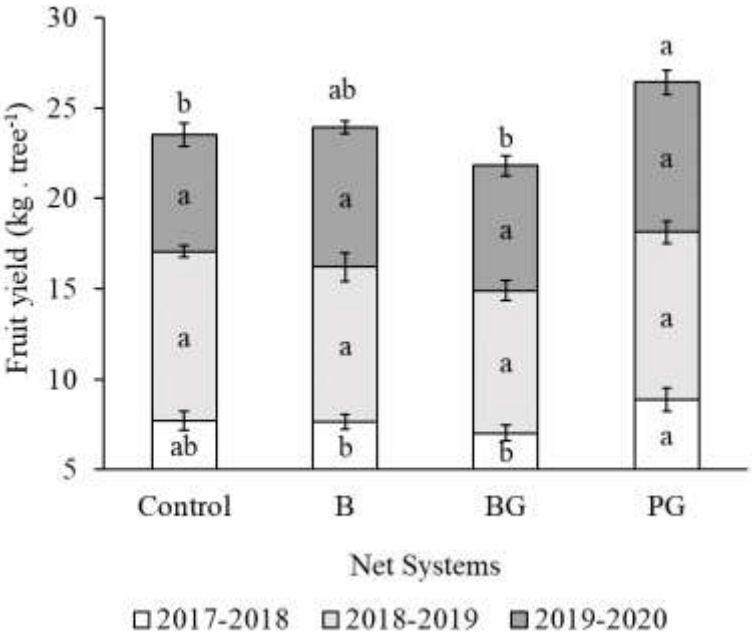
Fuente: Elaboración propia.

Figure 3. Daily pattern of relative humidity (A and B) and vapour pressure deficit (C and D) as affected by Black (B), Blue-gray (BG) and Pearl-gray (PG) colored nets in comparison to uncovered trees (Control) during 2018-2019 (A and C) and 2019-2020 (B and D) year seasons in a hazelnut orchard.



Fuente: Elaboración propia.

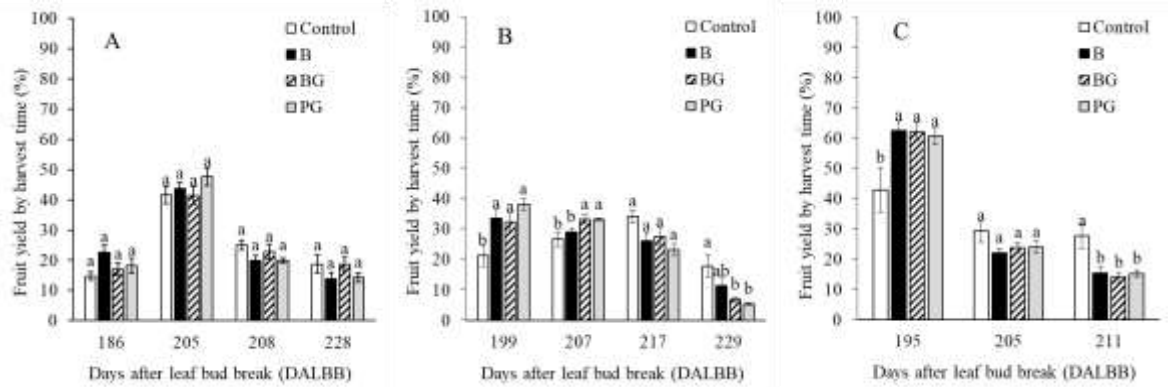
Figure 4. Cumulative fruit yield as affected by Black (B), Blue-gray (BG) and Pearl-gray (PG) colored nets in comparison to uncovered trees (Control) in a hazelnut orchard. Different letters between columns indicate statistical significance at the 0.05 probability level. Bars indicate standard error for n=6.



Fuente: Elaboración propia.

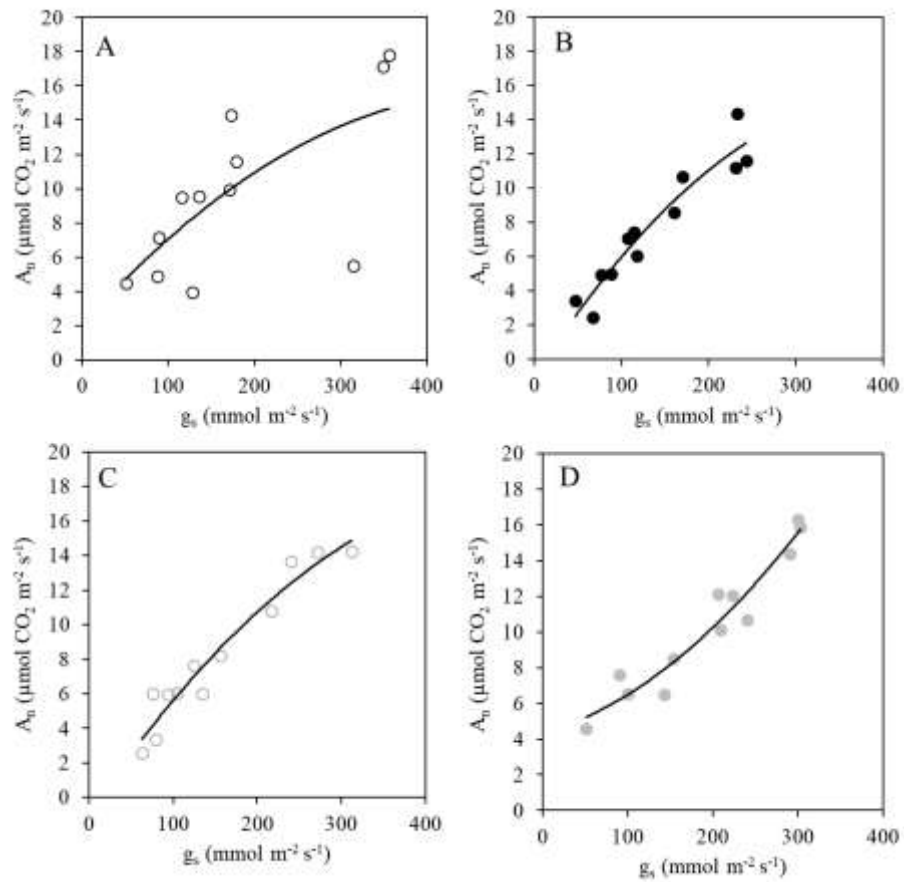


Figure 5. Variation on fruit yield per harvest time as affected by Black (B), Blue-gray (BG) and Pearl-gray (PG) colored nets in comparison to uncovered trees (Control) in a hazelnut orchard during 2017-2018 (A), 2018-2019 (B) and 2019-2020 (C) year seasons. Different letters between columns indicate statistical significance at the 0.05 probability level. Bars indicate standard error for n=6.



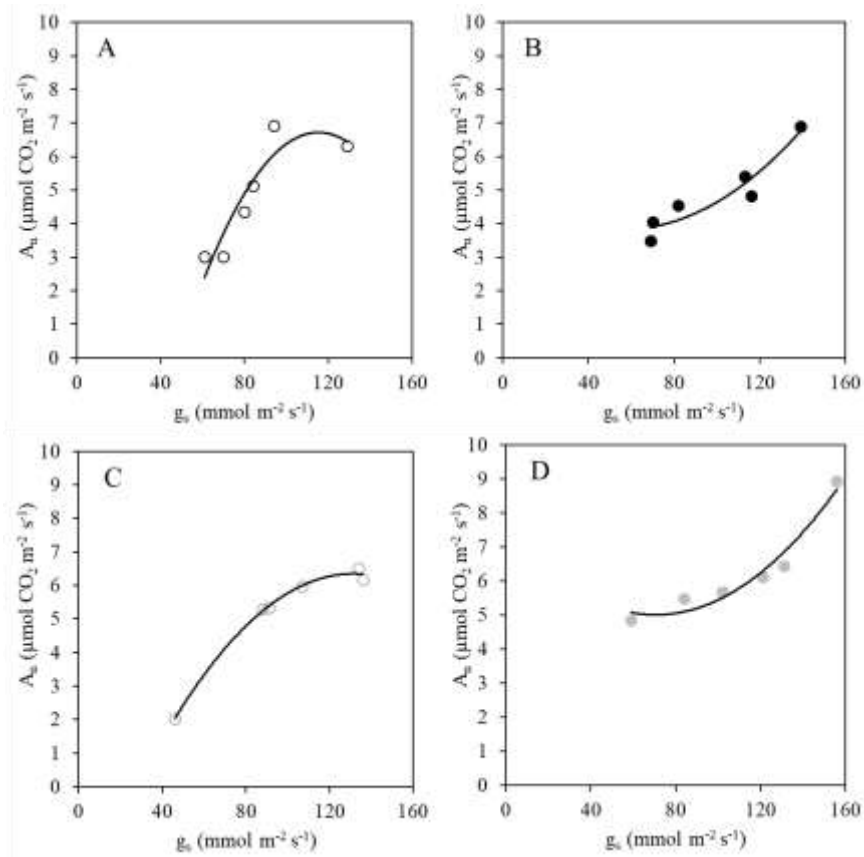
Fuente: Elaboración propia.

Figure 6. Relationship between photosynthesis rate ( $A_n$ ) and stomatal conductance ( $g_s$ ) in hazelnut leaves as affected by uncovered (A), Black (B), Blue-gray (C) and Pearl-gray (D) net systems. Leaf gas exchange measurements were carried out under controlled light conditions.



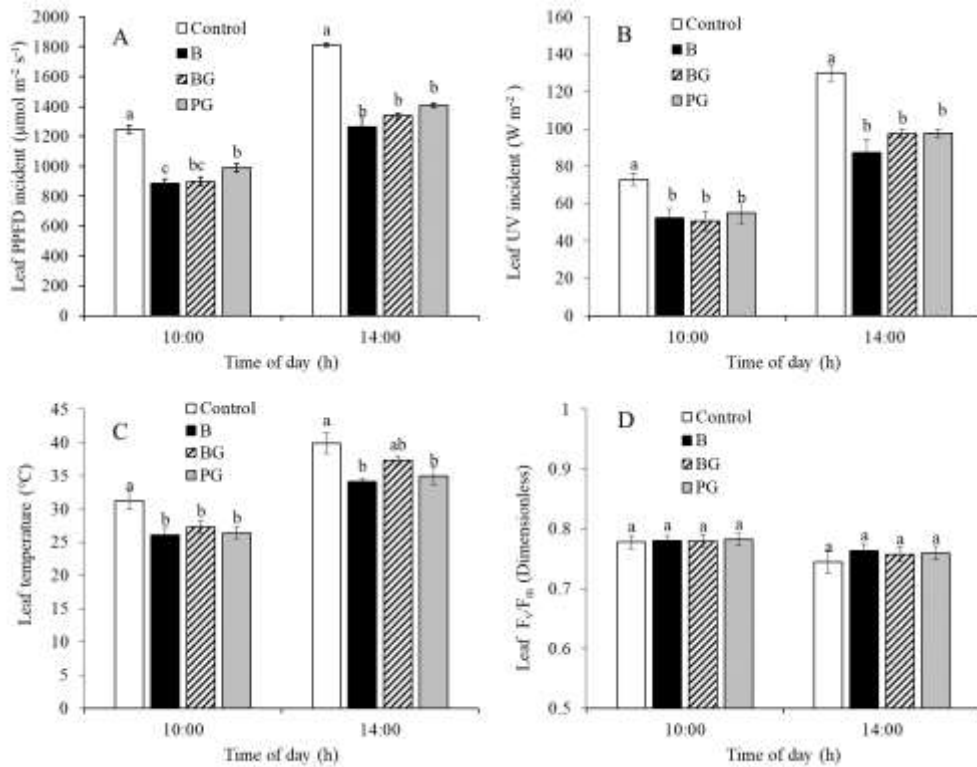
Fuente: Elaboración propia.

Figure 7. Relationship between photosynthesis rate ( $A_n$ ) and stomatal conductance ( $g_s$ ) in hazelnut leaves as affected by uncovered (A), Black (B), Blue-gray (C) and Pearl-gray (D) net systems. Leaf gas exchange measurements were carried out under ambient light conditions.



Fuente: Elaboración propia.

Figure 8. Variation on leaf PPFD incident (A), leaf UV incident (B), leaf temperature (C) and leaf  $F_v/F_m$  (D) as affected by Black (B), Blue-gray (BG) and Pearl-gray (PG) colored nets in comparison to uncovered trees (Control) in hazelnut orchard. Different letters between columns indicate statistical significance at the 0.05 probability level. Bars indicate standard error for n=6.



Fuente: Elaboración propia.