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Effect of canopy structure on light environment in the intercropping zone under almond||winter wheat intercropping pattern Postprint

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Abstract

This study investigated the effects of fruit tree canopy structure on the light environment in intercropped crop zones under crop-fruit tree intercropping patterns, providing a theoretical basis for determining optimal high light-use-efficiency tree structures in fruit-grain intercropping systems. Using the almond (10-year-old) || winter wheat intercropping system in southern Xinjiang as the research subject, four almond tree shape treatments were established: spaced layer shape, vase shape, high-trunk shape, and small-crown semicircular shape, with a non-intercropped winter wheat field as the control. During the winter wheat grain-filling stage, radiation intensity across different wavebands, spectral composition, and diurnal variation patterns of photosynthetically active radiation (PAR) were measured zonally in the intercropping area. The results showed: 1) The light environment quality of intercropping areas corresponding to the different tree shapes, from high to low, ranked as small-crown semicircular shape, high-trunk shape, vase shape, and spaced layer shape. The average total radiation intensity in the intercropping areas of these tree shape treatments was 55.63%, 46.54%, 37.87%, and 28.76% of the control, respectively, while the photosynthetically active radiation intensity was 55.84%, 44.57%, 35.52%, and 26.40% of the natural light control, respectively; 2) Compared with the natural light control, radiation intensity in all wavebands in the intercropping area decreased to varying degrees, with the reduction magnitude of PAR, blue-violet light, yellow-green light, and red-orange light regions exceeding the average total radiation reduction, while the reduction magnitude of ultraviolet, near-infrared, and far-infrared regions was lower than the average total radiation reduction. Taking the west side under-canopy zone of the spaced layer shape as an example, the total radiation in this area was reduced to 11.37% of natural light; blue-violet light, yellow-green light, red-orange light, and photosynthetically active radiation were reduced to 7.98%, 8.42%, 8.62%, and 8.30% of the control, respectively;

ultraviolet, near-infrared, and far-infrared were reduced to 12.30%, 15.94%, and 23.00% of the control, respectively; 3) Among the light quality parameters, the ratio of "red-orange light/far-infrared" exhibited high sensitivity to changes in canopy structural characteristics, with a coefficient of variation of 23.34%, and could serve as a primary indicator for evaluating the light environment in intercropping areas; 4) Canopy structural indicators such as crown width, trunk height, tree height, and presence/absence of a main trunk significantly influenced the diurnal variation trends of PAR in intercropping areas, particularly in the east side region. Based on these comprehensive results, under the southern Xinjiang almond || winter wheat intercropping system, pruning measures such as crown control, trunk raising, and leader reduction can improve light conditions in the intercropping area, with the small-crown semicircular shape providing the optimal light environment.

Full Text

Preamble

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Effect of Tree Canopy Structure on Light Environment in Intercropping Zones of Almond||Winter Wheat Systems

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Abstract
Intercropping of fruit trees and cereals represents a major cropping pattern in southern Xinjiang. As trees age and canopy volumes increase in intercropping systems, low-light stress due to tree canopy shading becomes the primary driver behind dramatic reductions in crop yield. However, given the fragile ecological environment of southern Xinjiang and food security concerns, this system has persisted for an extended period. This study investigated the relationship between canopy structure and light conditions in intercropping systems to provide a theoretical basis for selecting canopy structures suitable for optimal production. Using a 10-year-old almond tree and winter wheat intercropping system as the study object, four canopy structures were examined: delayed open-central shape, open-center shape, high-stem shape, and semicircle small-canopy shape, with monoculture winter wheat serving as the control. During the wheat grain-filling stage, radiation intensity across different wavebands, spectral composition, and diurnal variations of photosynthetically active radiation (PAR) were measured in different zones of the intercropping area. The results showed that:

(1) In terms of light environment quality in intercropping zones, the ranking from best to worst was semicircle small-canopy shape, high-stem shape, open-center shape, and delayed open-central shape. The average total radiation intensity under these four canopy shapes was 55.63%, 46.54%, 37.87%, and 28.76% of the control, respectively, while PAR intensity was 55.84%, 44.57%, 35.52%, and 26.40% of the control. (2) Compared with the control, radiation intensity in each waveband decreased to varying degrees. Reductions in PAR, blue-violet, yellow-green, and red-orange light were greater than the average reduction in total radiation, whereas reductions in ultraviolet, near-infrared, and far-infrared light were smaller than the average reduction in total radiation. For example, in the western region under the delayed open-central shape canopy, total radiation decreased to 11.37% of natural light, while blue-violet, yellow-green, red-orange light, and PAR decreased to 7.98%, 8.42%, 8.62%, and 8.30% of the control, respectively; ultraviolet, near-infrared, and far-infrared light decreased to 12.30%, 15.94%, and 23.00% of the control, respectively. (3) Among all light quality parameters, the ratio of red-orange light to far-infrared light was most sensitive to canopy structural changes, with a coefficient of variation of 23.34%, and can serve as a primary indicator for evaluating light environments in intercropping zones. (4) Canopy structural indices such as canopy width, trunk height, tree height, and presence of a central trunk significantly affected the diurnal variation trend of PAR in intercropping zones, particularly in eastern regions. Based on these results, pruning measures including canopy control, trunk raising, and leader removal can improve light conditions in intercropping zones under southern Xinjiang almond||winter wheat systems, with the semicircle small-canopy shape providing the optimal light environment.

Keywords: Almond/winter wheat intercropping; Tree canopy structure; Spectrum; Photosynthetically active radiation; Almond tree; Winter wheat

Introduction

Southern Xinjiang possesses unique geographical and environmental advantages for developing characteristic forestry and fruit industries, with abundant sunlight and large diurnal temperature variations. By 2013, the fruit tree cultivation area in five prefectures of southern Xinjiang (Kashgar, Hotan, Kizilsu, Aksu, and Bayingolin) had reached 1.002 million hectares (statistics from Xinjiang Uygur Autonomous Region Forestry and Fruit Office). The fruit-grain intercropping composite planting pattern represents one of the primary agricultural production systems in this region. In 2013, the cultivation area for wheat (*Triticum aestivum*) and cotton (*Gossypium hirsutum*) in southern Xinjiang was 1.222 million hectares, with approximately 850,000 hectares intercropped with fruit trees. As tree age and canopy volume continue to increase, shading-induced low-light stress has become a critical factor causing substantial yield reductions in intercropped wheat, particularly during the grain-filling stage when low-light stress adversely affects photosynthate synthesis and allocation, significantly impacting both yield and quality.

How to select and develop high light-efficiency tree forms that ensure high-quality, high-yield fruit production while alleviating shading stress on intercropped crops is an urgent problem facing agricultural production in southern Xinjiang. Guo et al. and Wang et al. employed the "PAR saturation spatiotemporal window" methodology to investigate jujube (*Zizyphus jujuba*) and apricot (*Armeniaca sp.*)||winter wheat intercropping systems in southern Xinjiang, demonstrating that fruit tree intercropping caused severe losses in PAR saturation spatiotemporal windows for winter wheat, preventing full expression of wheat' s light utilization capacity and ultimately leading to yield reductions. Under 6-year-old jujube trees with 3 m × 4 m spacing, the minimum duration during flowering was only 3.6 hours; under 7-year-old apricot trees with 6 m × 7 m spacing, the minimum PAR saturation spatiotemporal window occurred during winter wheat grain-filling. Tian et al. studied light competition in four typical fruit-crop intercropping systems in the Loess Region of western Shanxi, finding that apple (*Malus pumila*) exhibited greater competitive intensity than walnut (*Juglans regia*) when intercropped with the same crop. Research on leaf canopy effects on transmitted light quality indicates that different wavelengths are attenuated at different rates when passing through leaf canopies, with plant leaves absorbing 0.8–0.9 of ultraviolet and photosynthetically active radiation but only approximately 0.1 of near-infrared radiation. After selective absorption by leaves, the R/FR ratio in natural light changes significantly. In summary, within fruit-grain intercropping systems, the light environment in intercropping zones is closely related to light interception by the upper canopy structure. However, previous research has primarily focused on how species, row spacing, and other factors affect total radiation and PAR, with few reports on how different tree forms influence light environments, particularly spectral composition, in intercropping zones. Therefore, this study used the southern Xinjiang almond (*Amygdalus communis*)||winter wheat intercropping system as experimental material to investigate how tree form structure affects spectral composition changes and photosynthetically active radiation intensity in different intercropping zones, providing a reference for selecting appropriate tree forms for almond||winter wheat intercropping systems in southern Xinjiang.

Materials and Methods

1.1 Experimental Materials

The experiment was conducted during 2014–2015 in an almond high-yield demonstration orchard in Tuwumusitang Township, Shache County, Kashgar Prefecture, Xinjiang. The experimental fruit trees were planted in 2005 with a spacing of 6 m × 7 m in north-south rows. The planting pattern was almond||winter wheat intercropping without relay crops, with wheat planted along tree rows and an intercropped wheat planting width of 6 m. Four almond tree form treatments were established: delayed open-central shape, small-canopy shape, high-stem shape, and open-center shape (specific structural indices are provided in Table 1). Each plot contained five trees planted continuously along the row (and the corresponding wheat intercropping area within 0.5–3.5 m on both east and west sides of the tree row), with three replications. Twelve plots were established across the four treatments, with individual plot areas of 168 m², including 144 m² of intercropped wheat. The specific layout is illustrated in Figure 1 [Figure 1: see original paper]. A nearby field of monoculture winter wheat served as the control. The delayed open-central shape and small-canopy shape structures were developed through multi-year training, while the high-stem shape and open-center shape were both modified from the delayed open-central shape. The high-stem shape was created by gradually removing lower main branches through trunk-raising modification over 2–3 years, while the open-center shape was developed by gradually reducing trunk height through leader removal over two years to form a non-central-trunk shape. All other production management practices remained consistent.

1.2.1 Spectral Index Measurement in Intercropping Zones

A UniSpec-SC single-channel portable spectrometer (optimal sensing range: 300–1,100 nm; resolution: <10 nm; accuracy: <0.3 nm) was used to measure spectral composition in the intercropping zones of each plot. A total of 54 measurement points were established per treatment, with specific locations and distribution shown in Figure 1. During the wheat grain-filling stage, measurements were taken on clear days during three time periods: 9:00–10:00 (morning), 12:00–13:00 (noon), and 15:00–16:00 (afternoon) local time (East 6th Zone). Control measurements were taken simultaneously in the nearby monoculture wheat field (probe height consistent with other measurement points), with the probe height maintained at the same level as the intercropped wheat plants. Measurements were repeated for three consecutive days.

1.2.2 Diurnal Variation Measurement of Photosynthetically Active Radiation (PAR) in Intercropping Zones

During the wheat grain-filling stage, a PAR monitoring system from a HOBO U30-NRC micro-weather station (Onset Computer Corporation, USA) was used to measure PAR variation in intercropping zones (measurement range: 0–2,500 mol·m ^{2}·s ^{1}; spectral range: 400–700 nm; accuracy: ±5%; resolution: 2.5 mol·m ^{2}·s ^{1}). On clear days, continuous diurnal PAR measurements were taken from 11:00 to 19:00, with recordings every 10 minutes. Each treatment had 18 measurement points, with specific probe locations and distribution shown in Figure 1. Probe height was maintained consistent with wheat height, and measurements were repeated for three consecutive days.

1.3 Data Processing

Measured data were pooled and analyzed by zone using Microsoft Excel 2010 and SAS statistical software.

Results

2.1 Effects of Tree Form Treatments on Light Quality Distribution in Intercropping Zones

As shown in Figure 2 [Figure 2: see original paper] and Table 2 , different almond tree forms significantly affected light intensity and quality distribution in wheat intercropping zones. The spectral distribution diagrams revealed that compared with the far-canopy zone, radiation intensity across the 310-1,130 nm wavelength range decreased to varying degrees in both the near-canopy and under-canopy zones. The delayed open-central shape treatment showed the greatest reduction, the semicircle small-canopy shape the smallest, and the other two treatments were intermediate. The delayed open-central shape exhibited low values in both under-canopy and near-canopy zones on both sides of the canopy. The high-stem shape showed better light conditions in near-canopy zones compared to under-canopy zones on both east and west sides. The open-center shape showed minimal difference between under-canopy zones on both sides but lower values in near-canopy zones. The semicircle small-canopy shape showed small differences between the eastern under-canopy zone and far-canopy zone, with slightly lower values in other zones.

Table 2 demonstrates significant differences in light conditions among the four tree form treatments in intercropping zones. The delayed open-central shape treatment showed extremely significantly lower average radiation intensity across all wavebands compared to the semicircle small-canopy shape treatment. The open-center shape treatment showed significantly lower average radiation intensity across all wavebands except total radiation compared to the semicircle small-canopy shape. Except for the semicircle small-canopy shape, radiation intensity across all wavebands in under-canopy and near-canopy zones on both east and west sides of the other three treatments was extremely significantly lower than in the far-canopy zone. In the small-canopy shape treatment, radiation intensity in the western under-canopy zone and near-canopy zone was significantly lower than in the far-canopy zone for all wavebands except total radiation (some data not shown). The reduction magnitude varied among different wavebands in different intercropping zones, resulting in complex changes in the proportion of each waveband' s intensity relative to total radiation. In under-canopy and near-canopy zones across the four tree form treatments, the proportion of 310–400 nm (ultraviolet), 710–760 nm (near-infrared), and 760–1,130 nm (far-infrared) light to total radiation increased compared to the far-canopy zone, with far-red light showing the largest proportional change, while the proportions of 400–510 nm (blue-violet), 510–610 nm (yellow-green), and 610–710 nm (red-orange) light decreased.

2.2 Effects of Tree Form Treatments on Attenuation of 310–1,130 nm Light Quality in Intercropping Zones

Table 3 shows that light intensity in intercropping zones under all four tree form treatments was attenuated to varying degrees compared to natural light. Comparisons among different wavebands within the same treatment and zone revealed that blue-violet, yellow-green, and red-orange light (i.e., photosynthetically active radiation) showed greater reduction than the average reduction in total radiation, forming a rapid attenuation zone, while ultraviolet, near-infrared, and far-infrared light showed smaller reduction than the average reduction in total radiation, forming an inert attenuation zone. Variance analysis of the same waveband across different treatments indicated that the delayed open-central shape treatment had extremely significantly lower proportions of all wavebands relative to natural light compared to the semicircle small-canopy shape treatment, and the open-center shape treatment had significantly lower proportions than the semicircle small-canopy shape.

2.3 Effects of Tree Form Treatments on Light Quality Parameters in Intercropping Zones

Table 4 shows that light quality parameters varied among different intercropping zones under the four tree form treatments, with some differences reaching extremely significant levels. The UV/blue-violet ratio ranged from 0.175 to 0.250, with a coefficient of variation (CV) of 17.39%, and the delayed open-central shape treatment differed extremely significantly from the other three treatments. The red-orange/blue-violet ratio ranged from 0.834 to 0.863, with a CV of 2.13%, and the delayed open-central shape treatment differed extremely significantly from the other three treatments. The red-orange/far-infrared ratio ranged from 0.651 to 1.018, showing a large variation range with a CV of 23.34%, and the delayed open-central shape treatment differed extremely significantly from the other three treatments. The near-red/far-red ratio ranged from 1.275 to 1.683, with a CV of 13.70%, showing consistent variance analysis results with the red-orange/far-infrared ratio. The PAR/total radiation ratio ranged from 0.574 to 0.691, with a CV of 9.06%. Among all light quality parameters, the red-orange/far-infrared ratio showed the largest CV and was most sensitive to canopy structural characteristics, effectively reflecting the impact of canopy shading on light quality composition in intercropping zones.

2.4 Effects of Tree Form Treatments on Diurnal Variation of Photosynthetically Active Radiation (PAR) in Intercropping Zones

Influenced by solar incidence angle and canopy light transmission, diurnal variation trends of PAR in intercropping zones differed substantially among tree form treatments (Figure 3 [Figure 3: see original paper]). In the delayed open-central shape treatment, the far-canopy zone showed a distinct single-peak curve, while the other two near-canopy and under-canopy zones showed no obvious peaks, remaining at low levels throughout the day from 10:00 to 19:00 (PAR intensity <

500 mol·m ^{2}·s ^{1}). In the high-stem shape treatment, the eastern under-canopy and far-canopy zones showed a bimodal curve with peaks at 10:00 and 13:00, while the western and eastern near-canopy zones showed a single-peak curve with peaks at 10:00 and 13:00, respectively. The western under-canopy zone remained at low levels throughout the day (PAR intensity $<$ 400 mol·m ^{2}·s ^{1}). Compared with the delayed open-central shape, light conditions in the eastern under-canopy and near-canopy zones were improved before 15:00. In the open-center shape treatment, the two near-canopy zones showed a single-peak curve, while the other three zones showed a bimodal curve. However, except for the far-canopy zone (peak at 16:00) and the eastern near-canopy zone (peak at 11:00) which showed significant peaks, the other three zones had low peaks. Compared with the delayed open-central shape, light conditions in the eastern near-canopy zone were improved before 16:00. In the semicircle small-canopy shape treatment, the two near-canopy zones showed a single-peak trend, while the other three zones showed a bimodal trend. Compared with the other three treatments, this treatment showed higher peaks with longer duration. Compared with the delayed open-central shape, light conditions were significantly improved in the eastern under-canopy zone before 15:00, the eastern near-canopy zone before 17:00, and the western near-canopy zone from 15:00 to 19:00.

Discussion

3.1 Impact of Fruit Tree Canopy on Light Radiation Intensity in Intercropping Zones

Light is crucial for crop growth, development, and yield formation, serving not only as an energy source for photosynthesis but also as a trigger signal affecting plant development. After passing through the leaf canopy via transmission, absorption, and reflection, radiation intensity at the canopy bottom undergoes irreversible reduction. Our findings align with previous research, showing that after natural light passes through the fruit tree canopy to reach the intercropped crop canopy, irreversible attenuation occurs in all intercropping zones. The degree of attenuation varies significantly among zones due to different canopy structures, with far-canopy zones showing higher light intensity than under-canopy and near-canopy zones. Under identical row orientation and spacing, the small-canopy shape treatment provided higher light intensity in intercropping zones than the other three tree forms, followed by high-stem shape and open-center shape, with delayed open-central shape showing the lowest values. Total radiation intensity in intercropping zones ranged from 11.37% to 79.97% of natural light.

Canopy interception and absorption not only affect light intensity and distribution but also alter transmitted light quality composition through selective absorption by chlorophyll. Jiang et al. found that after natural light was absorbed and reflected by apple leaves to the lower canopy, total radiation and absolute radiation of each waveband decreased dramatically, but the reduction magnitude differed among wavebands, with UV-A, UV-B, visible light, and infrared light decreasing by 48.16%, 62.95%, 65.06%, and 14.74%, respectively. Niu et al. discovered that solar radiation passing through apple canopies formed rapid attenuation zones at 530–560 nm and 672–703 nm wavelengths, and inert attenuation zones between 738–746 nm. Li et al. found that in a paulownia||wheat intercropping system, spectral composition in intercropping zones changed continuously due to the tree canopy, with the most significant differences occurring from grain-filling to maturity. Our results are consistent with these findings, showing that after incident light reached the intercropped crop canopy, the 400–510 nm (blue-violet), 510–610 nm (yellow-green), and 610–710 nm (red-orange) regions showed greater reduction than the average reduction in total radiation in the same zones, while the 310–400 nm (ultraviolet), 710–760 nm (near-infrared), and 760–1,130 nm (far-infrared) wavebands showed smaller reduction than the average reduction in total radiation.

Numerous studies have demonstrated that light distribution in intercropping zones of fruit-grain systems is jointly influenced by tree species, row orientation, spacing, and canopy structural characteristics. Ding et al. suggested that jujube trees have a short overlapping growth period with intercropped crops and sparse branches with high light transmittance, making them suitable for fruit-crop intercropping. Guo et al., Wang et al., and Li et al., using the "saturation spatiotemporal window" methodology, showed that the duration of PAR saturation windows in intercropping systems is affected by tree species and row spacing, with different crop growth stages having different saturation PAR intensities, further affecting the duration of saturation spatiotemporal windows in intercropping alleys. Ji et al. analyzed diurnal variation of shading zones and canopy light transmittance within forest networks in coastal areas of northern Jiangsu through theoretical calculations, finding that northern shelterbelts had minimal marginal effects, east-west shelterbelts were intermediate, and southern shelterbelts were most severe, with north-south row orientation being superior to east-west. Li et al. suggested that in intercropping systems, spacing should not be less than 1/2 tree height to avoid mutual shading. Zhang et al. concluded that when tree species and row orientation are fixed, adjusting spacing to achieve optimal configuration ensures rational light distribution and high economic benefits in intercropping systems. Our results show that modifying the delayed open-central shape through leader removal to create an open-center shape reduced branch quantity by 60.28% and eliminated non-fruiting areas (from 14% to 0) without substantially changing tree height, trunk height, or canopy width, increasing average total radiation intensity in intercropping zones by 32.68%. Gradual trunk-raising modification of the delayed open-central shape increased trunk height from 0.6 m to 1.9 m, reduced branch quantity by 32.22% and canopy volume by 26.25%, and increased total radiation intensity in intercropping zones by 61.82%. Compared with delayed open-central shape, open-center shape, and high-stem shape, the small-canopy shape treatment reduced canopy volume by 59.40%, 66.86%, and 44.95%, respectively, while increasing total photosynthetically active radiation in intercropping zones by 99.30%, 50.20%, and 21.73%, respectively.

3.2 Impact of Fruit Tree Canopy on Light Quality Parameters in Intercropping Zones

Light intensity and quality composition regulate plant morphogenesis and organ development as signal substances. Plant photomorphogenesis is primarily controlled by phytochrome absorbing R/FR and cryptochrome absorbing blue/UV-A light; therefore, the proportional composition of different wavebands is significant for plant growth and development. Jiang et al. found that after natural light passed through and was reflected by apple leaves to the lower canopy, spectral composition changed and the red/far-red (R/FR) ratio decreased significantly. Research on maize-soybean relay intercropping showed that compared with monoculture soybean canopy light environments, the lower soybean canopy experienced changes in red light, blue light, far-red light, and their proportional relationships. Our results demonstrate that after natural light passed through the upper fruit tree canopy to the lower intercropped crop canopy, light quality parameters changed across different treatments and intercropping zones, with some differences reaching extremely significant levels. R/FR-related ratios (red-orange/far-infrared and near-red/far-red) showed large variation ranges, with the red-orange/far-infrared ratio showing the widest variation and being most sensitive to fruit tree canopy structural characteristics, effectively reflecting the impact of canopy shading on light quality composition in intercropping zones.

3.3 Impact of Canopy Structure on Diurnal Dynamics of Photosynthetically Active Radiation in Intercropping Zones

Photosynthetically active radiation (PAR) represents solar radiation energy between 400–700 nm that plants can directly use for photosynthesis and is closely related to crop productivity. In fruit-grain intercropping systems, diurnal variation dynamics of PAR in intercropping zones are jointly influenced by solar trajectory and dynamic canopy shading. With fixed row spacing, canopy structure (tree height, canopy width, trunk height, presence of central trunk, branch density, and branch distribution) further affects diurnal variation trends of PAR in intercropping zones. Our results indicate that in a 7 m row spacing system, when average canopy width is 5 m and tree height is 4.5 m (semicircle small-canopy shape), all zones except the western under-canopy zone can maintain relatively high PAR intensity for certain durations. When canopy width exceeds 7 m and tree height exceeds 6 m (delayed open-central shape), PAR intensity in both side near-canopy and under-canopy zones remains low throughout the day. With unchanged tree height and canopy width, raising trunk height to 1.9 m (high-stem shape) improved PAR intensity in eastern under-canopy and near-canopy zones before 15:00. Leader removal to create an open-center shape improved PAR intensity in the eastern near-canopy zone before 16:00.

When row orientation, spacing, and other factors are fixed in fruit-grain intercropping systems, tree form significantly affects light intensity, duration, and spectral composition in crop intercropping zones. In this study, the western under-canopy zone of almond tree treatments showed the poorest light conditions, while the far-canopy zone showed optimal conditions. Pruning measures including canopy control, trunk raising, and leader removal improved light conditions in intercropping zones, though the degree of impact and primary affected zones differed among measures. Light conditions during wheat grain-filling in intercropping zones ranked from best to worst as: semicircle small-canopy shape, high-stem shape, open-center shape, and delayed open-central shape. After light was intercepted and absorbed by the upper canopy and reached the crop canopy, different wavebands were reduced to different extents, ultimately altering light quality composition ratios. The red-orange (610–710 nm)/far-infrared (760–1,130 nm) ratio was most sensitive to fruit tree canopy structural characteristics and can serve as an indicator for evaluating light quality environments in intercropping zones.

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Note: Figure translations are in progress. See original paper for figures.

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