Wheat Yield Response to Photosynthetically Active Radiation Distribution in Paulownia Shelterbelt Systems: Postprint

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Abstract

This study focused on the Paulownia-wheat shelterbelt network composite ecosystem, an important agroforestry management model in the Huang-Huai-Hai Plain region. Through continuous fixed-point observations of photosynthetically active radiation (PAR) within the system and investigations of wheat yield from 2013 to 2015, combined with correlation analyses between PAR during different wheat growth stages and wheat yield, thousand-grain weight, and grain number, we investigated the distribution of PAR within the system and the response of wheat yield to it. The results showed that both PAR and light transmittance increased with increasing distance from the shelterbelt, with significant changes within the range of 10 m (approximately 1 times tree height), and increased slowly thereafter. Among all growth stages and all measurement points, the minimum value of light transmittance occurred at the observation point 2 m from the shelterbelt during the grain filling and maturity stage. The correlations between wheat yield per unit area and PAR during the entire growth period, between grain number and PAR during the wheat flowering stage, and between thousand-grain weight and PAR during the wheat grain filling and maturity stage all reached extremely significant levels (r=0.918, P=0.000; r=0.926, P=0.000; r=0.922, P=0.000). Shading of wheat by the shelterbelt during the flowering stage directly affected wheat grain number, while shading during the grain filling and maturity stage directly affected wheat thousand-grain weight. The spatial variation in wheat yield within the system could be explained by differences in wheat grain number and thousand-grain weight. The linear regression equation between wheat yield (y) and PAR during the entire growth period (x) was: y=0.121 3x+95.117 (R2=0.842). After testing, there was no significant difference between simulated and measured values of the equation (P=0.609), and the prediction accuracy reached 91.8%. Based on this equation, wheat yield at various points within the system can be predicted using PAR observation values. The results of this study lay a foundation for establishing a prediction model for the overall productivity of the Paulownia-wheat shelterbelt network composite ecosystem and provide a theoretical basis for optimizing the structure of the Paulownia shelterbelt network composite ecosystem.

Full Text

Preamble

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Response of Wheat Yield to Photosynthetically Active Radiation Distribution in Paulownia Shelterbelt Networks*

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Abstract: The Paulownia fortuneii-wheat intercropping system represents one of the most important agroforestry ecosystems in the Yellow-Huai-Hai River Plain region of China. This study investigated light distribution patterns and their impact on wheat productivity through continuous monitoring of photosynthetically active radiation (PAR) from 2013 to 2015, combined with yield surveys and correlation analyses between PAR and wheat yield components at key growth stages. The results demonstrated that both PAR and light transmittance increased significantly with distance from the shelterbelt within 10 m (approximately one tree height), after which the increase became gradual. The minimum transmittance occurred at the 2 m observation point during the grain-filling stage. Highly significant correlations were observed between wheat yield per unit area and PAR during the entire growth period ($r = 0.918$, $P = 0.000$), between grain number and PAR at flowering ($r = 0.926$, $P = 0.000$), and between 1000-grain weight and PAR during grain-filling ($r = 0.922$, $P = 0.000$). Shelterbelt shading during flowering directly affected grain number, while shading during grain-filling directly influenced 1000-grain weight, explaining the spatial variation in wheat yield within the system. The linear regression equation between wheat yield (y) and PAR during the entire growth period (x) was $y = 0.1213x + 95.117$ ($R^2 = 0.842$). Validation showed no significant difference between predicted and measured values ($P = 0.609$), with prediction accuracy reaching 91.8%. This equation enables yield prediction at different positions within the system based on PAR observations. These findings provide a theoretical foundation for developing productivity prediction models for Paulownia-wheat shelterbelt systems and optimizing system structure.

Keywords: Paulownia shelterbelt; Wheat; Growth period; Photosynthetically active radiation; Transmittance; Yield

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1. Materials and Methods

1.1 Study Area Description

The study was conducted in Mawu Village, Nanxi Town, Changge City, Henan Province (34.23°N, 114.06°E). The region has a mean annual temperature of 14.5°C, with the lowest monthly average of 0.1°C in January and the highest of 27.3°C in July. The frost-free period averages 214 days, annual precipitation is 711 mm, and annual sunshine duration is 1,883 hours with a sunshine percentage of 54%. The soil is sandy loam; chemical properties including pH, organic matter, available phosphorus, available potassium, and total nitrogen content are presented in .

1.2 Experimental Shelterbelt Description

The monitored shelterbelt network consisted of a rectangular grid measuring 160 m east-west and 320 m north-south. The configuration comprised a single-row east shelterbelt, a road with four-row west and north shelterbelts, and a road with two-row south shelterbelt. In March 2011, one-year-old *Paulownia fortuneii* '9501' seedlings with average diameter at breast height (DBH) of 4.6 cm and height of 3.4 m were planted at 4 m spacing. Wheat cultivar 'Yumai 13' was sown at 150 kg·hm ^{2} with uniform field management. Tree growth measurements from December 2014 are summarized in .

1.3 PAR Monitoring

On October 1, 2013, observation points were established at distances of 2 m, 5 m, 10 m, 15 m, 25 m, and 40 m from the center of each shelterbelt, extending both westward from the east belt and eastward from the west belt, and both northward from the south belt and southward from the north belt. Two additional control points were placed in the center of the network, totaling 24 observation points. At each location, a quantum sensor (LI-COR, USA) measuring 2.38 cm diameter × 2.54 cm height was installed at 2.5 m above ground. All sensors were connected to a CR-1000 data logger (Campbell, USA) that scanned and recorded data every minute. Data were downloaded monthly for three consecutive years.

1.4 Wheat Yield Survey

Within the shelterbelt network, six sample transects were established at distances of 80 m, 150 m, and 230 m from the north shelterbelt, and 40 m, 70 m, and 110 m from the east shelterbelt. At each transect, 1 m × 1 m quadrats were positioned corresponding to the PAR observation points, yielding 72 total quadrats. At wheat wax ripening stage, all plants within each quadrat were harvested by complete removal, threshed manually, and air-dried. Subsamples representing 20% of the air-dried weight were oven-dried at 80°C for 72 hours to calculate wheat yield per unit area, grain number, and 1000-grain weight [19].

1.5 Data Analysis

Daily PAR values at each observation point were calculated following the method of Duan et al. [21], from which PAR and transmittance were determined for three critical growth periods affecting wheat yield [19]: flowering stage, grain-filling stage, and the entire growth period. One-way ANOVA and Duncan' s multiple comparisons were used to analyze differences in wheat yield, grain number, and 1000-grain weight among observation points. Pearson correlation analysis with two-tailed significance testing was performed between 2015 yield data and PAR during the three key periods. Linear regression models were developed for significant, high-correlation relationships. The 2014 PAR data were then used to validate the yield model through K-W rank-sum tests and linear fitting against measured yields. Data analysis was conducted using Microsoft Excel 2010 and SPSS 20.0, with figures prepared using Origin 9.0.

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2. Results

2.1.1 Effects on PAR During Different Wheat Growth Stages

The combined effects of location, season, and time of day create variations in solar elevation angle, causing changes in photon flux density [22]. As shown in [Figure 1: see original paper], within the Paulownia shelterbelt system, light competition from the belts caused the number of photons received by crops to increase gradually with distance from the shelterbelt before stabilizing, with PAR exhibiting the same pattern. During the flowering stage, grain-filling stage, and entire growth period, PAR from all four cardinal directions increased with distance from the shelterbelt at a decreasing rate, stabilizing beyond 10 m (approximately one tree height). This indicates that PAR was essentially unaffected by shelterbelt shading beyond one tree height.

2.1.2 Effects on Light Transmittance During Different Growth Stages

[Figure 2: see original paper] demonstrates that transmittance increased with distance from the shelterbelt during any given growth stage, with the most pronounced effects within 10 m. Beyond this distance, the rate of increase declined. Across all growth stages and observation points, minimum transmittance occurred at the 2 m point from the south shelterbelt during grain-filling, reaching a minimum value of 0.43. This coincides with Paulownia entering full leaf stage, when crown volume and surface area increase, enhancing reflection, absorption, and shading [26].

2.2 Effects of Paulownia Shelterbelt on Wheat Yield Distribution and Components

Wheat yield per unit area varied with distance from the shelterbelt (). ANOVA revealed no significant differences in yield between the 2 m and 5 m points from the east shelterbelt, or among the 5 m, 10 m, 15 m, and 25 m points. However, yields at 2 m and 5 m were significantly lower than at 40 m. For the west shelterbelt, yields at 5 m, 10 m, 15 m, 25 m, and 40 m did not differ significantly but were all significantly higher than at 2 m. Similar patterns were observed for the south shelterbelt. For the north shelterbelt, no significant differences existed between 2 m and 5 m, or among 5 m, 10 m, 15 m, and 25 m, though yield at 2 m was significantly lower than at 10 m, 15 m, and 25 m.

Grain number and 1000-grain weight are key yield components [19]. For the east shelterbelt, no significant differences in grain number occurred among 2 m, 5 m, 10 m, and 15 m, or among 10 m, 15 m, 25 m, and 40 m, though grain number at 2 m was significantly lower than at 25 m and 40 m. For the west shelterbelt, grain number at 2 m was significantly lower than at all other distances. For the south shelterbelt, grain number at 2 m was significantly lower than at 5 m, 10 m, 15 m, and 25 m. No significant differences in grain number were found among the five distances from the north shelterbelt.

For 1000-grain weight, values at 10 m, 15 m, and 25 m from the east shelterbelt were significantly higher than at 2 m and 5 m. Similar patterns occurred for the north shelterbelt. For the west shelterbelt, values at 15 m, 25 m, and 40 m were significantly higher than at 2 m and 5 m, with the 10 m value significantly higher than at 2 m. For the south shelterbelt, the 2 m value was significantly lower than at all other distances.

2.3 Response of Wheat Yield and Components to PAR

The systematic reduction of PAR within the shelterbelt system due to shading created spatial variation in wheat yield [23]. Differences in wheat yield among observation points could be explained by differences in PAR received during the entire growth period. Specifically, closer proximity to shelterbelts resulted in more severe shading, less PAR, and greater yield reduction. The correlation between PAR during the entire growth period and wheat yield was highly significant (r = 0.9174, P = 0.000) ([Figure 3c: see original paper]), with a stronger coefficient than correlations between yield and PAR during flowering (r = 0.8873, P = 0.001) ([Figure 3a: see original paper]) or grain-filling (r = 0.9121, P = 0.000) ([Figure 3b: see original paper]).

Grain number per unit area was highly significantly correlated with PAR during flowering (r = 0.9262, P = 0.000) ([Figure 4a: see original paper]), with a stronger coefficient than correlations with PAR during grain-filling (r = 0.9214, P = 0.000) ([Figure 4b: see original paper]) or the entire growth period (r = 0.8942, P = 0.000) ([Figure 4c: see original paper]).

The 1000-grain weight was highly significantly correlated with PAR during grain-filling (r = 0.9217, P = 0.000) ([Figure 5b: see original paper]), with a stronger coefficient than correlations with PAR during flowering (r = 0.917, P = 0.000) ([Figure 5a: see original paper]) or the entire growth period (r = 0.9206, P = 0.000) ([Figure 5c: see original paper]).

Based on these results, three linear regression models were established: wheat yield (y) vs. entire growth period PAR (x): y = 0.1213x + 95.117 (R^2 = 0.842); grain number (y) vs. flowering PAR (x): y = 11.861x + 9,295.8 (R^2 = 0.8578); and 1000-grain weight (y) vs. grain-filling PAR (x): y = 0.0155x + 30.821 (R^2 = 0.8496). The slope of the yield-PAR equation (0.1213) indicates that each 1 mol · m ^{2} reduction in PAR decreased wheat yield by 0.1213 g · m ^{2}. During flowering, PAR affected yield through grain number (each 1 mol · m ^{2} reduction decreased grain number by 12 grains · m ^{2}). During grain-filling, PAR affected yield through 1000-grain weight (each 1 mol · m ^{2} reduction decreased weight by 0.0155 g).

2.4 Validation of the Relationship Between PAR and Wheat Yield

The 2014 PAR data were substituted into the linear regression equation to generate simulated yield values. K-W rank-sum tests showed no significant difference between simulated and measured values (P = 0.609). Linear regression between simulated and measured values produced a slope near 1 and intercept near 0, indicating close agreement and a prediction accuracy of 91.8% ([Figure 6: see original paper]). Therefore, the established relationship can reliably predict wheat yield at any point in the system based on PAR observations.

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3. Discussion and Conclusion

Numerous factors can reduce crop productivity in agroforestry systems, but light competition may be the dominant limiting factor under certain conditions [24]. This study demonstrated that PAR increased with distance from shelterbelts during all growth stages, with substantial changes within 10 m (one tree height) and minimal changes beyond. This aligns with findings from Chen et al. [25]. The minimum transmittance occurred at the 2 m point during grain-filling, indicating maximum shading impact during this period when Paulownia reaches full leaf stage with increased crown volume and surface area, enhancing light interception [26].

Wheat yield, grain number, and 1000-grain weight all varied with distance from shelterbelts. The highly significant positive correlation between wheat yield and PAR during the entire growth period indicates that light competition is the primary cause of spatial yield variation within the Paulownia shelterbelt system, consistent with previous research [27-28]. The highly significant correlations between flowering PAR and grain number, and between grain-filling PAR and 1000-grain weight, suggest that shelterbelt shading directly affects these yield components during their respective critical periods, thereby explaining spatial yield differences.

As an important agroforestry model in the Yellow-Huai-Hai Plain, the Paulownia shelterbelt system improves crop environmental conditions while providing timber, partially alleviating land-use conflicts. However, traditional systems lack systematic structural research, limiting comprehensive benefits. This study addressed key technical issues by establishing and validating relationships between PAR distribution and wheat yield. These results provide a reference for developing productivity prediction models and optimizing shelterbelt structure for the Paulownia-wheat system.

In this study area, a high-yield agricultural region without significant disasters during the study period, the shelterbelt system did not demonstrate obvious protective benefits but rather caused yield reductions through shading. However, under extreme weather conditions such as dry-hot winds or severe convection, the system would likely exhibit its functions of improving microclimate and ensuring stable, high yields [4,29].

Optimizing Paulownia shelterbelt structure requires balancing ecological protection with minimizing crop yield impacts. Reducing light competition is an effective approach, achievable through pruning to increase clear bole height and reduce crown surface area [30], or by optimizing spacing and belt width to increase porosity and reduce shading [31].

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