Agroforest Syst (2026) 100:43
https://doi.org/10.1007/s10457-025-01377-4

Characterizing canopy light penetration in black walnut (*Juglans nigra*) cultivars to inform selection for alley cropping

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Received: 15 July 2025 / Accepted: 24 October 2025 / Published online: 13 January 2026
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Abstract Eastern black walnut (*Juglans nigra* L.) is a nut-producing tree species that breaks dormancy late in the spring, allowing a winter alley crop to ripen before substantial canopy shade is formed. However, there is a high level of variation in the timing and structure of tree canopy development within the black walnut cultivar collection maintained at the University of Missouri Center for Agroforestry (UMCA). To identify cultivars with high levels of compatibility with winter alley cropping, we measured the amount of photosynthetically-active radiation transmitted (PARt) through the canopy. Eight physical traits were also measured to assess their relationship with light interception and to gain insight on characters that lead to greater understory light extinction. Significant differences between cultivars were seen in PARt, particularly on Julian date 132 (May 12) where a two-fold difference was observed in PARt between the most contrasting cultivars. Traits such as date of bud break, tree shape and live canopy ratio were associated with levels of PARt, providing preliminary support for strong component drivers of light displacement/penetration during spring. This study provides the first exploration of genetic variation in black walnut for above-ground compatibility with an understory crop, and in doing so, reports meaningful genetic variation exists for study and use. New context is reported for design of subsequent genetic, physiological, and plant-plant interaction studies. For example, there is not a negative relationship between leafing duration and fruit production, and late-leafing varieties, which are more suitable for agroforestry, remain productive in comparison to early-leafing ones. Additionally, these data may inform the selection or breeding of cultivars with improved complementary for alley cropping with winter grains, as well as management strategies (pruning) to improve light penetration in black walnut alley cropping systems.

Keywords Crown Shape · Phenology · Tree canopy · Photosynthetically-active radiation · Interspecific competition · Bud break

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10457-025-01377-4.

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Introduction

The increasing global demand for food, timber and ecosystem services may be addressed by intensifying the photosynthetic carbon assimilation per unit of arable land (Hussain et al. 2021). Towards this effort, strategies such as genetic improvement of staple crops and more efficient use of fertilizers will be necessary but not sufficient to meet predicted requirements (Murchie et al. 2009). Novel agronomic practices that incorporate trees, such as alley cropping systems (ACS), can support current approaches by bolstering carbon assimilation and productivity per unit land area (Forrester et al. 2013; He et al. 2013). The expanded use of ACS also offers environmental benefits through increasing ecosystem health and the sequestration of atmospheric carbon dioxide (Forrester et al. 2013; He et al. 2013; Pavlidis and Tsihrintzis 2018; Wolz et al. 2018). However, tree canopies limit light availability for understory crops (Artru et al. 2017; Gong et al. 2015; Li et al. 2016). Tree-crop combinations that effectively partition resources between the crop and tree species need to be developed, including to address light energy availability for crop growth. The phenological and architectural traits of walnut (*Juglans spp*.) generally are complementary to the requirements of winter cereal crops (Arenas-Corraliza et al. 2018; Dufour et al. 2013; Zhang et al. 2015), but there may be genetic variation within the species that allows for system improvement. Characterizing the diversity in canopy and light interception characteristics in eastern black walnut (*J. nigra* L.) presents an opportunity to identify tree cultivars ideal for North American agroforestry systems.

Today, ACS adoption is of increasing relevance in the East and Midwest U.S. agricultural landscape. For example, over 890 hectares of a chestnut (*Castanea mollissima*) -hay alley system were established in northern Kentucky between 2022 and 2024 (Propagate Group PBC, 2025). Diversification of temperate alley cropping systems holds great potential with eastern black walnut, hazelnut (*Corylus avellana*), and pecan (*Carya illinoinensis*), along with a variety of crops, but specific attention needs to be given to genetic variation of the tree cultivars with respect to the extent of competition with the crop cultivated in the alley.

Multiple tree canopy traits impact the spatio-temporal pattern of photosynthetically active radiation availability to the understory crop (PARt) (Mourelle et al. 2001). Bud break and canopy foliation are the most relevant phenological traits for complementarity in ACS and other mixed-species systems (Dupraz et al. 2018; West 2014). Tree species with delayed phenological timing may offer reduced shading on winter grain crops while maturing in the spring (Artru et al. 2017; Dufour et al. 2013). In addition, tree architectural dimensions, crown shape, canopy volume and leaf morphology vary by species and affect PARt (Hagemeier and Leuschner 2019; Mourelle et al. 2001; Sanusi et al. 2017). Mourelle et al. (2001) found foliage biomass, the number of branches, leaf area index (LAI), and crown width to be the best predictors for PARt within six temperate hardwood species. Leaf morphology and distribution in the canopy is also highly specific to species and appear to be related to the ecological role as early-succession species (e.g., *J. nigra*) or late-succession species (e.g. *Fagus grandifolia*) (Hagemeier and Leuschner 2019; Mourelle et al. 2001).

Variation in phenological and morphological traits occurs within an individual species, potentially due to varying selection pressures across geographies (Gailing et al. 2012; Sprinz et al. 1989). Leaf morphology was shown to differ significantly among cultivars in sweet chestnut (*C. sativa*) (Serdar and Kurt 2011) and apple (*Malus domestica* Borkh.) (Stephan et al. 2008). Canopy architecture also varied significantly by cultivar in apple (Costes et al. 2003; Stephan et al. 2008), peach (*Prunus persica)* (Janick 2010), olive (*Olea europea* L.) (Bayazit 2012; Rallo et al. 2020), as well as in walnut species (Mosivand et al. 2013). Fady et al. (2003) demonstrated strong genetic variability in Persian walnut (*J. reiga*) for adaptive and wood quality traits in a network of juvenile field tests across Europe. Additional research on black walnut showed high levels of variation in canopy architecture, bud break, and autumn crown retention (CrRt) within a population of 25 genotypes (Pang et al. 2021).

Characterizing cultivar-level variation in PARt, however, is largely unexplored. The diversity present within black walnut provides an opportunity to investigate how multiple component traits contribute to understory light availability throughout the spring. The main objective of this research is to

evaluate effects of cultivar characteristics on PARt. In turn, this information can be used to select cultivars that enhance the effectiveness of ACS. It is anticipated that this approach may be replicated with other hardwood tree crop species such as Persian walnut (*Juglans regia*) and Chinese chestnut (*Castanea mollissima*) to aid their integration onto cropland. Moreover, tree breeding programs can use characterized germplasm to inform crossing designs and selection criteria, representing a first step towards improving tree crops for complementarity in mixed species systems.

Methods and materials

Study site

The study site is located at the Horticultural and Agroforestry Research Center in New Franklin, Missouri (39 °01′ 05 N, 92 °45′ 42 W), in USDA Hardiness Zone 6b and consists of two repositories encompassing 0.9 hectares (Repository A) and 1.4 hectares (Repository B), respectively (Fig. 1). The site receives around 1000 mm of rainfall annually, predominantly in the winter and spring. Both repositories sit on deep well-draining deposits of loess derived Menfro silt loam (5–15% slope), considered well-suited to black walnut cultivation (Wallace and Young 2008). During tree establishment in 1996, herbicide was applied in 1-m strips along the tree lines. The plots were mowed throughout the growing seasons and were fertilized with 27.2 kg of nitrogen in the spring and 7.3 kg in the fall per hectare. Pruning followed recommendations detailed in Webber et al. (2022).

Plant materials

Black walnut trees are spaced 12-m apart in an off-set grid pattern. In 1995–1997, trees were field-grafted into the repositories with named nut cultivars from various locations across the Midwest US. All ramets were genotyped by microsatellite SSR markers to confirm their correct identity and were relabeled if necessary (Zhao et al. 2018). From this collection, 11 cultivars (Table S1) that displayed a broad range of phenological and architectural traits, including leafing date, season length, harvest date, canopy shape, and leaf size were selected based on data collected between 2002 and 2009. For each cultivar, three ramets were selected randomly from within the repositories for this study conducted in 2021.

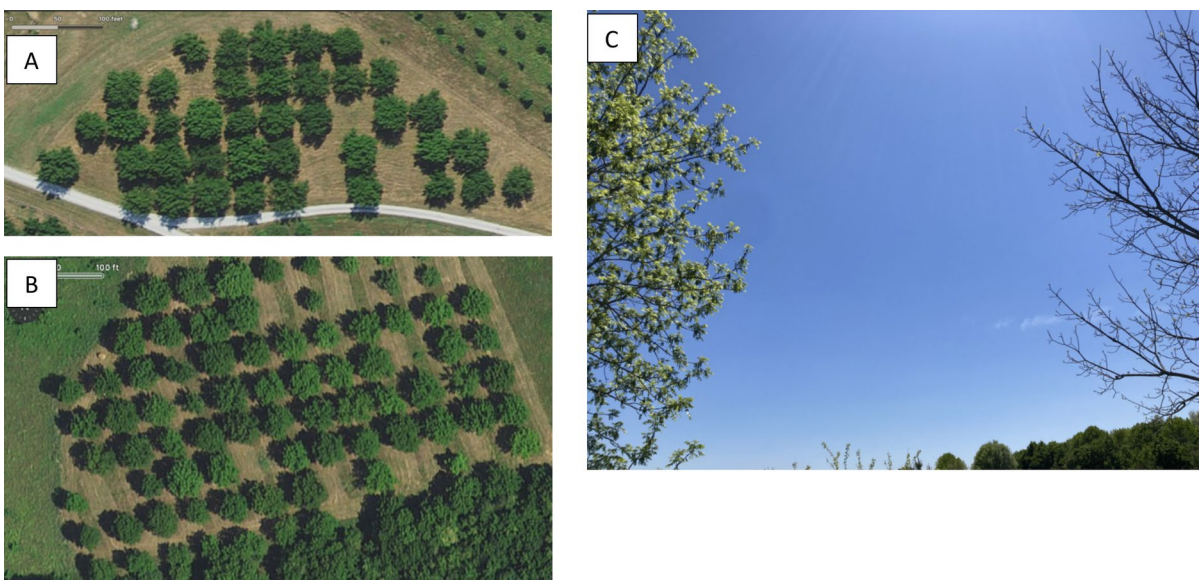


Fig. 1 Repositories A (*top)* and B (*bottom*) of black walnut cultivars were established in 1996 in New Franklin, MO. Two adjacent canopies with contrasting phenology (C): 'Shessler' (*left*) has begun vegetative shoot expansion and catkin development throughout its canopy and 'Thomas' (*right*) is at an earlier stage

Phenology data collection

Every week beginning in mid-April, trees were monitored for signs of bud break. They were classified according to a 5-stage scale, a method commonly used in hardwood tree phenology research (Gričar et al. 2017; Pang et al. 2021), where 1 is dormant and 5 is leaf expansion (Fig. 1c). Bud break was defined as date where 50% of the canopy had small leaves bursting from the bud (stage 4). On October 8, trees were visually evaluated for retention of foliage. The amount of foliage remaining on the tree was estimated to the nearest 10% and recorded as CrRt.

Quantification of light penetration through the tree crown

To establish a baseline, penetration of PAR through the tree crowns was measured with a LP-80 AccuPAR (Meter Environment) in mid-April 2021 before the trees had broken dormancy. Thereafter, additional measurements were taken every 7–10 days during clear weather conditions between 11:00am and 2:00 pm. One reading of open sky was taken immediately before a tree was measured to calibrate the device. In the understory of each tree, an inner-ring of 8 readings was taken adjacent to the trunk with the device aimed in each cardinal and intercardinal direction. An additional outer-ring of 8 readings was taken at the midpoint between the trunk and canopy dripline (Fig. 2), were averaged to create a value representing each tree per sampling time. While recording measurements, the AccuPAR was held at ground-level. Reading locations were marked on the ground for consistency. Measurements were collected on each tree until mid-June when canopy growth had ceased. Means were calculated for the outer-ring, the inner-ring, and all data points independent of ring, respectively, for each tree and used for subsequent analysis.

AccuPAR divided the understory PARt readings by the corresponding open sky PAR reading to determine the percentage of light transmitted through the canopy to the understory, defined as Tau. Geographic location as well as time and date were recorded by the AccuPAR for estimation of solar zenith angle, beam fraction. Data stored in the AccuPAR were uploaded with LP-80 Utility software (Meter Environment).

Tree architecture

Single-image photogrammetry was used to capture two images of each tree: one with north–south orientation and one with east–west orientation. A scale bar with a known length was included in the photograph for reference. Image analysis was performed using ImageJ software (imagej.nih.gov/ij/) to determine tree height, canopy width, and height from ground to beginning of live canopy (HLC). Tree height was defined as the distance from the ground to the highest branch tip, W defined as the furthest distance between two lateral branches on the same plane and HLC defined as the height of the lowest lateral branch

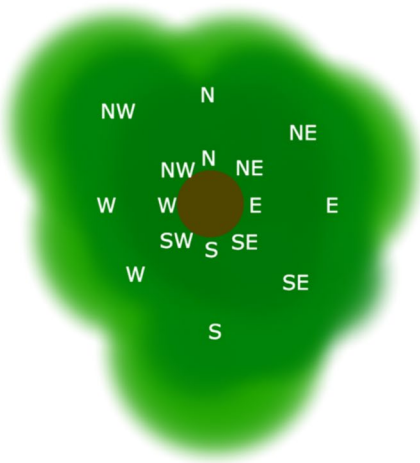




Fig. 2 Locations of the 16 PARt readings included an inner ring of 8 measurements adjacent to the trunk and an outer ring at approximately 50% of the distance to the dripline (bottom). Direct sun beams infiltrating a fully-leafed canopy at an outer-ring measurement location

tip. From these measurements, composite variables were created, namely the ratio of tree height occupied by live crown [height-HLC)/height], abbreviated as (LCR), and a width-to-height ratio to capture the crown shape seen in Fig. 3. Final values of each tree were calculated by taking a mean of the values measured from both orientation images. The circumference of the trunk was measured 10 cm above the graft union with measuring tape and values were converted to diameter. As opposed to DBH, this method controls for uneven heights of graft unions between trees which may skew the data.

Leaf area

In July 2021, three leaves were sampled from each ramet of each cultivar. Samples were taken from the most recently formed leaf on a given stem from random points of the canopy that could be accessed using an orchard ladder. Samples were labeled and immediately refrigerated. An LI-3000C (LI-COR Biosciences) was used to measure the leaf area of the samples and the number of leaflets on each leaf was recorded. Mean leaf area (LA) and mean leaflet surface area (LtA) were calculated from these measurements.

Data analysis

One-way analysis of variance (ANOVA) was used to test significant differences in light penetration (Tau values) for phenology, architectural traits, and leaf and leaflet surface areas among cultivars on individual measurement dates. Analyses were conducted with Tau represented in three fashions: incidental Tau (TauI): the Mean Tau values of the inner and outer-ring measurements at respective single time points; cumulative Tau (TauC): the additive amount of understory light penetration to the respective date; and Tau Percentage (TauP): a tree's Tau measurement at a single time point relative to its baseline reading at dormancy. Using the "agricolae" package (de Mendiburu 2021) on R (R Core Team 2023), ad-hoc Fisher's least significant different (LSD) tests were performed using an alpha of 0.05 to compare means of cultivars. A Pearson's correlation and linear regression analysis was used to assess for predictors of the response variable Tau. This was repeated for each Tau measurement date. Variables demonstrating a relationship with Tau were incorporated into a multiple linear regression model by adding variables in descending order of their correlation with Tau. If both a composite variable and its component variable (e.g., canopy width a component of canopy shape) were both correlated with Tau, only the variable with the stronger relationship was utilized. Various



Fig. 3 Crown architecture varies by tree due to combinations of genetic, environmental, and management factors. 'Mystery' (*top*) has higher crown shape and live crown ratio (LCR) than 'Thomas' (*bottom*). Tree photos taken with reference bar for scale

models were tested to gain insight on which variables explained the largest amount of variation in the response variable.

Results and discussion

Wide variation observed for bud break time

The earliest tree initiated its bud break on April 8, Julian date (jd) 98, and the latest tree initiated on May 7 (jd 127). Figure 4 illustrates the wide range of bud break dates observed, with significant differences between cultivars ($p = < 0.01$) (Table 1). For some cultivars, variation in bud break date among ramets was relatively large, such as for 'Emma K', possibly due to field-level or rootstock effects. In some cultivars, bud break timing and subsequent foliation largely avoid the critical period where winter crops are most sensitive to shade based upon grain filling phenology in Missouri (Artru et al. 2017; Dufour et al. 2013) (Table 1). For example, 'Shessler' had developed extensive crown vegetation with 44% of Tau already intercepted when 'Myers' had only begun to break dormancy. This high level of bud break variation is potentially due to differing physiological adaptations related to chilling hour requirements and spring frost avoidance specific to the cultivar's geographic region of origin. Most of the cultivars used in this study originated from states north of the study site and thus broke dormancy later than wild trees in the area (Michler et al. 2007).

Architectural trait analysis

The fixed-effects ANOVAs for each architectural trait indicate that there were significant differences amongst cultivars for most architectural and

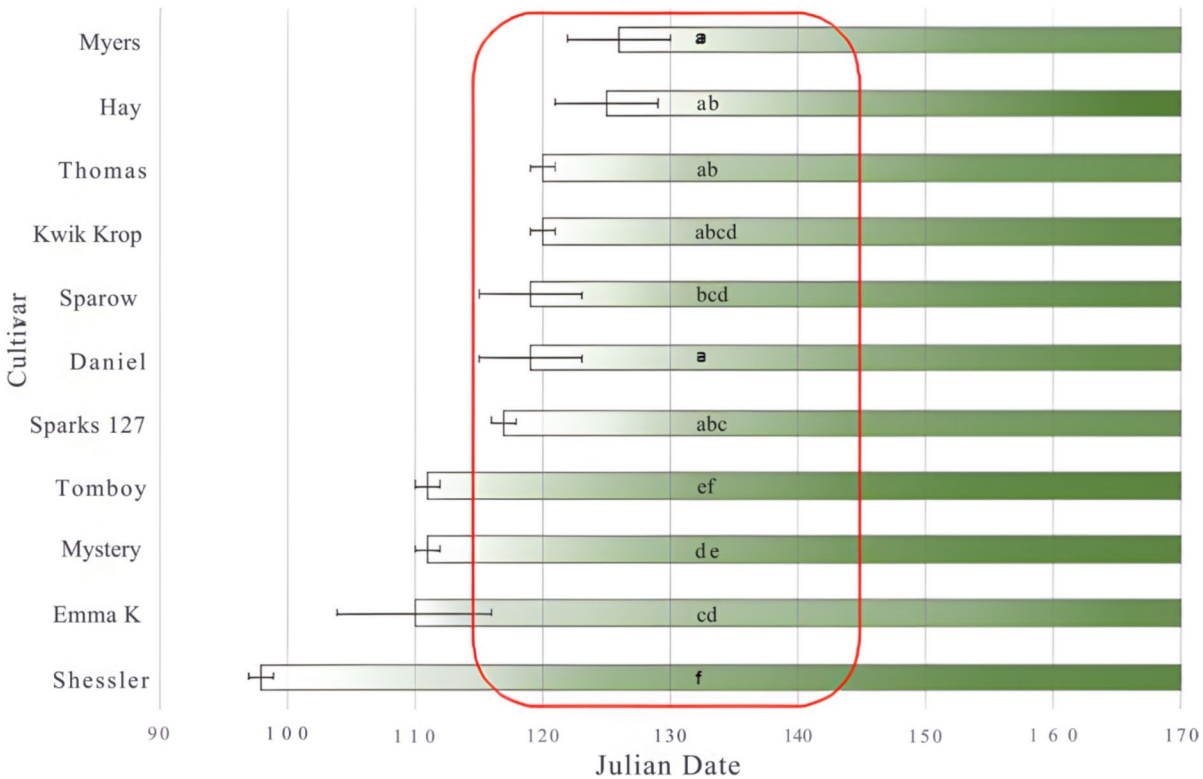


Fig. 4 Spring phenology of each cultivar begins with bud break. Horizontal bars are white at bud break and gradually fill in green corresponding with Tau values by Julian date (jd) until June 15 (jd 166). The red box indicates critical period of wheat development and filing between April 25 (jd 115) and May 25 (jd 145). Mean separation values reflect cumulative Tau at 132 Julian days

Table 1 Architectural (top), phenological and leaf morphological (bottom) data collected from 11 black walnut cultivars

Cultivar	Width (m)	Height (m)	Crown Shape	Live Crown Ratio	Trunk Diameter (cm)	LA (cm^2)	LtA (cm^2)	Bud break	Crown Retention
Daniel	7.88 (bcd)	10.03 (ab)	0.79 (abc)	0.68 (abc)	43.7 (ab)	294.4	21.9	119 (bc)	0.30 (d)
Emma K	8.03 (bcd)	9.68 (ab)	0.83 (abc)	0.64 (c)	47.4 (a)	304.9	18.7	110 (d)	0.73(abc)
Hay	6.61 (cd)	9.51 (abc)	0.69 (bc)	0.67 (bc)	36.8 (bc)	304.9	18.0	125 (a)	0.57 (c)
Kwik Krop	8.07 (abcd)	9.94 (ab)	0.81 (abc)	0.67 (bc)	43.5 (ab)	278.0	15.4	120 (b)	0.30 (d)
Myers	6.49 (d)	10.22 (ab)	0.63 (c)	0.65 (c)	36.8 (bc)	288.7	18.4	126 (a)	0.60 (c)
Mystery	10.19 (a)	10.55 (a)	0.97 (a)	0.71 (ab)	45.2 (ab)	332.2	18.0	111 (d)	0.90 (ab)
Shessler	8.64 (abc)	9.97 (ab)	0.87 (ab)	0.67 (bc)	40.5 (abc)	218.3	14.8	98 (e)	0.97 (a)
Sparks 127	6.63 (cd)	8.49 (c)	0.78 (abc)	0.64 (c)	32.5 (abc)	241.0	17.0	117 (c)	0.20 (d)
Sparrow	7.49 (bcd)	9.58 (ab)	0.78 (abc)	0.68 (abc)	44.6 (c)	251.9	15.1	119 (bc)	0.67 (bc)
Thomas	8.35 (ab)	10.31 (a)	0.80 (a)	0.70 (a)	-	-	-	120 (b)	0.70 (bc)
Tomboy	8.31 (abcd)	9.22 (bc)	0.90 (a)	0.67 (bc)	42.8 (ab)	279.1	17.8	111 (d)	0.63 (c)
p Value	p<0.0542	p<0.05	p<0.10	p<0.10	p<0.1	p>0.1	p=>0.1	p<0.01	p<0.01

Values are given with 95% confidence intervals. Below cultivar values is the p value for the trait along with a descending ranking of cultivars with LSD letters. Cultivars sharing a letter are not significant

phenological traits, as seen in Table 1. Bud break showed the greatest mean separation ($p < 0.01$) followed by CrRt ($p < 0.01$), height ($p < 0.05$), width ($p < 0.05$) and crown shape ($p < 0.1$). In contrast, LCR and HLC, from which it is derived, were not significant, likely due to the pruning of lower branches throughout the orchard, overshadowing any potential cultivar differences. Leaf and leaflet surface area also showed no differences, possibly due to low numbers of samples/ramets or from non-random collection of samples in inaccessible areas of the canopy. Although some traits lacked differences between cultivars, there still may be tree-level associations with understory Tau values.

Bud break has a strong relationship with light penetration

Architectural, morphological and phenological traits as well as Tau values (incidental and cumulative) were included in a Pearson's correlation analysis. Correlations were stronger when Tau was calculated using the outer ring of PAR measurements, likely due to the inner ring containing greater levels of shade and causing more uniform measurements across all

Table 2 Pearsons correlations between outer ring TauI, TauC and TauP on May 12 (jd 132) and nine phenological and morphological traits of black walnut. Values approaching 1 are blue in color, values near zero are white and values approaching − 1 are red in color

	Width	Height	HLC	Crown Shape	LCR	Leaflet area	Bud break	CrRt	Tree Diameter	TauI	TauP
Height	0.415*										
HLC	-0.071	0.509**									
Crown Shape	0.924***	0.041	-0.290								
LCR	0.376*	0.118	0.794***	0.366*							
Leaflet area	0.012	0.049	-0.258	0.051	0.268						
Leaf area	0.163	0.036	-0.339	0.175	0.423*	0.8.52***					
Bud break	-0.457**	0.011	0.007	-0.505**	-0.025	0.216					
Crown Retention	0.402*	0.355	0.093	0.292	0.153	-0.297	-0.528**				
Tree diameter	0.520**	0.362*	-0.013	0.430*	0.279	0.258	-0.253	0.198			
TauI	-0.556**	0.032	0.289	-0.631***	-0.324	0.090	0.786***	-0.710***	-0.361*		
TauP	-0.580***	0.073	0.242	-0.670***	-0.231	0.100	0.798***	-0.600***	-0.359*	0.870***	
TauC	-0.585***	-0.039	0.379*	-0.640***	-0.479**	0.010	0.646***	-0.554**	-0.357*	0.875***	0.741***

***: $p < 0.001$, **: $p < 0.01$, *: $p < 0.05$. HLC-Height to Live Crown, LCR-Live Crown Ratio, TauI-Incidental Tau, TauP-Tau Percentage, TauC-Cumulative Tau

trees. Thus, outer ring measurements were exclusively used in the correlation analysis and for all subsequent analyses. Strongly correlated pairs of variables are highlighted in Table 2. The results indicate strong negative correlations (< -0.55) between Tau and crown width, crown shape and autumn CrRt. Strong positive correlations (> 0.55) were observed between Tau values and bud break. There was nearly a 0.8 correlation between TauI/TauP and bud break. Moderate but significant correlations were seen between LCR and cumulative Tau (0.479) as well as tree diameter and TauI (0.361). Leaf and leaflet surface areas had no significant correlations with Tau.

The correlations suggest that high levels of understory light penetration are found in trees with low values for crown width, crown shape, and live crown ratio. By choosing cultivars that exhibit these architectural traits (e.g., 'Hay', 'Myers' and 'Sparks 127') and by periodic pruning of outer limbs and lower branches, growers could optimize the amount of PAR reaching the understory crops. Moreover, the strong relationship between Tau and bud break supports the potential to improve complementarity with spring-ripening crops by selecting cultivars that have late bud break dates (e.g., 'Thomas', 'Kwik Krop', 'Hay' and 'Myers'). The trees exhibiting early defoliation in the fall (low CrRt) also showed high spring Tau values. These shorter season length individuals present an opportunity for more complex agricultural systems using multiple alley crops that optimize the land use efficiency. The associations observed in this experiment between architectural, phenological traits and Tau levels should be tested on additional replicated populations. Once validated, the associations could be implemented as a method to efficiently identify seedling individuals that have potential in ACS. Moreover, the trait relationships seen here in black walnut could be tested in other tree crop species such as Persian walnut, Pecan (*Carya illinoinensis*) or Chinese Chestnut.

Changes in percent light penetration over the course of canopy development

Mean Tau values of the outer-ring measurements at respective single time points were defined as TauI. Baseline TauI readings were not significantly different among cultivars prior to bud break, suggesting that woody biomass was not a driver of cultivar-specific shading effects. TauI values declined as foliage began filling the canopies (Fig. 5). Significant differences ($p = < 0.05$) in TauI were identified amongst cultivars on all measurement days, but the largest variation in percentage light penetration among cultivars was observed on May 12, julian day (jd) 132 ($p < 0.01$) (Table S2). On this date, 'Hay', 'Myers', and 'Daniel' showed significantly higher (35.9, 33.0 and 27.3%, respectively) TauI than 'Sparrow', which was chosen for comparison because it had a TauI value closest to the group mean. 'Shessler' and 'Tomboy' trees, which presented early bud break, had developed dense canopies at this time point and had significantly less (32.2 and 27.1%) TauI than 'Sparrow'. Interestingly, only 'Myers' presented lower TauI than 'Tomboy' trees at each sampling, whilst TauI values were similar between 'Daniel' and 'Shessler' after jd 145. Although informative to understory light dynamics, TauI values can only give a snapshot of light transmittance at a specific moment in time. Furthermore, the ranking of cultivars by their TauI values tend to change somewhat at each measurement point. A more stable metric may aid in interpretation of broad patterns. TauP values are reported in Fig. S1 and Table S4.

Cumulative light penetration over the course of canopy development

The overall understory accumulation of PARt throughout the spring is perhaps a more useful metric in characterizing a cultivar's level of complementarity with winter crops. To quantify PARt in the aggregate, TauC values are expressed by adding each new reading to the previous. Figure 6 illustrates the rise in TauC across the experimental period. Similar to TauI, there were significant differences ($p = < 0.05$) in TauC between two or more cultivars at all measurement points, and the greatest number of significantly different groups occurred on May 12 (jd 132) in the middle of the critical period (Table S3). On this date, cultivars 'Daniel' and 'Hay', had significantly higher TauC (13.8 and 14.5%, respectively) than 'Sparrow', which again best reflected the group average. 'Shessler' and 'Tomboy' had significantly lower (22.2 and 16.8%) TauC than 'Sparrow', as consequence of the early bud break in these cultivars. Cultivar rankings based on TauC were rather consistent at each data collection time and display a clearer pattern of each cultivar's Tau levels throughout the experimental period. High levels of light accumulation in the understory may translate to proportional increases in growth and yield of alley crops. Data presented here can be compared with the specific photosynthetic needs of the crop species and facilitate design of plant-plant interaction studies. Additionally, the data inform selection of cultivars that provide improved understory light conditions for alley cropping winter grains and a basis for developing selection criteria in breeding. A similar approach of quantifying TauC of cultivars during the summer and autumn periods could identify other cultivar-crop combinations for effective ACS.

Date of bud break is the most influential driver of canopy light penetration during the spring

Simple linear regressions were used to test if architectural and phenological traits are predictive of incidental Tau. Traits were chosen based on having moderate or high Pearson's correlation coefficients with outer ring Tau values on jd 132 and included crown shape, CrRt, LCR and bud break. The results of the linear models are plotted in (Fig. 7). Regressions for each trait were statistically significant ($p = < 0.01$). The R^2 value was highest for bud break (0.66), suggesting it has the most important role in predicting Tau. The remainder of the traits had R^2 values below 0.5. When these variables were combined in the multiple linear regression model, there was appreciably more prediction power than any one variable alone. The fitted fixed effects regression model:

$$[\text{TauI} = 0.389 + \text{CrS} * -0.223 + \text{CrRt} * -0.019 + \text{LCR} * -0.707 + \text{bud break} * -0.009]$$

was significant and explained over 80% of the variation in Tau (adjusted $R^2 = 0.805$, $F(4, 26) = 31.93$, $p < 0.01$). The explanatory power of this model is

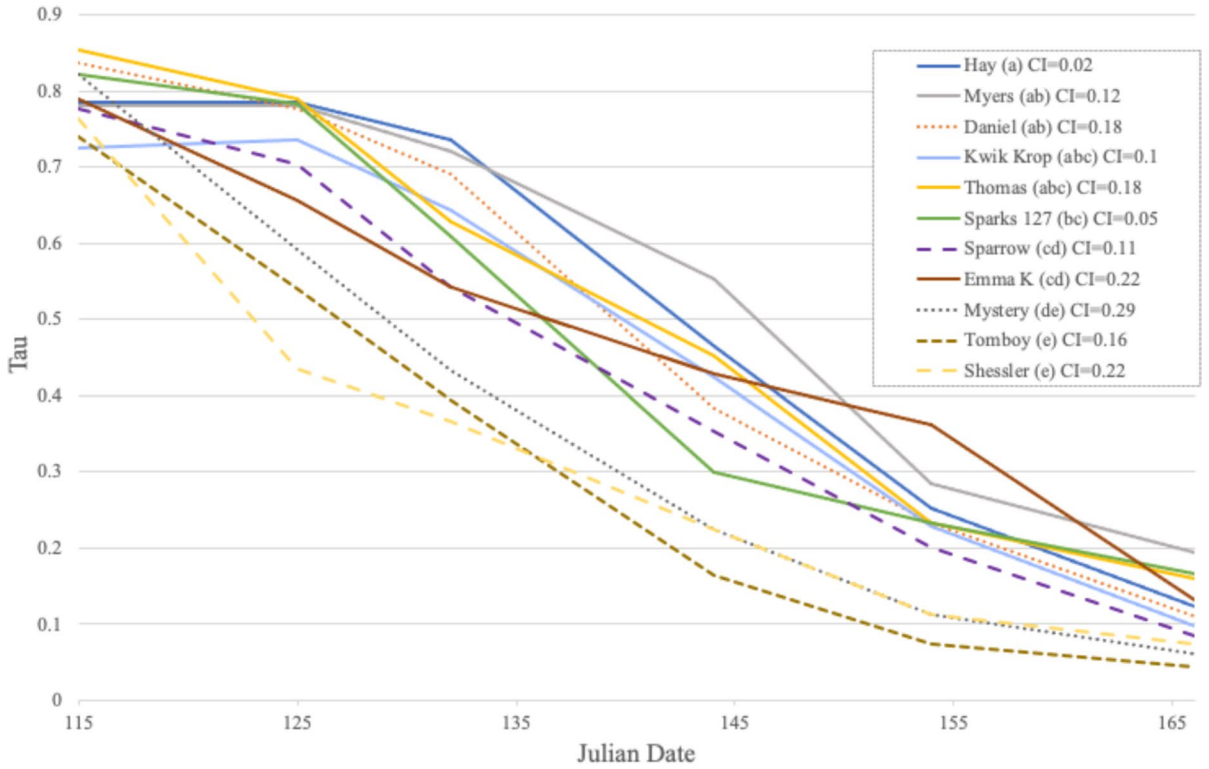


Fig. 5 Incidental Tau values by Julian date (jd) of each cultivar from April 15 (jd 115) to June 15 (jd 166). The 95% confidence intervals and LSD groups are provided in the legend based upon jd 132

similar to the model developed by Mourelle (2001) that used tree species and biomass as covariates to explain 80% of variation in PARt observed in temperate hardwood species. It is possible that the residual variation is due to additional component traits not measured in this study as well as environmental factors, edge effect and rootstock influence. However, bud break as leading explanatory variable for TauI presents great opportunity for selection and systems design, as the order of bud break among cultivars is consistent from year to year (Bishop et al. 2024; Meier et al. 2022) and the character appears to be under strong genetic control in *Juglans* (Bernard et al. 2020).

Cultivar selection

When ranking cultivars by TauI or TauC there are specific cultivars that consistently allow for greater light penetration. While phenological and architectural traits related to complementarity may be present throughout the *J. nigra*, the data presented here suggest 'Myers', 'Daniel', 'Sparks 127' and 'Hay' have increased potential for use in ACS with spring-ripening crops such as winter wheat and barley. Nut crop productivity and quality varies amongst these cultivars. UMCA historical data shows that 'Hay' and 'Sparks 127' have high kernel percentage and overall yields (Meier et al. 2022). The historical data also shows that 'Hay' displays the most consistent productivity (i.e., low alternate-year bearing) than any other cultivar used in this study. 'Myers' and 'Daniel' have high kernel percentage but relatively low yields (Table S1).

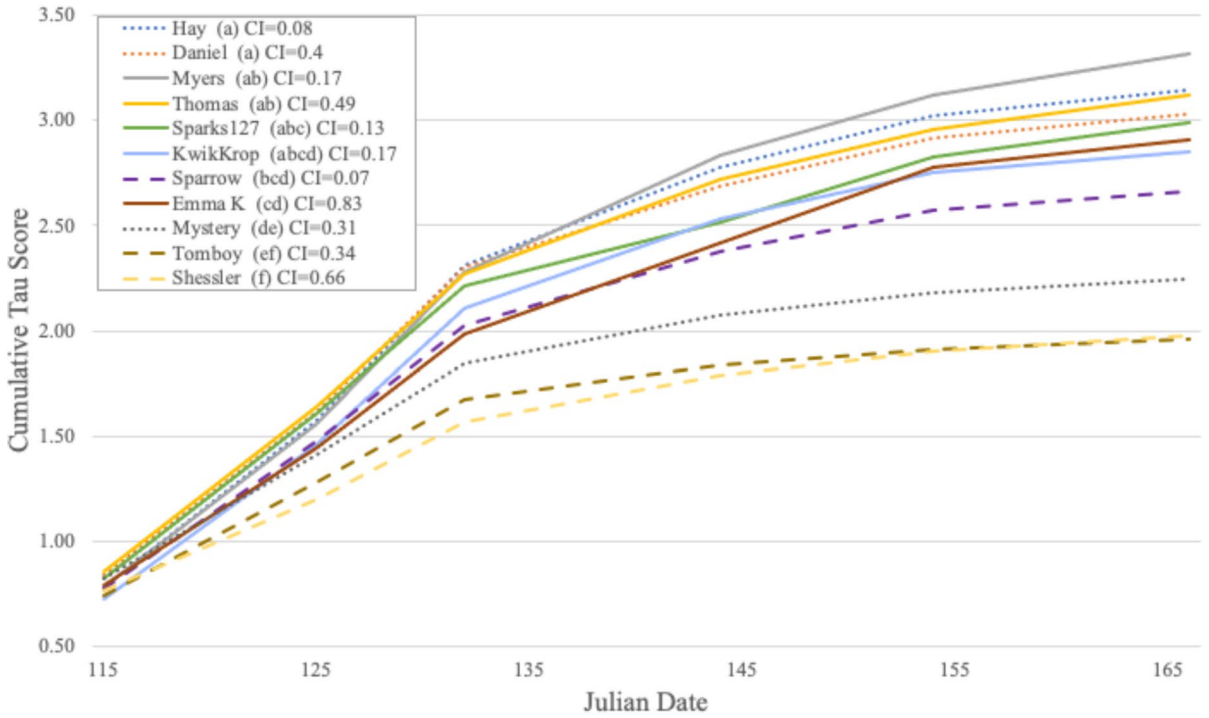


Fig. 6 Cumulative Tau values by Julian date (jd) of each cultivar from jd 115–165. Values represent the accumulation of PAR throughout the experimental period. The 95% confidence intervals and LSD groups are provided in the legend based on jd 132

It is important to note that there were less significant differences in Tau on the final measurement date of June 15 (jd 166), suggesting that there may be less cultivar-specific shading effects in the summer months. While this date is past the critical period for grain filling/ripening for winter wheat, it is relevant for considering summer alley crops. However, observationally, 'Sparks 127', 'Daniel', and 'Kwik Krop' had significantly less retention of foliage in the autumn, indicating that there may have been increased understory PARt during late-summer and fall. Further experimentation into PARt throughout the remaining growing season would highlight cultivars that may be complementary with summer and fall crops. Additionally, agroforestry practices such as silvopasture and forest farming may have unique requirements for shade and sun at specific times of the growing season and would benefit from this research as well. In such cases, optimizing canopy shade for animal shelter, mushroom production or high-value specialty crops would entail corresponding tree cultivar selection.

While characterization for crown light penetration can highlight superior cultivars, it does not explain the mechanisms driving differences seen. Identifying factors correlated with PARt levels through the tree crown may facilitate the characterization of other black walnut populations as well as inform selection criteria in breeding programs interested in complementarity traits.

Conclusion

The design and successful implementation of mixed-species and agroforestry systems requires consideration of complementarity between component species at competition vectors. In this study, we examined black walnut cultivars for characteristics relevant to light availability for understory crops. The results showed that there are cultivars that may be ideal for use in mixed systems where understory light during the spring is desirable. This research could be built upon by examining complementarity with different

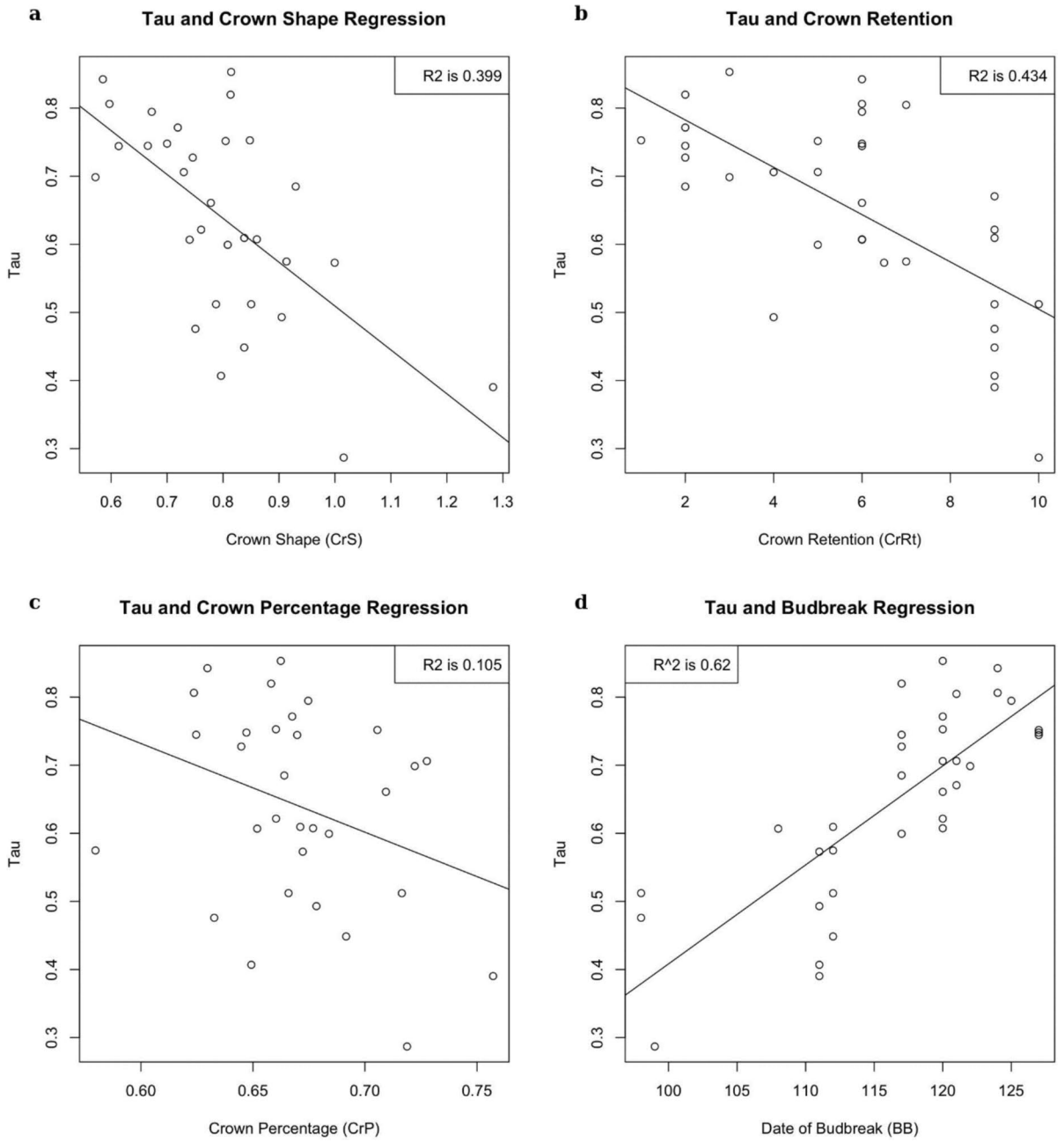


Fig. 7 Linear models regressing TauI on May 12 (jd 132) with crown shape (**a**), crown retention (**b**), live crown ratio (**c**) and bud break date (**d**)

tree crop species, crop species or during different growing seasons. Moreover, correlation and linear regression analysis of component traits suggest that bud break date, tree shape, and live crown ration most strongly influence light penetration. As the dynamics of competition in ACS become better understood, researchers and growers can begin to design and implement highly productive agroforestry systems that also provide ecosystem services by increasing landscape heterogeneity.

Author contributions BB and RR conceived and wrote the initial draft of the manuscript. BB, MC, and RR contributed to experimental design. BB and FT contributed to data collection; FT and FF contributed technical expertise to light infiltration data collection. BB, FTC, RR, NM, MC, and FF contributed to manuscript content and revising. BB prepared figures and tables. All authors contributing to manuscript framing and revisions.

Funding This work is supported by the U.S. Department of Agriculture, Agricultural Research Service, under agreement No. 58–6020-0–007, and the University of Missouri Center for Agroforestry and the USDA/ARS Dale Bumpers Small Farm Research Center. Any opinions, findings, conclusion, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the U.S. Department of Agriculture.

Data availability Data is provided upon request by the corresponding author.

Declarations

Conflict of interests The authors declare no competing interests.

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