



A review to frame the utilization of Eastern black walnut (*Juglans nigra* L.) cultivars in alley cropping systems

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Abstract Agroforestry adoption is gaining considerable traction in the temperate US with growing popularity and government incentives (e.g., the Partnerships for Climate-Smart Commodities Project) for systems with greenhouse gas mitigation potential. The identification of complementary species combinations will accelerate the expansion of temperate agroforestry. Since the mid-19th century, European timber plantations have taken advantage of the late-leaving habit of walnut (*Juglans* spp.) to grow a spring grain crop between the tree rows. Such alley cropping systems increase land-use efficiency and provide extensive environmental benefits. A parallel but underutilized opportunity in North America involves incorporating eastern black walnut (*Juglans nigra* L.) cultivars into alley cropping systems (ACS). Eastern black walnut, henceforth referred to as black walnut, is native to North America and exhibits architectural and phenological characters for reduced competition with winter cereal crops grown in alleys. Black walnut also produces nutritious nuts, and cultivars with improved kernel percentage and mass offer potential to cultivate the species as a domesticated orchard crop, as opposed to just the high-quality timber for which it is well-known. However, field observations

suggest significant variation in tree architecture and phenology amongst cultivars, which is likely to influence complementarity with winter grains. Comprehensive characterization of trait genetic diversity is needed to best leverage germplasm into productive systems. Here, we review literature related to implementing ACS with consideration of cultivar-dependent traits that may reduce interspecific competition. While the focus is directed toward black walnut, broad characterization of other underutilized fruit/nut species will allow for robust diversification of ACS.

Keywords Agroforestry · Genetic diversity · Interspecific competition · Light infiltration · Phenology

Introduction

Monoculture systems dominate the agricultural landscape of the Midwest United States. While exceedingly productive, its environmental impacts are far-reaching. The use of frequent tillage practices on landscapes subject to wind erosion combined with minimal use of cover crops has caused nearly a one-third, or 12 million hectares, loss in in carbon-rich topsoil across the midwestern Corn Belt (Thaler et al. 2021). As a direct result, there has been a reduction in crop yields equaling a \$3 billion annual loss in farm income in this region. Additionally, top soil disturbance causes stored

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carbon to oxidize into the atmosphere, contributing to substantial greenhouse gas emissions (GHG) (Wang et al. 2020). In 2019, crop cultivation in the U.S. was responsible for an emitting and estimated 368mt of CO₂-eq, an equivalent of an additional 80 million passenger vehicles on the road (Environmental Protection Agency 2022). As a result of elevated GHG in Earth's atmosphere, a 2021 report by the Intergovernmental Panel on Climate Change (IPCC) states that the rate of sea-level rise has tripled in the last 50 years. Temperatures are also predicted to rise above 1.5 °C by the year 2040, causing an increase in the occurrence of extreme weather (Masson-Delmotte et al. 2021). Strategies to mitigate the environmental impact of monoculture cropping are critical moving forward.

Agroforestry practices improve the net impact of agricultural production (Pavlidis and Tsihrintzis 2018). One such practice, alley cropping (i.e., growing crops between rows of trees), emphasizes using trees and shrubs as productive components of the farm, providing income from timber, fruits, nuts and multi-functional landscapes (Mander et al. 2007; Lovell et al. 2017). Trees and shrubs integrated into annual cropland reduce soil erosion, improve watershed health, and increase biodiversity (Udawatta et al. 2002; Stamps et al. 2009; Bentrup 2014; Vacek et al. 2018; Wolz et al. 2018). The addition of woody biomass also aids in the sequestration of CO₂ as above and belowground terrestrial carbon pools. In less than ten years, an experimental ACS plot in Germany observed a more than doubling of soil organic carbon (Nii-Annang et al. 2009). A meta-analysis by DeStefano and Jacobson (2018) supports soil carbon sequestration by agroforestry systems, showing that soil organic carbon increased between 26 and 34% (depending on soil depth) when agricultural land was transitioned into agroforestry. Udawatta and Jose (2011) estimated that even modest adoption of alley cropping systems (ACS) and other tree-based agroforestry practices would offset annual U.S. energy emissions by 34%. Furthermore, mixed-species ACS release up to 83% less nitrous oxide, an even more potent GHG, due to increased utilization of soil nitrogen (Wolz et al. 2018). While the climate mitigation and ecological arguments for integrating trees on cropland are strong, incentivized adoption will likely arise with increased on-farm productivity and profitability (Lovell et al. 2017).

Farmers need an economic rationale to adopt new strategies for managing their land and farming operations. Demonstrating alternative land-use practices that increase bottom line farm profitability or provide more stable revenue streams may help provide such a rationale. Evidence presented thus far suggests increasing on-farm crop diversity can reduce profit volatility inherent in commodity agriculture (Brandes et al. 2016; Harkness et al. 2021). Specifically, uncorrelated revenue streams derived from multi-species ACS with grains, fruit, nuts and timber offer opportunity for financial stability by distributing risk and enhancing land-use efficiency (Stamps et al. 2009; Xu et al. 2019). Economic analyses of ACS on several sites in Missouri and Nebraska indicated profitable grain and legume yields planted between tree rows, in some cases with no significant difference in yield compared to the row crop monocultures (Godsey 2000; Stamps et al. 2009). Economic and spatial analyses by Wolz and DeLucia (2019) supported these findings, determining timber ACS in the midwestern U.S. was a more favorable long-term investment than conventional corn production or forestry alone when targeting the appropriate environments. Also, government incentives such as the Environmental Quality Incentives Program offer farmers \$123.5 per hectare for alley cropping and more for socially disadvantaged farmers (Arango-Quiroga et al. 2019) although most contracts have terms of only 1–3 years.

Despite the potential of ACS in the Midwest, adoption is relatively low. While farmers are interested in incorporating agroforestry (Mattia et al. 2018), scaling the adoption of ACS with specialty nut crops, such as Chinese chestnut (*Castanea mollissima*), hybrid hazelnut (*Corylus avellana* L. × *C. americana* Marshall) or eastern black walnut, depends on the development of improved cultivars through breeding and selection (Coggeshall 2011; Mori et al. 2017; Revord et al. 2019). A challenge to designing agroforestry systems is identifying compatible tree species and cultivars/breeding selections with desirable commercial traits and reduced interspecific competition with grain or cereal crops grown in alleys (Santi and Fernandez 2014; Desclaux et al. 2016).

This paper discusses the potential of an underutilized nut tree, eastern black walnut, to scale opportunity for ACS integration into the Midwest U.S. agricultural landscape. In doing so, we review the market and genetic improvements of eastern black walnut

as a nut crop and detail cultivar-specific phenological traits relevant to winter cereal complementarity. This approach is the first step towards identifying and developing agroforestry-adapted cultivars of black walnut, which can be applied to many other tree crop species.

Black walnut for alley cropping

Juglans, A model genus for ACS diversification

Although the majority of global land currently utilizing ACS is found in the tropics, identifying instances of ACS in temperate regions can provide insights into how the practice may be implemented in North America (Wilson and Lovell 2016). China has integrated fruit and nut trees onto croplands for centuries as a method of diversification and food security. Examples include Chinese chestnut with soybeans (*Glycine max* L. Merr.) in Yunnan Province, apricot (*Prunus armeniaca* L.) with wheat (*Triticale aestivum* L.) in the Northwest region, and apple (*Malus domestica* Borkh.) with soy and peanuts (*Arachis hypogaea* L.) in the Loess Plateau region (Gao et al. 2013; Raj and Lal 2014; Qiao et al. 2020). The practice has since spread to Europe with winter cereal grain traditionally grown in alleys created between tree rows of sweet chestnut (*Castanea sativa* Mill.) in Galicia, Spain. In addition, rows of poplar (*Populus* spp.) and black locust (*Robinia pseudoacacia* L.) are successfully alley cropped with rye (*Secale cereale* L.) in the lower Lusatia region of Germany (García Queijeiro 1997; Nii-Annang et al. 2009).

While it is evident that temperate agroforestry utilizes many genera of trees, the most common is *Juglans*, which is studied in 34% of all field experiments (Wolz and DeLucia 2018). This genus comprises wind-pollinated, monoecious hardwood trees in the *Juglandaceae* family (Zhu et al. 2019). Persian walnut (*J. regia*) is the most commercially successful agricultural species in the genus, growing on 440,000 acres in the US and producing a crop valued at nearly \$1.3 billion annually (USDA 2020). Persian walnut has been successfully alley cropped with tea (*Camellia sinensis* L. Kuntze) in the Yunnan Province of China, vegetables in Great Britain and (Leshem et al. 2009) grapevines in Italy (Leshem et al. 2009; Nerlich et al. 2012; Paris et al. 2019). Unfortunately,

commercial cultivation of Persian walnut in the U.S. is restricted to states with warm mild climates found in California and surrounding states (Ebrahimi et al. 2017) and requires irrigation. Cold-tolerant *Juglans* species such as *J. cinera* L. and the Japanese walnut, *J. ailantifolia* Carr. and hybrids thereof also exist across the eastern North American landscape and produce edible nuts (Brennan et al. 2020; Pike et al. 2021). However, in comparison, black walnut is more broadly adaptable and disease resistant and thus presents a compelling option for expansion of North American temperate ACS.

A nut crop with growing potential for the Midwest U.S

Eastern black walnut has extensive native range across the eastern U.S., extending from the Great Lakes Region to Florida and Texas (Salek and Hejckmanova 2011). Black walnut timber and veneer is exceptional, with a standing stock valued at over a half-trillion dollars, it is one of the most valuable hardwood in North America (Newton et al. 2009). Additionally, there is a regional market for the edible nuts, including uses in ice cream, beer, and baked goods (Wendholt Silva 2016). An estimated 15.9 million kilograms are harvested annually to support products made from both their nuts and shells (Coggeshall 2011; Wendholt Silva 2016). Black walnuts have the highest protein content of commercially grown nuts and higher levels of many vitamins and minerals than the Persian walnut (*J. regia*), the most economically important nut-tree species of the genus (Câmara and Schlegel 2016). Current research also suggests that black walnut consumption may have protective effects against cardiovascular disease, neurodegeneration, diabetes and various cancers (Câmara and Schlegel 2016; Vu et al. 2020). These effects are associated with anti-inflammatory metabolites such as flavonols, hydroxybenzoic acids, ellagitannins, and the species' unique fatty acid and vitamin profiles (Vu et al. 2020). Additionally, the shell is a high-value material used in industrial cleaning applications, oil well drilling, painting, and cosmetics industries (Michler et al. 2008).

The supply of black walnut kernels for current regional markets is primarily derived from harvesting wild, unimproved seedling trees (Coggeshall 2011). After processing, the amount of edible kernel

recovered from these nuts is only 10–15% of total nut weight, 4–8x less than the highly-domesticated Persian walnut (Reid 1990). As a result, nuts from wild trees a low price (\$0.35/kg) due to their low kernel percentage. An additional deterrent to the establishment of commercial plantings of black walnut is alternate bearing (i.e., the inter-annual yield variation). Nut quality attributes, including light kernel color and mild flavor, also vary across wild stands and harvesting practices, resulting in challenges to consistently meet consumer preferences (Reid et al. 2009). Cultivars noted for high nut production and kernel quality are available commercially. In contrast to wild sources, nuts derived from cultivated varieties exhibit > 30% kernel and other preferred attributes, resulting in wholesale purchases of hulled, wet in-shell nuts around \$1.65/kg by Hammons Products (Stockton, MO, USA). These trees tend to have a sprawling canopy with profuse flowering and fruiting along lateral and spur branches. This type of crown structure indicates high yields and is distinctly separate from the upright branchless attribute of timber cultivars (Reid et al. 2009). However, they are simply wild selections or chance seedlings (Zhao et al. 2017), not the products of organized breeding programs. While these currently available cultivars have enabled modest-sized first-generation orchards, there is great potential for their use in systematic breeding to develop new commercial releases that help standardize and scale the industry.

Walnut-based ACS with winter crops

Black walnut has been utilized for timber in Europe since first introduced in the 17th century and is grown for timber on an estimated 20,000 ha across 14 European countries (Šálek and Hejčmanová 2011; Goodman et al. 2013; Nicolescu et al. 2020; Pelleri et al. 2020). In addition to the high-quality wood, European growers note that black walnut trees better resist pests, diseases, and drought conditions than *J. regia* (Salek & Hejčmanová 2011). However, even with good management practices, black walnut plantations have a minimum timber rotation period of 40 years (Nicolescu et al. 2020). In response, some European farmers have alley-cropped wheat (*Triticum aestivum*, *T. durum* Desf.) and barley (*Hordeum vulgare* L.) between the tree rows to generate revenue while the trees mature. The Dauphiné Province in southeastern

France has been intercropping trees since antiquity as both timber and nut crops (Dupraz and Liagre 2008). In this region, 1500 ha of black walnut and hybrids (*J. nigra* × *J. regia*) are alley cropped, representing 80% of all walnut plantations under 10 years of age (Dupraz 1994). Adopters of walnut–wheat ACS may have unknowingly buffered their grain crops against abiotic stressors. Recent modeling research of walnut–wheat ACS under various climate scenarios has predicted a reduction of heat, drought and nitrogen stressors up to 35% in the wheat crop (Reyes et al. 2021).

The integration of black walnut trees with winter crops can increase land-use efficiency and productivity, as measured by the land equivalency ratio (LER), a productivity ratio comparing the yield of mixed cropping systems with their component monocultures (Mead and Willey 1980). An LER value higher than 1.0 indicates that the system's yield is greater than the sum of its parts. There have been several experiments examining the LER in walnut ACS with winter crops. Zhang (2014) showed Persian walnut–wheat systems in northwest China had significant yield advantages with an average LER of 1.45. Similar research conducted in western Spain reported LER as high as 2.08 and 1.72 in Persian walnut ACS with barley and winter wheat, respectively (Arenas-Corraliza et al. 2018). Exploration of tree physiology that lessens the competitive interactions with winter cereals would offer direction for improving system productivity and diversifying ACS with other underutilized tree fruits and nuts.

Interspecific competition in black walnut ACS

Resource partitioning in ACS occurs due to above-ground competition for light and belowground competition for water and nutrients. Belowground competition occurs when tree and alley crop roots utilize similar soil horizons for nutrient and water uptake (Zamora et al. 2008, 2009). Such belowground competition can occur during key phenological stages (e.g., heading, grain filling), reducing row crop yields (Jose et al. 2000; Zamora et al. 2009; Fletcher et al. 2012). Fortunately, when planted near row crops, black walnut's root architecture reduces competition by adapting to deeper soil profiles (Andrianarisoa et al. 2016; Cardinael et al. 2015). Cultural practices can further reduce this root-zone overlap, such as root

barriers, trenching, and annual “ripping” which may have positive effects on nut productivity in maturing orchards. However, despite managing belowground competition, crops growing directly adjacent to tree rows yielded less and grew to only 70% the height of those grown in the center of the alley (Miller and Pallardy 2001; Zamora et al. 2008).

Multiple studies show that shade can reduce cereal crop yield up to 50% (Chirko et al. 1996; Friday and Fownes 2002; Li et al. 2008; Dufour et al. 2013), and the magnitude of yield reduction depend on the intensity of shade and the physiological stage of the crop plant when the shade is introduced. Winter wheat and barley are planted in autumn, enter the flowering stage in spring, and are typically harvested in early summer. Artificial shading experiments on wheat crops have defined a critical period beginning 10–30 days before flowering. Heavy shade during this period can significantly decrease the number of grains per spike and overall grain weight at the final harvest. (Abbate et al. 1997; Dufour et al. 2013; Artru et al. 2017). However, if modest shade is provided, by a dormant tree canopy for instance, yields of wheat and barley can increase by 19% compared to full-sun treatments (Arenas-Corraliza et al. 2019). There may be additional critical periods not yet identified that are relevant to other potential alley crops harvested in the summer or fall.

Landscape-level design strategies to reduce competition for light in ACS are numerous. Tree rows can be spaced wider to decrease the amount of canopy shade. Naturally, black walnut ACS with tree rows spaced 24 m apart produced greater alley crops than systems with rows spaced half as wide (McGraw et al. 2008; Stamps et al. 2009). This approach, however, can introduce high levels of spatial heterogeneity of crop irradiance, potentially resulting in uneven ripening and pre-harvest sprout damage (Dupraz et al. 2018; Vetch et al. 2019). Moreover, addressing aboveground competition with wider rows is undesirable, as it reduces the number of trees per acre and future income from the tree crop or timber harvest. Tree row orientation is also essential in maximizing light transmittance to crops in ACS and is a design decision that cannot be modified as after establishment. Modeling research on light competition shows that a North-South tree row orientation optimizes crop irradiation in hybrid walnut–wheat ACS located in latitudes greater than 50°. This is likely due to alley rows being

closer to parallel with light beams originating from a south direction (or north direction if in the global south). In contrast, an East–West orientation is preferable in latitudes less than 40° latitude (Dupraz et al. 2018) where the tree rows would be closer to parallel with the sun’s path in the sky, reducing shading onto the alley crops. However, in temperate zones between those latitudes, where much of the Midwest U.S. lies, tree phenology is a more significant factor of winter crop irradiation in ACS than row orientation (Dupraz et al. 2018). Thus, selecting tree species with delayed canopy formation can minimize aboveground competition for light. While not all tree crop species have black walnut’s late-leaving habit, opportunities to improve and diversify temperate ACS will come from exploring tree phenology, physiology, and form to identify new species-specific traits that reduce competition for light.

Consideration must be given to black walnut’s allelopathy, where the phenolic compound juglone can inhibit germination and growth of nearby growing species (Jose and Holzmüller 2008). Fortunately, studies suggest wheat, corn, and barely only demonstrate slight growth reduction following exposure to juglone (Jose and Gillespie 1998a, b; Kocacaliskan and Terzi 2001), while soybean, alfalfa, and strawberry experiences greater inhibition (Ercisli et al. 2005; Kocacaliskan and Terzi 2001). Nevertheless Jose and Gillespie (1998a) report a significant decline in soil juglone concentrations starting 2.45 m from the tree row, which is relatively short compared to an alley width, and it’s estimated to take as many as ten years before soil juglone concentrations increases to a level requiring mitigation efforts. That said, management of soil juglone concentrations in the alley is possible through tree root pruning via subsurface “ripping”, as is done to mitigate belowground competition for nutrients and water, as most soil juglone appears to originate from the roots (Jose et al. 2000; Jose and Gillespie 1998a).

Application and advancement of black walnut ACS

Germplasm characterization for complementarity

Black walnut is one of the last temperate tree species to break dormancy in the spring and develop a full

canopy (Mori et al. 2017). This behavior is thought to be an evolutionary adaptation to avoid spring frost damage to emerging buds and flowers, which occurs at temperatures below -3°C (Reid et al. 2009). Late bud break makes black walnut ideal for alley cropping with winter grains. Once its canopy is foliated, black walnut shows the most of amount of understory light infiltration compared to five common hardwoods (Mourelle et al. 2001). However, considerable genetic diversity for all spring phenological traits and tree architecture suggests thorough germplasm characterization will aid understanding of component traits that drive complementarity and how these traits vary amongst cultivars. For example, in central Missouri, bud break dates range over nearly 30 days within the species (unpublished). Genetic variation for spring vegetative growth and canopy architecture is, however, not well characterized. Still, it appears diverse based on field observations, including traits like date of full crown closure, lateral branching behavior and overall canopy shape and size shape. Such characteristics contribute to photosynthetically active radiation (PAR) transmission through the canopy during the critical period for spring crops. Thus, teasing out their relative importance to transmissibility will offer insights to improving complementarity.

Germplasm availability is a major limitation to characterizing phenology and tree architecture. Collections that possess accessions/cultivars in replication and under relatively uniform conditions are required to draw comparisons amongst genotypes. Mature repositories, however, represent a long-term commitment of resources (i.e., funding, labor, space) and are thus quite rare. A repository of 70 black walnut cultivars was curated starting in 1996 at the Horticultural and Agroforestry Research Center in New Franklin, Missouri (39.01°N) to assemble specimens with high kernel percentage for replicated evaluation, conservation, and breeding (Coggeshall and Woeste 2010). From 2002 to 2009, phenological characters (e.g., date of bud break, flowering, and harvest) were recorded (unpublished), which sheds light on phenological variation relevant to alley cropping with winter wheat. Table 1 highlights the diversity in bud break within cultivars in the University of Missouri Center for Agroforestry (UMCA) collection, which may reflect their diverse geographic origin.

Variation in bud break date should be compared with the key developmental stages of winter crops

Table 1 Bud break dates of select black walnut cultivars. Date of bud break is recorded as days after ‘Schessler’, the earliest leafing cultivar, breaks bud. This occurs on April 8th on average. Confidence intervals at 95% are stated after bud break

Cultivar	Bud break date
Schessler	0 ± 1
South Fork	2 ± 1
Football	3 ± 1
Davidson	3 ± 1
McGinnis	4 ± 3
Jackson	4 ± 2
Krause	4 ± 1
Brown Nugget	4 ± 2
Emma K	6 ± 4
Rupert	6 ± 2
Tomboy	6 ± 2
Mystery	6 ± 3
Sparks 127	11 ± 5
Ohio	11 ± 6
Pound #2	12 ± 5
Kwik Krop	13 ± 4
Surprise	13 ± 6
Sparrow	14 ± 5
Daniel	15 ± 6
Bowser	17 ± 5
Hare	17 ± 5
Clermont	19 ± 6
Thomas	19 ± 6

to gain insight into the potential interspecific interactions. Figure 1 displays the seasonal phenology of several black walnut nut cultivars and winter wheat, with the critical period for winter wheat enclosed in red. Bud break and harvest dates are based on historical data, while leafing and full canopy closure dates are estimated to depict these phases conceptually. More precise observation of the progression of vegetative development beginning at budbreak until full canopy closure would likely show additional variation to select individuals with greater complementarity for winter wheat.

Light transmittance through tree canopy can be influenced by multiple characters and varies by species (Mourelle et al. 2001); looking at bud break timing alone may not be sufficient. Morphological attributes such as total leaf area, tree dimensions and branching structure may all influence transmittance of PARt in the understory (Talbot and Dupraz

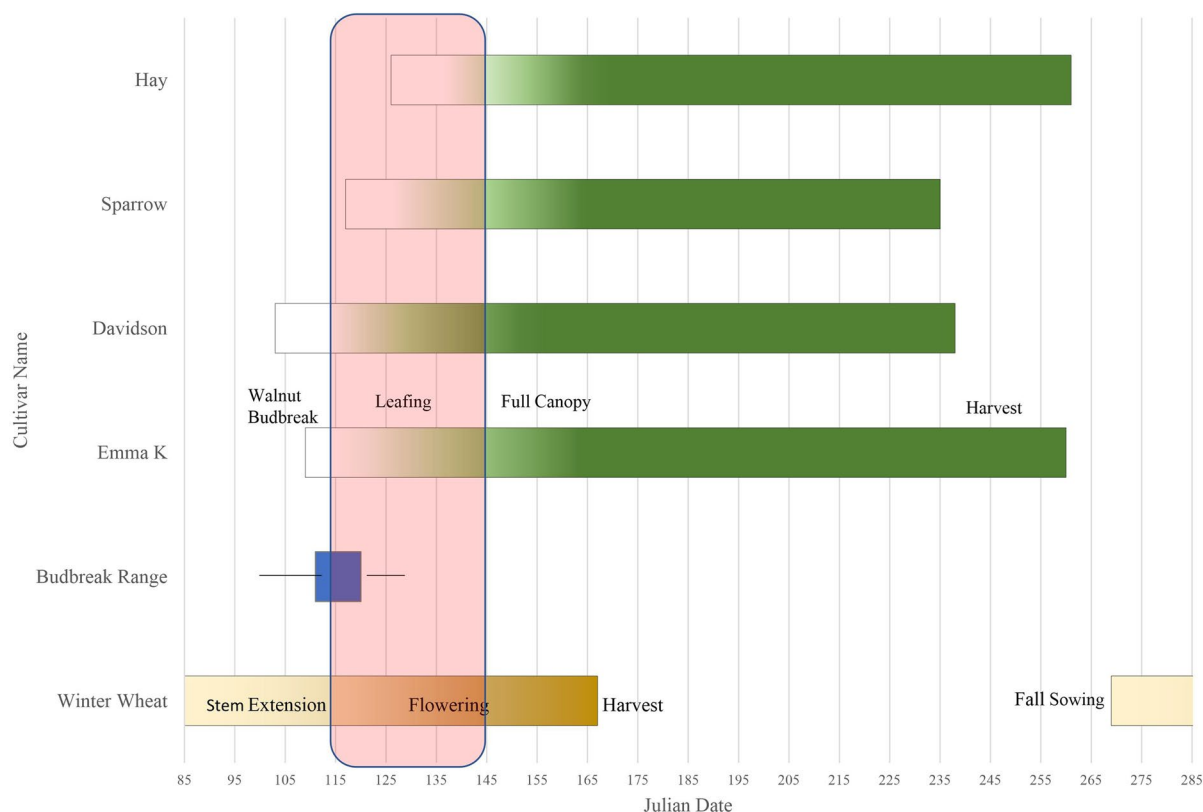


Fig. 1 The budbreak date of black walnut cultivars spans across the critical period (red box) where winter wheat is most sensitive to shade. The box plot in blue shows budbreak dates

for the whole cultivar collection to demonstrate genetic variation and the opportunity to select for greater complementarity

2011; Tang et al. 2019). To capture the suite of traits related to complementarity, characterization of cultivars throughout the critical period is required. Methodologies for physical measurements of isolated trees have been well established in forest management and tree physiology research (Grayson et al. 2012; Fawcett et al. 2020; Zhou et al. 2020). Modern techniques such as drone-acquired normalized vegetation index (NDVI) using multi-spectral sensors allow high-throughput and precise estimation of vegetative growth throughout the spring (Fawcett et al. 2020). Light detection and ranging (LIDAR) technology can accurately create 3D models of trees to analyze architectural parameters (Wang et al. 2008). While effective at tree biomass estimation, these approaches require expensive equipment and do not directly measure wavelengths of light utilized in photosynthesis. Field measurements of PARt using handheld devices such as the AccuPAR LP-80 present an

inexpensive alternative to remote sensing and provide data relevant to crop growth in the understory.

Breeding black walnut cultivars

Genetic improvement of black walnut is in its early stages. Although breeding has not yet pursued alley cropping complementarity, it is feasible for such objectives to be integrated into current goals of improving nut quality. In 2001, the UMCA initiated a black walnut breeding program to improve the species for orchard nut production (Coggeshall 2011). The program began by assembling 84 black walnut cultivars identified on-farm or in the wild and named and propagated due to a high kernel percentage. Phenotypic data were collected on this collection between 2002 and 2013, demonstrating variation in economically important nut quality characters, phenological traits (Table 1), and resistance to walnut anthracnose

(Reid et al. 2009; Coggeshall 2011; McKenna and Coggeshall 2018). Through both open and controlled pollinations, around 1500 progeny were produced from 2002 to 2008, comprising the program's first breeding generation. Progeny were evaluated from ages five to eight to identify outstanding individuals, namely for spur bearing, kernel percentage, mass, yield and low alternate bearing. Breeding selections from the UMCA program have shown significant improvements in these commercial attributes compared to the previous generation of cultivars.

While most breeding goals of black walnut related to increased crop quality and resistance to stressors, there is an opportunity to include compatibility with winter cereals as an additional consideration in selection. Improved tree cultivars, along with advances in shade-tolerance of grain/cereal crops, would aid in effective resource partitioning on agroforestry land. A black walnut breeding generation spans five years seed-to-seed, a relatively short generation time for temperate tree nuts. If seedlings can be phenotyped during this juvenile period for desirable traits, time delays common in tree breeding could largely be avoided and genetic gain accelerated. Moreover, as relevant alleles are identified, marker-assisted selection (MAS) and culling would be possible at year 1. Research on *J. regia* has identified and validated a marker for budbreak timing (Bernard et al. 2020), and quantitative trait loci (QTL) have been detected, explaining a portion of the variation in harvest date and several nut quality parameters (Aradhya et al. 2019). Similarly, research with the 'Sparrow' × 'Schessler' *J. nigra* mapping population at UMCA has identified QTL related to floral heterodichogamy and budbreak with future mapping targets of spur-bearing habit and kernel percentage.

Future directions

The unique architectural and phenological traits of black walnut make it a compelling option for nut-based ACS. Characterization of cultivars for optimal complementarity will allow farmers to make informed decisions on the design of their agroforestry operations. To understand the mechanisms behind this complementarity, correlations between PART, tree phenology, and morphology must be established. These associations will allow for rapid identification

of ideal cultivars for ACS. Additionally, associations between tree architecture and PART may guide spacings and pruning regimes for maximum light infiltration into the understory.

Exploration of the genetic basis of traits governing PART may accelerate the development of cultivars with enhanced complementarity. The use of full-sibling experimental populations would allow for analysis of inheritance patterns as well as dominance and additive effects. Breeders could use this information to choose crosses with high likelihood of desirable traits in the progeny. In addition, if the black walnut mapping population reveals QTL for traits related to tree architecture and foliation patterns, as has been achieved in other hardwoods (Socquet-Juglard et al. 2013; Du et al. 2016), MAS of black walnut seedlings with both high yields and enhanced complementarity would be possible.

In addition to winter cereal grains, black walnut may be compatible with warm-season crops such as corn and soy, particularly during the juvenile stage of the trees. Black walnut cultivars with sparse summer canopies and defoliation in August, when corn and soybeans are ripening, may allow for reduced competition and ACS adoption across a much wider range of sites in the midwestern corn belt. Both of these crops, however, are sensitive to juglone which the black walnut secretes from its roots (Jose and Gillespie 1998a; Hejl and Koster 2004), although may only be a concern in mid to late-stage systems. Research will be needed to design and validate best management practices for ACS with black walnut and warm-season crops that mitigate vectors of summer light displacement and juglone. In addition to ACS, tree cultivars with high levels of spring PART may be ideal for other agroforestry systems, particularly silvopasture environments, where light infiltration levels through tree canopy have been shown to affect forage quality and animal weight gain (Fannon et al. 2019). Late-leaving trees cast minimal shade on the pasture during spring while providing protection against heat and drought conditions to both pasture and livestock in summer (Fike et al. 2017; Beegle 2019).

Conclusions

Increasing landscape diversity offers solutions to both ecological degradation and economic instability.

Agroforestry practices provide an opportunity to integrate substantial populations of native productive tree species onto an otherwise homogenous environment. The potential of one such practice, walnut-wheat ACS in the Midwest US has been illustrated, emphasizing the importance of interspecific phenological complementarity. While ongoing research will identify optimal tree cultivars for use in such systems, farmers need not wait to integrate trees on their land as field grafting can occur many years after rootstock establishment.

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Data availability Data is available upon request from the corresponding author.

Declarations

Conflict of interest The authors declare no conflicts of interest exist.

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