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Black walnut alley cropping is economically competitive with row crops in the Midwest USA

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Abstract. The maize–soybean rotation (MSR) dominates the Midwest United States and degrades many ecological functions. Black walnut (*Juglans nigra* L.) plantation forestry (PF) and alley cropping (AC) are two alternative land-uses that can enhance productivity and restore ecosystem services. Given the lack of robust market mechanisms to monetize ecosystems services, we tested whether the profitability of PF and AC could drive adoption in the Midwest. Publically available data on black walnut soil suitability, timber prices, crop productivity, and cash rents were combined in a high-resolution spatial analysis to identify regions where these alternatives can outcompete MSR. To avoid selecting an arbitrary discount rate at which to make comparisons, we determined the threshold discount rate necessary to make PF or AC economically competitive with MSR. We show that, with a 5% discount rate, PF and AC could be more profitable on 17.0% and 23.4% of MSR land, respectively. Contrary to the common assumption that woody agricultural alternatives should first be adopted in marginal row crop areas, the economic competitiveness of PF and AC was not correlated with MSR productivity. Instead, black walnut growth rate was the central driver of PF and AC competitiveness, underscoring a necessary shift away from the current MSR-centric perspective in defining target regions for land-use alternatives. Results reveal major opportunities for landowners and investors to increase profitability by investing in PF and AC on both "marginal" and productive MSR land.

Key words: *agroforestry; discount rate; intercropping; land-use change; marginal land; silvoarable.*

Introduction

The maize–soybean rotation (MSR) is the dominant land-use in the Midwest United States (Fig. 1a). Though extremely productive, MSR degrades many ecological functions (Foley 2005, USEPA 2007, 2012), is sensitive to future climate change (Mistry et al. 2017), and its profitability is volatile (Brandes et al. 2016). Alley cropping (AC), an agroforestry practice that grows crops in alleys between tree rows, is an alternative land-use that can enhance productivity and restore ecosystem services (Thevathasan and Gordon 2004, Jose 2009, Tsonkova et al. 2012). For example, AC can sequester substantial amounts of carbon (Udawatta and Jose 2012) and reduce nitrogen losses via nitrate leaching (Dougherty et al. 2009, Wolz et al. 2018a) and nitrous oxide emissions (Beaudette et al. 2010, Wolz et al. 2018a). While these environmental benefits can certainly increase landowners' interest in agroforestry (Mattia et al. 2016, Winans et al. 2016), they have failed to drive adoption due to the lack of robust market mechanisms to monetize their value. Profit remains the central driver for adoption of sustainable agricultural strategies.

Here, we evaluate the economic competitiveness of two specific land-use alternatives containing black walnut (*Juglans nigra* L.): AC and plantation forestry (PF). PF was included to test whether AC can outcompete its respective tree and crop monocultures. *Juglans* is the most common tree genus in temperate AC, used in 34% of field experiments (Wolz and DeLucia 2018). Whether sold as veneer or less valuable saw logs, black walnut commands higher prices than all other temperate timber species (Appendix S1: Fig. S1). Furthermore, black walnut is an ideal species for AC because of its short growing season, sparse canopy (Moss 1964), large taproot, and deep rooting system (Yen et al. 1978). While allelopathic interference of crop growth from juglone can occur in black walnut AC, management interventions such as root pruning can minimize its impact.

Alternative agricultural practices are typically targeted at so-called "marginal" lands, which have low MSR productivity and contribute disproportionally to negative externalities (Richards et al. 2014). However, recent studies suggest that there are strong economic opportunities for land-use alternatives across existing MSR land (Brandes et al. 2016, 2018). We combine publically available data on black walnut soil suitability, timber prices, crop productivity, cash rents, and land cover to (1) evaluate where PF and AC can be economically competitive with MSR without monetization of any environmental benefits or direct government assistance; and (2) determine if the resulting PF and AC target regions coincide with marginal MSR land.

The economic competitiveness of a given land-use alternative depends on the profitability of the alternative relative to that of MSR. However, perennial crops are typically considered less sensitive to soil and climate than annual crops. Consequently, we hypothesized that competitive areas for black walnut PF and AC would exist across the region but be concentrated on marginal MSR land.

Merging high-resolution site suitability and profitability analyses enable us to move beyond previous studies of

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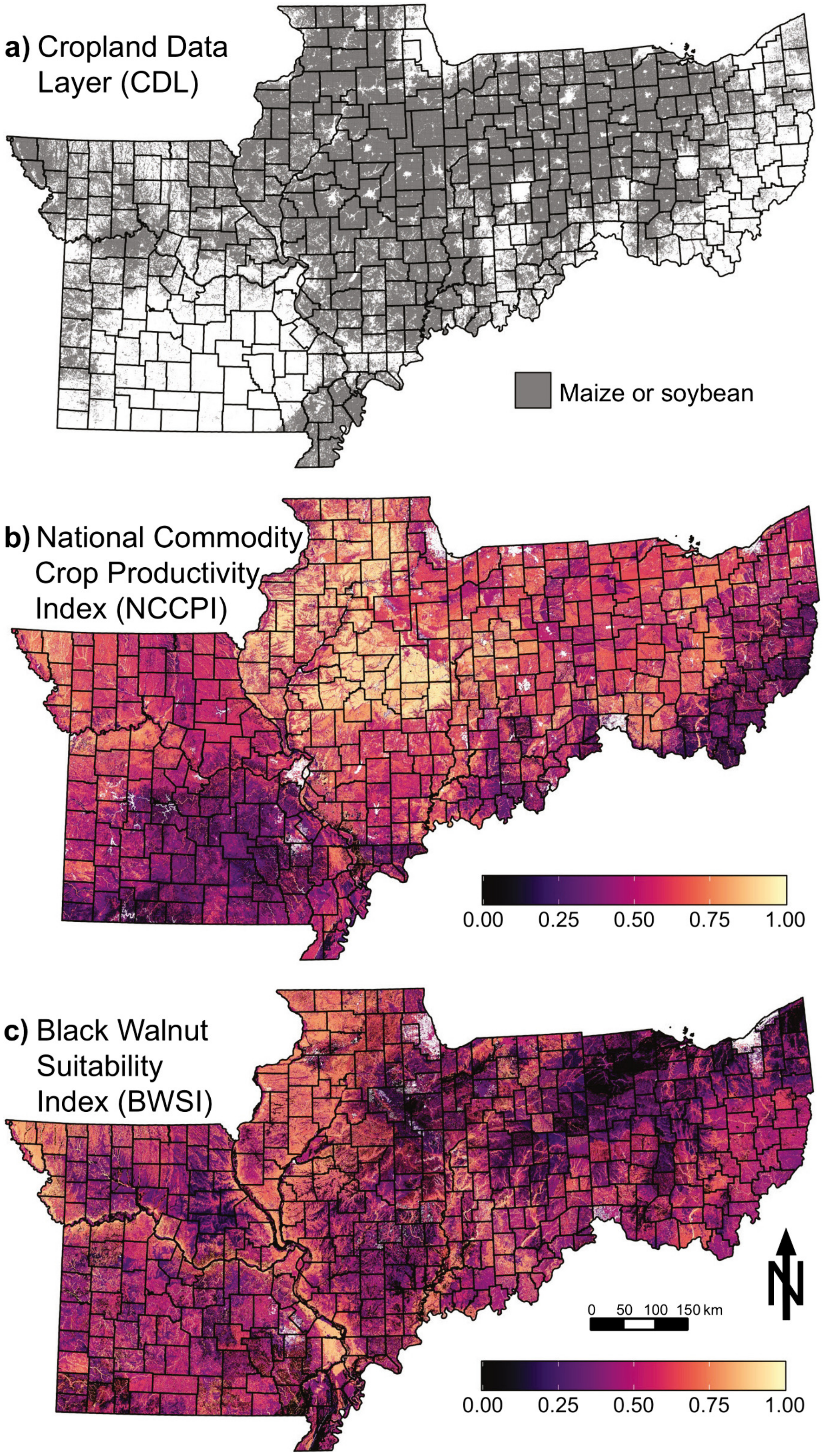

FIG. 1. Maps of spatial input variables to the model: (a) 2016 Cropland Data Layer (CDL; USDA NASS 2016a), (b) National Commodity Crop Productivity Index (NCCPI; Dobos et al. 2012), and (c) Black Walnut Suitability Index (BWSI; Wallace and Young 2008).

coarse-scale profitability (Yemshanov et al. 2007, Frey et al. 2010) or basic site suitability at high resolution (Reisner et al. 2007, Wang and Shi 2015). In addition, most previous studies assume a fixed discount rate (i.e., the time value of money), which limits generalization of results. Instead, we solve for the threshold discount rate that makes an alternative economically competitive with MSR, providing a continuous response variable for enhanced decision making.

Methods

All analyses were performed at 10 × 10 m resolution using the raster version of the National Soil Survey Geographic Database (gSSURGO; USDA NASS 2017). Analyses focused on existing MSR land ("cultivated land") in Missouri, Illinois, Indiana, and Ohio, the only four states with sufficient data on black walnut soil suitability. Cultivated land was identified using the 2016 Cropland Data Layer (CDL) created by the USDA National Agricultural Statistics Service (USDA NASS 2016a), a spatially explicit raster data layer identifying crop locations based on satellite imagery (Fig. 1a). All data integration and calculations were performed using the R statistical computing software version 3.4.0 (R Core Team 2017). Prior to analysis, historical economic data were adjusted to 2016 US using the consumer price index (U.S. Bureau of Labor Statistics 2017).

Cropland rent

Average cash rental rates of cropland for each county in 2008–2016 were obtained from USDA NASS (2016b). Over 80% of cropland was MSR in over 93% of counties, so these values were taken to represent the cash rental rate for MSR. Nine-year mean values were calculated for each county (Appendix S1: Fig. S2) to remove variability caused by market and climate fluctuations. To estimate cash rental rate for each map unit m in each county c, we followed the method of Brandes et al. (2016) to scale county-level rent by an index of maize-soybean productivity. The productivity index used was the National Commodity Crop Productivity Index, Version 2.0 (NCCPI), which is available in gSSURGO and calculates an index of maize-soybean productivity based on a range of soil and climate characteristics (Dobos et al. 2012). Important factors that influence NCCPI include soil pH, cation exchange capacity, organic matter, available water capacity, precipitation, and bulk density.

A coefficient D was calculated for each county c to describe the increase in cash rent per unit increase in NCCPI:

$$D_c = \overline{R_c}/\overline{\mathrm{NCCPI}_c} \tag{1}$$

where $\overline{R}_c$ is the nine-year mean cash rental rate for county c, and $\overline{\mathrm{NCCPI}_c}$ is the area-weighted mean NCCPI for cultivated land in county c. Missing values of $\overline{R}_c$ (in 11 counties with little cultivated land) were estimated using a linear regression model with $\overline{\mathrm{NCCPI}_c}$ across all counties (Appendix S1: Fig. S3). Using this coefficient, cash rental rate $R_{m,c}$ for each map unit m in each county c was calculated as

$$R_{m,c} = D_c \times \mathrm{NCCPI}_m, \tag{2}$$

where NCCPI_m is the NCCPI of map unit m.

Black walnut growth model

To find all publications measuring diameter at breast height (DBH) of field-grown black walnut, a literature search was conducted on the Web of Science Core Collections requiring the key phrases of either "black walnut" or "*Juglans nigra*" along with "growth," "diameter," or "DBH." The search returned 274 publications using a search window of 1900–2016. All retrieved publications were mined to extract measurements of DBH and the year of measurement. A total of 12 publications provided useable data, spanning from one to 109 yr after tree establishment and DBH ranging from 0.5 to 58.3 cm (Fig. 2). Compiled data were fit using a Korf growth model (Zeide 2002), which reliably predicts black walnut growth in the field. Significant estimates of each Korf model parameter were obtained, with high precision from the fitted model ($P < 0.02$, $r^2 = 0.78$).

To estimate the potential growth rate of black walnut on each soil map unit m, the fitted growth model from the literature data was scaled using the Black Walnut Suitability Index (BWSI; Wallace and Young 2008). As for NCCPI, BWSI exists in gSSURGO and calculates a suitability index for black walnut based on a range of soil properties and environmental conditions. Important factors that influence BWSI include flood frequency and duration, water table depth, depth to restrictive soil layer, soil texture, available water capacity, and soil pH. The fitted growth model from the literature data was set to represent a BWSI of 0.4, which is the area-weighted mean BWSI of all land in the four states studied. The growth curve for each map unit m was scaled linearly by BWSI_m and converted into an maximum potential diameter increment ($\mathrm{DI}_{m,y}$) for each year y (Appendix S1: Fig. S4). The scaled range of possible growth curves closely matched the range in literature data.

To model black walnut growth and profitability on each map unit m, the DI_m trajectory was supplied to a black walnut growth and financial model adapted from one created at the University of Missouri Center for Agroforestry (Godsey 2006). The model establishes trees with an initial diameter at breast height ($\mathrm{DBH}_{m,1}$) equal to 0.6 cm (the diameter of typical nursery stock) and an initial stand density. Tree DBH increases annually as a function of $\mathrm{DI}_{m,y}$ and the estimated intraspecific competition in the stand. To estimate intraspecific competition each year, a crown diameter (CD) and crown competition factor (CCF) are calculated following Čavlović et al. (2010) as

$$\mathrm{CD}_{m,y} = 0.311 + 0.177 \times \mathrm{DBH}_{m,y} \tag{3}$$

$$\mathrm{CCF}_{m,y} = \frac{\mathrm{SD}_{m,y-1} \times (\pi \times \mathrm{CD}_{m,y}{}^2/4)}{10000} \times 1.27 \times 100 \tag{4}$$

where $\mathrm{SD}_{m,y\text{-}1}$ is the stand density in year $y - 1$. CCF is then used to calculate a growth ratio (GR) using an equation developed by Schlesinger (1996) in 20 field plots in Illinois and Missouri as

$$\mathrm{GR}_{m,y} = \min\begin{pmatrix} 1, 1.411 - \left(0.00485 \times \mathrm{CFF}_{m,y}\right) \\ -\dfrac{7.643}{\mathrm{CCF}_{m,y}} \end{pmatrix} \tag{5}$$

Therefore, $\mathrm{GR}_{m,y}$ ranges from 0 to 1 and represents the reduction in DI_m due to intraspecific competition. The predicted DBH for year $y + 1$ on map unit m is then calculated as

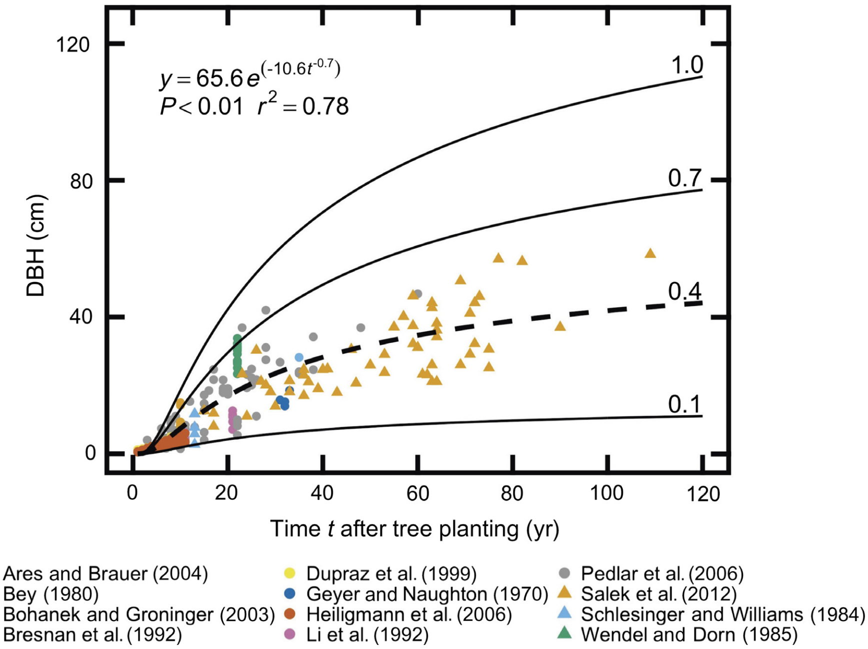

FIG. 2. Growth of black walnut DBH reported in the literature (Geyer and Naughton 1970, Bey 1980, Schlesinger and Williams 1984, Wendel and Dorn 1985, Bresnan et al. 1992, Li et al. 1992, Dupraz et al. 1999, Bohanek and Groninger 2003, Ares and Brauer 2004, Heiligmann and Schneider 2006, Pedlar et al. 2006, Šálek et al. 2012). The dashed line is the Korf fitted curve of the literature data, with the equation shown. This literature fit has a BWSI of 0.4, which is the area-weighted mean BWSI of all land in the four states studied. Black walnut growth in the model was then scaled from the Korf fitted curve by BWSI, as demonstrated by the examples (solid lines) labeled by the BWSI they represent.

$$\mathrm{DBH}_{m,y+1} = \mathrm{DBH}_{m,y} + \mathrm{DI}_{m,y} \times \mathrm{GR}_{m,y} \tag{6}$$

Tree height (H) was estimated following Šálek and Hejcmanová (2011) as

$$H_{m,y} = -21.2551 + 32.3733 \times \log(\mathrm{DBH}_{m,y}) \tag{7}$$

As trees grow and intraspecific competition increases, tree thinning events are triggered in year y when GR_y becomes <0.8. Each thinning event reduces stand density by removing a fixed proportion of trees, thereby reducing CCF in year y + 1, increasing GR, and allowing DBH to grow at a faster rate. Thinning events effectively maintain CCF between 75 and 125 and GR between 0.75 and 1.0. Doyle thousand board-foot (Doyle-MBF) volume of harvested trees was calculated from DBH using USDA Forest Service volume tables and a conservative form class of 78 (Mesavage and Girard 1946).

Alley crop yield

Maize, soybean, wheat, and alfalfa (*Medicago* sp.) are the most common species used in temperate AC experiments (Wolz and DeLucia 2018). Consequently, the cash rent income for alley crops in year y and map unit m in county c ($\mathrm{ACR}_{m,c,y}$) was calculated as the maximum value of the potential cash rents of (1) a maize–soybean rotation, (2) wheat, and (3) pastureland (Eq. 8).

Pastureland cash rent values were assumed to be unaffected by the presence of trees (Garrett et al. 2004), so county-level values were obtained directly from USDA NASS (2016b) and scaled for each map unit m in county c using a scaling procedure analogous to Eqs. 1 and 2. Missing values for pastureland cash rent in 69 counties were estimated using a linear regression model with county cropland cash rent (Appendix S1: Fig. S5).

For maize, soybean, and wheat, potential alley crop cash rent ($\mathrm{ACR}_{m,c,y,\mathrm{crop}}$) is sure to decrease over time as tree-crop competition decreases alley crop yields. To estimate these cash rent trajectories, alley crop yield trajectories were first calculated as follows. Average maize, soybean, and wheat (*Triticum* sp.) yields for each county were obtained from USDA NASS (2016b). Ten-year mean values were calculated for each county to remove variability caused by market and climate fluctuations. For maize and soybean, the 10 most recent years (2007–2016) were used. Wheat yield data for 2008–2016 were unavailable for most counties, so data from the 10 prior years (1998–2007) were used. To estimate monoculture crop yield for each map unit m in county c, a scaling procedure analogous to Eqs. 1 and 2 was used. Crop yield data were missing in 14, 21, and 51 counties for maize, soybean, and wheat, respectively. Missing data were estimated using linear regression models of crop yield between species (Appendix S1: Fig. S6), or, if all crop yield data was missing, then using linear regression models of crop yield and $\overline{\mathrm{NCCPI}_c}$ (Appendix S1: Fig. S7).

Then, to estimate the trajectory of alley crop yields following tree establishment, data from all temperate and subtropical AC studies that report relative yield of maize, soybean,

$$\mathrm{ACR}_{m,c,y} = \max\left(\frac{\mathrm{ACR}_{m,c,y,\mathrm{maize}} + \mathrm{ACR}_{m,c,y,\mathrm{soybean}}}{2}, \mathrm{ACR}_{m,c,y,\mathrm{wheat}}, \mathrm{ACR}_{m,c,y,\mathrm{pasture}}\right) \tag{8}$$

or wheat were extracted from the catalog of AC literature developed by Wolz and DeLucia (2018; Appendix S1: Tables S1–S3). Studies that report alley crop yield but did not have a monoculture crop control, and therefore could not estimate relative yield, could not be included. Furthermore, studies that report relative yield without accounting for the uncropped area within tree rows and provided no data on the size of the uncropped area could not be included. For each crop species, a linear regression was fit between relative yield ($RY_{y,\mathrm{crop}}$) and years since tree planting, y. The resulting regression models were used to discount the monoculture crop yields on each map unit m in each county c ($Y_{m,c,\mathrm{crop}}$) and create an estimated alley crop yield time series for each year y of the black walnut rotation ($ACY_{m,c,y,\mathrm{crop}}$):

$$ACY_{m,c,y,\mathrm{crop}} = Y_{m,c,\mathrm{crop}} \times RY_{y,\mathrm{crop}} \quad (9)$$

Each yield time series ($ACY_{m,c,y,\mathrm{crop}}$) was then converted into a potential cash rent time series ($ACR_{m,c,y,\mathrm{crop}}$) using linear regression models between average county-level cash rent and crop yields (Appendix S1: Fig. S8).

PF and AC economic parameters

Parameters supplied to the black walnut model in addition to the DI_m trajectory (Appendix S1: Table S4) were taken primarily from Godsey (2006), Yemshanov et al. (2007), and Schultz and DeLoach (2004) unless otherwise noted below. Initial stand spacing for PF was 3.7 × 3.7 m, which is typical of black walnut PF across North America. Initial stand spacing for AC was 3.4 × 9.8 m, which was the mean spacing of systems in the literature used to develop the alley crop yield trajectories. In addition to the trees, an herbaceous groundcover was established within PF. Seedling cost of inexpensive, unimproved seedlings was used since evidence suggests negligible growth differences between unimproved and improved seedlings (Ares and Brauer 2004). Trees dying during establishment were not replanted.

Relatively intense, active management of the trees was assumed in both AC and PF. Consequently, tree mortality after the establishment year was assumed negligible. The effect of fertilization on black walnut growth is likely small for young trees (Nicodemus et al. 2008) and negligible in the long term (Pedlar et al. 2006). Therefore, no fertilization costs were included for PF or AC. No chemical site preparation costs were included in either system since land coming out of row crops can be assumed to be weed free. Within-row weeds were controlled using herbicides in years 1–14, and the herbaceous groundcover in PF was mowed during years 1–5. Removing lateral branches in black walnut is critical to maintain timber quality and value (Schlesinger and Weber 1987). The pruning labor requirement in AC (P. Scheercousse, *personal communication*) is higher than for PF since the lower stand density does not encourage as much self-pruning of branches.

The final timber harvest was triggered independently on each map unit m when $DBH_{m,y}$ reached 71 cm, which is the minimum size required to sell veneer logs within the highest price bracket in the region (e.g., IN DNR 2017). While determining an optimized rotation length for each map unit m could potentially improve economic return, most timber managers are currently managing stands toward a target DBH, so optimizing rotation length was not included in this analysis.

At each thinning and the final harvest, 70% of black walnut trees were sold as veneer quality logs. Given the strict quality requirements for veneer logs, the remaining 30% of trees were assumed to fail the quality control and were sold as saw logs. Extension publications documenting historical select-grade veneer stumpage prices for logs at least ~71 cm in diameter (Appendix S1: Fig. S9a) and saw log stumpage prices (Appendix S1: Fig. S9b) were mined for data over the last 40 yr in each state. The mean value of all years and states for each market was used as the model input. Prices for select-grade veneer logs were used as a more conservative estimate instead of prices for prime-grade logs. Prices for harvested logs with diameters <71 cm were discounted using data from the same extension publications (Appendix S1: Fig. S10). The model ran for a maximum of 200 yr, at which time any unharvested trees were harvested regardless of size. Although black walnut can also produce a marketable nut, veneer- and nut-focused management regimes are very different (Schlesinger and Funk 1977, Garrett et al. 2011). Consequently, no nut production was included in the current model.

Economic evaluation

The cropland rent ($R_{m,c}$) represents the average annual income received by a landowner from MSR operators for each map unit m in each county c. Black walnut PF or AC becomes economically competitive with MSR when the profitability of the alternative enterprise meets or exceeds the threshold of $R_{m,c}$. The long-term, heterogeneous cash flow of PF and AC cannot be compared directly to $R_{m,c}$, but first must be converted into a homogeneous cash flow over the timber rotation length, or an annual equivalent value (AEV), which is calculated as

$$AEV = \frac{i \times NPV}{1 - (1+i)^{-N}} \quad (10)$$

where i is the discount rate, N is the timber rotation length, and NPV is the net present value of the heterogeneous cash flow (Klemperer 1996). NPV is calculated as

$$NPV = \sum_{y=0}^{N} \frac{C_y}{(1+i)^y} \quad (11)$$

where C_y is the net cash flow in year y (Klemperer 1996). For each map unit m in each county c, there exists threshold discount rates $TDR_{PF,m,c}$ and $TDR_{AC,m,c}$ such that $AEV_{PF,m,c}$ and $AEV_{AC,m,c}$ are equal to $R_{m,c}$. A Levenberg-Marquardt nonlinear least squares solver was used to solve for the TDR values via the lsqnonlin function in the pracma package in R.

Sensitivity analysis

To assess the impact of different model parameters on TDR, a sensitivity analysis was performed by varying parameters from the base level supplied to model for this analysis. A base level of 0.7 was used for BWSI. Median values of MSR rent and crop yields were chosen as base levels. Parameters were independently varied by ±60% in increments of 5%. All establishment and maintenance costs were scaled collectively, as were alley crop yields. In addition, two alternative scenarios were used to specifically test model sensitivity to stumpage price. For these scenarios, the minimum and maximum historical stumpage prices of state annual means were used.

Results

Suitability indices

Values for both NCCPI and BWSI varied in a complex spatial pattern across the landscape (Figs. 1b and 1c). Correlation between county-level area-weighted means of NCCPI and BWSI was extremely low (Spearman correlation, $P < 0.01$, $r^2 = 0.19$; Appendix S1: Fig. S11), indicating an opportunity for differential success among alternative systems.

Black walnut growth

The final harvest year of black walnut ranged from 40 in AC and 43 in PF to 200 (the maximum number of years modeled). Map units with BWSI < 0.6, corresponding to soils that are "somewhat suited," "poorly suited," and "unsuited" for black walnut (Wallace and Young 2008) were unable to grow trees to the desired final harvest diameter of 71 cm within 200 yr. Map units with BWSI in 0.6–0.8, 0.8–0.975, and 0.975–1.0, corresponding to soils that are "moderately suited," "well suited," and "very well suited" for black walnut had a median rotation length of 93, 59, and 44 yr in PF, respectively. Both PF and AC reached the final harvest diameter with around 25 trees/ha. All PF systems that reached mature diameter earlier than 200 yr underwent six thinning events, whereas AC only required four thinning events since its initial stand density was much lower. Example modeled trajectories of black walnut growth are shown in Appendix S1: Figs. S12 and S13. At maximum BWSI, revenue from thinning events contributed around twice as much as revenue from the final harvest to the AEV of PF or AC. The relative importance of thinnings increased as BWSI decreased since lower growth rates push back the final harvest.

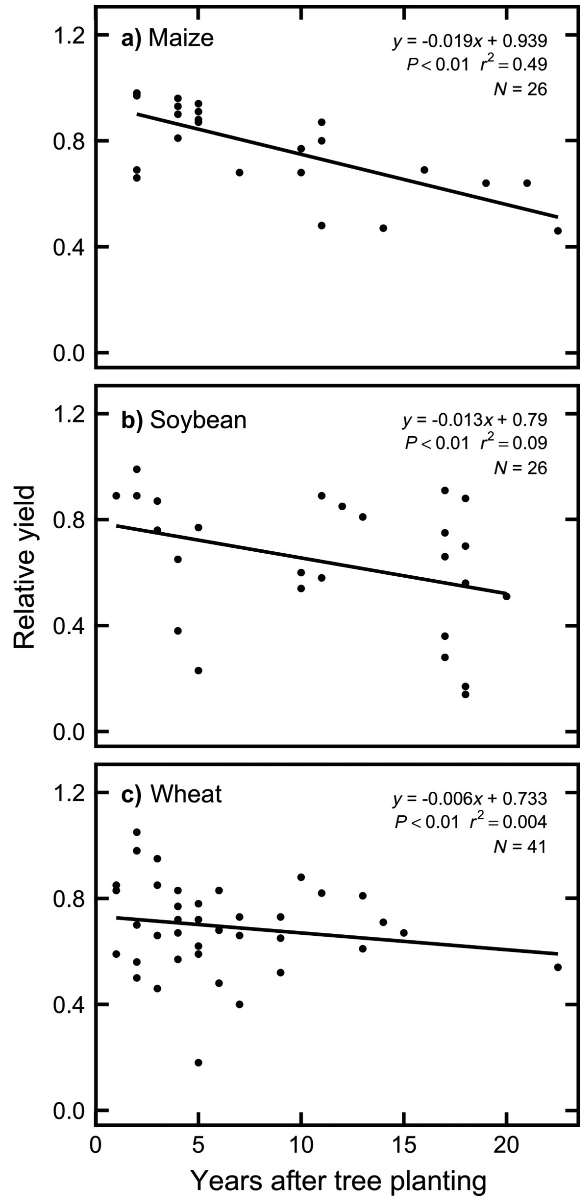

Fig. 3. Literature values of (a) maize, (b) soybean, and (c) wheat yield in temperate and subtropical alley cropping (AC) relative to monoculture controls. Each point represents one site-year.

Alley crop yields

Mined literature provided relative yield data for a total of 93 site-crop-year combinations. Data spanned from 1 to 23 yr after tree establishment, and relative yields ranged from 0.14 to 1.05. Maize, soybean, and wheat all exhibited significant declines in relative yield with tree age ($P < 0.01$), although variability in relative yield was high for soybean and wheat (Fig. 3). The largest yield declines were observed in maize, then soybean, and finally wheat with little yield reduction over time.

The flexible alley crop selection approach effectively simulated a typical sequential transition from maize–soybean rotation (first 7–11 yr) to wheat (until year 10–44) to pasture (remaining years in the black walnut rotation). The timeline of this sequence depended on the relative growth rates among the crops and county-level crop economics. At maximum BWSI, alley crops contributed approximately one-third as much as the final timber harvest to the AEV of AC. The relative importance of alley crops increased as BWSI decreased, becoming effectively the sole contributor to AEV at extremely low BWSI.

Economic evaluation

Black walnut PF (Appendix S1: Fig. S14) and AC (Fig. 4) exhibited competitive TDRs in many regions across the four states studied. The higher the TDR, the more competitive the alternative system is with MSR. Therefore, the percentage of cultivated land where PF or AC outcompeted MSR

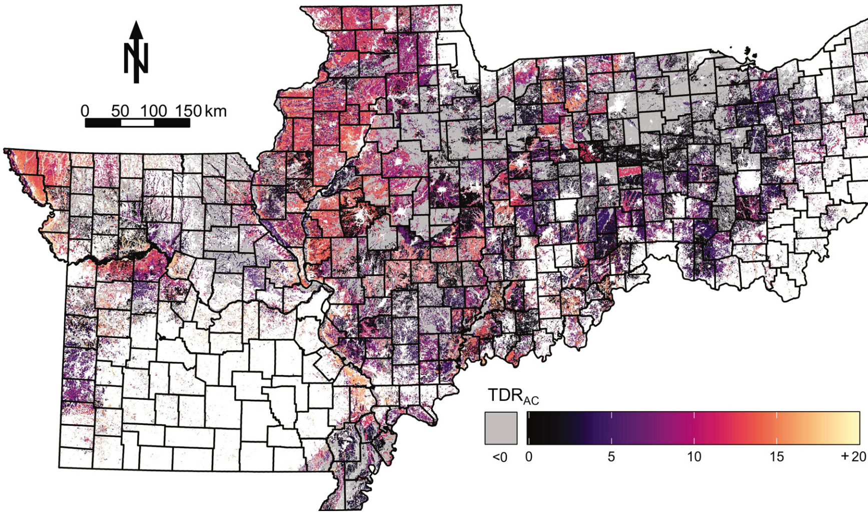

FIG. 4. Distribution of the threshold discount rate (TDR_{AC}) at which the annual equivalent value (AEV) of AC and maize–soybean rotation (MSR) are equal across the four states studied. Gray areas are cultivated land on which either BWSI = 0 or TDR_{AC} < 0. White areas are non-cultivated land.

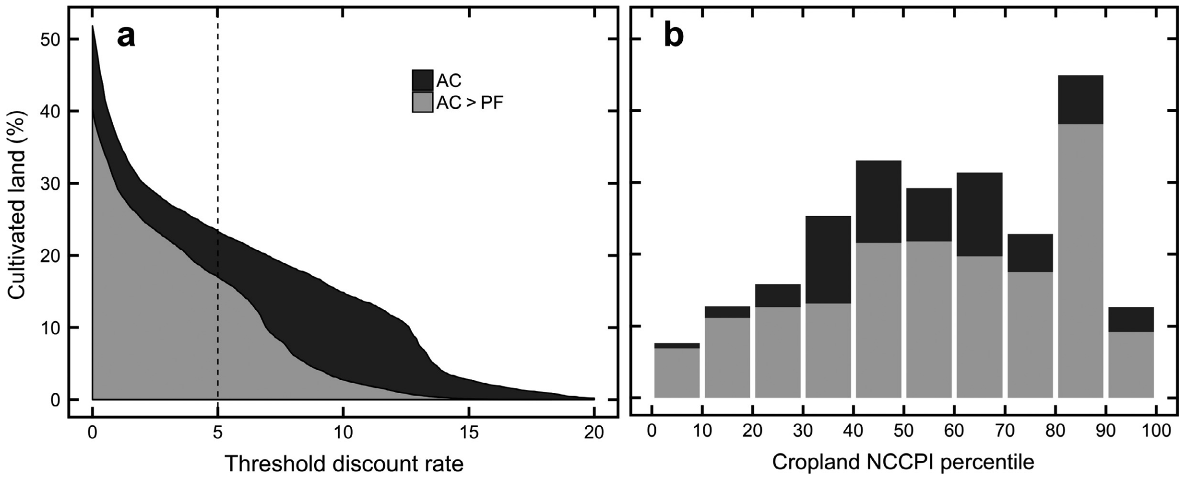

FIG. 5. (a) Percentage of cultivated land as a function of TDR, on which black walnut AC and/or plantation forestry (PF) has a higher annual equivalent value (AEV) than MSR. The dashed line indicates a TDR of 5%. (b) Percentage of cultivated land in each NCCPI class on which black walnut AC and/or PF has a higher AEV than MSR at a TDR of 5%. NCCPI classes are defined in terms of percentiles of NCCPI (e.g., the 0–10 NCCPI percentile includes the 10% of cultivated land with the lowest NCCPI). "AC > PF" indicates that AEV_{AC} and AEV_{PF} are both greater than MSR cash rent, but $AEV_{AC} > AEV_{PF}$.

(i.e., where PF or AC has a higher AEV than MSR) increased with decreasing TDR (Fig. 5a). Map units with negative TDR were automatically classified with MSR being the most competitive system and removed from further analyses. Area-weighted mean values of TDR_{PF} and TDR_{AC} were 5.4% and 6.9%, respectively. Across all map units that had a $TDR_{PF} > 0$ and $TDR_{AC} > 0$, TDR_{AC} was an average of 2.7 percentage points higher than TDR_{PF}, representing the additional economic value generated by the alley crops.

In an example scenario with a selected TDR of 5%, PF and AC outcompeted MSR on 17.0% and 23.4% of cultivated land, respectively (Fig. 5a). The geographic distribution of this area was visualized as an example of target regions for PF and AC for a given TDR (Appendix S1: Fig. S15). The economic competitiveness of PF and AC was not correlated with NCCPI (Fig. 5b). Instead, cultivated land at the high and low extremes of NCCPI contained the lowest proportion of land where PF or AC was competitive.

Sensitivity analysis

From the baseline set of parameters used in this analysis, TDR was most sensitive to changes in BWSI (Fig. 6). A ~4% change in BWSI caused an approximately 1 percentage point change in TDR. Sensitivity of TDR to all other model parameters was <±5 percentage points across the parameter ranges of ±60%. Results were similar for AC and PF. The second most influential model parameter was veneer stumpage price, with an ~17% change in price driving a 1 percentage point change in TDR. The ±60% tested range of

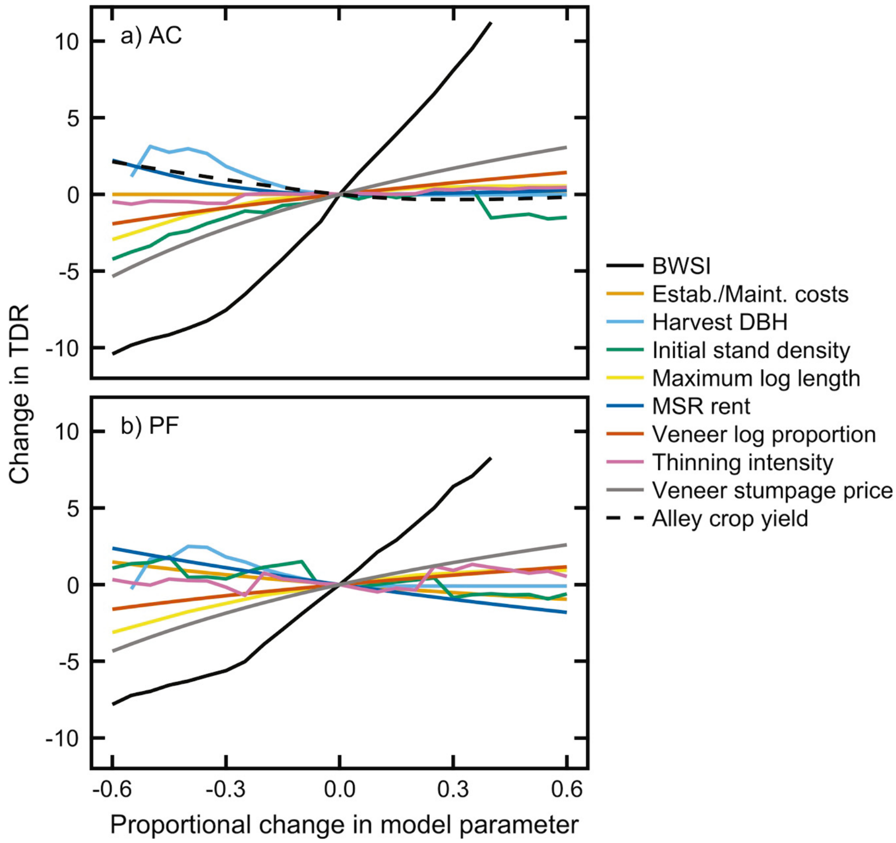

Fig. 6. Sensitivity analysis of TDR to model input parameters for (a) PF and (b) AC. Input parameters were varied by ±60% in increments of 5%. Only those parameters that had a non-negligible impact on TDR are shown. All establishment and maintenance (Estab./Maint.) costs were scaled collectively, as were alley crop yields.

stumpage prices included 88% of all stumpage prices observed over the last 40 yr. Sensitivity to all model parameters was monotonic except for harvest DBH and initial stand density, which had clear maxima.

Using the minimum or maximum historical stumpage prices in the model instead of the means did not change the overall trends illustrated in Fig. 5, although the magnitude of competitive regions did change (Appendix S1: Fig. S16). When the minimum historical stumpage prices were used, PF and AC outcompeted MSR on 9.1% and 19.4% of cultivated land, respectively. In contrast, when the maximum historical stumpage prices were used, these levels rose to 23.2% and 27.4%, respectively. The 2.5-fold difference in the competitive proportions of cultivated land for PF between the minimum and maximum price scenarios was approximately proportional to the difference in prices. In contrast, the competitive proportion of cultivated land for AC was much less sensitive.

Illustrative counties

Results from four counties with varying NCCPI and BWSI were visualized at higher resolution to illustrate contrasting examples (Fig. 7). Perry County, Missouri had low NCCPI and high BWSI, resulting in some of the highest observed values of TDR_{PF} and TDR_{AC}. However, finer scale analysis revealed that BWSI takes an unfavorable shift in the northeast portion of the county, which lies in the flood plain of the Mississippi River. While this area has similarly low NCCPI, unsuitable black walnut growth prevented PF or AC from outperforming MSR. This demonstrates how certain landforms can influence the competitiveness of PF and AC counter to the prevailing conditions within a county. Both BWSI and NCCPI are high across Stark County, Illinois. Here, local variation in soil type and topography influenced the competitiveness of PF and AC at a much finer scale. Map units with high BWSI drove fast tree growth and a strong economic return that outcompeted MSR even where NCCPI is high. Coles County, Illinois offered little opportunity for PF or AC, with high NCCPI and low BWSI across the county. While a central valley did have a high BWSI-low NCCPI combination that would have likely resulted in favorable TDRs, this area is already forested. Finally, even though MSR was relatively uncompetitive in DeKalb County, IN, low black walnut growth rates prevented PF or AC from becoming suitable alternatives beyond just two small areas.

Discussion

Our results project strong economic competitiveness of black walnut PF and AC with MSR. However, contrary to our hypothesis, high TDRs were found on both marginal and ideal MSR soils (Fig. 5b), indicating that the marginal land concept is inadequate in identifying target regions for

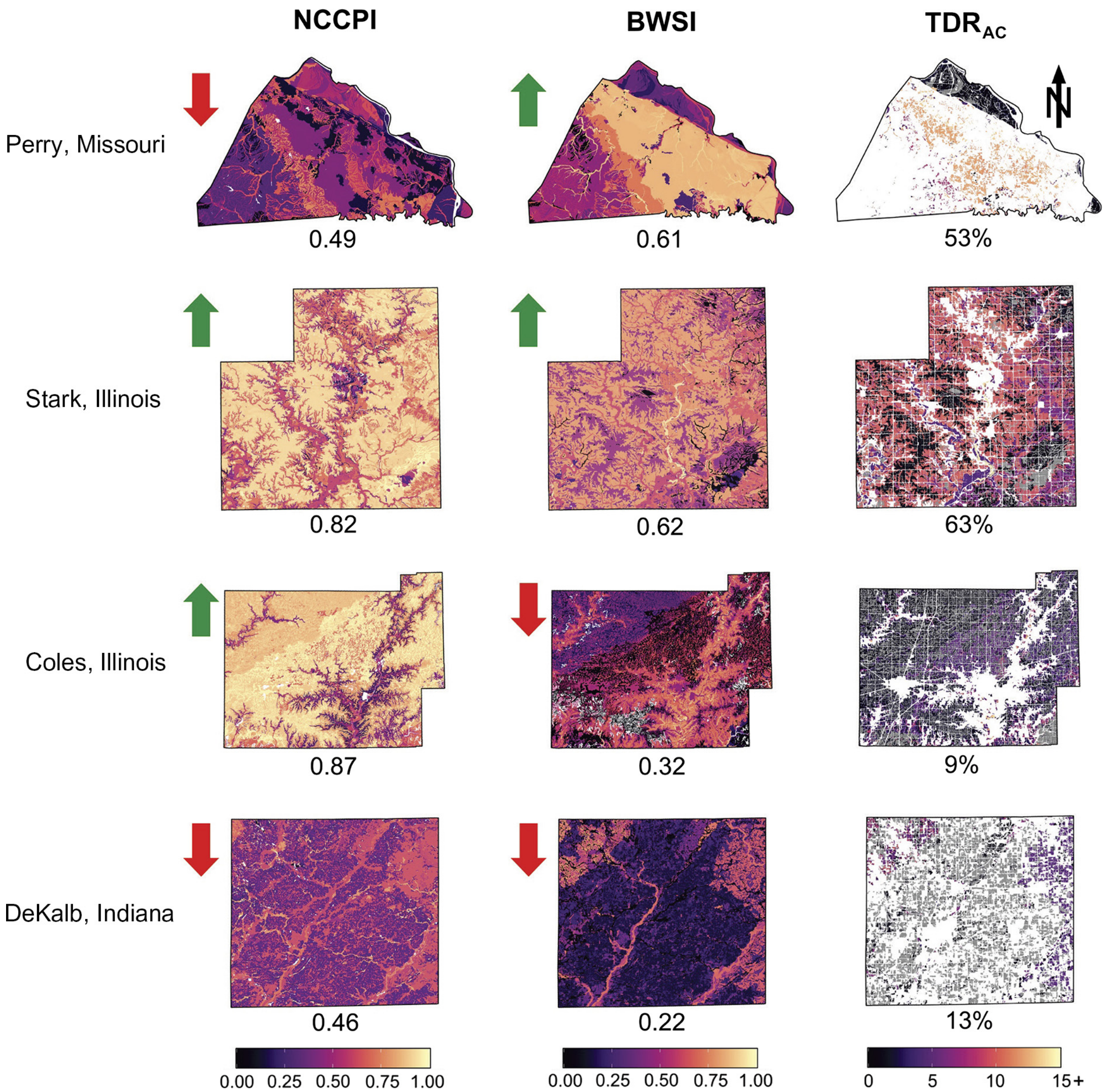

FIG. 7. Comparison of example counties by their NCCPI, BWSI, and TDR_{AC}. Counties were selected to provide a range crop and black walnut suitability. Numbers under each NCCPI and BWSI map indicate the area-weighted mean for cultivated land. Numbers under each TDR_{AC} map indicate the percentage of cultivated land on which $TDR_{AC} \geq 5\%$.

PF or AC. Instead, black walnut growth rate was the central driver of PF and AC competitiveness (Fig. 6). These results demonstrate that the soil suitability of alternatives is more important than MSR productivity in determining optimal land-use allocation. A shift away from the current MSR-centric perspective in defining target regions for land-use alternatives is necessary.

Overall, our results likely underestimate the potential of PF and AC since we did not consider the economic value of enhanced non-provisioning ecosystem services, such as carbon sequestration, reduction of greenhouse gas emissions, decreased soil erosion, and soil nutrient retention (Rhodes et al. 2016). Furthermore, while no direct support payments to landowners were included in the analysis, MSR cash rents are still indirectly inflated by government subsidies to row crop farmers. Our analysis also only included existing MSR land, although substantial areas of pastureland would likely be more profitable as black walnut AC with hay or silvopasture. For example, much of central Perry County has high BWSI but is currently in pasture or hay rather than row crops (Fig. 7). Incorporating geospatial data that identifies environmentally sensitive areas (SooHoo et al. 2017, Brandes et al. 2018) or the current extent of existing agroforestry practices (Herder et al. 2017) could further hone the identification of target regions for MSR alternatives.

Accounting for climate change would also likely increase the relative profitability of PF and AC over MSR. Substantial climate change impacts are projected over the time frame of black walnut rotations (IPCC 2014). Impacts are expected to reduce end-of-century MSR yields by ~70% (Mistry et al. 2017). In contrast, temperate AC can stabilize crop performance by moderating drought (Nasielski et al.

2015), reducing erosion and improving soil fertility (Udawatta et al. 2008, Torralba et al. 2016), and reducing the impact of pest outbreaks (Stamps et al. 2002). Hardwood tree productivity is also expected to decrease over the next century due to climate change, although predicted changes are much smaller than those for crops, up to just 20% (Jiang et al. 2015). Utilizing tree species with shorter rotations can reduce risk by allowing producers to switch to more adapted species as climate changes. Furthermore, AC resilience to future climate change could be improved by enhancing traditional AC with multiple woody species and tree crops for food or fodder (Wolz et al. 2018b).

In contrast, transitioning large areas of MSR to PF or AC would alter the regional supply and prices of timber and crops, potentially reducing timber profitability compared to the relatively small existing industries. Furthermore, black walnut pest and disease pressure could increase as connectivity among stands increases. These macroeconomic and landscape-scale phenomena are difficult to predict and are beyond the scope of this analysis. However, it is important to note that these results do not suggest that all acreage above an acceptable TDR necessarily be converted to PF or AC, but, rather, this analysis should be used as a tool to identify target regions and prioritize adoption. For example, policymakers could set a target AC adoption rate and then use the high-resolution analysis to identify the ideal land to meet this goal (Brandes et al. 2018).

The black walnut growth projected here corresponds well to results from previous studies (Schultz and DeLoach 2004, Yemshanov et al. 2007). One weakness of prior studies, however, is that fixed thinning and harvest years were assumed across all scenarios. This permits harvest volume, but not harvest timing, to affect profitability. The wide range of growth rates examined here necessitated the use of growth-triggered management events. Furthermore, the non-monotonic sensitivity of TDR to harvest DBH and initial stand density (Fig. 6) reaffirm the potential for improving timber profitability via management optimization. The aim of our analysis, however, was not to examine optimal economic strategies, but rather to compare land-use alternatives under standard management.

The decline in maize relative yields in the reviewed literature corresponds well to theory since maize utilizes a C_4 photosynthetic pathway and cannot tolerate the shade created by maturing trees. In contrast, soybean, which utilizes a C_3 pathway, performs better as an alley crop (Reynolds et al. 2007). The low yield decline in wheat is driven by its complementary phenology to most tree species (Dufour et al. 2013). The compiled literature data provides a first approximation of AC relative yield trajectories, but further research permitting the development of more complex models based on tree species and biometrics is critical. Biophysical agroforestry models (Malézieux et al. 2009) and systematic experimental designs (Vanclay 2006, Leakey 2014) will be indispensable tools for evaluating tree-crop interactions in future research.

The consistently higher profitability of AC compared to PF was driven by a range of advantages such as reduced intraspecific competition, lower establishment costs, and earlier revenue from thinnings. Nevertheless, both alternatives studied here were relatively simple. There are many known methods of increasing the profitability of PF and AC. For example, interplanting with nitrogen-fixing trees or shrubs increased black walnut DBH by 31–351% after 13 yr (Schlesinger and Williams 1984). Mixed-species systems can accumulate higher biomass (Piotto 2008) and be more drought resilient (Pretzsch et al. 2013) than single-species systems. Furthermore, leveraging high value fruit or nut trees in AC can reduce the time to financial maturity and diversify farm revenue streams (Lovell et al. 2017, Wolz et al. 2018b).

While several economic metrics can be used to compare land-use alternatives, AEV was chosen here because of the robust estimates available of MSR cash rent (2016b), which serve as a direct comparison for AEV. The examples presented in Fig. 5b and Appendix S1: Fig. S15 utilized a TDR of 5%. While lower rates are usually accepted for long-term timber investments, 5% is typical of the minimum returns required by institutional investors and is, therefore, representative of the rate of return required to drive investment into alternative land uses such as PF and AC (Yemshanov et al. 2007).

One important assumption of our approach is that BWSI linearly scales the literature-derived black walnut growth trajectory. Since BWSI was never robustly validated against field growth data (Wallace and Young 2008), this relationship is uncertain. The range of modeled growth trajectories and literature-derived data gives us confidence in the chosen method (Fig. 2). Nevertheless, the sensitivity analysis here and that of others (Niu and Duiker 2006) indicate that improving our understanding of how soil characteristics influence tree growth is critical. The paucity of soil-based growth models for species other than black walnut is the primary hurdle to applying our approach more broadly, although Jiang et al. (2015) have recently pushed the boundaries to include a wide range of North American species.

Conclusions

Widespread environmental issues caused by MSR demand the evaluation of potential alternatives. Agroforestry practices, especially AC, show great potential as scalable agricultural alternatives that can enhance production while simultaneously improving sustainability. In this high-resolution analysis, black walnut PF and AC displayed strong potential as economically competitive land-use alternatives, with target regions identified across all MSR productivity classes. These results suggest a more general conclusion that restricting the evaluation of land-use alternatives to lands marginal to MSR may miss substantial opportunities for highly profitable alternatives on productive MSR land. Together, the dynamic tree growth model, high-resolution visualizations, and using discount rate as a continuous response variable, comprise a novel, robust tool for landowners and investors to identify target regions for land-use alternatives and prioritize investment opportunities. This economic rationale will be critical to drive adoption of agroforestry and other sustainable agricultural land-uses.

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