ASSESSMENT OF TRADEOFFS AMONG ECOSYSTEM SERVICES OF WETLAND RESERVE EASEMENTS

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ABSTRACT

Carbon storage, attainment of desired wildlife conditions, and potential timber yields for 30 of the oldest Wetland Reserve Easements in Arkansas were quantified. Observed and projected values were used to evaluate tradeoffs among carbon storage, wildlife habitat desired conditions, and merchantable yield. Plantations with relatively higher stocking had higher carbon storage and merchantable yields and were projected to continue to grow over the next 35 years. Low stocking, as a result of lower planting survival or volunteer recruitment, resulted in plantations with about half of the total carbon storage and merchantable yield. Only 18 percent of plantations were within stocking targets and only a handful of plantations were or were projected to be within desired conditions when various habitat metrics were considered. Enhancing tree survival through improved establishment methods as well as use of tending operations may be required to accelerate and enhance achievement of desired conditions while optimizing carbon and yield.

INTRODUCTION

The Wetland Reserve Program (WRP) was established under the Food, Agriculture, Conservation, and Trade Act of 1990 (Farm Bill) (Public Law 101-624. 101st Congress 28 November 1990) and continued as the Wetland Reserve Easements component of the Agricultural Conservation Easement Program in the 2014 Farm Bill reauthorization (NRCS 2023). This voluntary program aims to restore wetlands through financial incentives to retire marginal cropland using mainly permanent easements. Afforestation and hydrological modifications are conducted to establish processes that would ideally allow recovery of wetland functions. Since the program's inception, over 440,000 ha have been enrolled in the Lower Mississippi Alluvial Valley (LMAV) (USDA 2023).

In general, little is known about what ecosystem services and functions we can expect from restored wetlands, the timeframe in which services and functions may materialize, and how they compare to those of historical wetlands (Mitsch and others 1998). A general absence of effective long-term monitoring using consistent evaluation criteria has further complicated evaluating the efficacy of easements in restoring wetland functions and services (Berkowitz 2013, King and others 2006, Rewa 2005, Ruiz-Jaen and Aide 2005, Suding 2011). Along with a lack of long-term monitoring, forest successional patterns in which initial hydrologic and floristic conditions influence outcomes, and lack of coherent performance standards are persistent obstacles to evaluating wetland restoration and afforestation in the LMAV (Berkowitz 2013). Generally, the timescale required for afforested easements to reach maturity extends much longer than that of post-restoration monitoring requirements. Because of the variability among afforested bottomland hardwood successional patterns, evaluating restoration performance within short monitoring timeframes is ineffective.

Quantifying ecosystem services and evaluating their tradeoffs provides a standardized

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restoration assessment and allows linking of ecological outcomes and societal values (Suding 2011). As an increasing number of WRP plantations are reaching canopy closure, assessing potential tradeoffs among the services provided by bottomland afforestation may provide essential information for landowners and decisionmakers. The Lower Mississippi Valley Joint Venture, Forest Resource Conservation Working Group emphasized managing forests within the LMAV to enhance structural diversity and meet the habitat requirements of forest-dependent wildlife (Wilson and others 2007). Enhancement of habitat quality for priority wildlife, however, may come at a cost of lower potential timber production or carbon storage or both in the form of retention of less merchantable trees and reduced stand stocking. Ultimately, by evaluating restoration through an ecosystem services framework, we may be able to objectively assess restoration efforts and better understand the outcomes of management alternatives. Evaluating restoration through an ecosystem services framework may inform silvicultural strategies implemented within WRP plantations that meet program objectives of maximizing wildlife habitat while also optimizing carbon storage and providing merchantable timber to mitigate management costs. Furthermore, use of simulation models in such evaluations may mitigate the need for long-term monitoring data.

The goal of this study was to use an ecosystem services approach to evaluate restoration efforts on the oldest enrolled Arkansas WRP easements, ranging from 15 to 23 years since planting. Specifically, we used field inventory data to 1) quantify carbon storage, attainment of desired wildlife conditions, and merchantable yield; and 2) evaluate potential tradeoffs among wildlife desired conditions, carbon storage, and timber yield.

METHODS

Study Area

Thirty WRP easements across nine Arkansas counties (Ashely, Chicot, Desha, Drew, Lee, Phillips, Prairie, White, and Woodruff) were selected. All easements were within the LMAV, which is characterized by a history of flooding and significant human alteration of the landscape. Within the LMAV, total forest area is estimated at 3.07 million hectares (7.6 million acres) encompassing approximately 28 percent of the total land area. The LMAV is located within the subtropical region of the Northern Temperate Zone between 29° and 37°N latitude and ranges from 89° to 92°W longitude. Across the Northern Temperate Zone, annual precipitation ranges from 100 to 160 cm. The northern portion of the LMAV has a growing season of 185 days, while the central and southern portions have a growing season of 229 and 245 days, respectively. Daily average January temperatures across the LMAV range from 3 °C to 11 °C. In July, temperatures average to 27 °C and can regularly exceed 38 °C. The dominant soil orders within the LMAV are Alfisols, Inceptisols, Entisols, and Vertisols, with elevation ranging from 30 to 91 m above sea level (Gardiner and Oliver 2005).

Sampling Design and Measurements

The 30 easements represented a subset of the oldest easements in Arkansas, ranging from 15 to 23 years since planting. This subset was selected using a stratified random sampling approach in which all enrolled easements with a closing date before 2003 were grouped by age, area, county, and watershed membership. For each county, easements were placed into one of four bins constructed by cross-tabulating easement area and closing date. Easement age and area were divided into two classes based on available county data. Easement membership to watershed subbasin (8-digit hydrologic unit) was recorded using the U.S. Geological Survey Watershed Boundary Dataset (USGS 2018). Subbasin membership was used to ensure a minimum of one easement within each subbasin was included in the sample. Easements were randomly selected from each stratum (combination of easement age, easement area, and watershed subbasin). The selected easements encompassed the range of available conditions, spanning a wide range of planted tree species [e.g., cherrybark oak (*Quercus pagoda*), Nuttall oak (*Q. texana*), water oak (*Q. nigra*), overcup oak (*Q. lyrata*), swamp chestnut oak (*Q. michauxii*), baldcypress (*Taxodium* *distichum*), sugarberry (*Celtis* spp.), and green ash (*Fraxinus pennsylvanica*)], planting spacing (e.g., 3.7 m versus 4.6 m), site preparation (e.g., ripping, disking, none), ownership (e.g., private, State, Federal), and early survival and stocking conditions.

Within each easement, 1 to 8 hardwood plantations were sampled in 2018 and 2019 for a total of 105 plantations. The number of plantations selected per easement was dependent upon easement area and heterogeneity of plantations; larger, heterogeneous easements warranted a higher number of sampled plantations to represent the heterogeneity in current conditions. Within each plantation, 2–21 sampling plots were established along linear transects across compositional and structural heterogeneity, for a total of 804 plots. Linear transects were randomly selected from a grid overlay and plots were located at fixed 50- to 200-m intervals along transects based on field conditions with shorter spacing used for heterogeneous conditions (i.e., more plots) and larger spacing for homogenous conditions (i.e., fewer plots).

A series of concentric, nested, fixed-area, circular plots were established for vegetation measurements. Plots were 0.04 ha for overstory [live trees with diameter at breast height (d.b.h.) ≥7.6 cm], while saplings (height ≥1.3 m and d.b.h. <7.6 cm) were tallied in 0.01-ha subplots. Seedlings (0.3 to <1.3 m in height) and nontree vegetation were measured within three quadrats (1 m^2 each) placed at the end of one of three radial transects (5.7 m each) at azimuths of 0, 120, and 240 degrees from magnetic north. For overstory, status, species identity, d.b.h., origin (i.e., volunteer versus planted), tree height, crown attributes, vigor class, and vine and cavity presence were recorded. When present, the number and size class of each cavity was recorded. Cavity size was categorized as either small (3–25 cm in diameter) or large (≥25 cm). Total tree height was measured to the tallest live branch excluding dieback. Crown diameter was measured as the average horizontal distance for the widest axis and its perpendicular axis. Saplings were identified to species, and d.b.h., total height, and height to live crown were measured.

Analytical Approach

To quantify carbon storage and merchantable yield, total dry biomass was estimated using individual tree d.b.h. measurements and species-specific allometric equations (Jenkins and others 2003) as made available in the Southern Variant of the Forest Vegetation Simulator (FVS) (FVS Staff 2008). A carbon fraction of 0.5 was used to convert dry biomass to carbon content using the carbon submodel of the Fire and Fuels Extension of FVS (Rebain 2010). Timber yield was calculated as the sum of merchantable biomass of individual trees adjusting for tree quality as indicated by field tree vigor classification. Tree estimates were pooled at plot and plantation levels for summarization.

Wildlife habitat suitability was assessed using Mahalanobis distance (D^2) as a metric of a plantation's deviation from desired reference conditions (Etherington 2019, Mahalanobis 1936). D^2 represents the distance of each plantation from the center of a multivariate space reflecting desired condition metrics defined by the Wilson and others (2007) to meet habitat requirements of forest-dependent wildlife (table 1). To quantify desired reference conditions, target stocking levels of 60–80 percent were used to identify within-target sampled plantations (Goelz 1995). A subset of 19 sampled plantations meeting stocking requirements were used. Using this subset of plantations allowed for defining the multivariate reference space using 12 comparable metrics, circumventing the need to permute plausible habitat metrics for hypothetical reference plantations. The 12 metrics of desired habitat included canopy cover, basal area, stocking, overstory vine presence, dominant trees per unit area, midstory canopy cover, ground cover, hard mast regeneration presence, quadratic mean diameter (QMD), trees per unit area, snags (d.b.h ≥10 cm) per unit area, and cavity trees per unit area (table 1). To convert D^2 values into probabilities with a 0–1 scale, with one reflecting desired reference conditions, the inverse of Chi-squared cumulative distribution function, with n = 12, was used (Etherington 2019). Thus, plantations with a D^2 value less than that expected by chance would have probabilities closer to one and were more likely within desired reference conditions (Etherington 2019).

Table 1—Desired forest conditions to meet habitat requirements of forest-dependent wildlife species

Forest condition	Target	Conditions that may warrant management
Canopy cover (percent)	60–80	>90
Basal area (m^2/ha)	16–20	>28
Stocking (percent)	60–80	>100
Vines in overstory (percentage of inventory plots)	40–60	<30
Super-emergent trees (percentage of inventory plots)	10–20	<5
Super-emergent trees (per acre)	4–6	<1
Midstory canopy (percentage of stand)	30–60	<20
Vines in midstory (percentage of inventory plots)	50–70	<30
Understory canopy cover (percentage of stand)	40–50	<30
Ground cover (percent)	20–50	<20
Cane present (percentage of inventory plots)	20–40	<20
Regeneration of hard mast tree species (percentage of inventory plots)	30–50	<20
Logs that provide coarse woody debris (per acre)	2–4	<2
Cavity trees (snags) >4 inches diameter at breast height (per acre)	4–6	<4
Large "den" trees or "unsound cull" trees (per 10 acres)	1–4	<1

Wilson and others (2007)

Hardwood plantations developmental trajectories were projected forward 35 years (2019–2054) using FVS. Individual tree model inputs included standard site attributes, inventory design information, and individual tree metrics (Dixon 2002). FVS projections were incorporated to evaluate potential tradeoffs among wildlife habitat suitability, potential timber yield, and carbon storage by comparing metrics for each service over the 35-year projection period. Because FVS projects individual tree growth reliably, only four primary habitat metrics (i.e., basal area, stocking, QMD, and trees per unit area) were used to evaluate desired conditions of future plantations. The multivariate reference space defined by the four primary habitat metrics for a set of 22 hypothetical plantations was used to calculate D^2 and its probabilities for future plantations.

RESULTS

Carbon

Total (aboveground and belowground) carbon storage ranged from 4.8 to 81.9 tonnes/ha (fig. 1). Plantations in Desha and Chicot Counties had the lowest total carbon, while Monroe, White, Prairie, and Drew plantations had the highest stored carbon estimates. Aboveground carbon storage ranged from 3.8 to 66.9 tonnes/ha and reflected similar across-county patterns as those shown for total carbon storage (fig. 1). Sampled plantations were projected to continue accumulating total carbon within the next 30 to 40 years, with the rate of increase declining near 2054 (fig. 2). Plantations in Monroe County were projected to continue to contain the highest total carbon. Desha and Chicot plantations were projected to continue to contain the lowest total carbon. Ashley and Woodruff plantations were projected to have similar stored carbon trajectories, considering the similarity in their initial carbon storage conditions at time of sampling. Differences between counties in aboveground carbon storage trajectories were the same as those for total carbon.

Yield

Observed merchantable yield ranged from 1.7 to 84.8 tonnes/ha (fig. 3). Desha and Chicot Counties had the lowest merchantable yields, whereas Monroe, Prairie, Drew, and White

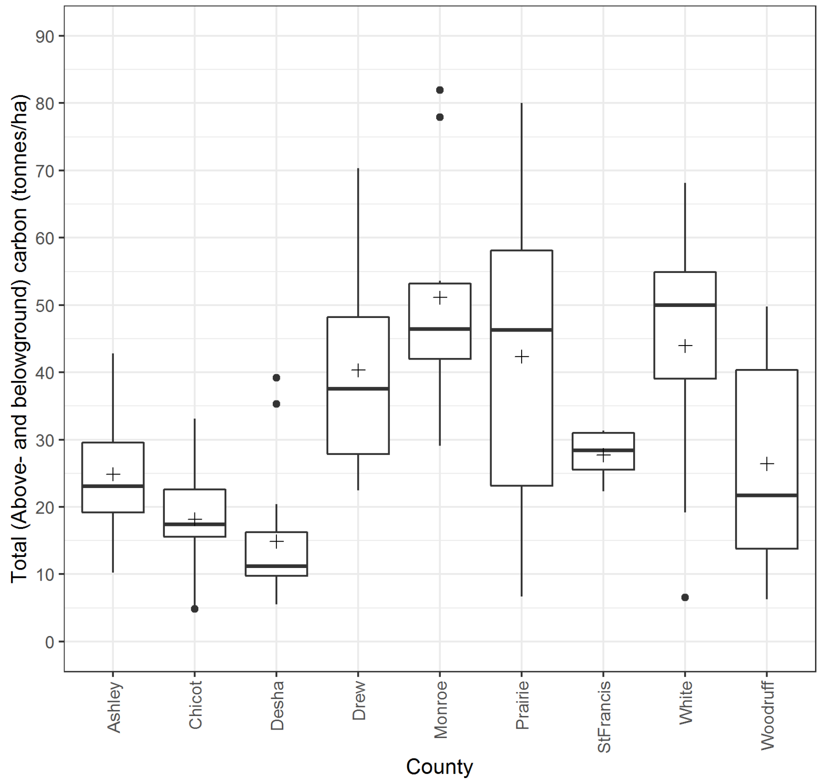

Figure 1—Total carbon, aboveground and belowground, for 105 hardwood plantations within 30 of the early enrolled Wetland Reserve Program easements across nine Arkansas counties. Mean and median shown as a plus and horizontal line, respectively. Upper and lower box bounds indicate third and first quartiles, respectively. Vertical whisker represents minimum and maximum values; dots represent outliers.

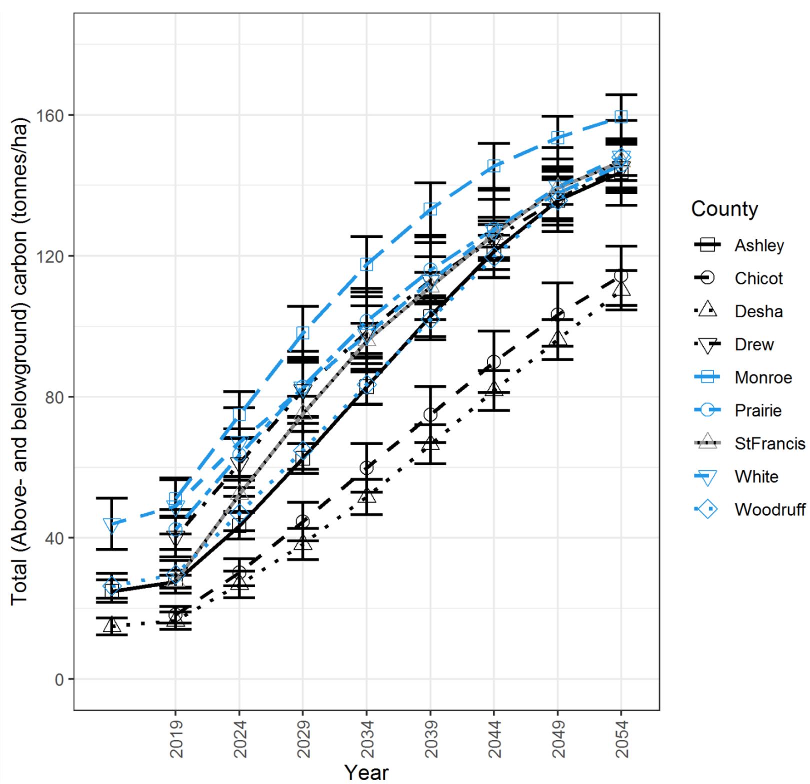

Figure 2—Projected mean estimates and standard error bars of total carbon, aboveground and belowground, for 105 hardwood plantations within 30 of the early enrolled Wetland Reserve Program easements across nine Arkansas counties.

Counties had the highest yields. Within county variability in merchantable yield was highest for Prairie County, whereas lowest variability was for St. Francis County. Overall, plantation level QMD ranged from 10.4 to 21.6 cm, indicating marginal timber merchantability of the sampled counties at current conditions. Simulated yield over a 35-year period showed a continual increase in merchantable yield over time (fig. 4). Merchantable yield highest estimates were for Monroe County throughout the simulation period. Lowest yield estimates were projected for Desha and Chicot Counties. Yield estimates for Ashley, White, Woodruff, Prairie, and St. Francis Counties converged over the simulation period (fig. 4).

Desired Conditions

Target stocking levels of 60–80 percent were used to identify within-target sampled plantations (Goelz 1995). A subset of 19 sampled plantations meeting stocking requirements were used to define the multivariate reference space, reflecting desired conditions across 12 metrics. The 19 reference plantations belonged to 13 easements across 6 counties. For the remaining 86 plantations, the majority (88 percent) represented lower than target desired stocking, while 10 plantations had higher than target stocking. In general, Prairie, Monroe, White, and Drew plantations had higher stocking values, exceeding 80 percent stocking. Desha and Chicot plantations were consistently low, with none exceeding 60-percent stocking. A total of 49 plantations (47 percent of those sampled) were below 44-percent stocking and represented understocked conditions at an average establishment age of 20 years.

Mahalanobis distance, D^2, representing the proximity of plantations current conditions to desired reference conditions, varied greatly among and within counties (fig. 5). Values of D^2 ranged from 14.6 to 1,952.8 for the 86 nonreference plantations. Inverse Chi-square probabilities showed that only four to six plantations had D^2 small enough to be within the desired reference conditions defined by the 12 observed habitat metrics (fig. 5). The four plantations most likely within desired reference conditions had 0.07 to 0.26 probabilities of D^2 less than that expected by chance, and the additional two plantations had probabilities of 0.04 each. Although reference plantations were selected based on attainment of desired stocking, stocking for the six plantations closest to desired reference conditions ranged from 55 to 88 percent, indicating that stocking alone was not the primary determinant of D^2. For the remainder of the plantations, D^2 values were from 27.9 to 1,952.8 with associated probabilities of 0–0.01 (fig. 5). When habitat metrics were truncated to four using hypothetical plantations, only five plantations across five counites had probabilities of 0.5 or higher, indicating a higher likelihood of meeting desired conditions.

Projecting developmental trajectories over the next 35 years, from 2019 to 2054, showed a decline in the number of plantations approaching desired conditions for wildlife habitat for most counties (fig. 6). In 2024, four plantations (4 percent of all plantations) were projected to have probabilities of 0.5 or higher, while four, five, three, and two plantations were projected ($P \geq 0.5$) in 2029, 2039, 2049, and 2054, respectively. Plantations with low current stocking (i.e., Chicot and Desha; below 30-percent stocking) transitioned toward desired conditions within the next 10 years or more and remained within targets over a period of 5–10 years. Without management, higher current stocking plantations deviated more from desired conditions over the projection period. Across all projection periods, plantations with higher likelihood of attaining desired conditions were consistently among the lowest in merchantable yield and total carbon storage.

DISCUSSION

Carbon, merchantable yield, and attainment of desired wildlife conditions were quantified for a representative sample of the oldest enrolled WRP easements in Arkansas to provide a standardized restoration assessment linking ecological outcomes and societal values (Suding 2011). At plantation age of 15–23 years, low stocking levels (i.e., Ashley, Desha, and Chicot easements) resulted in about half of the total carbon storage, aboveground plus belowground, expected for bottomland hardwood afforestation in the LMAV (Shoch and others 2009). Plantations with higher stocking at similar age, due to higher planting survival or volunteer recruitment, had twice the amount of total carbon storage and

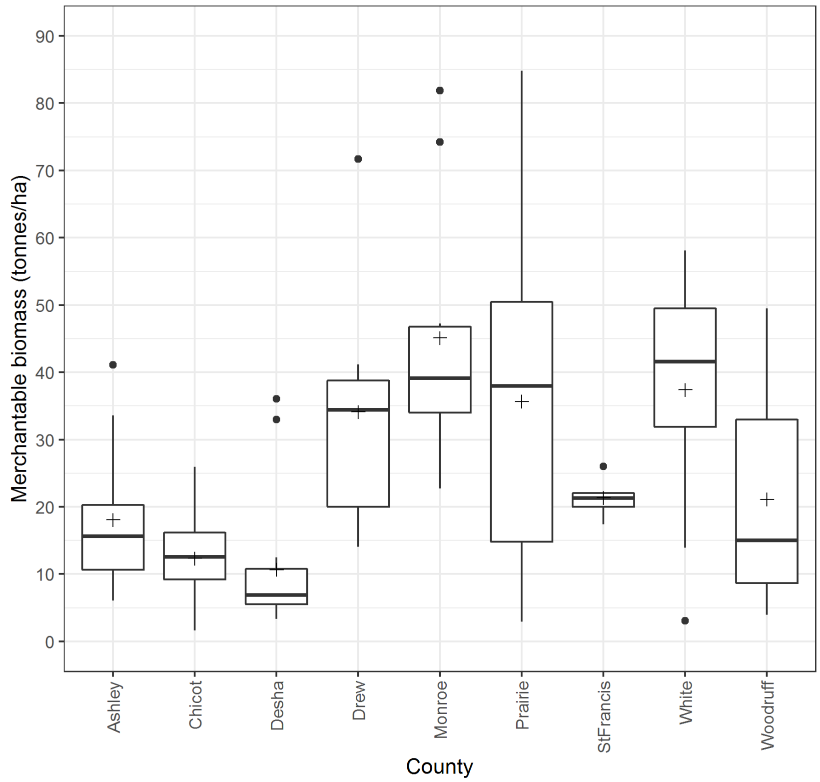

Figure 3—Merchantable biomass for 105 hardwood plantations within 30 of the early enrolled Wetland Reserve Program easements across nine Arkansas counties. Mean and median shown as a plus and horizontal line, respectively. Upper and lower box bounds indicate third and first quartiles, respectively. Vertical whisker represents minimum and maximum values; dots represent outliers.

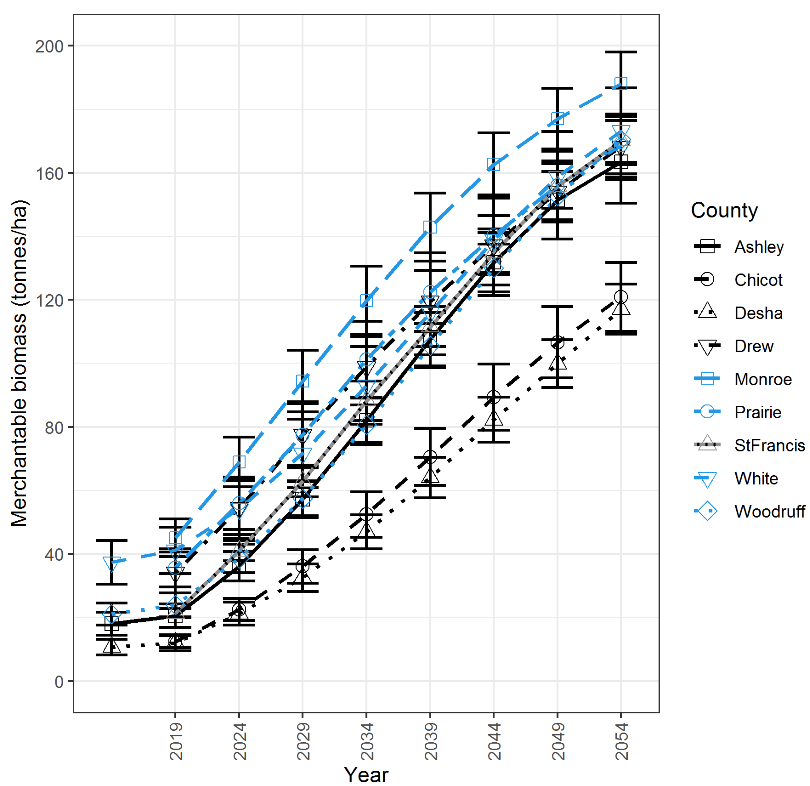

Figure 4—Projected mean estimates and standard error bars of merchantable biomass for 105 hardwood plantations within 30 of the early enrolled Wetland Reserve Program easements across nine Arkansas counties.

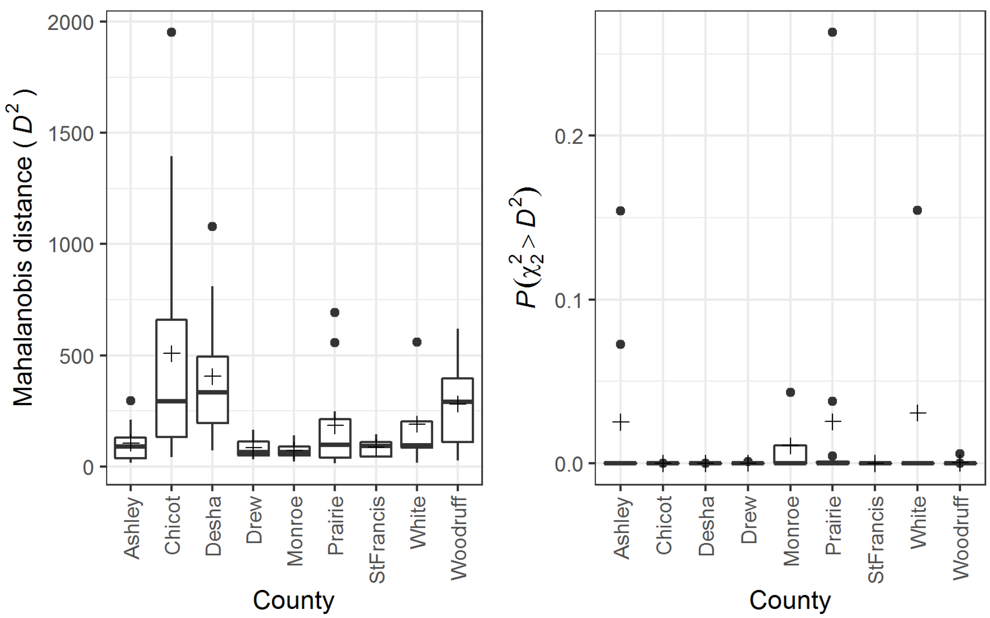

Figure 5— (left) Observed Mahalanobis distances (D^2) and (right) inverse Chi-squared probabilities, indicating proximity to desired wildlife habitat reference conditions of 86 hardwood plantations, within 30 of the early enrolled Wetland Reserve Program easements, across 9 Arkansas counties. Mean and median shown as a plus and horizontal line, respectively. Upper and lower box bounds indicate third and first quartiles, respectively. Vertical whisker represents minimum and maximum values; dots represent outliers.

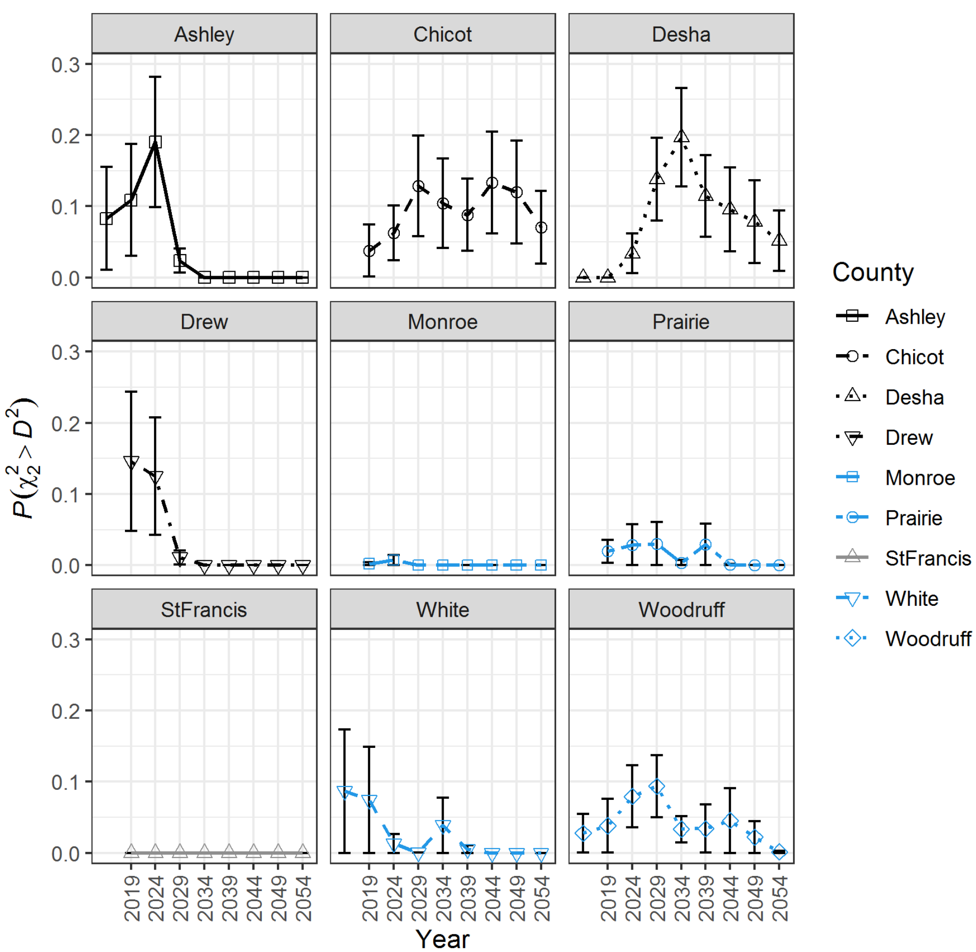

Figure 6—Mahalanobis distances (D^2) and inverse Chi-squared probabilities indicating projected proximity to desired conditions of 105 hardwood plantations, within 30 of the early enrolled Wetland Reserve Program easements, across nine Arkansas counties.

were comparable to those presented elsewhere (Shoch and others 2009). Inflection points in total carbon trajectories were projected around age 55 years since planting, with estimates of 110 to 160 tonnes/ha, indicating plantations transition into understory reinitiation stage when enhanced structural diversity would be expected (Oliver and Larson 1996). Higher potential merchantable yields were associated with higher stocking. Despite marginal merchantability as indicated by QMD, plantations in Prairie, Monroe, White, and Drew had >30 tonnes/ha on average (fig. 3). Regardless, proximity to processing facilities as well as timber quality, product class, and markets would largely influence timber provision potential from those plantations. While plantations with higher stocking were associated with higher carbon storage and potential timber yields, only 19 plantations were within desired stocking targets for wildlife habitat. When 12 habitat metrics were used to determine desired conditions, only 4–6 plantations had $P \geq 0.04$ with a maximum likelihood of 0.26 of attaining desired conditions. Truncating reference habitat conditions to four density-centric metrics resulted in the identification of five plantations with $P \geq 0.5$, indicating a higher likelihood of meeting desired conditions. Only a handful of plantations were projected to have high likelihoods of attaining desired conditions, with attainment of desired conditions lasting from 5 to 10 years.

With only 18 percent of plantations within stocking targets, a majority of plantations do not currently meet desired conditions for forest-dependent wildlife. Although plantations with low initial stocking were projected to transition toward desired conditions, their low carbon and potential yield coupled with their transitory period within future desired conditions highlight the need for alteration of plantation establishment practices. Enhancing planting survival through use of narrower spacing, higher planting density, improved planting stock, or better matching of species and sites would aid in accelerating the achievement of desired stocking (Stanturf and others 2004), with associated higher carbon storage and earlier timing of tending treatments albeit at potentially higher cost and effort (Stanturf and others 2001). Active tending and more intensive afforestation strategies may also be required to achieve and maintain desired conditions. Most plantations in this study would likely require thinning in the 2029–2034 timeframe (fig. 6), at ages of 25 to 38 years, with mean merchantable yields from 41.6 to 60.2 tonnes/ha of lower value pulpwood at an average QMD of about 11.7 to 14.2 cm (fig. 4). Such low commercial pulpwood thinning potential reflects an afforestation strategy that seeks to reduce establishment costs per unit area, thus limiting the options to regulate a plantation's future structure and mitigate management costs via timber production (Stanturf and others 2004). Enhancing structural diversity via thinning would result in forgone plantation level carbon storage compared to no management scenario (D'Amato and others 2011, Krcmar and others 2005). However, thinning to release residual trees from competition would improve residual tree vigor and future plantations merchantability (Goelz and Meadows 1997).

Although this study considered carbon storage, potential timber yield, and wildlife habitat suitability, additional ecosystem services provided by the WRP were not assessed. Although plantation deviation from desired structural reference conditions was assessed, landscape level metrics of habitat connectivity, edge structure, or species diversity was not considered. It was also beyond the scope of this study to evaluate tradeoffs using ecosystem service valuation. Future research evaluating optimization models of ecosystem service interactions and drivers of the WRP at specific spatial scales could inform future management practices and guide restoration efforts.

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