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Establishment success of conservation tree plantations in relation to silvicultural practices in Indiana, USA

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Abstract. In the Central Hardwood Forest region of the United States, the variable and somewhat unpredictable establishment success of hardwood tree plantations has traditionally been attributed to competing vegetation and damage due to animal browse. We examined operational plantation establishment success (1–5 years following planting) as it relates to use of particular silvicultural practices. Silvicultural histories were obtained for 87 randomly selected plantations throughout Indiana and field data were collected from each to determine tree survival, tree vigor, and abundance of surrounding vegetation. Survival was highest at sites that were treated with herbicide prior to planting and that had been mechanically planted (as opposed to hand planted). The percentage of trees with evidence of dieback was highest on sites at which browse protection measures had been used, likely reflecting a combination of damage due to inherently high white-tailed deer (*Odocoileus virginianus* Zimmermann) populations at such sites and ineffectiveness of current browse protection measures. Sites planted by a professional forester and those with herbicide applied subsequent to planting had a higher percentage of trees deemed free-to-grow. Subsequent herbicide application did not reduce cover or height of competing vegetation; however, when used in conjunction with mechanical site preparation techniques, overall cover and height of herbaceous vegetation was reduced.

Introduction

The success of conservation tree plantations in the Central Hardwood Forest region of the United States depends primarily on seedling persistence through the establishment period (i.e., 1–5 years following planting). This is largely a function of nursery stock quality (Zaczek et al. 1996; Dey and Parker 1997; Ward et al. 2000) and silvicultural practices (Malac and Heeren 1979; Miller 1993; Karlson 2002). Competing vegetation (Cogliastro et al. 1990; Kolb et al. 1990; Gordon et al. 1995; Willoughby and McDonald 1999) and damage due to animal browse (Marquis 1974; McClenahen and Hutnik 1979; Gordon et al. 1995; Gillespie et al. 1996; Martin and Baltzinger 2002) have been cited as two principal causes of low plantation establishment success. A variety of measures have been taken to mitigate the effects of these pressures, including the use of herbicides (Cogliastro et al. 1990, 1993; Gordon et al. 1995; McGill and Brenneman 2002), cover crops (OMNR 1994), various site preparation techniques (Karlson 2002), and animal browse controls (Gillespie et al. 1996; Dubois et al. 2000; Harmer and Gill 2000; Ward et al. 2000; Martin and Baltzinger 2002). Most scientific studies concerning the effectiveness of silvicultural treatments on plantation establishment, however, are installed under controlled conditions that are rarely achieved operationally. Thus, little information is available concerning how effective these measures are when applied on an operational scale.

In Indiana, approximately 150,000 non-industrial private forest (NIPF) landowners control 85% of the 1.8 million ha of forest (Tormoehlen et al. 2000), 97% of which is comprised of hardwoods (Miles 2001). Landowners plant trees primarily to create a legacy for future generations, provide food and habitat for wildlife, conserve the natural environment, and produce timber (Ross-Davis et al. in review). Plantations consist primarily of hardwoods, with eastern white pine (*Pinus strobus* L.) occasionally interplanted as trainer rows. Federal and state government initiatives provide the infrastructure necessary for afforestation and reforestation on a large scale, as many different technical and financial assistance programs are available to landowners to offset costs associated with plantation establishment. These include various federal and state-operated cost-share programs, tax credits, and tax deductions (MacGowan et al. 2001). For instance, under the Classified Forests program, assessed value of land is reduced to $2.50 per ha and technical aid is provided to NIPF landowners by the Department of Natural Resources; under cost-share arrangements, the federal government may provide up to 75% of the initial costs of tree planting (Nagubadi et al. 1996). Landowners who reforest land with the ultimate goal of commercial timber harvest may also qualify for a tax credit and deduction (Hoover 2002). Similar government-supported programs are available throughout the USA, and worldwide, to promote tree planting. Many NIPF landowners use some type of cost incentive program for afforestation, however, few reports have quantitatively assessed the establishment success of these tree plantations.

Identification of silvicultural practices that promote or deter plantation establishment will help to improve afforestation success. Additionally, determining the operational success of recently planted afforestation projects will help to evaluate whether government-supported cost-share and tax incentive programs are currently achieving their goals. This information could then be used by policy makers to help refine incentive programs to target specific silvicultural practices that improve plantation establishment success. Thus, the objectives of this study were to (i) examine survival and vigor of seedlings planted on fields throughout Indiana 1–5 years following planting and (ii) identify silvicultural practices that lead to successful plantation establishment.

Materials and methods

Site selection and sampling

As part of the Central Hardwood Forest region, a diverse assemblage of broad-leaved deciduous trees dominates Indiana's forests. Sedimentary deposits, modified by a series of three glacial advances and retreats during the Pleistocene, characterize the underlying substrate (Thompson 2002). The climate is classified as humid, mid-continental with no strong seasonal variation in precipitation. Mean annual precipitation in Indiana is 105.4 cm, with a mean temperature in July of 23.5 °C and in January of −3.3 °C (Purdue Applied Meteorology Group 2001).

Nursery records were obtained from both Indiana Department of Natural Resources Division of Forestry bareroot nurseries (Vallonia and Jasper-Pulaski). In 2001, approximately 85% of the 5.5 million hardwood seedlings grown in nurseries throughout Indiana were produced in these nurseries (USDA-Forest Service 2002). All nursery sales between 1997 and 2001 that consisted of at least 300 seedlings of one or more of the three most abundantly sold species [black walnut (*Juglans nigra* L.), yellow poplar (*Liriodendron tulipifera* L.), and northern red oak (*Quercus rubra* L.)] were reviewed. From over 2,000 nursery orders that met these criteria, 200 orders were randomly selected for survey.

Of the 200 individuals contacted, 92 completed the telephone survey, and due to unwillingness to allow visitation or catastrophe (e.g., fire), field data were collected from 87 of the sites (distributed throughout Indiana) from May to August 2002. Each landowner provided information on plantation size, planting density, site preparation techniques, cover crop establishment, planter experience, planting method, subsequent herbicide application, use of alternative forms of vegetation control, and browse protection measures. Planting method distinguished between mechanical (tractor-hauled coulter with trencher and packing wheels) and hand tools (shovels, post-hole diggers, dibbles, and augers). Alternative forms of vegetation control included mowing between rows of planted trees and mulching. Browse protection measures included applying repellent or shelters to individual trees and hunting. Planting plans were obtained for all sites that had a plan prepared by a professional forester (87% of sites) to help verify information gathered from the initial survey.

Plantations were sampled using 0.04 ha plots (20 m × 20 m), established randomly throughout each site. The number of plots per site was based on plantation area: 10% of the total area was sampled for plantations < 2.4 ha (25% of sites), 2–10% of the total area (i.e., six 0.04 ha plots) was sampled for plantations between 2.4 and 12 ha (60% of sites), and 2% of the total area was sampled for plantations > 12 ha (15% of sites). Within each plot, the total number of living trees was determined for each species planted. Volunteer trees were not included in this count, and planting densities provided by the landowner were field-verified. Free-to-grow (FTG) status [i.e., the minimum height allowing freedom from competition that impedes growth (Belli et al. 1999)], was assessed for each planted tree. An individual tree was considered FTG if it had a minimum height of 1.5 m and the surrounding vegetation in at least three quadrants of a 1.5 m radius did not exceed two-thirds the total height of the planted tree. The number of leaders, used as a measure of browse severity, was recorded for each tree and any evidence of dieback of the terminal shoot was noted. Vegetation percent cover was estimated within each plot, distinguishing between (i) grasses, sedges, and rushes, (ii) herbaceous vegetation, and (iii) naturally regenerating trees, shrubs, and woody vines. The average height for each cover type (i.e., (i)–(iii) was calculated from four height measurements taken randomly throughout each plot.

Data analysis

Each site was considered an experimental unit. Plantation establishment success was defined by a combination of seedling survival and vigor, the former calculated as seedling survival percentage (SSP) = (number of surviving trees/number of planted trees) × 100 (Karlson 2002) and the latter defined by a combination of FTG status, number of leaders, and evidence of dieback on the terminal shoot. Kruskal–Wallis tests were used to compare (i) measures of plantation establishment success between plantations that had or had not (a) been planted by a professional forester, (b) been mechanically planted, (c) been established with a cover crop, (d) received subsequent herbicide application, (e) used alternative forms of vegetation control, or (f) employed browse protection and (ii) cover and height of competing vegetation between sites for which herbicide had or had not been applied subsequent to planting. Subcategories of planting methods, alternative vegetation control, and browse protection measures were pooled for analysis. Spearman rank correlations were used to relate (i) plantation establishment success to cover and height of competing vegetation and (ii) FTG status to evidence of dieback and percentage of trees with three or more leaders within the six most frequently occurring hardwood species in year 5. Analysis of variance (ANOVA) was used to compare (i) plantation establishment success with method of site preparation (i.e., no site preparation, mechanical site preparation only, chemical site preparation only, and both mechanical and chemical site preparation), (ii) cover and height of competing vegetation among sites receiving various site preparation techniques, and (iii) the percentages of individuals (a) FTG at age 5, (b) with evidence of dieback, and (c) with three or more leaders, with Tukey's test used to distinguish among mean differences. Due to the large inherent variation in this type of research, we considered treatment effects to be significant if $p \leq 0.10$. Normality and homoscedasticity were assessed using Shapiro–Wilks' and Levene's tests, respectively. Percentage data which were not normal or heteroscedastic were transformed using log $[(p + 0.5)/(1.5 - p)]$, where $p = 1/x$, that is, each percentage (x) was represented as a proportion (p). All other data that were not normal or heteroscedastic were transformed using square root transformation. All data are reported as original means with standard errors. SPSS version 10.1 (2000) was used for all statistical tests.

Results

Characterization of surveyed plantations

Approximately 68% of the surveyed plantations were established on land that had previously been in crops, either corn or soybeans, while 17% were established on pastures. The remaining 15% of plantations were established on riparian buffers

Table 1. Species[a] sampled within tree plantations established throughout Indiana between 1997 and 2001 with associated percent frequency of occurrence

Common name	Latin name	Frequency (%)
Northern red oak	*Quercus rubra* L.	18.3
Black walnut	*Juglans nigra* L.	17.6
White oak	*Q. alba* L.	11.1
Yellow poplar	*Liriodendron tulipifera* L.	9.1
Eastern white pine	*Pinus strobus* L.	8.9
White ash	*Fraxinus americana* L.	8.6
Black cherry	*P. serotina* Ehrh.	6.1
Bur oak	*Q. macrocarpa* Michx.	6.0
Black oak	*Q. velutina* Lam.	2.6
Green ash	*F. pennsylvanica* Marsh.	2.0
Swamp chestnut oak	*Q. michauxii* Nutt.	1.7
Bald cypress	*Taxodium distichum* (L.) Rich.	1.2
Chinkapin oak	*Q. muehlenbergii* Engelm.	1.0
Other species[b]		5.7

[a] Nomenclature follows Hardin et al. (2001).
[b] Other species consisted of 23 hardwood and 5 conifer species (5.3 and 0.4% of total frequency, respectively).

(5%) or a combination of crop fields, pastures, and/or riparian buffers (10%). The sites were generally found on uplands (93%), with the remainder in riparian bottomlands (7%). All sites were relatively flat, and each site had the capacity to be mechanically prepared or planted.

The majority of respondents claimed to have received a cost-share from a government program (87%), though 13% were unsure of the specific program used. Cost-share programs included the Conservation Reserve Program (74%), Stewardship Incentives Program (3%), Wetland Reserve Program (3%), Wildlife Incentive Habitat Program (1%), and other miscellaneous programs (6%).

Assessment of weather data from 1997 to 2001 showed no extreme deviations from normal precipitation in Indiana during the primary growing period (i.e., 1 May–30 September) throughout the 5 years, as precipitation ranged from 71 to 123% of average (Purdue Applied Meteorology Group 2001).

Over 15,000 trees, representing 41 species (Table 1), were sampled across the 87 sites. The most abundant of these included northern red oak, black walnut, white oak (*Quercus alba* L.), yellow poplar, eastern white pine, white ash (*Fraxinus americana* L.), and black cherry (*Prunus serotina* Ehrh.).

Seedling survival

There were no differences in SSP among years ($p = 0.736$), which ranged from 59.02 (year 2) to 70.45% (year 3). SSP differed among sites receiving different site preparations ($p = 0.024$), with SSP higher at chemically prepared and chemically/mechanically prepared sites than at mechanically prepared sites (Table 2). SSP was

Table 2. Silvicultural history of 87 sampled tree plantations established throughout Indiana between 1997 and 2001. Treatments with different letters within a column for a sub-set of rows were significantly different at $\alpha = 0.10$

Silvicultural parameter (n = number of respondents)	Percentage of sites (%)	SSP[a]	Evidence of dieback[a]	Three or more leaders[a]	FTG[a,b]
Planter ($n = 87$)					
Professional forester	75	68.48a	82.12a	25.77a	23.21a
Landowner	25	60.07a	86.94a	25.63a	8.62b
Site preparation ($n = 86$)					
Mechanical	21	52.17a	84.74a	23.05a	14.17a
Chemical	38	72.61b	82.56a	25.00a	20.69a
Mechanical and chemical	15	70.43b	79.78a	26.14a	22.51a
No site preparation	27	66.16ab	86.00a	28.67a	20.35a
Cover crop ($n = 87$)					
Planted	14	65.66a	83.52a	24.88a	16.10a
Not planted	86	66.46a	83.33a	25.87a	20.07a
Planting method ($n = 86$)					
Mechanically planted	88	68.47a	83.98a	27.11a	20.36a
Hand planted	12	49.72b	76.70a	17.74b	9.81b
Subsequent herbicide application ($n = 87$)					
Applied	87	67.64a	83.61a	26.06a	21.31a
Not applied	13	57.46a	81.61a	23.52a	7.16b
Alternative vegetation controls ($n = 87$)					
Used	56	67.01a	82.57a	24.96a	18.29a
Not used	44	65.50a	84.27a	26.73a	21.11a
Browse controls ($n = 87$)					
Used	38	63.03a	87.89a	26.56a	15.25a
Not used	62	68.38a	80.59b	25.23a	22.13a

[a] Expressed as percentage of trees.
[b] Free-to-grow.

also higher for seedlings that had been mechanically planted (as opposed to hand planted) ($p = 0.041$; Table 2). Although not statistically significant, mean SSP was higher on sites planted by a professional forester ($p = 0.234$). Cover crop establishment ($p = 0.912$), herbicide application subsequent to tree planting ($p = 0.371$), use of alternative vegetation controls ($p = 0.681$), and use of browse protection measures ($p = 0.267$) did not affect SSP (Table 2). SSP was negatively correlated with both cover ($p = 0.022$) and height ($p = 0.014$) of herbaceous vegetation (Table 3).

Vigor

The percentage of trees with evidence of dieback remained above 80% across the 5 years and did not differ among years ($p = 0.287$). The percentage of trees with evidence of dieback was highest on sites for which browse protection measures had

Table 3. Average cover and height of (i) grasses, sedges and rushes, (ii) herbaceous vegetation, and (iii) naturally regenerating trees, shrubs and woody vines within 87 afforestation efforts sampled throughout Indiana categorized by method of vegetation control and associated correlations with percent survival of planted trees. Treatments with different letters within a row for a sub-set of columns were significantly different at $\alpha = 0.10$. Asterisks indicate significant correlations between seedling survival percentage (SSP) and abundance of vegetation

Type and measure of abundance of vegetation	Site preparation				Subsequent herbicide application		SSP[a]
	None	Mechanical	Chemical	Mechanical and chemical	Yes	No	
Grasses, sedges, rushes							
Cover[b]	37.07a	32.96a	33.81a	46.89a	36.41a	36.73a	0.115
Height[c]	91.25a	87.33a	87.41a	80.11a	87.47a	86.25a	−0.174
Herbaceous vegetation							
Cover[b]	37.69b	41.75b	37.33ab	25.71a	35.84a	41.90a	−0.244*
Height[c]	87.48ab	99.75b	89.40ab	76.99a	89.82a	84.79a	−0.263*
Trees, shrubs, woody vines							
Cover[b]	5.27a	5.94a	5.91a	7.32a	5.53a	9.07a	−0.007
Height[c]	92.59a	95.11a	72.46a	79.86a	82.11a	93.65a	−0.032

[a] Spearman's rho (*r*).
[b] Percent cover.
[c] Centimeters (cm).

been used ($p = 0.013$; Table 2). Site preparation ($p = 0.477$), cover crop establishment ($p = 0.825$), planter experience ($p = 0.160$), planting method ($p = 0.254$), herbicide application subsequent to tree planting ($p = 0.769$), and use of alternative forms of vegetation control ($p = 0.681$) did not affect the percentage of trees with evidence of dieback.

The percentage of trees with three or more leaders differed among years ($p = 0.014$), with percentages in years 1 (21.56%) and 5 (22.98%) significantly lower than in year 3 (32.28%). A higher percentage of trees with three or more leaders was evident on sites that had been mechanically planted ($p = 0.020$; Table 2). Site preparation ($p = 0.442$), cover crop establishment ($p = 0.721$), planter experience ($p = 0.796$), herbicide application subsequent to tree planting ($p = 0.511$), use of alternative forms of vegetation control ($p = 0.626$), and use of browse protection measures ($p = 0.512$) did not affect the percentage of trees with three or more leaders.

The percentage of FTG trees differed by plantation age ($p < 0.001$), increasing with age and ranging from 2.22% in year 1 to 48.86% in year 5. A significant increase in FTG individuals occurred between years 4 and 5. Across the 5 years, the percentage of trees considered FTG was significantly higher on sites planted by a professional forester ($p = 0.020$), on sites that were mechanically planted ($p = 0.076$), and on which herbicide had been applied subsequent to planting ($p = 0.045$; Table 2). Notably, 94% of plantations established by a professional forester received herbicide treatment following planting, compared to only 59% for those plantings established by someone else, and 95% of mechanically planted sites received herbicide treatment following planting, compared to only 40% of hand-planted sites. Site preparation ($p = 0.767$), cover crop establishment ($p = 0.544$), use of alternative forms of vegetation control ($p = 0.793$), and use of browse protection measures ($p = 0.200$) did not affect the percentage of trees considered FTG.

Vigor of the six most frequently occurring hardwood species

The percentage of FTG individuals varied among the six most frequently occurring hardwood species in year 5 ($p = 0.038$). A higher percentage of black cherry was FTG at age 5 (75.61%; $n = 5$) followed by white ash (68.70%; $n = 10$), yellow poplar (63.99%; $n = 10$), white oak (52.49%; $n = 9$), black walnut (46.63%; $n = 14$), and northern red oak (30.35%; $n = 13$; Figure 1). The percentage of individuals with evidence of dieback also varied among the six most frequently occurring hardwood species ($p = 0.015$). A higher percentage of northern red oak and white oak individuals had evidence of dieback in year 5 (98.06%), compared to yellow poplar (86.04%; Figure 1). The percentage of individuals with three or more leaders also varied among the six species ($p < 0.001$). Black cherry had the highest percentage of individuals with three or more leaders (62.81%; Figure 1). Irrespective of species, FTG status in year 5 was negatively correlated with evidence of dieback ($r = -0.355$; $p = 0.005$), but was not correlated with the percentage of individuals with three or more leaders ($r = 0.167$; $p = 0.199$). When the six species were examined individually, only for northern red oak ($r = -0.707$; $p = 0.007$) and

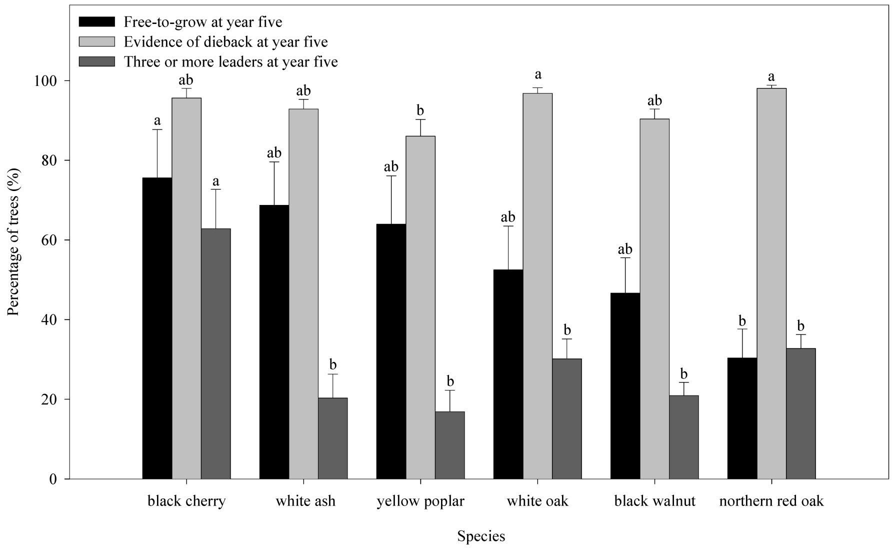

Figure 1. Percentage of individual trees within the six most frequently occurring hardwood species at age 5 considered free-to-grow, with evidence of dieback, and with three or more leaders within sampled plantations established throughout Indiana in 1997. For each response variable, different letters indicate significant differences among species at $\alpha = 0.10$.

white oak ($r = -0.621$; $p = 0.074$) was the percentage of FTG individuals in year 5 negatively correlated with the percentage of individuals with evidence of dieback. For yellow poplar, the percentage of FTG individuals in year 5 was correlated with the percentage of individuals with three or more leaders ($r = 0.741$; $p = 0.014$).

Competing vegetation

There was no difference in cover or height of (i) grasses, sedges, and rushes ($p = 0.396$ and 0.829 for cover and height, respectively), (ii) herbaceous vegetation ($p = 0.401$ and 0.905, respectively), or cover of (iii) naturally regenerating trees, shrubs, and woody vines ($p = 0.429$) across the 5 years. Height of naturally regenerating trees, shrubs, and woody vines differed across the 5 years ($p = 0.002$), with heights increasing from years 1, 2, and 3 (54.92 ± 14.43, 68.23 ± 11.00, and 78.57 ± 13.35 cm, respectively) to heights of 97.97 ± 8.78 cm and 135.35 ± 22.94 cm in years 4 and 5, respectively. Significant differences were found only between years 1–3 and year 5. While subsequent herbicide application did not reduce the cover or height of competing vegetation (p ranging from 0.328 to 0.949), there was a difference in cover and height of herbaceous vegetation among different site preparation techniques ($p = 0.048$). Herbaceous cover and overall height were significantly lower on sites that had been both chemically and mechanically prepared relative to mechanically prepared sites (Table 3).

Discussion

Seedling survival

Of all variables measured, only site preparation techniques and planting method affected survival: SSP was highest at sites that had been chemically or chemically/mechanically prepared and sites that had been mechanically planted. The former finding, in combination with the negative correlations between SSP and both cover and height of herbaceous vegetation, confirm previous studies which found that competing vegetation is a primary deterrent to plantation establishment success (Cogliastro et al. 1990; Kolb et al. 1990; Gordon et al. 1995; Willoughby and McDonald 1999). It is well documented that mechanical site preparation exposes mineral soil for colonization of early successional germinants from the extant seed bank and seed rain (Froud-Williams et al. 1983; Mohler 1993; Scopel et al. 1994; Pearson et al. 1995). Mechanically prepared sites yielded the highest cover and height of herbaceous vegetation, which likely was the reason for this treatment yielding in the lowest mean SSP. Although claimed to slow the spread of weeds (OMNR 1994), cover crop establishment did not seem to increase survival or improve vigor of planted trees within the first 5 years following planting. This may be due to ineffectiveness of cover crops with regard to improving survival and vigor of planted seedlings or insufficient statistical power as a result of the low percentage of sites at which a cover crop had been planted (14%).

The increase in SSP on mechanically planted sites is of particular interest when combined with the statistically insignificant difference in SSP between plantations established by professional foresters and those established by the landowners themselves. It appears to be planting method (mechanical vs. hand), not necessarily the experience of the planter, that affects SSP. This result may be partly explained by differences in the time required to plant trees on former farmland mechanically versus by hand. Rates exceeding 1,000 trees per hour have been reported using mechanical planters (Thompson 1984; Wray 1997; Slusher 1999), while rates of 500 trees per day have been documented for hand-planted sites (Wray 1997). Particularly for large plantations, bareroot stock may have been left in the open air for longer periods at hand-planted sites and consequent root drying may have led to increased susceptibility to transplant shock as a result of diminished root growth potential (Ritchie and Dunlap 1980). It is well known that water is a limiting factor for survival following transplanting (Kozlowski 1976; Larson 1980); thus, minimizing potential water stress during and following planting is crucial for success. It has also been demonstrated that the dibble (i.e., planting bar) is not suitable for planting large hardwood seedlings due to difficulty associated with creating a hole large enough for the root mass (Boyette and Brenneman 1978). For those sites that were planted using a dibble (50% of hand-planted sites), the consequent forcing of roots into the hole may have resulted in poor root orientation (e.g., j- and l-rooted seedlings), which may decrease both survival and growth rate of planted seedlings (Lacaze 1968; Brisette and Barnett 1988).

Vigor

Herbicide application subsequent to tree planting increased the proportion of planted trees considered FTG. This may be associated with the corresponding decrease in mean herbaceous cover, although not statistically significant, on sites receiving subsequent herbicide application. Although there was no significant difference in SSP between sites planted by a professional forester and those planted by the landowner, planter experience did affect the percentage of trees considered FTG, which was significantly higher on sites planted by a professional forester. FTG was also significantly higher on mechanically planted sites. These results may be partly attributable to the greater proportions of these sites that received herbicide application. They may also be related to better stock storage, handling during planting, and more knowledgeable species selection based on site conditions.

The percentage of trees without evidence of dieback was highest on sites at which browse protection measures had not been used, likely reflecting damage due to inherently high white-tailed deer (*Odocoileus virginianus* Zimmermann) populations at sites for which browse protection measures were employed. This implies that current browse protection measures (e.g., shelters, repellents, and hunting) are not effectively preventing damage to planted trees and alternative measures should be sought. There was a significantly higher percentage of planted trees with three or more leaders at mechanically planted sites. This may be a function of terminal bud damage during the mechanical planting operation or higher susceptibility of seedlings to deer browse given increased use of herbicides. The differences in the percentage of trees with three or more leaders among years is likely related to a combination of weather conditions (e.g., early frost causing dieback of new growth) and variable browsing pressures from deer populations.

Of the six most frequently occurring hardwood species, a significantly higher percentage of black cherry individuals were FTG relative to northern red oak. The high percentage of FTG black cherry is likely due to its fast initial growth rate (Marquis and Brenneman 1981). Northern red oak often dies back during the first few years following planting (e.g., Johnson 1975), allowing one or more of the dormant buds near the root collar or on the previous flush to produce new shoots. This, in combination with inherently episodic shoot growth (Sander 1979), likely contributed to the low percentage of FTG individuals for this species at year 5.

It is clear that the first year following planting is most critical to plantation establishment success: neither SSP nor percentage of trees with evidence of dieback differed significantly among years. This may be attributable to (i) a preponderance of species-site mismatches (pers. obs.), (ii) transplant shock associated with bare-root nursery stock and/or (iii) heavy and relatively consistent animal browse and competition pressures through space and time.

Recommendations for successful plantation establishment

Highest plantation establishment success in this study resulted from careful weed control (namely applying herbicides prior to and after planting) and professional planting using a mechanical planter. Mechanical site preparation in the absence of weed control is likely to stimulate herbaceous vegetation growth, which may lead to decreased SSP. Although subsequent herbicide application did not increase SSP, it did appear to increase the rate at which planted trees became FTG. To prevent the formation of multiple leaders, care must be taken when using a mechanical planter not to damage the terminal bud. Current browse control methods are relatively ineffective and new treatments may be needed to reduce browse damage.

Based on our results, substantial improvements could be made in establishment of tree plantations on an operational scale in Indiana. Mean SSP across all years was 66% and only 49% of trees were FTG at age 5. The silvicultural treatments which improved plantation establishment, particularly herbicide application to control competing vegetation, should be emphasized in future plantings. Programs which provide technical and financial assistance to help landowners establish plantations should concentrate on those silvicultural treatments which improved seedling performance. Because many of the challenges to successful afforestation in this region are likely to be similar on many other field plantings (e.g., weed control and planting quality), we expect that the results found here have application to many afforestation projects across the USA and worldwide. Careful planting of quality nursery stock by experienced planters, combined with aggressive chemical weed control should help to improve plantation establishment on private land.

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