THE AMERICAN CHESTNUT AND FIRE: 6-YEAR RESEARCH RESULTS

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Abstract—American chestnut [*Castanea dentata* Marsh. (Borkh.)] is an iconic species with important ecological and utilitarian values, but was decimated by the mid-20th century by exotic fungal species from Asia. Successful restoration will require sustainable silvicultural methods to maximize survival and afford chestnut a competitive advantage over natural vegetation. The study examined effects of prescribed burning and commercial tree harvesting on survival and height growth of planted American chestnut on the mid-Cumberland Plateau in Tennessee. American chestnuts grew best in patch clearcuts compared to areas that had been commercially thinned. A severe drought during the establishment year probably led to decreased survival and growth rates. However, 6-year survival was highest for trees with smaller ground-line diameter and taller stem heights at the time of planting and in units that had lower levels of percent full sunlight in the first year after planting. Prescribed burning did not affect survival or height growth, but browsing by deer was more common in burned versus unburned areas.

INTRODUCTION

The American chestnut [*Castanea dentata* Marsh. (Borkh.)] was a dominant canopy tree in many hardwood forest types in eastern North America until decimated by primarily two exotic pathogens from Asia. Ink disease (causal agent *Phytophthora cinnamomi* Rands) and chestnut blight [causal agent *Cryphonectria parasitica* (Murr.) Barr] reduced the species primarily to recurrent understory sprouts on upland sites with well-drained sandy soils (Anagnostakis 2001, 2012). American chestnut has been extirpated as a canopy tree throughout its former range since the early to mid-20th century. Restoration will require artificial regeneration of trees with durable resistance to ink disease and chestnut blight, as natural resistance in American chestnut to these pathogens is relatively low (Griffin 2000).

American chestnut was extirpated prior to the emergence of modern ecological or forestry research programs. Consequently, little is known regarding American chestnut's response to natural or anthropogenic disturbance. Although the species has shade-tolerant characteristics (Joesting and others 2007), American chestnut was probably disturbance-dependent, with some life-history characteristics similar to oak (*Quercus* L.) genera (Wang and others 2013). Phylogeny studies indicate oaks and chestnuts are closely related within the Fagaceae (Beech) family (Kremer and others 2007), and could share similar responses to disturbances such as fire. Experimental research, exploratory analysis, and long-term observations have established the premise that oaks are well adapted to fire (Abrams 1992), but similar information on American chestnut is lacking. An increase in *Castanea* (Mill.) pollen coincided with an increase in charcoal abundance, suggesting that chestnut was favored by fire and a warming climate in New England forests ca. 1,500 years ago (Delcourt and Delcourt 1998, Foster and others 2002).

Historical literature and studies of remnant trees revealed that American chestnut is a species with one of the most prolific sprouting capabilities following disturbances (Hawley and Hawes 1912, Matoon 1909, Paillet 1984). American chestnut grows faster in height than competing species following disturbances or when planted in high-light environments (Frothingham 1924, Jacobs and Severeid 2004, McEwan and others 2006). Fast growth and prolific sprouting may be an adaption to frequent disturbances, including fire (Foster and others 2002, Russell 1987). American chestnut has thinner bark than oak, however, and fire damage may predispose the tree to disease (Hawley and Hawes 1912, Russell 1987). Baker (1884) described American chestnut as "greatly injured" by fire, and Matoon (1909) noted that American chestnut sprouts were particularly prone to rot if the parent stump was infected with disease. Throughout its range, prescribed fire was often used to facilitate

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gathering chestnuts, and often the fire would escape and damage the timber (Hough 1878). Despite chestnut's apparent susceptibility to fire, these early accounts should be viewed in the context of the era in which they were written, a time when fire was not actively controlled and was often condemned (Brose and others 2001). We can hypothesize from these early accounts that too frequent or severe fire was detrimental to chestnut's ability to gain dominance (Russell 1987). Infrequent, low-intensity fires may have favored species' expansion, particularly in the northern extent of the species' range (Foster and others 2002), suggesting that fire should be evaluated for viability as a process to be used in American chestnut restoration activities.

Regeneration harvests or intermediate stand treatments that reduce overstory stand density increased growth of American chestnut seedlings compared to trees planted under full canopy conditions (Clark and others 2012a, McCament and McCarthy 2005, Rhoades and others 2009). Effects of prescribed burning and interactions with harvesting have only been tested with American chestnut when fire was prescribed prior to direct seeding of nuts (McCament and McCarthy 2005). In particular, only two studies have directly examined the response of planted American chestnut seedlings to fire after seedlings were planted. One study will be described herein, and the other was conducted outside the species range using fire simulation (Belair and others, in press). We discuss effects from various disturbances, including prescribed burning and commercial tree harvesting, on 6-year old planted American chestnuts. We modeled probabilities for survival and deer browse, as well as height predictions for artificially regenerated American chestnut seedlings based on silvicultural treatments, seedling size at planting, and selected environmental influences.

METHODS

This study was established on forest property owned and managed by University of the South, in Franklin County, near the town of Sewanee, TN. The site is on the Weakly Dissected Plateau Landtype Association of the mid-Cumberland Plateau (Smalley 1982), and native American chestnut sprouts were present in the stand. Annual precipitation averages 150 cm per year and is greatest from December through March. Soils can be described as Hartsells-Lonewood-Ramsey-Gilpin and developed in residuum from sandstone. The study site was a 20.2-ha hardwood stand and was subdivided into three approximately equally sized blocks based on topographic characteristics. Site index (base age 50) for northern red oak was approximately 20 m. In the winter of 2006–2007, all three blocks were thinned to 15 m^2 ha^{-1} of basal area using thinning from below, and within each block, two patch clearcuts 0.1 to 0.2 ha in size were harvested. Patch clearcuts within each block were a minimum of 90 m apart.

Within each block, prescribed burn units of 1.0 to 1.8 ha, including at least one of the patch clearcuts and part of the thinning area, were established, with burns originally slated for March 2007. The original experimental design was a randomized block design with three blocks and a two by two factorial with thinning versus patch clearcuts and burning versus no burning as the two factors. Due to logistical constraints related to a severe drought that created unsuitable burning conditions throughout the desired burn window (U.S. Drought Monitor 2014), only one block was burned in 2007 (table 1). The burn was conducted on March 7 and was moderate in intensity with 0.9 to 1.8 m flame heights. The original experimental design was further compromised when two of the patch clearcuts were entered and hand-thinned in July 2009 (table 1). The hand-thinning consisted of removal of red maple (*Acer rubrum* L.) and sourwood (*Oxydendrum aboreum* L. DC.) seedlings using hand-saws and machetes. In addition, a January 2010 tornado affected two experimental units, a patch clearcut and a thinning unit (table 1). The tornado-affected thinning unit was salvage-logged within a few weeks following the tornado. The tornado and the salvage logging effectively removed all overstory trees in the thinned experimental unit. In March 2010, the original prescribed burn plan was implemented, but the burn did not reach the thinning unit in block 2. Recorded flame heights and tree scorch marks in each experimental unit were used to classify fires into mild (flame heights $\leq$ 0.9 m) and moderate intensity (flame heights > 0.9 m) (table 1). All prescribed burns were set with backing fires ignited with drip torches.

In March 2007, immediately following the prescribed burn, we planted 5 American chestnuts and 35 northern red oak seedlings in each experimental unit. The experimental material was pure American chestnut provided by the American Chestnut Foundation from a Cumberland Plateau seed source. Bare-root (1-0) nursery seedlings were produced in the Georgia State nursery in Bryomville, GA using protocols developed to produce relatively large seedlings with fibrous root systems (Kormanik and others 1994). Evidence of root rot caused by *Phytophthora cinnamomi* was not evident on any seedlings. Seedlings were planted using JIM_GEM® KBC bars modified to increase bar width to 30 cm to accommodate planting of larger seedlings. The American chestnut seedlings were planted on a 3-m by 3-m spacing randomly intermixed with the northern red oak seedlings. Each seedling was measured for ground-line diameter (GLD) and height to the tallest live bud at the time of planting in 2007 and then again in years 2008–2012 after trees had set bud (August through March). Other categorical measurements included survival, presence or absence of deer browse to the terminal bud, dieback of the main stem, and chestnut blight. Blight was identified as a vertical ellipsoid shaped canker on the stem that was sometimes sunken or slightly swollen. The canker had vertical cracking or fissuring of the bark with mycelial fans just below the bark surface (visible with a 5X hand lens), and/or with orange stromata protruding from the bark (cf. Griffin and Elkins 1986). Chestnut blight was recorded on live trees, and we continued to record the presence of blight each year after the tree died. Stem dieback and deer browse were recorded on live trees. We documented if a basal sprout had replaced the original leader as the tallest stem.

During the first growing season (2007), we measured the amount of photosynthetically active radiation (PAR) (µmol m^{-2} s^{-1}) above the terminal bud, and above the widest margins of each live American chestnut and northern red oak seedling's crown using an AccuPar ceptometer. Percent full sun (PFS) was estimated by comparing the average PAR measurements from each seedling to PAR measurements taken at the same time from a ceptometer placed in full sun approximately 0.2 km away. Tree PFS values were averaged across live chestnut and northern red oak seedlings within each experimental unit to give an estimate of the experimental unit's PAR. We did not use individual PFS values taken at each live American chestnut because we had a relatively low sample size within each experimental unit ($n \leq 5$) that increased variability and gave a relatively poor representation of the amount of sunlight during the first growing season created by the treatments. Additionally, PFS measurements taken above live trees could not be used to model survival probabilities (described below).

We will only discuss results from the American chestnut planting in this paper. Due to the deviation from the original experimental design, data were analyzed with exploratory methods using logistic regression and multiple linear regression model building techniques. All analyses were conducted using SAS (SAS Institute 2009). Logistic regression (PROC LOGISTIC) was used to predict survival and deer browse using the following dichotomous or continuous independent variables: year since planting (1 to 6), burning prior to planting (burn versus no burn), seedling height at planting, ground-line diameter at planting, PFS in 2007, the tornado (yes or no), and chestnut blight (yes or no). We tested three class variables to identify experimental units that were commercially thinned and not hand-thinned, and units that represented commercial patch clearcuts with and without hand- thinning, respectively, within the appropriate years. We also tested three class variables to identify experimental units that had been burned in 2010 with two intensities (not burned, a mild intensity burn, and a moderate intensity burn). Logistic regression models were built using methods described by Hosmer and Lemeshow (2000) and Menard (2010). The final model was selected after conducting chi-square tests for differences between AIC values of the candidate predictor models; the most parsimonious (model containing the least number of variables with the most explanatory power) was selected as the final model. A Hosmer-Lemeshow goodness of fit statistic was used to test the null hypothesis that the model explained the variation in the data, and p-values of less than 0.10 were interpreted as poorly fit models. We examined the Area Under the ROC (Receiver Operator Characteristic; defined by sensitivity versus 1-specificity) Curve (AUC), which is a measure of explained variation, and we considered models with an AUC value greater than 0.5 to have good explanatory power (Menard 2010). Surviving seedlings and those with deer browse were coded as successful (1), and dead seedlings and seedlings without browse as unsuccessful (0) in the logistic regression models to predict survival and deer browse probabilities.

PROC REG was used to conduct multiple linear regression to predict seedling height. Potential independent variables tested included the same dichotomous and continuous variables used in the logistic regression models in addition to dieback of the main stem (yes or no) and deer browse to the terminal bud (yes or no). The linear regression models were built using methods described by Wasserman and Kutner (1990). The final model was selected after conducting chi-square tests for differences between AIC values of the candidate predictor models; the most parsimonious model was selected as the final model. We used PROC REG to test diagnostics for heteroscedasticity of error terms, and normality assumptions were tested by examining frequency plots of residuals in PROC UNIVARIATE. Parameter estimates and associated p-values for the final model were produced using PROC GLM because, unlike PROC REG, the GLM procedure does not assume data are balanced for categorical variables.

RESULTS

General Trends across Experimental Units

Average height and GLD at planting were 115 cm (SE = 4.6) and 9.5 mm (SE = 0.4), respectively, and varied from 28 to 190 cm in height and from 4.9 mm to 16.7 mm in GLD. PFS in 2007 averaged 31 (SE = 1.7) across all experimental units and ranged from 13 percent (unit 3) to 64 percent (unit 10) (table 1). By the sixth growing season, trees averaged 236 cm (SE=40) in height and had 39 percent (SE = 6) survival across all experimental units (table 1). Experimental units varied greatly in terms of height and survival. Deer browse averaged 42 percent (SE = 8) in year 1, and decreased to 20 percent (SE = 7) and 0 percent in year 4 and 6 after planting, respectively. Stem dieback averaged 23 percent (SE = 7) in year 1, 40 percent (SE = 9) in year 4, and 22 percent (SE = 9) in year 6 after planting. Chestnut blight increased from 2 percent (SE = 2) in year 1 to 41 percent (SE = 6) in year 6 after planting and was present in all experimental units except a thinning unit in block 2. Sprouting occurred in every year, but was lowest in year 6 after planting.

Survival Predictions

The logistic regression model to predict survival adequately explained the variation according to the goodness of fit test (P = 0.97) and the AUC value (0.76). Chestnut blight, prescribed burning, combined effects of harvesting and hand-thinning, and the tornado were not included in the model to predict survival. PFS in 2007 was the most significant predictor of survival probabilities, and survival probabilities decreased as PFS increased (table 2). Year since planting was the second most significant predictor of survival. Height at planting had a weak but positive relationship to survival. Although the main effects of planting height and interactions with GLD and PFS had p-values greater than 0.05, inclusion of these effects in the model significantly lowered the AIC value. The negative effect of increasing PFS values in 2007 on subsequent survival weakened as tree height at planting increased (fig. 1). As GLD increased, survival was predicted to decrease according to the logistic regression model. Taller trees had the best survival despite GLD, particularly for trees taller than approximately 140 cm at planting. Trees predicted to have the highest survival had small GLDs and tall heights at the time of planting and were planted in relatively low light environments.

Deer browse Predictions

The logistic regression model for deer browse adequately explained the variation according to the goodness of fit test (P = 0.90) and the AUC value (0.79). The effects of GLD, chestnut blight, harvesting, and the tornado were not included in the model to predict deer browse. Year since planting was the most significant predictor of deer browse, and deer were less likely to browse as year since planting increased (table 2). Burning prior to planting and planting height were significant predictors of deer browse probabilities. Deer browse was more frequent in areas that had burned prior to planting and on seedlings with smaller stem heights. Shorter trees planted in burned areas 1 year after planting had the highest deer browse probabilities, and taller trees planted in unburned areas 6 years after planting had the lowest deer browse probabilities.

Height Predictions

The final multiple regression model for seedling height had an R^2=0.51 (F = 29.95, p < 0.0001). We transformed height using a natural log function to avoid heteroscedasticity. Prescribed burning prior to and after planting, GLD at planting, chestnut blight, and deer browse were not significant predictors of height in the multiple regression model. Year since planting, height at planting, PFS in 2007, stem dieback, the tornado, and harvesting treatments were significant predictors of total height (table 3). Height at planting was positively related to total height, and PFS in 2007 was negatively related to total height. Stem dieback was negatively related and was the most significant predictor of total height. In year 6, dieback was predicted to decrease stem height by approximately 150 cm in patch clearcuts that were hand-thinned and not affected by the tornado (fig. 2). Trees were predicted to be 293 cm tall in patch clearcuts that were hand-thinned, 162 cm tall in patch clearcuts that were not hand-thinned, and 136 cm tall in commercially thinned units by year 6 after planting, given mean PFS (31 percent), mean height at planting (115 cm), and no effect of tornado or dieback (fig. 2). The tornado increased these predicted heights by 129 cm, 71 cm, and 59 cm in the patch clearcuts with hand-thinning, patch clearcuts without hand-thinning, and the commercially thinned units, respectively.

DISCUSSION

Results should be interpreted with caution for two primary reasons. First, sample size was relatively low, restricting the power of the statistical analysis and the ability to test predictions from the models on a subset of data. Low sample size is related to the difficulty in securing American chestnut experimental material (Hebard 2013). Second, deviations from the original experimental design (e.g., alteration of prescribed burning, the unplanned hand-thinning, and the tornado) were sometimes confounding, and also led to difficulty in making inferences. The analysis used individual trees as independent observations, when the individual tree was originally designed to be a subsample of the larger experimental unit. This deviation from the original experimental design may have caused an increase in Type I errors (accepting significance of effects when there was no effect). For example, the tornado affected units that burned the same year as the tornado, making separation of burning intensity and tornado effects on survival and height impossible. Units 10 (patch clearcut) and 12 (commercial thin) in block 3 were the only units that burned prior to planting, and they also had relatively high PFS in 2007. The impacts of the pre-plant burn on PFS in the first growing season could be confounded with effects of localized site conditions because only one block burned prior to planting. Furthermore, a severe drought that occurred the year of planting also complicates interpretation of results. The drought was characterized as exceptional by the end of the first growing season and severe by the end of the second growing season (U.S. Drought Monitor 2014). Despite these limitations, this study gives some insight into the effects of various disturbances on planted American chestnut seedlings.

Survival

Our results are consistent with previous studies that found American chestnut survival was not limited by low light levels (Clark and others 2012a, Rhoades and others 2009). The species has certain shade-tolerant characteristics such as a low light saturation point (~200 µmol m^{-2} s^{-1}) and light compensation point (~30 µmol m^{-2} s^{-1}) (Knapp and others, in press; Joesting and others 2009; Wang and others 2006) that allow seedlings to survive in shaded environments. Survival was limited by high light conditions in this study, in contrast to previous studies that indicate American chestnut was highly productive under an open canopy or full sun conditions (Clark and others 2012a, Latham 1992, Wang and others 2006). However, the relationship between survival and PFS in 2007 was confounded by low replication of the pre-plant burn and a drought. Units 10 and 12 had relatively low 6-year survival rates (0 and 40 percent, respectively) and relatively high PFS values in 2007 (64 and 37 percent, respectively), and appeared to be on a slightly more xeric topographic area compared to other units. These two units were also the only units to have been burned prior to planting. We could not determine if the relatively high PFS values recorded in the first growing season in these two units were related to the effects of the pre- plant burn or to the xeric site conditions. We hypothesize the effect of the 2007 and 2008 drought interacted with site conditions to affect the relationship between PFS in the first growing season and subsequent survival. Trees planted on xeric sites, such as units 10 and 12, would experience more stress during drought compared to trees on more mesic sites, leading to lower survival rates (Gustafson and Sturtevant 2013). The physiological mechanisms that probably mitigate the negative effects of drought in American chestnut may have been compromised as light levels increased. Drought has been shown to decrease stomatal conductance, transpiration, and leaf xylem water potential in northern red oak seedlings (Jacobs and others 2009). These functions would have been further decreased as PFS increased, as has been shown in shade-house studies (Brown 2012, Wang and others 2006).

The negative effect of PFS in the first growing season on seedling survival in subsequent years was partially mitigated if the tree had a relatively large stem height at planting (fig. 1), probably because the tree had more above-ground structure to physiologically compensate for the negative effects of the drought. By year 6, trees planted with the tallest stem heights under the highest level of PFS had similar survival to shorter trees planted under lower level of PFS. An alternative hypothesis to explain the negative relationship between PFS and survival could be because competition increased over time in units that had high PFS in 2007. However, competition data (not shown) indicated that competition did not increase in density or height in relation to PFS levels in 2007.

Root-collar diameter or GLD can be used as a proxy for root system development, as it has been highly correlated to root volume or number of roots in American chestnut and oak species (Clark and others 2000, 2010, 2012b, Jacobs and others 2004). The negative relationship between GLD and survival was surprising given that seedling size at planting, particularly related to root system morphology, has been positively related to survival in other Fagaceae species such as oak (Dey and others 2008). Large seedling GLD at planting could be a less important indicator for improving survival of American chestnut seedlings compared to oak species. Seedling size at planting did not affect survival after five growing seasons for American chestnut seedlings in high or low light conditions (Clark and others 2012a), after 1 year in shelterwood or clearcut plantings (Clark and others 2010), or after four growing seasons underplanted in a midstory removal (Belair and others, in review). In greenhouse studies, American chestnut's root-to-shoot ratio was lower than oak species across a range of light availability (Latham 1992), suggesting chestnut allocates more energy to the stem growth at the expense of root development. Another study found that the American chestnut seedlings increased root development compared to shoot development as PFS increased (Wang and others 2006). In this study, the negative effect of GLD was only significant in the presence of the PFS variable. Trees were not able to support a larger root system, particularly if planted in low light conditions. At higher light levels, drought conditions appeared to be the primary limiting factor for survival. Height at planting also interacted with GLD, and the negative effect of GLD was partially mitigated if the seedling was tall. Taller seedlings at planting would presumably have more leaf area to assimilate carbon for maintenance of below-ground structures (Wang and others 2006).

Most units that burned in 2010 contained trees that sprouted following the burn (table 1), potentially diminishing the effect of burning on survival. The ability of American chestnut to sprout following topkill has been well documented for sprouts from mature rootstock (Paillet 1984, 1988), but few studies have sought to quantify the response of planted seedlings to topkill (Belair and others, in press).

Deer browse

The negative relationship of seedling height to deer browse was consistent with previous studies that have shown shorter hardwood seedlings are more likely to be browsed (Oswalt and others 2006). The positive effects of prescribed burning on the abundance and exposure of available browse and mast for deer consumption has been documented (Dills 1970, Ivey and Causey 1984). Prescribed burning probably increased browsing to planted seedlings by attracting deer to the burned area. The logistic regression did not show a significant effect of harvest treatments on deer browse in the presence of other significant variables, but the data do suggest that browse on chestnut seedlings was more frequent in thinned areas (39 percent) compared to patch clearcuts (7 percent) 4 years after planting (table 1). Deer browse to planted seedlings was not apparent after 2010, probably because the University of the South instituted new hunting pressure within the forest property that reduced deer population levels. Our results indicate that burning could negatively affect restoration attempts in areas with high deer populations, particularly for smaller size seedlings. Protection measures, such as trees shelters, could reduce browse effects, but they are expensive and might create a microclimate conducive to chestnut blight (Ponder 1995).

Height

Prescribed burning, either before or following seedling planting, did not affect height of seedlings. Our results were not in agreement with a previous study that found prescribed burning prior to planting increased growth of direct-seeded chestnuts in harvested and in unharvested forests (McCament and McCarthy 2005). The lack of replication of the pre-plant burn probably made response to this treatment more difficult to detect. We partially attribute the negligible effect of post-planting prescribed burning on height to the ability of American chestnut to prolifically sprout following topkill (Matoon 1909, Paillet 1984). In addition, prescribed fires are often highly variable and patchy in nature even within a relatively small spatial area (Arthur and others 2012). The fires probably did not affect every planted tree or their competition similarly. This high variation could lead to the inability to detect fire as a significant effect. Other variables besides prescribed burning were more important in influencing height of American chestnut seedlings.

Height at planting was predicted to positively influence total height, suggesting tree size at planting will be important in affecting overall competitiveness of American chestnut seedlings. The importance of seedling quality has been clearly demonstrated with oak species (Dey and others 2008) and has been shown to positively affect growth of American chestnuts planted in regeneration harvests (Clark and others 2012a). The negative effect of PFS on height was surprising given that American chestnut grows best as percent full sun increases (Latham 1992, Wang and others 2006), but as with survival, we attribute this response to influences from the 2-year drought that occurred at the time of planting. The drought probably interacted with PFS and local site conditions to reduce the ability to assimilate carbon under the highest light levels, particularly on more xeric sites.

Seedlings should be planted in areas where dieback is less likely to occur. While not empirically tested, dieback was more common in thinned stands (43 percent) versus patch clearcut stands (15 percent) after one growing season (table 1). Planting in commercially thinned stands reduced height compared to patch clearcut stands, probably because trees were limited by available light after the first growing season in thinned areas, particularly as drought effects diminished. Trees had higher rates of dieback in thinned areas because they were compensating for low light levels by sacrificing stem growth to maintain existing root structures (Latham 1992). Hand-thinning within the patch clearcuts increased height, similar to other studies that have shown competition control will increase height growth of planted hardwood seedlings (Spetich and others 2002). The tornado positively affected height probably because the tornado and salvage logging acted as a release to trees planted in the affected area.

CONCLUSIONS

This is one of the first empirical studies to document the ability of planted American chestnut seedlings to sprout following topkill by fire. Treatment effects of burning and harvesting were probably influenced and confounded by external disturbances, including a 2-year long drought and a tornado followed by salvage logging. Prescribed burning had a negligible effect on survival and height of planted American chestnut seedlings after 6 years, but burning appeared to attract deer. More browse was documented on seedlings planted in burned versus unburned areas. Given that American chestnut planting stock is difficult to procure and quite valuable, we would not currently recommend using prescribed burning in areas where American chestnut seedlings have been planted in order to avoid losses or injury. Furthermore, injury to seedlings from prescribed burning could potentially interfere with their ability to resist diseases such as blight.

Seedlings in this study were more influenced by harvesting, amount of PFS in the first growing season, and seedling size at planting than by prescribed burning. However, PFS in 2007 was probably reduced by a drought, and its effects should be interpreted with caution. Managers seeking to efficiently use limited resources to artificially regenerate American chestnut should plant seedlings with large stem heights in areas treated using a regeneration harvest, like a patch clearcut used in this study. Planting within commercially thinned areas may not be a viable option in restoration of American chestnut in the short term. Trees may be able to be successfully released several years after being planted in a commercial thinning, but these trees may have stagnate height growth or even dieback in the meantime. This study also suggests that during a severe drought, American chestnut may not be able to survive or grow if planted in environments with relatively high light levels and/or on xeric sites. Future research with more replication is needed to confirm or reject predictions made in this study, particularly regarding seedling response to various environmental conditions and silvicultural treatments, including prescribed burning.

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Table 1—Survival, total height, deer browse, stem dieback, chestnut blight, and sprouting after 1 (2007), 4 (2010), and 6 (2012) growing seasons for American chestnut seedlings planted in experimental units affected by harvesting, prescribed burning in 2007 and 2010, percent full sun in 2007, hand-thinning, and tornado

Block		1	1	1	1	2	2	2	2	3	3	3	3	
Unit Number		1	2	3	4	5	6	7	8	9	10	11	12	All
Harvest Type[a]		PC	PC	T	T	PC	PC	T	T	PC	PC	T	T	
Burning 2007[b]		No	No	No	No	No	No	No	No	No	Mod	No	Mod	
PFS 2007		33	19	13	21	24	24	20	39	40	64	34	37	31
Hand-thinning 2009		Yes	No	No	No	Yes	No	No	No	No	No	No	No	
Tornado 2010		No	Yes	No	Yes	No	No	No	No	No	No	No	No	
Burning 2010[b]		No	Mild	No	Mild	No	Mod	No	No	No	Mod	No	Mod	
Survival (percent)	2007	100	100	80	60	80	100	80	20	80	40	80	60	73
	2010	40	60	80	60	80	40	80	20	40	0	80	40	51
	2012	20	60	20	60	80	40	80	20	20	0	40	40	39
Total Height (cm)	2007	124	148	127	101	130	141	167	18	116	60	122	142	127
	2010	343	254	119	114	263	217	103	110	75	--	149	61	164
	2012	558	408	178	262	343	313	129	127	138	--	57	64	236
Deer browse (percent)	2007	20	60	20	0	20	60	25	0	100	100	0	67	42
	2010	0	33	25	33	0	0	25	100	0	--	0	50	20
	2012	0	0	0	0	0	0	0	0	0	0	0	0	0
Stem Dieback (percent)	2007	20	20	100	0	0	0	0	100	0	50	25	33	23
	2010	0	33	50	67	0	50	75	100	0	--	25	50	40
	2012	0	0	0	0	33	0	25	0	0	--	100	50	22
Chestnut blight (percent)	2007	0	0	20	0	0	0	0	0	0	0	0	0	2
	2010	60	60	20	0	25	60	40	0	20	0	40	20	32
	2012	60	40	80	40	25	60	40	0	40	0	80	20	41
Sprout from base (percent)	2007	20	20	0	0	0	0	0	0	0	50	25	0	9
	2010	0	33	25	0	0	50	25	100	0	--	25	50	20
	2012	0	0	0	0	0	0	0	0	0	--	50	0	4

[a] PC=patch clearcut; T=Commercial thinning; PFS=percent full sun.
[b] Prescribed burns were described as mild or moderate (Mod) in intensity.

Table 2—Parameter estimates (standard errors in parenthesis), Wald chi-square statistics, and p-values for variables and interactions in logistic regression models to predict survival probabilities (n = 354) and deer browse (n = 188)

Variable	Parameter estimate	Wald	p
Survival			
Intercept	1.0050 (0.3045)	10.8937	<0.0001
YSP	-0.3105 (0.0737)	17.7282	<0.0001
HT-115.12[a]	0.0100 (0.0058)	2.4305	0.1190
1/GLD- 0.114	14.6810 (5.7973)	6.4131	0.0113
(PFS^2/100)-11.136	-0.1030 (0.0174)	34.9944	<0.0001
(HT-115.12)*(1/GLD- 0.114)	0.2631 (0.1466)	3.2193	0.0728
(HT-115.12)*[(PFS^2/100)-11.136]	0.0008 (0.0004)	3.3269	0.0682
Deer browse			
Intercept	1.9002 (0.7559)	6.3193	0.0119
YSP	-0.4556 (0.1281)	12.6419	0.0004
HT	-0.0176 (0.0057)	9.6655	0.0019
Burn 2007	1.9382 (0.6019)	10.3683	0.0013

[a] To avoid multicollinearity, continuous variables were first centered by subtracting the mean before being used in transformations. YSP=year since planting, HT=planting height, GLD=planting ground-line diameter, PFS=percent full sun in growing season 2007.

Table 3—Parameter estimates (standard errors in parenthesis) and associated F and p values for a multiple regression model to predict height (n = 187)

Variable	Parameter estimate	F	p
Year	0.0368 (0.0250)	2.16	0.1431
Height at planting	0.0036 (0.0011)	11.57	0.0008
PFS 2007	-0.0141 (0.0042)	11.22	0.0010
Dieback	-0.7126 (0.0807)	78.06	<0.0001
Tornado	0.3623 (0.1466)	6.11	0.0144
Patch Clearcut (PC) without hand-thinning (no HT)			
Intercept	4.8905 (0.1929)	15.92	<0.0001
PC HT	0.5948 (0.1455)	15.92	<0.0001
Thin	-0.1755 (0.0840)	15.92	<0.0001
Patch Clearcut (PC) with hand-thinning (HT)			
Intercept	5.4853 (0.2282)	15.92	<0.0001
PC no HT	-0.5948 (0.1455)	15.92	<0.0001
Thin	-0.7702 (0.1383)	15.92	<0.0001
Commercial thinning (Thin)			
Intercept	4.7150 (0.1939)	15.92	<0.0001
PC no HT	0.1755 (0.0840)	15.92	0.0381
PC HT	0.7702 (0.1383)	15.92	<0.0001

YSP=year since planting, PFS 2007=percent full sun in growing season 2007.

Note: Height was transformed by the natural log. Intercepts and parameter estimates unique to each level of the harvesting class variable are given.

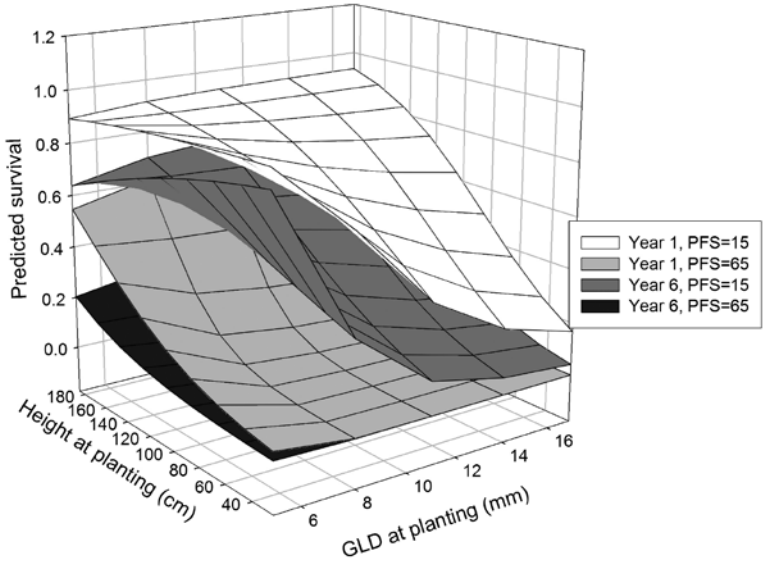

Figure 1—Predicted survival probabilities for American chestnut seedlings based on tree height and ground-line diameter (GLD) at planting for high and low values of percent full sunlight (PFS) at years 1 and 6 after planting.

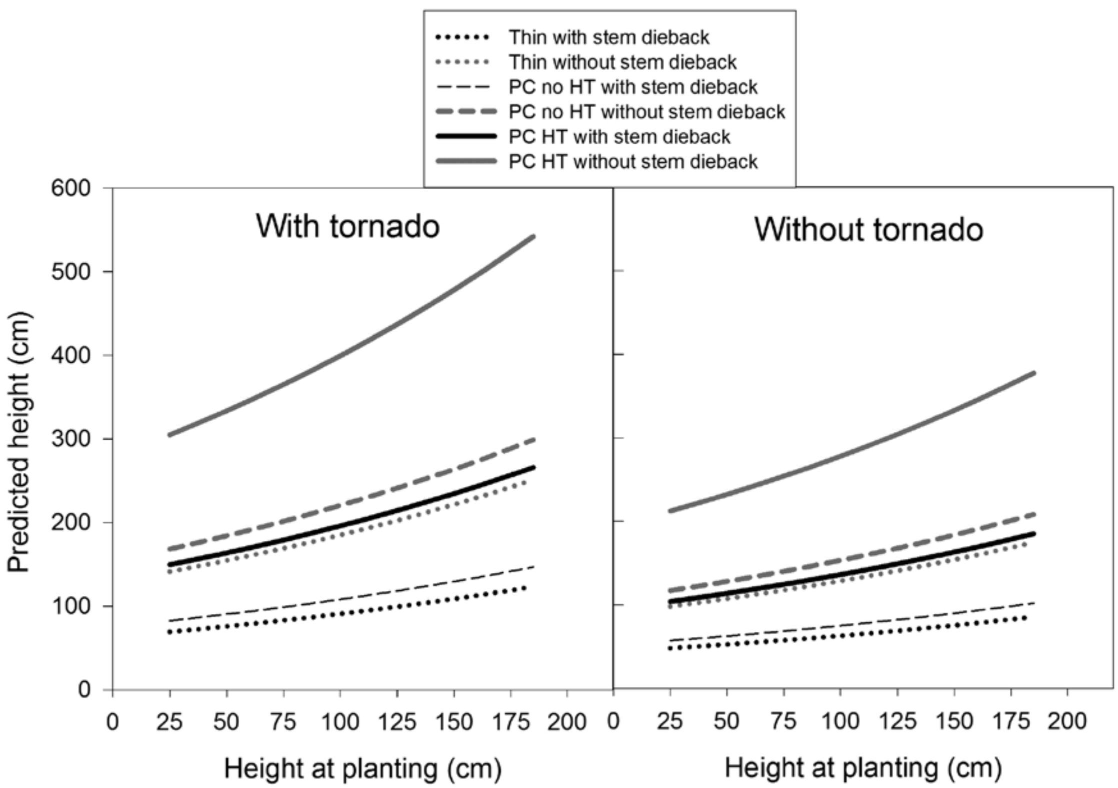

Figure 2—Predicted height 6 years after planting for trees growing under 31 percent full sun in areas affected or not affected by the 2010 tornado. Predictions are shown by planting height and stem dieback occurrence for three harvesting treatments: commercial thinning (Thin), patch clearcuts (PC) with hand-thinning (HT), and patch clearcuts (PC) without hand-thinning (no HT).