Hybrid Aspen Response to Shearing in Minnesota: Implications for Biomass Production

Grant M. Domke, Andrew J. David, Anthony W. D'Amato, Alan R. Ek, and Gary W. Wycoff

ABSTRACT

There is great potential for the production of woody biomass feedstocks from hybrid aspen stands; however, little is known about the response of these systems to silvicultural treatments, such as shearing. We sought to address this need by integrating results from more than 20 years of individual tree and yield measurements in hybrid aspen (*Populus tremuloides* Mich. × *P. tremula* L.) stands in north central Minnesota. Specifically, tree and stand-level responses are described in terms of sucker density, early diameter and height characteristics, volume, and biomass production. Overall, shearing treatments increased the density of hybrid aspen stems, relative to preshear densities at the same age. In addition, average stem diameter and volume as well as stand-level biomass were considerably greater in hybrid aspen stands relative to similarly aged native aspen stands also established via shearing treatment. These findings illustrate that coppice systems using hybrid aspen provide great potential to rapidly produce biomass feedstocks, with little management investment.

Keywords: carbon storage, coppice, *Populus tremuloides, Populus tremula*, yield

Renewed interest in the use of woody biomass for energy has created an opportunity for the development of silvicultural systems that can produce high levels of biomass over shorter rotations than traditional approaches to plantation management (Weih 2004, Dickmann 2006). One area within this arena where there is a great deal of potential is the management of short-rotation hybrid aspen (Liesebach et al. 1999, Karacic et al. 2003, Rytter 2006). In particular, early successional hardwood tree species—such as those in the *Populus* genus—typically exhibit rapid initial height and diameter growth, making these species ideally suited for short-rotation forestry applications aimed at maximizing biomass production over short timescales (Johnsson 1953, Karacic et al. 2003, Rytter 2006). In many cases, greater levels of early growth have been achieved through the use of aspen hybrids, such as the cross between quaking aspen (*Populus tremuloides* Michx.) and European aspen (*Populus tremula* L.). The improved growth of hybrid aspen over the parental species is thought to be the result of heterosis. Li and Wu (1997) suggest that the improved growth of hybrid aspen might be caused by overdominance interaction between two alleles, one from the *P. tremula* parent and the other from the *P. tremuloides* parent, at the same locus.

In addition to the rapid growth of these hybrids, their prolific root sprouting presents potential management options for the production of woody biomass using coppice methods after initial plantation establishment (Liesebach et al. 1999). Moreover, the use of existing aspen rootstocks as sources of regeneration for subsequent rotations provides a silviculturally straightforward and cost-effective means for sustaining these systems over multiple short rotations (Hofmann-Schielle et al. 1999). Finally, the expansion of aspen root systems with each subsequent rotation may provide a long-term opportunity for increasing belowground carbon storage on these sites (King et al. 1999).

Most research on hybrid aspen has focused on the quantitative genetics and early growth of selected genotypes in highly controlled field and laboratory environments (Benson and Einspahr 1967, Li and Wu 1997, Tullus et al. 2007). Very few studies have examined the response of hybrid aspen to silvicultural treatments at operational scales. In the mid-1980s, the Aspen/Larch Genetics Cooperative at the University of Minnesota began a series of hybrid aspen planting trials in north central Minnesota. These trials were initiated to compare hybrid aspen (*P. tremuloides* × *tremula*) stand characteristics to native aspen (*P. tremuloides*) stand characteristics on similar sites. In the mid- to late 1990s, the hybrid aspen stands were sheared to compare hybrid aspen sucker density and growth with native aspen suckering and growth. Shearing is an effective technique for stopping the flow of auxin from the aboveground portion of the tree to the root system, initiating the development of new meristems and preexisting primorida on the roots, which often develop into suckers (Schier 1981, Perala 1983, Frey et al. 2003). During that period, two native aspen stands, which were representative of much larger aspen sites in the study area, were added to the study to more closely compare hybrid aspen stand attributes with native aspen stand attributes. Funding and personnel changes, as well as operational constraints over the 23-year study period, limited sampling and measurement in certain years. Nevertheless, this study is one of the largest and longest of its kind and the data provide

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This article uses metric units; the applicable conversion factors are: centimeters (cm): 1 cm = 0.39 in.; cubic decimeters (dm^3): 1 dm^3 = 61.023 $in.^3$; meters (m): 1 m = 3.3 ft; square meters (m^2): 1 m^2 = 10.8 ft^2; cubic meters (m^3): 1 m^3 = 35.3 ft^3; hectares (ha): 1 ha = 2.47 ac; kilograms (kg): 1 kg = 2.2 lb.

Table 1. Description of study sites, sample sizes, and site activities.

Site	Area (ha)	Site index (m at base age 50 yr)	Date	Stand age (yr)	Site activity	No. of plots	Plot size (m^2)
Hybrid 1	12	24.4	Mar. 1986	1	Planted		
			Jan. 1998	13	Sampled	28	81
			Mar. 1998	13	Sheared		
			Dec. 1998	1	Sampled	26	4
			Aug. 2001	4	Sampled	23	10
			Apr. 2008	10	Sampled	27	16
			May 1986	1	Planted		
			Mar. 1993	8	Sampled	16	405
			Mar. 1994	8	Sheared		
Hybrid 2	8	21.3	Nov. 1998	5	Sampled	14	4
			May 2008	14	Sampled	23	16
			Apr. 1991	1	Planted		
			Dec. 1997	7	Sampled	26	81
Hybrid 3	12	21.3	Mar. 198	7	Sheared	19	4
			Apr. 2008	10	Sampled	26	16
			Jan. 1998	1	Clearcut		
Native 1	2	21.6	Apr. 2008	10	Sampled	5	16
			Jan. 1998	1	Clearcut		
Native 2	2	21.6	Apr. 2008	10	Sampled	5	16

useful reference points for future studies on hybrid aspen growth and yield.

The study results are used to examine (1) regeneration response of hybrid aspen pre- and postshearing, (2) native and hybrid aspen tree characteristics (height, diameter, and volume) pre- and post-shearing, and (3) native and hybrid aspen volume and biomass production postshearing. In addition, the findings are used to evaluate potential silvicultural options for managing hybrid aspen stands and their implications to carbon storage and biomass production for energy.

Methods

Site Conditions and Treatment History

This study was conducted in five stands located near Grand Rapids, Minnesota (47°15′N, 93°30′W). The most common soil type on the sites was Stuntz very fine sandy loam (Glossoboric Hapludalf; Natural Resources Conservation Service 2009). All sites had the same ecological classification (UPM Blandin Paper Company system) with site indices ranging from 21.3 to 24.4 m for native aspen at a base age of 50 years (Cheryl Adams, pers. comm., UPM Blandin Paper Company, Nov. 6, 2009). The climate is continental with warm summers (mean July temperature, 20°C), cold winters (mean January temperature, −14°C), and 731 mm of precipitation, about half of which occurs during the growing season (National Oceanic and Atmospheric administration 2004). The five sites were treated with glyphosate (Accord) before planting and sheared at different dates over the course of the study (Table 1). All sites were sheared in late winter or early spring under frozen ground conditions to minimize damage to root systems. Shearing was consistent on all sites and occurred by cutting and felling stems with a "KG" blade mounted on a crawler tractor. The shearing equipment used in this study was to apply a treatment without cost consideration. Current methods often use brushsaws. Table 1 summarizes stand information. All hybrid aspen stands in the study were planted with a mixture of hybrid aspen families to ensure genetic diversity and ameliorate major pest problems (Roberds and Bishir 1997, Weih 2004).

Sampling Methods

Plot and sample sizes varied across sites and sample periods in this study (Table 1). Permanent plot centers were established in the hybrid 1 and hybrid 3 sites and nonpermanent plots were taken in the hybrid 2, native 1, and native 2 sites. In all cases, a systematic line plot design was used with transect locations determined by a random start and plot centers established along these transects. All live native and hybrid aspen stems were measured in each plot. This is noteworthy because hybrid aspen suckers may develop from the established root systems of the planted hybrid aspen seedlings before shearing.

The tree variables of interest in this study were stems per hectare, dbh, total tree height, individual tree volume, total stand volume, and aboveground biomass production. Tree diameter was measured at 1.3 m aboveground using calipers, and total height was measured using a telescoping measuring rod or, when necessary, a digital hypsometer. Stem volume was calculated using individual tree height and diameter information and an equation originally developed by Gevorkiantz and Olsen (1955) and modified by Ek (1985) for small aspen stems:

$$V = FBH,$$

where V is the peeled volume of an individual stem (m^3), F is the cylinder form factor, (for trees <9.14 m in height, $F = 0.42 + 0.02[9.14 - H]$; for trees ≥9.14 m, $F = 0.42$), B is the basal area (m^2) computed from dbh outside bark, and H is tree height (m). Stand volume estimates were calculated according to Ek and Brodie (1975):

$$Vs = 0.4972(H - 4.5)^{1.9139}N^{0.1439},$$

where Vs is total stem volume (1 ft^3/ ac = 0.0670 m^3/ha) from 0.15-m stump to tip of all trees ≥0.30 m tall, H is average dominant height (ft; 1 ft = 0.3048 m), and N is trees per acre (1 ac = 0.405 ha). Individual tree biomass was calculated according to Jenkins et al. (2003):

$$bm = Exp(\beta_0 + \beta_1[\ln]\, dbh),$$

where bm is total aboveground oven-dry biomass (kg) for trees 2.5-cm dbh and larger, β_0 is −2.2094, β_1 is 2.3867, dbh is diameter at breast height (cm), Exp is exponential function, and ln is natural log base "e" (2.718282).

Table 2. Pre- and postshear stem density information for the five study sites.

Site	Age (yr)	Status	Type	Stems per hectare: Mean	Standard deviation	CV (%)
Hybrid 1	13	Preshear	Sapling	234	261	112
			Sucker	1,456	1,150	79
			Total	1,690	1,274	75
	1	Postshear	Sucker	32,790	23,355	71
	4	Postshear	Sucker	40,720	27,171	67
	10	Postshear	Sucker	6,521	4,410	68
			Sapling	406	340	84
	8	Preshear	Sucker	164	185	113
			Total	570	445	78
Hybrid 2	5	Postshear	Sucker	8,119	6,387	79
	14	Postshear	Sucker	2,149	1,776	83
			Sapling	504	275	55
	7	Preshear	Sucker	979	867	89
			Total	1,483	966	65
Hybrid 3	1	Postshear	Sucker	14,177	11,409	80
	10	Postshear	Sucker	4,396	3,326	76
Native 1	10	Postshear	Sucker	7,537	1,874	25
Native 2	10	Postshear	Sucker	8,525	4,377	51

Table 3. Descriptive statistics of the measured and calculated individual tree characteristics: tree height (m), dbh (cm), and volume (dm^3) for grouped sites: Hybrid 3 (age, 7 yr) and hybrid 2 (age, 8 yr) aspen saplings and suckers before shearing treatments, hybrid 1 and hybrid 3 (age, 10 yr) suckers postshearing, and native 1 and native 2 (age, 10 yr) suckers postshearing.

Grouped sites	No. of plots	Tree characteristics	Mean	Standard deviation	CV (%)
Hybrid 2 and hybrid 3 (preshear saplings)	41	Height (m)	4.54	1.44	32
		dbh (cm)	3.38	1.42	42
		Volume (dm^3)	3.35	3.41	102
		Height (m)	2.89	1.28	44
Hybrid 2 and hybrid 3 (preshear suckers)	37	dbh (cm)	1.60	0.87	54
		Volume (dm^3)	0.66	0.93	141
		Height (m)	9.19	2.18	24
Hybrid 1 and hybrid 3 (postshear suckers)	53	dbh (cm)	6.05	2.02	33
		Volume (dm^3)	16.26	13.82	85
		Height (m)	5.93	1.41	24
Native 1 and native 2 (postshear suckers)	10	dbh (cm)	3.60	1.00	28
		Volume (dm^3)	4.02	2.35	58

Data Analysis

Because of the variability in plot and sample sizes across sites and sample periods and the lack of control plots at each site, only descriptive statistics were used to analyze treatment effects, tree characteristics, and yield information. Plot-level data were used throughout the analysis. All statistical analysis was conducted using R statistical software, Version 2.10.0 (The R Foundation for Statistical Computing 2009).

Results

Stem Density

Pre- and postshear stem density information is presented in Table 2. There was considerable variation in stem density across plots within hybrid aspen stands, but mean stem density increased on all three sites after shearing. Ten years postshearing stem density in the hybrid 1 site was nearly 3.9 times (mean = 6,521) that of the 13-year-old presheared stand. The hybrid 3 site had 1,483 stems/ha 7 years postplanting and 10 years after shearing stem density increased nearly 3.0 times to 4,396 stems/ha. The hybrid 2 site had substantially fewer stems (mean = 570) than the other two hybrid aspen sites before shearing. Fourteen years postshearing, stem density increased nearly 3.8 times that of the presheared stand to 2,149 stems/ha. Because of the late addition of the native aspen stands, stem density was not measured before shearing. Ten years postshearing the native 1 and native 2 sites had 7,537 and 8,525 stems/ha, respectively.

Tree Characteristics

Given that the sampling periods were not aligned for the different sites and the shearing treatments occurred at different times, data were combined according to pre- and postshear stand ages to focus our analysis of tree characteristics and yield information. Pre- and postshear site combinations and tree characteristics are summarized in Table 3.

Preshear hybrid aspen suckers (which arose from the planted seedlings and were several years younger at the time of shearing) and saplings were compared on the hybrid 2 and hybrid 3 sites (Table 3). The preshear hybrid aspen saplings were more than 1.5 times (mean = 4.54) taller than preshear hybrid aspen suckers (mean = 2.89) and there was less variability within the sample (coefficient of variation [CV] = 32%). Preshear saplings also had greater diameter growth (mean = 3.38 cm) than the hybrid aspen suckers (mean = 1.60 cm) on the two sites and substantially higher individual tree volume and biomass production than hybrid aspen suckers (Table 3). Preshear hybrid aspen tree characteristics on the hybrid 2 and hybrid 3 sites were also compared with postshear native and hybrid aspen sucker characteristics. In all cases, postshear native and hybrid

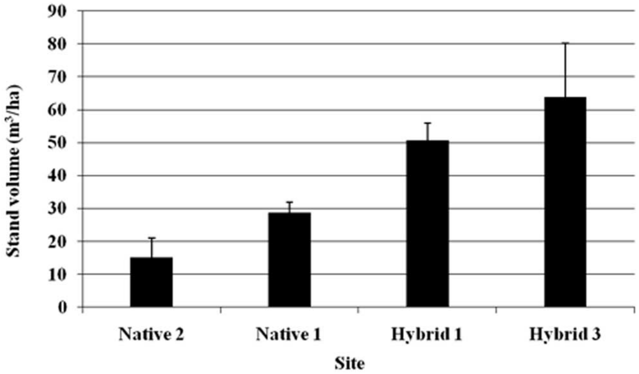

Figure 1. Estimated total stand volume (m^3/ha) from the 0.15-m stump to the tip of all trees ≥0.30 m tall for postshear 10-year-old native and hybrid aspen stands. Native 1 and 2 sites (site index = 21.6), hybrid 1 site (site index = 24.4), and hybrid 3 site (site index = 21.3). Values are means ± SE.

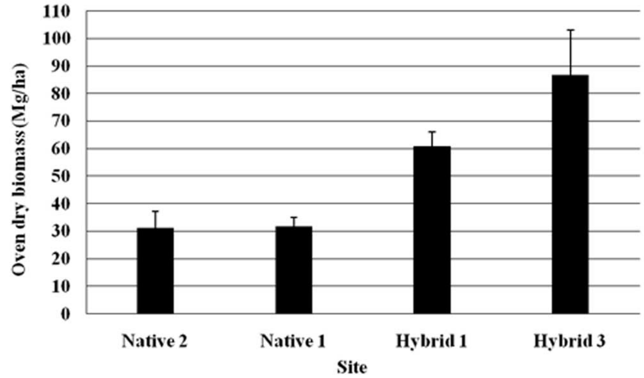

Figure 2. Estimated total aboveground biomass (oven-dry mg/ha) for trees 2.5-cm dbh and larger for postshear 10-year-old native and hybrid aspen stands. Native 1 and 2 sites (site index = 21.6), hybrid 1 site (site index = 24.4), and hybrid 3 site (site index = 21.3). Values are means ± SE.

aspen tree characteristics were greater than preshear values (Table 3).

Postshear aspen suckers from the hybrid 1 and hybrid 3 sites (both age 10 years) were compared with aspen sucker characteristics on the native 1 and native 2 sites of the same age. Hybrid aspen suckers were more than 1.5 times taller (mean = 2.18) than native aspen suckers (mean = 1.41) with no difference in height variability between the grouped sites (CV = 24%). Aspen sucker diameters in the hybrid 1 and hybrid 3 sites were nearly 1.7 times greater than sucker diameters in the native 1 and native 2 sites with a small difference in diameter variation between the two grouped sites (Table 3).

Volume and Biomass Production

Stand volume and biomass production were compared on the 10-year-old native (native 1 and native 2) and hybrid (hybrid 1 and hybrid 3) aspen sucker stands. Stand volume was substantially higher on both hybrid aspen sites relative to the native aspen stands (Figure 1). The hybrid 3 site had the highest stand volume (mean = 63.94), which was more than 4.2 times that of the native 2 site. Individual tree biomass in the hybrid sites was more than 3.6 times (mean = 14.43) greater than in the native sites (3.97) of the same age. Stand-level biomass production was calculated using the mean stems per hectare on the native and hybrid aspen sucker sites. The hybrid aspen sites produced substantially more biomass per hectare than the native aspen sites of the same age (Figure 2). The hybrid 3 site averaged nearly 2.8 times (mean = 86.66) as much biomass per hectare as the native 2 site (mean = 31.34).

Discussion

Renewed interest in the use of woody biomass for energy has created an opportunity for the development of silvicultural systems that can produce high levels of biomass over shorter rotations than traditional approaches to plantation management. This is one of only a few studies examining hybrid aspen sapling and sucker response to shearing treatments at an operational scale. The results suggest that hybrid aspen yield can be substantially higher than the already high-yielding parental species and that shearing is a viable option for increasing stand density on marginally stocked sites.

Stem Density

Shearing hybrid aspen sapling and sucker stands ranging in age from 7 to 13 years substantially increased initial hybrid aspen sucker density on all sites (Table 2). These results are consistent with a similar shearing study conducted in native aspen stands with similar site index in north central Minnesota (Perala 1983). Hybrid aspen sucker density increased on the hybrid 1 site from years 1 to 4 after the shearing treatment and subsequently began to decrease. The initial increase is not surprising, given native aspen suckers typically continue to appear in the first 2 years after treatment (Brown and DeByle 1987). Thereafter, self-thinning begins and continues throughout the life of the stand (Peet and Christensen 1987). Preshear sucker density in young hybrid aspen stands may also contribute to postshear regeneration success. In this study, the hybrid 1 site had the highest mean sucker density and the lowest mean sapling density of the three hybrid aspen sites at the time of shearing (age 13 years) and produced more than two times as many suckers per hectare in the 1st year postshearing as the next highest hybrid aspen site (Table 2). The higher preshear sucker densities would generally be a sign of higher root densities, which would translate into higher postshear sucker densities (Graham et al. 1963, Frey et al. 2003).

There are several other factors that may have contributed to the differences in sucker density after shearing. These include preshear stand age; family variation; differences in site index, soil moisture, and soil temperature; and varying levels of harvesting and traffic impacts to existing root systems (Li and Wu 1997, Frey et al. 2003). Despite large differences in stand density before and after shearing and extensive self-thinning in the 10 years postshearing, all three hybrid aspen stands exceeded full stocking recommendations (Perala 1983) for native aspen in the last sample period. These findings suggest that shearing is a viable option for improving stocking in young hybrid aspen stands.

Tree Characteristics

Preshear 7- and 8-year-old hybrid aspen saplings and suckers were compared on the same sites (hybrid 3 and hybrid 2). The planted hybrid aspen saplings were substantially larger than the hybrid aspen suckers (Table 3). This is not surprising because the planted hybrid aspen seedlings must establish strong root systems before producing suckers. This may occur in as little as 3 years under ideal conditions but when herbivory and vegetative competition exists, the process may take much longer.

A comparison of preshear 7- and 8-year-old hybrid aspen saplings to postshear 10-year-old native aspen suckers revealed that the native aspen stands had slightly higher mean diameter and volume and markedly higher mean height (Table 3). This may be caused by age but may also be the result of competition for light with other aspen suckers. As aspen stem density increases and light levels decrease, suckers must forage for light and allocate resources to height growth rather than diameter growth (Comeau 2002). In the preshear hybrid aspen stands, stem density was relatively low, with stems scattered individually or in pockets, so competition for light was not as severe as it typically is in native aspen sucker stands of similar age. These height characteristics are consistent with other studies, which have found that planted hybrid aspen saplings require a period of adaptation and root expansion before vigorous height and diameter growth can begin (Luoranen et al. 2006). Even with this adaptation period, the preshear 7- and 8-year-old hybrid aspen saplings in this study had similar mean diameter and volume per tree as the postshear 10-year-old native aspen suckers. The height and diameter characteristics from the hybrid aspen saplings in this study are also consistent with hybrid aspen studies in Sweden, Finland, and Estonia (Yu 2001, Rytter 2006, Tullus et al. 2007). As with differences in sucker density, differences in stand age, family, and microclimate may also be contributing to these trends in height characteristics (Barnes 1966).

Postshear native aspen sucker heights and diameters were also compared with postshear hybrid aspen sucker characteristics in stands of the same age. The 10-year-old hybrid aspen stands were substantially taller and had higher mean diameter than the native aspen sucker stands (Table 3). Hybrid aspen suckers were more than 3 m taller and 2 cm in diameter larger at breast height than native aspen suckers of the same age. These large increases point to hybrid vigor, although it must be noted that stand density was higher in the native aspen stands. The increased height and diameter growth of the hybrid suckers resulted in a concomitant increase in individual stem volume. Mean hybrid aspen stem volume in the 10-year-old stands was more than 4.0 times higher than native stems of the same age. The improved volume is not surprising given the diameter and height characteristics and results from similar studies in the Midwest and Scandinavia. For example, a study in Iowa found that the mean annual increment (MAI) of hybrid aspen stems at age 10 years was approximately 1.42 dm^3, which is consistent with results from the postshear hybrid aspen sites (MAI = 1.62) in this study (Hall et al. 1982). Similarly, Yu et al. (2001) found that mean estimated stem volume of 5-year-old hybrid aspen was 3.9 times that of native European aspen (*P. tremula*) in Finland. That said, microclimatic variation and differences in stand density and site index across the sites may have contributed to the large difference in tree volume.

Stand Volume, Biomass Production, and Carbon Storage

Stand volume varied substantially across the four 10-year-old stands. This was likely because of differences in stand density and individual tree volume across the four sites. The hybrid aspen stands (hybrid 1 and hybrid 3) had much lower stem density (Table 2) than the native aspen sites (native 1 and native 2) but substantially higher individual tree volumes (Table 3), resulting in markedly higher stand volume estimates (Figure 1).

The 10-year-old hybrid aspen stands produced more than twice as much biomass per hectare as the 10-year-old native aspen stands (Figure 2). These yields are consistent with those found in hybrid aspen stands in Sweden (Rytter and Stener 2003, Rytter 2006), Germany (Liesebach et al. 1999), and Iowa (Hall et al. 1982) and native aspen stands in north central Minnesota (Perala 1983). Nonetheless, these findings should be interpreted with caution. In particular, the biomass equation used to calculate oven-dry weight of aboveground woody material was developed through a large-scale, nationwide meta-analysis (Jenkins et al. 2003). Although this equation is useful, stand-specific, local or regional equations would be more appropriate to accurately estimate woody biomass production.

Much of the renewed interest in hybrid aspen and other fast-growing tree species has revolved around renewable fuels and the potential fossil fuel offsets of using woody biomass for energy (Kauter et al. 2003); however, there is also potential for substantial belowground carbon storage with the expansion of living root systems. The root systems of most tree species die when the aboveground portion of the tree is removed (King et al. 2007); however, the root system of most *Populus* spp. in the section *Populus* (formerly Leuce; Eckenwalder 1996) remains active for decades and, in some cases, centuries after the aboveground portion of the tree is killed (Kemperman and Barnes 1976). These belowground structures provide the carbohydrates necessary for root suckers to establish after harvest (Barnes 1966, Frey et al. 2003). As root suckers grow, they contribute to the expansion of the belowground clonal root system and the process is repeated after each harvest or stand-replacing disturbance. Although some root die-off occurs after major disturbances, most of the belowground structures continue to grow and can extend many hectares in some parts of the aspen range although most are restricted to less than a hectare in size (Kemperman and Barnes 1976). With the establishment of short-rotation hybrid aspen plantations comes the establishment of long-term belowground carbon storage structures. These structures immediately begin storing carbon and continue to expand with each subsequent aboveground disturbance. As such, the use of hybrid aspen systems for the production of biofuel feedstocks may also offer an opportunity to increase belowground carbon storage and enhance the carbon offset potential of these areas.

Silvicultural Methods for Stand Development

The establishment of high-density, large-area plantations is currently constrained by limited quantities of high genetic quality planting stock, both seedling and clonal origin. Silvicultural approaches to overcome planting stock availability and high establishment costs have been examined on an operational scale. A recommended practice includes (1) controlling competing vegetation before planting 250–370 well-distributed trees/ha; (2) protecting planted seedlings from herbivory; (3) growing the trees for 6–8 years, allowing root systems to sufficiently develop and occupy much of the area between trees; and (4) cutting these sapling-size trees and producing a sucker stand. This approach adds 4–6 years to the first rotation (suckers reach heights of uncut stems very quickly). Another establishment method calls for interplanting hybrid aspen in every sixth row in larch (*Larix* spp.) plantations where pulpwood clearcut harvests are planned for age 20–25 years. These approaches have the advantage of low establishment costs and the deployment of rapid growing feedstock of limited availability.

Harvesting Considerations

Seasonality, cutting height, and equipment limitations are three important harvesting considerations in short-rotation coppice systems. Harvest timing is important given the interactions between apical dominance and seasonal fluctuations in carbohydrate reserves (Bates et al. 1993, Bell et al. 1999, Frey et al. 2003). In most native aspen stands in the Lake States regeneration success is not a concern so timing of the harvest, at least for the sake of regeneration, is not a major consideration (Mundell et al. 2008). In contrast, on sites where hybrid aspen is deliberately planted at low densities with the intention of increasing stem density through shearing, harvesting should be done during the dormant season to maximize sucker response. In addition, the height at which stems are harvested may be important when considering regeneration in young native and hybrid aspen stands. In particular, Bell et al. (1999) found that increasing the cutting height in young native aspen stands reduced sucker production and stem mortality and increased sprouts and overall sprout height. Finally, equipment capable of efficiently harvesting large quantities of small-diameter, high-density material on uneven terrain is not common in the Lake States. This type of equipment would be necessary for large-scale short-rotation systems to be cost-effective in the region.

Conclusion

This study, although somewhat limited statistically, shows that the use of hybrid aspen in combination with shearing treatments provides an effective and straightforward approach for generating woody biomass for energy relative to native *Populus* species. The use of coppice silvicultural systems with this forest type also provides an opportunity to increase belowground carbon storage, because of, in large part, the presence and expansion of clonal root systems over time in these areas. These increases in carbon are particularly important to consider in areas where hybrid poplar is being planted on former agricultural lands, because this will allow for the proper accounting of greenhouse gas offsets related to feedstock production within biofuels life cycle analyses (Searchinger et al. 2008). As such, future work examining the patterns of belowground carbon storage in these areas will be critical for generating reliable estimates of the impacts of these practices on regional patterns of carbon sequestration.

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