CHAPTER 5
Ecology and silviculture of poplar plantations

John A. Stanturf, Cees van Oosten, Daniel A. Netzer, Mark D. Coleman, and C. Jeffrey Portwood

Introduction

Poplars are some of the fastest growing trees in North America and foresters have sought to capitalize on this potential since the 1940s. Interest in growing poplars has fluctuated, and objectives have shifted between producing sawlogs, pulpwood, or more densely spaced "woodgrass" or biofuels. Currently, most poplar plantations are established for pulpwood or chip production on rotations of 10 years or less, but interest in sawlog production is increasing. Sid McKnight (1970) characterized cottonwood as a prima *donna* species: under ideal conditions, growth rates are just short of spectacular. Just as this can be applied to all poplars, it is equally true that all poplars are demanding of good sites and careful establishment. Growing poplars in plantations is challenging, and good establishment the first year is critical to long-term success. If a grower lacks the commitment or resources to provide needed treatments at critical times, then species other than poplars should be considered. Successful poplar culture can be illustrated by the triangle in Fig. 1 — plant proven clones on good sites and provide timely, appropriate cultural treatments. Our objective in this chapter is to provide

J.A. Stanturf.[1] USDA Forest Service, Center for Bottomland Hardwoods Research, P.O. Box 227, Stoneville, MS 38776, U.S.A.
C. **van Oosten.** SilviConsult Woody Crops Technology Inc., 2356 York Crescent, Nanaimo, BC V9T 4N3, Canada.
D.A. Netzer. USDA Forest Service, North Central Research Station, Rhinelander, WI 54501, U.S.A.
M.D. Coleman. USDA Forest Service, Savannah River institute, P.O. Box 700, Building 760-15G, New Ellenton, SC 29809, U.S.A.
C.J. Portwood.[2] Crown Vantage Corp., 5925 N. Washington St., Vicksburg, MS 39180, U.S.A.
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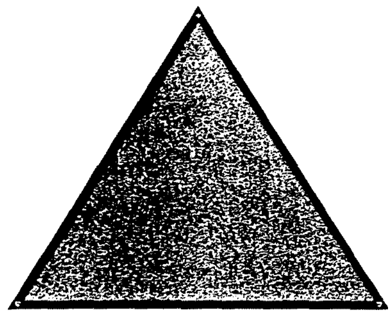
[1]Present address: Forestry Sciences Lab, 320 Green Street, Athens, GA 30602, U.S.A.
[2]Present address: Temple-Inland Forest, 207 N. Temple Drive, Diboll, TX 75941, U.S.A.

Fig. 1. Poplar plantation culture depends on three things: planting the best quality stock on high-quality sites and providing timely and appropriate cultural treatments.



growers with current information for establishing and tending poplar plantations, as practiced in North America. Where we have sufficient information, differences between the poplar-growing regions of the United States and Canada will be noted. Mostly information is available on eastern and black cottonwood, and their hybrids.

Propagation and production of planting stock

Great strides have been made in selecting and breeding superior poplar genotypes. One advantage of poplars is that superior material is quickly available for operational use because species of the ***Aigeiros*** and ***Tacamahaca*** sections used in North America are easy to propagate through asexual means, usually by vegetative propagation of unrooted dormant stem cuttings or sets (also called whips). This lends itself well to mass-propagation of selected varieties for operational use, but poor rooting ability may disqualify some genotypes. Eastern cottonwood (*Aigeiros* section) displays great variability in rooting ability. Interspecific hybrids within and between the ***Aigeiros*** and ***Tucumuhaca*** sections usually root well. Poplars in section *Populus* (the aspens) are difficult to propagate from stem cuttings, as are the interspecific hybrids between ***P. tremuloides*** and ***P. tremula.*** Two methods used in Canada for mass propagation of aspen are dormant root cuttings and seedlings from open-pollinated sources. Both methods are expensive and take longer to deploy superior genotypes.

Planting stock *types*

Poplar stock can be produced in several different types and is mostly a function of ease of propagation, desired end product, and cost (Table I). Unrooted dormant cuttings (Fig. 2) are produced from l-year-old stem material, varying in length

Table 1. Conditions under which certain poplar stock types can be used.

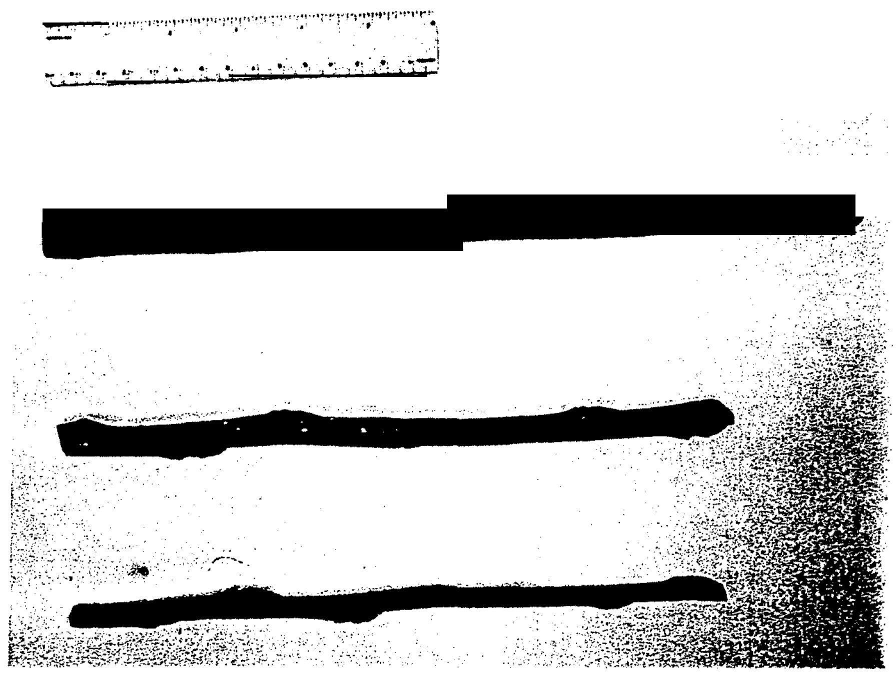
	Unrooted stock		Rooted stock		
			Bare root		
	Cuttings	Sets	Small	Sets	Container
Density of plantation (stems ha-')	>700	<400	>700	<400	>700
Plantation purpose	Fibre and solid wood	Solid wood	Fibre and solid wood	Solid wood	Research trials; new stoolbeds; extreme drought conditions at planting
Soil moisture conditions	Good	Excellent	Good	Good	Needs irrigation if planted in full leaf
Weed control	Excellent	Reasonable	Excellent	Reasonable	Excellent
Threat of browsers	High"-low	High	Low	High	Low
Timing of planting	U.S. South: early winter				
	U.S. Midwest, Pacific Northwest, and Canada: late winter to early spring	Late winter to early spring	Late winter to late spring	Late winter to late spring	Late winter to late spring (irrigated)

"With a high threat of browsers, deer fencing may be necessary.

from mini (2-3 cm) to regular cuttings (15 cm to a maximum of about 1 m long). When planted in soil, adventitious roots grow from stem pieces, but viable buds must be present for stems to form. Unrooted dormant sets can be cut from 1- or 2-year-old dormant material, but roots develop better from I-year-old material. Sets vary in length from 1.5 m to as long as 5 or 6 m. As with cuttings, buds are necessary for new stems to develop.

Planting unrooted dormant cuttings or sets in a nursery bed and allowing them to grow a viable root system produces rooted cuttings. Rooted cuttings (also called barbatelles) can be out-planted as dormant bareroot cuttings, equivalent to a 1-O seedling. Container plants are produced from seed, root cuttings (aspen), or small single-bud hardwood or greenwood cuttings. These plants are usually dormant

Fig. 2. Dormant, I-year-old, unrooted hardwood cuttings of poplar. The large cutting on the top is optimum; the cutting on the bottom is less likely to give an established plant. Photo by Don Dickmann.



when planted, but they can be planted after breaking dormancy in the same growing season, if done immediately and there is sufficient time remaining in the season to develop an adequate root system.

Stock production systems

Unrooted dormant cuttings and sets

Most production of poplar planting stock takes place in stoolbed nurseries (Fig. 3). A stool is a stump from which new sprouts emerge. Stools may be started from any stock type, but normally dormant cuttings are used. Stools are cut back annually to a height of 5-15 cm in winter, thus producing l-year-old sprouts every year. When very tall planting stock is required, the stools are cut back every other year to produce a 2-year-old set. Harvested sprouts are sawn into cuttings or sets in early winter in the southern U.S. and late winter or early spring elsewhere in North America. Stock must be refrigerated and remain dormant waiting out-planting. Storage is in coolers or freezers, depending on the length of storage. For the best production of the healthiest stock, the lifespan of a stoolbed should be limited to 3-7 years.

Fig. 3. Eastern cottonwood nursery in the Lower Mississippi Alluvial Valley. Fitler Plantation, Fitler, MS. Note irrigation system. Photo by Jeff Portwood.

The density of the stools in beds is typically 0.3 x 0.3 m, or slightly less than 0.1 m^2 per stool. The density of the stools determines the caliper of the sprouts and controls the number of viable buds. The grower wants a uniform sprout with a basal caliper that only slightly exceeds the maximum set by the customer, thereby minimizing waste. Each cutting or set must have dormant viable buds. When the stools are planted too widely, sunlight that penetrates the canopy stimulates buds to develop into sylleptic branches, rendering the sprouts useless for cuttings. Varieties vary enormously in their tendency to form sylleptic branches. For instance, *deltoides* x *nigra* (D×N) hybrids are usually not a problem, whereas many ***trichocarpa* x *deltoides*** (T×D) or ***trichocarpa*** x ***nigra*** (T×N) hybrids grow prolific amounts of sylleptic branches.

Weed control strategies

Competition from weeds is a serious threat during establishment of new stool-beds. Herbicides provide the most effective control of weeds (Table 2). Mulching can be used to control weeds, but they re-establish over time and the mulch can create habitat for rodents. Sawdust has been used as mulch, but it will tie up available nitrogen and can acidify the soil. During site preparation, grasses and broad-leaved weeds can be effectively controlled with a tank mix of glyphosate (various formulations as Roundup®, Accord@, Vision*) and 2,4-dimethylamine (2,4-D). Repeated applications of glyphosate may be needed for control of perennial grasses (e.g., quack grass, reed canary grass) that spread by rhizomes. After cuttings are planted, a pre-emergent or pre-bud-break herbicide application is advisable. Choice will vary by location, soil texture and pH, and weed species.

Table 2. Partial list of herbicides for use in poplar plantations. Always check the label for current registration, rates, and application timing. Labels are available online at websites such as <http://picol.cahe.wsu.edu>. Most chemical companies provide downloads of their latest herbicide labels at their websites. Where rates of application have not been listed, the EPA# is provided under the Region column.

Active ingredient	Product name	Manufacturer	Application	Timing	Rates (imperial units)	Rates (metric units)'	Region
2,4-D Dimethylamine	Various	Various	Post-emergent weed control	Apply as a shielded spray to kill old stumps	1-2 pints	1.2-2.3 L	U.S.
Azafenidin	Milestone	DuPont	Pre-emergent weed control	Apply prior to bud flush	5–10 oz	0.35-0.7 kg	U.S. (label pending)
Clopyralid	Transline	DowAgro Sciences	Selective post-emergent weed control	Apply as a broadcast foliar spray over trees or banded or directed	1/3 to 2/3 pints not to exceed 1 1/3 pints/year	0.39-0.77 L not to exceed 1.56 L/year	U.S.
Clopyralid	Stinger	DowAgro Sciences	Selective post-emergent weed control	Apply as a broadcast foliar spray over trees or banded or directed	1/3 to 2/3 pints not to exceed 1 1/3 pints/year	0.13-0.28 kg (active ingredient)	U.S.
Clopyralid	Transline	DowAgro Sciences	Selective post-emergent weed control	See label	See label	See label	Oregon and Washington EPA# 62719-259
Dichlobenil	Casoron 4G	Uniroyal	Pre- and post-emergent	Early spring and late fall	98–150 lb	110-174 kg	Canada
Diuron	Karmex DF	Griffin	Pre-emergent weed control	Apply to trees 1 year old and older	1-3 lb	1.12–3.36 kg	U.S. Prairie States — CO, MT, NE, SD, ND, ID, OR, WA
Diuron	Direx 4L	Griffin	Pre-emergent weed control	Apply to trees 1 year old and older	2-4 qt	4.7-9.4 L	U.S. Prairie States — CO, MT, NE, SD, ND

Table 2 *(continued)*.

Active ingredient	Product name	Manufacturer	Application	Timing	Rates (imperial units)	Rates (metric units)[b]	Region
Diuron	Diuron 4L	Drexel	Pre-emergent weed control	Apply preplant or dormant post-plant or as a shielded application	2-4 qt	0.56-1.68 kg (active ingredient)	Western Washington
Diuron	Diuron 80 DF	DowAgro Sciences	Pre-emergent weed control	Apply to trees 1 year old and older	2.5-5 lb	2.8-5.6 kg	U.S. Prairie States — CO, MT, NE, SD. ND
Fluazifop-p-butyl	Fusilade DX	Zeneca	Post-emergent grass control	Apply over actively growing trees to control grass	Split application (12 fl oz followed by 8 fl oz) Application timing is critical	Split application (0.88 followed by 0.58 L) Application timing is critical	U.S.
Fluazifop-p-butyl	Venture L	Zeneca Agro	Post-emergent grass control	Apply over actively growing trees to control grass		Up to maximum 2 L/ha & only one application per year	Canada
Glyphosate	Various	Various	Preplant site preparation, directed spray in older trees	Apply when trees are completely dormant or as a careful directed spray	3/4 to 3 qt	1.75-7 L	U.S., Canada
Imazaquin	Scepter 70 DG	BASF	Pre- and post-emergent weed control	Broadcast before and after bud break	2.8 oz	0.2 kg	U.S. (30 states)
Imazaquin/ pendimethalin	Squadron	BASF	Pre-emergent weed control	Preplant incorporated or pre-emergent	3-6 pints	3.5-7 L	U.S. (30 states)

Table 2 (continued).

Active ingredient	Product name	Manufacturer	Application	Timing	Rates (imperial units)[a]	Rates (metric units)[b]	Region
Linuron	Lorox DF	Griffin	Pre- and early post-emergent weed control	Broadcast before bud break or directed spray after bud break	2-4 lb Use less on light soils	2.25-4.5 kg Use less on light soils	Midwest U.S.
Linuron	Linex 4L	Griffin	Pre- and early post-emergent weed control	Broadcast before bud break or directed spray after bud break	2-4 pints Use less on light soils	2.3–4.7 L product Use less on light soils	Midwest U.S.
Oryzalin	Surflan A.S.	DowAgro Sciences	Pre-emergent weed control	Apply before weed flush Will not control active weeds	2 qt Not more than 8/year	4.1 L Not more than 18.7 L/year, 3 months between applications	U.S.
Oxyfluorfen	Goal 2XL Plus	Rohm & Haas	Pre-emergent weed control	Broadcast before bud break or directed spray after bud break	64 oz pre-bud break, 32 oz after bud break	4.7 L pre-bud break, 2.3 L after bud break	U.S.
Oxyfluorfen	Goal 1.6E	kohm & Haas	Pre-emergent weed control	Broadcast before bud break or directed spray after bud break	Not more than 10 pints/year	Not more than I 1.7 L/year	U.S.
Oxyfluorfen	Galigan 2E Oxyfluorfen Herbicide	Makhteshim-Agan of North American Inc.	Pre-emergent weed control	Broadcast before bud break or directed spray after bud break	See label	See label	Oregon and Washington EPA# 66222-28

Table 2

Active ingredient	Product name	Manufacturer	Application	Timing	Rates (imperial units)"	Rates (metric units)'	Region
Paraquat dichloride	Gramoxone Extra	Zeneca	Post-emergent weed control	Apply dormant postplant in combination with oxyfluorfen or oryzalin	2 pints	2.3 L	Southeast U.S.
Paraquat	Griffin BOA Herbicide	Griffin	Post-emergent weed control	See label	See label	See label	Oregon and Washington EPA# 1812-420
Pendimethalin	Pendulum 3.3 EC	American Cyanamid	Pre-emergent weed control	Broadcast before and after bud break	2.4-4.8 qt	5.6-l 1.2 L	U.S.
Quizalofop	Assure II	DuPont	Post-emergent grass control	Apply over actively growing trees to control grass	5-10 oz	0.37-0.73 L	MN
Sethyoxydim	Poast, Poast-Plus	BASF	Post-emergent grass control	Apply over actively growing trees to control grass	l-2 pints	1.2-2.3 L	U.S.
Sulfometuron methyl	Oust	DuPont	Pre-emergent weed control	See label restrictions	0.5–2 oz	0.04-o. 14 kg	WI, MN, WA, OR
Terbacil	Sinbar	DuPont	Pre-emergent weed control	Apply pre- or post-plant	l-2 lb	1.12–2.24 kg	WA, OR
Trifluralin	TRIAP 4HF	IAP	Soil incorporated	Preplant soil incorporated Older plantation incorporate to depth to not injure tree roots	See label	See label	Oregon and Washington EPA# 71058-l

Table 2 (concluded).

Active ingredient	Product name	Manufacturer	Application	Timing	Rates (imperial units)[a]	Rates (metric units)[b]	Region
Trifluralin	Trilin	Griffin	Soil incorporated	Pre-plant soil incorporated Older plantation incorporate to depth to not injure tree roots	1-2 pints, dependant on soil and rainfall	2.3-4.7 L, dependant on soil and rainfall	U.S.
Trifluralin	Trilin 5	Griffin	Soil incorporated	Preplant soil incorporated Older plantation incorporate to depth to not injure tree roots	0.8-3.2 pints, dependant on soil, rainfall, and age of planting	0.9-3.6 L	U.S.
Trifluraiin	Trilin 10G	Griffin	Soil incorporated	Preplan1 soil incorporated Older plantation incorporate to depth to not injure tree roots	5–20 lb, dependant on soil, rainfall, and age of planting	5.6-22.4 kg	U.S.
Trifluralin	Treflan	DowAgro Sciences	Soil incorporated	Preplant soil incorporated Older plantation incorporate to depth to not injure tree roots	1-4 pints, dependant on soil, rainfall, tree age	1.2–4.7 L, dependant on soil, rainfall, tree age	U.S.

[a]In pounds, lb (1 lb = 0.454 kg); ounces, oz (1 oz = 28.35 g; 1 fl oz = 28.41 cm^3); pints (1 pint = 0.568 dm^3); or quarts, qt (1 qt = 1.14 dm^3) product per acre (1 acre = 0.405 ha) unless specified.

[b]In kilograms (kg) or liters (L) product per hectare unless specified.

Several nurseries in the Pacific Northwest use oxyfluorfen to maintain a weed-free stoolbed. In British Columbia, dichlobenil (Casoron®) was used successfully immediately following planting. In the southern U.S., an oxyfluorfen plus paraquat or glyphosate (Goal@ plus Gramoxone® or Accord@) tank mix is used to control weeds. Leaves and succulent stems of very small cuttings can be damaged by splash of oxyfluorfen caused by overhead irrigation droplets, but cuttings usually grow out of any damage without lasting effects. In the Midwest, oxyfluorfen is also used to control weeds in newly planted dormant stool beds. Linuron (Lorox®) and oryzalin (Surflan®) also provide good weed control. If cuttings have active leaves, oryzalin may cause less damage than other herbicides.

It is common to use manual labour to hand-weed portions of stoolbeds. Weeding needs decline rapidly when the stock fully occupies the stoolbed and shades out the weeds. During the next fall and winter, leaf litter forms a layer of mulch, which effectively suppresses weeds.

Fertilization and irrigation

Nutrient deficiencies and moisture stress should be avoided in stoolbeds, but fertilization and irrigation schedules are very specific to local conditions (see Diagnosing nutrient deficiencies). Usually a balanced application of nutrients at the start of the growing season is sufficient. Direct foliar applications of nutrients can correct nutrient imbalances that develop during the growing season. An over-supply of nitrogen, however, can cause the crop to grow too fast, promote formation of sylleptic branches, and delay the onset of dormancy (especially when applied after early August). Excess nitrogen can also increase weed competition. Growers must be able to manipulate crop development by supplying or withholding nitrogen at the right times. The same principles apply to irrigation where the aim is to provide just enough water to maintain even growth. Over-irrigation can promote the development of sylleptic branches. Water should be withheld late in the growing season to promote hardening off and avoid frost damage.

Crop health, protection, and hygiene

The three most serious disease and pest problems facing the nursery grower are leaf rusts, blackstem diseases, and the cottonwood leaf beetle. Protection strategies are a combination of chemical control, cultural practices, and use of resistant varieties. High stoolbed densities favour foliage diseases such as Melampsora rusts, especially with overhead irrigation. Varieties with normally low susceptibility in plantations may develop serious problems in stoolbeds. The grower can avoid these varieties or use registered fungicides (e.g., Bayleton®). If Melampsora rust causes early defoliation, cuttings in this physiologically weakened state are more vulnerable to blackstem disease.

Blackstem diseases are caused by a number of organisms (*Cytospora chrysosperma*, *Phomopsis oblonga*, and *Colletotrichum gloeosporioides*) that are opportunistic on stressed plants. Blackstem is often considered a storage disease, and although improper storage can cause the disease to spread, it usually starts in a stressed plant well before it is put into storage. Stress can occur in the stoolbed because of drought, insufficient light or nutrients, frost damage, insect damage, or leaf diseases such as Melamspora rust. Upon out-planting, portions of the bark die off and turn black (hence the name blackstem disease). The disease spreads and usually leads to poor growth and often mortality. Diseased cuttings become a source of inoculum, and inadequate culling worsens the condition.

The cottonwood leaf beetle or CLB (***Chrysomela scripta***) is the most serious insect threat in stoolbeds and is a serious pest in plantations. The CLB defoliates developing leaves and in extreme cases feeds on the woody part of the stem. Monitoring for CLB must continue throughout the growing season as multiple generations are produced at about 1 -month intervals. Successful control is achieved with several commercial insecticides registered for use in eastern cottonwood and hybrid poplar in the U.S., including several formulations of carbaryl (Sevin®) and dimethoate (Dimate 4E®). Several Bt (Bacillus *thuringiensis*) products are available and Novodor® is used operationally in Minnesota.

Unrooted dormant branch cuttings

Dormant material can be harvested from branches of young plantations instead of stoolbeds. These are known also as serial cuttings. First-order branches near the top of the tree produce vigorous cuttings of sufficient diameter. A 2-year-old tree can provide 20-30 cuttings, depending on branching characteristics. In plantations of TxD hybrids, sylleptic branches can be used for cuttings. Sylleptic branches from the previous year grow to a reasonable size the second year, but only the l-year-old portion of these branches is used. This produces small-diameter cuttings, which are marginally suitable for planting in the field but can be used to establish stool beds. Branch cuttings also must be stored in coolers or freezers until planting.

Rooted dormant cuttings

Bareroot dormant cuttings can be used to establish widely spaced plantations for solid wood products (Table 1). This system of plant production is expensive, labour intensive, and is not normally undertaken to merely establish fibre plantations. After 1 year of growth in the nursery, the grower excavates bareroot plants with the root systems intact for out-planting in the field. Root systems may be trimmed to a manageable size at the nursery. Often the tops are also trimmed for easier handling or to balance top and roots. Bareroot stock is lifted in winter or early spring, while the trees are dormant. Large stock cannot be stored easily and must be transported and planted immediately. Large stock can be several meters tall, sometimes 2 years old, with large caliper. It requires machinery for planting; for example, a tractor-mounted auger for digging the planting hole.

Container nursery for rooted plants

Materials that can be produced in a container nursery may be grown from single-bud stem cuttings, root cuttings, or seed. Dormant single-bud hardwood cuttings are used for varieties that are difficult to propagate or if only a limited amount of material is available, such as from a breeding program. Each sprout or branch is divided into very small cuttings containing a single bud'and rooted in containers. Single-bud greenwood cuttings are collected from actively growing young, succulent green shoots and planted (with leaves) into a container, usually with rooting hormones in mist beds. This method is expensive and labour intensive, but can be used to quickly multiply a single mother plant into thousands of identical plants. Uses include establishing a new stoolbed with an improved genotype or for experimental purposes.

For the hard-to-propagate aspens (e.g., *P. rremuloides* and its hybrids), dormant root cuttings are placed in containers in a greenhouse in order to produce fully rooted plants with soil for out-planting. The container crop is initiated in the late winter in the greenhouse, and grows during the spring and summer into large plants with well-developed root systems. During the late summer, the containers are placed outdoors. The following winter, dormant seedlings are extracted from the containers, packaged, and stored in a cooler or freezer, pending out-planting the next spring.

Containerized seedlings can be produced for operational planting of aspen. In the Prairie Region of Canada, seed from open-pollinated trees is used to produce planting stock for reforestation. The seed is sown in containers in the late spring. With few exceptions, the new seedlings will be ready for out-planting that fall.

Stock harvesting, processing, and quality control

Although there are good arguments for and against monoclonal plantings, clones must be identified and kept separate in stoolbeds so that only appropriate clones are planted on a site. Harvesting and processing should be done one variety at a time to eliminate the risk of mixing with another. Harvesting can be of individual stems or by mowing or cutting many stems at once (called mass harvesting).

Harvesting

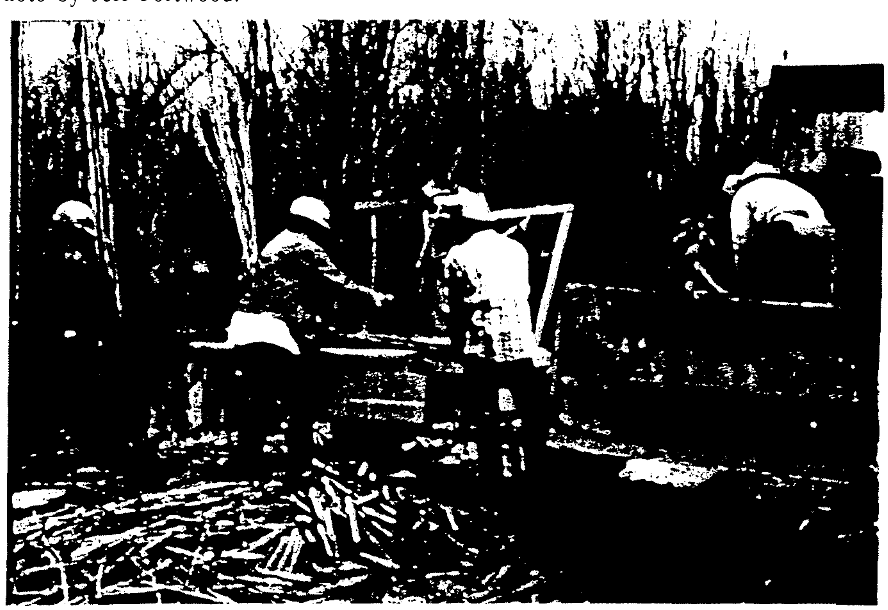
Individual stem harvest requires experienced personnel who can determine the quality of each sprout before its harvest and select against poorly formed, diseased, or undersized sprouts. This is positive selection of good material, as poor quality material is not cut. Individual stem harvesting has few options to mechanize, which is a disadvantage for large stoolbed operations. It is labour intensive and costly, although it could lead to savings at the processing plant. In mass harvesting, sprouts are cut with a hand-held brushing saw or a mower attachment to a tractor. In the southern U.S., a modified sugar cane harvester has proven successful. Mass harvesting achievs higher production levels at lower harvesting costs. Quality control costs will increase and there is more waste to handle because both good and bad material arrives at the processing plant.

Processing

Processing can be accomplished by individual stem or by applying assembly line techniques for mass processing. In the individual stem method, &he cutter uses a saw or hand-powered, hydraulic or pneumatic shears and processes each sprout separately (Fig. 4). Advantages of this system are high quality control through better recognition of defects, maximum recovery per sprout (especially when the variety is in short supply), quality control accountability by cutter, and more variety of tasks (packaging, counting, etc.). It also allows recovery of odd stock sizes (such as sets) from material not suitable for cuttings. Cutters work independently, and are not affected by assembly line breakdowns. This system works best for processing small to moderate quantities of cuttings of several varieties, but could be more costly than mass processing of large quantities.

In mass processing, sprouts are cut to size by a set of mechanized cutting saws, usually operated by one or two persons. Other workers sort the resulting cuttings, followed by additional workers packaging the stock. The main advantage is fast processing, which is especially beneficial when processing large numbers of a single variety. Disadvantages are bottlenecks caused by a breakdown of the mechanized saws or frequent changeovers to different stock sizes or other varieties. Cuts are not always at the correct location in relation to buds so there is greater waste.

Fig. **4.** Reducing dormant eastern cottonwood whips to cutting length. Fitler Plantation, Fitler, MS. Photo by Jeff Portwood.



Quality control

Quality control encompasses both culling substandard material and properly identifying varieties. Individual cuttings should meet size specifications, be properly formed and free of diseases such as blackstem or lack evidence of stem borers, and be dormant. Mixing or mislabelling varieties occurs frequently at nurseries. Harvesting and processing protocols are critical to minimize these problems. The nursery manager must maintain good records of each variety, by stock source, stoolbed, customer, etc. Advances in DNA technology allow for precise fingerprinting at reasonable costs and can be used by nurseries and customers alike to ensure identity. Variety contamination is a costly problem for the nursery and can lead to loss of customers.

Stock packaging and storage

Processed cutting stock should be packed in sealed plastic bags to prevent moisture loss. Each bag should be labelled with the variety name or number, the amount, packaging date, and nursery name. The bags are then placed in cardboard boxes or larger storage bins.

This makes quality control easier, facilitates the allocation of stock to planting areas, payment of planting contractors, and helps in the overall administration of the planting project. Sets up to 2 m in length can be packaged and stored in a similar fashion. Plastic sleeves can be cut to size to hold the material.

The boxes or bins are stored at +2°C to +4°C for short-term storage of up to 1 month, or at -2°C to –4°C for longer-term storage. Boxes can be stacked on a pallet, 2–4 boxes high and 4 boxes deep. Bins or pallets with boxes can be stacked on top of each other, but must have free air circulating between them to prevent over-heating and sprouting. If cold storage is not possible, stock can be stored in a snowbank (in the north) when temperatures are around freezing or in a shady and cool spot for short periods. In the southern U.S., there is a serious risk of the stock drying out during a dry winter or spring after planting. The stock can be soaked for a day or two in freshwater prior to planting as a preventive measure. Prolonged soaking should be avoided, however, as it promotes premature sprouting and may promote disease.

Site requirements and site selection

For poplar to live up to its reputation as the fastest growing species in North America, the best varieties must be planted on the best sites, with the best crop tending (Fig. 1). There is an unfortunate misconception that poplar likes wet sites; an inexperienced grower with a few acres of swampland who plants poplar and expects it to do well will be disappointed. Other misinformed forest managers have been known to plant poplar on very good quality land and expected fabulous growth without having to spend much effort on tending the crop. This point bears emphasizing: if a grower is not wholly committed to providing the necessary cultural treatments, especially early in the life of a plantation, then the grower should not plant poplars.

Site requirements

The site requirements for optimal performance of poplar can be stated simply as "Best performance can be expected on soils that are a well-aerated, have sufficient moisture and nutrients, are sufficiently deep (>1.0 meter to the water table), have a medium texture (sand/loam) and have a soil pH in the 5.0 to 7.5 range" (Baker and Broadfoot 1979). Poplars thrive under growing season conditions of high light intensity and warm temperatures. The influence of soil texture and drainage condition on site quality for poplar is summarized in Table 3.

Poplars grow well under many site conditions and it may be easier to list some factors that are generally ***unfavorable*** to poplar growth. The grower can control several of these factors. For example, poplar grows very well in the desert-like conditions of eastern Washington and Oregon, where climatic conditions are perfect — lots of sun and warm temperatures — but soils are mostly sand. Through fertigation (application of nutrients in the irrigation water) the grower can transform this high desert into a poplar forest. In the southeastern U.S., forest industry is investigating the feasibility of establishing short-rotation plantations, including poplar on deep sands. These plantations are located near existing mills and can be logged when most sites are too wet. Soil texture and drainage class determine to a great degree the suitability of a site for poplar (Table 3).

Unfavorable site conditions

Soils that are saturated and waterlogged during the growing season develop anaerobic conditions and starve the root systems of oxygen, leading to drought-like symptoms. The leaves turn yellowish-green and remain very small. The stressed tree exhausts its reserves and slowly dies. Most poplar varieties cannot tolerate anaerobic conditions for very long into the spring months and must have well-aerated soils by the beginning of June to survive and thrive. Younger trees are more vulnerable.

Some varieties do not tolerate saturated soil conditions in the winter very well either. For example, in northwest Washington and southwest British Columbia, hybrids of ***Populus trichocarpa* x *P. maximowiczii*** suffered significant loss of height and diameter growth the next growing season, whereas hybrid varieties of ***P. trichocarpa* x *P. deltoides*** do well under these circumstances.

Heavy soils (clay, clay loam, and silty clay loam textures) are considered less favorable for poplar growth than coarser textured soils, but the advent of better chemical weed control has improved the prospect for poplars on these soils.

Table 3. The influence of soil texture and drainage condition on site quality (very good - poor) for poplar. Shaded fields indicate potential to improve suitability through ditching, installing drain tile, subsoiling, or some combination (source: Dickmann and Stuart 1983).

	Natural drainage class		
Dominant profile textures	Well and moderately well drained	Somewhat poorly drained	Poorly and very poorly drained
Fine clay (>60% clay)	Fair	Fair	Poor
Clay (40–60%)	Fair	Fair	Poor
Clay loam and silty clay loam	Good	Poor	Poor
Loam. and silt loam	Good - very good	Fair	Poor
Loam and silt loam 25-50 cm over well-decomposed peat	Good - very good	Poor	Poor
Loam and silt loam marbled with well-decomposed peat	Good - very good	Fair-good	Poor
Sandy loam	Very good	Fair-good	Poor
Loamy sand	Very good	Fair-good	Poor
Sand	Poor	Fair	Poor
Sandy loam 35–100 cm over clay	Very good	Fair	Poor
Sandy loam 50-100 cm over loam - clay loam	Very good	Fair	Poor
Sandy loam 50–100 cm over sand	Good	Very good	Poor
Loamy sand 35-100 cm over clay	Very good	Fair	Poor
Sand - loamy sand 50-100 cm over loam - clay loam	Very good	Very good	Poor
Sand - loamy sand 100-150 cm over loam-clay	Good	Very good	Poor
Muck	N/A	N/A	Poor-fair

Because finer textured soils generally have poor aeration and poor drainage, they restrict equipment access during wet periods, making weed control difficult. Survival is reduced and growth during the first few years can be disappointing. The lack of rapid growth and early crown closure leads to an abundance of weed competition, slowing tree growth even more. Recent advances in pre-emergent herbicides and application technology have improved weed control, enabling poplars to be established successfully on these sites. Eastern cottonwood grows better on medium textured soils but performs acceptably on soils with as much as 90% clay as long as weed competition can be controlled.

Saline conditions are not tolerated by the poplar species in North America. ***P. trichocarpa*** is extremely intolerant of salt and so are its hybrids; ***P. delroides*** is slightly less intolerant. Salt damage to the trees resembles desiccation damage. Physiologically the tree suffers from drought stress. Leaves remain small and yellowish-green. Sometimes the leaf edges become necrotic. The condition worsens as summer drought sets in, resulting in tree mortality. Sensitivity to saljnjty should be a concern to growers who rely on irrigation or fertigation to manage their poplar crop, and adequate drainage must be provided along with sufficient water to flush salts through the rooting zone.

Poplars can perform well on shallow soils, although windthrow may be a problem. Shallowness of the rooting zone can be caused by a high water table that does not retreat during the summer, an impermeable soil layer, bedrock, soils that are naturally very compact, or compaction resulting from heavy machine traffic.

It js commonly thought that peat soils do not support good poplar growth. Peats are usually waterlogged and very acidic, but there are exceptions. Weed control on peat soils can be challenging. Access may be difficult at critical times due to waterlogging, precluding mechanical control. Soils with high organic matter content will bind and render ineffective many pre-emergent herbicides. Artificial drainage may be the key to successful poplar management on these soils. Several sites with a high peat component in northwest Washington and Oregon are reasonably well drained and support good growth of hybrid poplar. Windthrow damage is a real threat especially if water tables are shallow, but some poplar varieties are well suited to these conditions and hardly pose a serious windthrow problem.

Site selection

Despite being armed with the knowledge of site requirements, site selection can still be a daunting task. Sites are never uniform, and multiple combinations of sjte factors can occur. This is especially true for alluvial sites, where river action adds subsoil variability to a site under a blanket of uniform surface soil. It pays to determine soil texture, drainage conditions, subsoil properties, available nutrients, pH, and organic matter content. Where there is even a remote possibility of salinity, the site should be ruled out. If sjtes are subject to growing season flooding, historic inundation regimes should be determined.

Table 3 highlights several situations where drainage can be enhanced, leading to more favourable sjte condjtjons for poplar. Many otherwise suitable sites may require enhanced drainage. Improving and maintaining ditches, subsoiling, and installing drain tile can accomplish this. To maximize efficiency of planting and subsequent maintenance, block planting of a single variety is often desirable but may not provide maximum yields. A flexible, good performing variety may reduce the complexity of stand establishment but result in lower yields if site conditions vary substantially. Varieties can be easily matched with specific soil characteristics, leading to greater yields. There is also a school of thought that favours mixtures of varieties because site resources are more completely utilized and insects and disease problems are minimized.

Other important aspects of site selection are economic ones. A marginal site close to the mill may be more attractive financially than a good site farther from the mill. Transportation, mobilization, and management costs become prohibitive for sites too far from the mill site. Shape and size of a potential poplar site are also important. A small or odd-shaped area is awkward to manage. The length and orientation of plantation rows often determine the cost of cultivation maintenance. For large commercial operations, sites generally must be larger than 40 ha to be economical, although the concentration of acreage within a management area may be more critical. These factors have nothing to do with suitability of the soil, but everything to do with the suitability of the site.

Site preparation

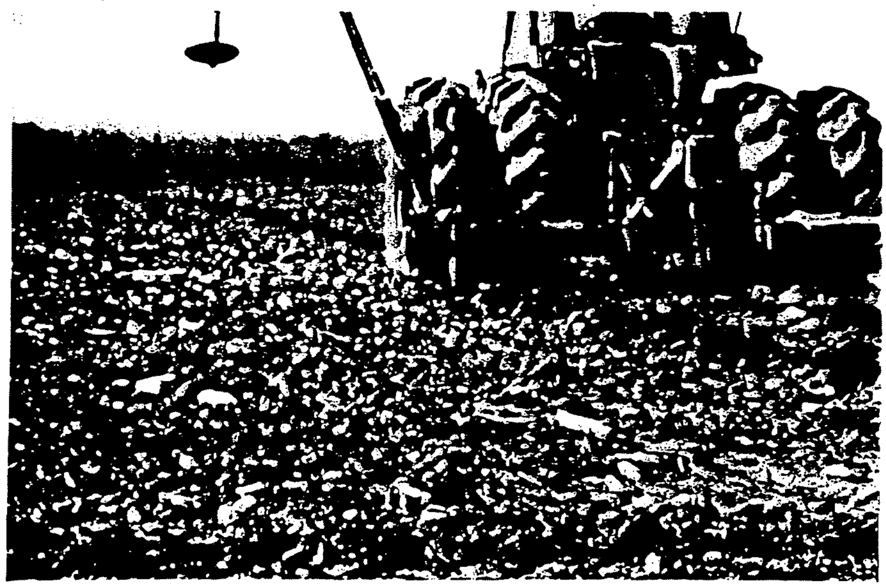
Proper site preparation for planting is essential to the successful establishment of poplar plantations. Without adequate site preparation, survival and growth of poplars may be drastically diminished. A thorough evaluation to determine specific soil and site conditions of a potential poplar plantation will aid in the selection of appropriate treatments to apply. The main benefits will be reduced planting costs; more effective herbaceous weed control, and reduced damage to young poplars in mechanical cultivation; and disruption of impervious soil layers, which will improve internal drainage and aeration. Bear in mind that the main purpose of site preparation is to get poplars off to a fast start and to provide easy access to the site for essential weed control.

There are many combinations of site prep methods in use today throughout North America, depending mostly on site conditions. Sites one might encounter include open pasture or agricultural land, cutover natural stands, or prior plantations. On prior pasture or farmland, site prep can be very simple. On cutover forest or prior plantations, site prep becomes complex and very expensive due to stumps, logging debris, and heavy vegetation.

Open agricultural land is commonly prepared using combinations of conventional and minimum tillage methods, such as disking, chisel plowing, subsoiling (Fig. 5), and mowing. Many poplar growers have added herbicide treatments to their arsenal of site prep tools in order to reduce early weed competition. Raised beds or bedding is relatively new to poplar culture but has a long history of success in pine plantation culture on poorly drained sites.

Where fertigation is used, site preparation is more complicated and involves heavy construction. An existing center pivot irrigation system may need to be removed. The old irrigation piping system could be utilized to reduce expenses; otherwise, a completely new irrigation system infrastructure must be developed. This involves installing pumping stations, underground water lines, mains, and submains. Following this intensive initial process, conventional site prep methods as described above are used. Finally, drip hose is laid and connected to submains and emitters are installed.

Fig. 5. Tractor with subsoil shank used to break up plow pans and to inject fertilizers prior to planting cottonwood cuttings on former agricultural fields in the Lower Mississippi Alluvial Valley. Photo by Jeff Portwood.



Preparation of sites after timber harvest is also more involved. The longer the previous rotation, the larger, and more troublesome will be the material still on the site. New growth of herbaceous and woody vegetation, stumps, roots, and compaction from logging traffic can further complicate this process. Conventional land clearing methods such as shearing, raking, piling, and burning have not changed much over the years. These are still the preferred methods used in the southern U.S. Poplar growers recognize the need for less intensive, more cost-effective means of clearing harvested plantations. In the West, site prep between existing stumps has been successful, using an orchard flail to reduce woody debris, followed by a rototiller to further grind and incorporate debris into the soil. This leaves stumps intact. The planting bed is prepared between old rows while the soil is still loose from tilling.

Location of rows should be clearly marked according to the selected spacing. The row should be slit or bedded to a depth sufficient for the length of cutting to be planted (Fig. 5). Slitting can be accomplished by modifying conventional farm equipment. Reasonably straight rows are important for cultivating and for spray machines to avoid damage to young plants. It is best to mark in both directions when cross cultivation is planned. When slitting, at least 15 cm of rainfall is required to fill trenches with silt before planting can begin.

Planting

Planting is a crucial phase of plantation establishment, and only quality planting stock should be used. Select genetically improved poplar cultivars, developed by U.S. Forest Service, university, and forest products industry researchers, are available for purchase from government, private, and industry nurseries or through industry-landowner assistance programs. Planting stock varies in length from 15 to 45 cm. Optimum cutting size is from I .O to 2.0 cm in diameter. Cuttings larger than 2.0 cm are excellent planting stock but are hard to handle.

Although either seedlings or cuttings can be used, cuttings are preferred planting stock for poplars throughout North America. They survive and grow as well as seedlings and cost less to produce and plant. Additionally, cuttings are more desirable than seedlings because genetically superior varieties can be expanded more rapidly through vegetative propagation.

In drier regions of North America, harvested poplar whips or cuttings should be soaked in fresh water for a minimum of 2 days to prevent them from drying out during storage and planting. Cuttings or even whips should not be exposed to drying conditions during transport to planting sites. Exposure to light for extended periods before planting is also harmful. A tarp will keep the stock in good shape. When planting will be delayed until after the start of the normal growing season, cuttings must be kept in freezer storage.

Planting spacing varies from 2.1 x 3.0 m to 4 x 4 m, depending on poplar species and the desired product size (pulpwood or sawlog). Poplars can be planted by machine or hand, but hand planting is more common (Fig. 6). The cutting must contact soil and be planted as deeply as possible to take full advantage of soil moisture. Depth of planting will vary with cutting length. Shallow planting usually results in poor survival and reduced height growth. Aboveground exposure should be minimized to reduce the likelihood of undesirable multiple sprouts. Nonetheless, about 5 cm should be left above ground so that cuttings are visible to equipment operators during early cultural treatments. Cuttings always should be planted with vegetative buds pointing upward. The tops of cuttings can be spray painted orange to insure proper orientation and speed planting. This also assists in monitoring planting contracts.

Poplars may be planted any time during the dormant season. In the southern U.S. this extends from the first severe frost in the fall until buds begin to open in the spring. In areas of North America that have frozen soil in winter, cuttings are normally planted in the spring when soil temperature reaches 4°C. In the Midwest, planting usually is done when the soil is warm enough to plant corn. Planting material should always be checked for dormancy before using; succulent green tissue of rapid growth may persist for a short time after the first fall frost, but the buds and current season's growth must have stopped growing and be hardened before cuttings are made. In addition, cuttings that have already sprouted are

Fig. 6. Planting dormant cottonwood cuttings in 3.7 x 3.7 m furrows in the Lower Mississippi Alluvial Valley. Photo by Jeff Portwood.

a poor risk. Delaying planting until after bud break of surrounding vegetation in the spring has been successful and affords an opportunity to plant sites that remain wet throughout the winter and flood during the normal planting season. Delayed planting is advantageous on low wet sites and should not be used on drier ridges unless irrigation is available. Cuttings should remain in freezer storage until planting.

Competition control

Competition in any form will affect poplar plantation growth and survival. Poplars must have full sunlight, adequate water, and nutrients for maximum growth potential (Demeritt 1990). Control of competing vegetation is critical to successfully establish poplar plantations (Schuette and Kaiser 1996; Von Althen 1981; Hansen and Netzer 1985). Weeds will compete better than poplars for available water and light, resulting in diminished growth or mortality. In addition to competition from vegetation, browsing by deer and rodents can reduce survival and growth, as will outbreaks of insects such as cottonwood leaf beetle early in the rotation (Ostry et al. 1989).

Weed control

Control of competing vegetation especially during the establishment years will allow poplars to survive and grow to the potential of the site. Competition control strategies vary by region and depend on annual rainfall, soils, and herbicide registration. In the southern U.S. newly planted eastern cottonwoods are sprayed in bands 0.9 m in width as needed directly over the tree rows with oxyfluorfen alone or in combination with herbicides such as imazaquin (Fig. 7). The area between rows is disked as needed to control invading weeds. The strategy in the Midwest is to broadcast apply herbicides such as linuron or imazaquin over entire plantations of dormant newly planted hybrid poplar cuttings (Hansen 1993; Hansen et al. 1993; Netzer and Noste 1978). This is followed by shallow cultivation as the herbicides become ineffective. In the Pacific Northwest weed control strategies vary, depending on the local rainfall patterns. Extremely low rainfall areas east of the Cascade Mountains are often irrigated, and herbicides such as trifluralin are soil-incorporated prior to tree planting. West of the Cascades, weed control strategies are similar to the Midwest, using capping herbicides and cultivation (Heilman et al. 1995).

Poplars typically are grown on sites that were recently in agriculture, and the weed complex is herbaceous broadleaves and grasses, although persistent woody vines are a problem in the southern U.S. Sites that have not been in crop production for several years may have additional woody brush and small trees. Control of all existing weeds can be done by applications of non-residual herbicides such as glyphosate, alone or in combination with 2,4-D. This is usually done the year prior to plantation establishment before mechanical site preparation begins. Sites

Fig. 7. Results of banded herbicide application over a I-month-old cottonwood plantation in the Lower Mississippi Alluvial Valley. Note top of planted cutting and sprout. Photo by Jeff Portwood.

subject to winter erosion should be planted in fall with a cover crop such as annual rye grass *(Lolium multiflorum*).

Weed competition must be controlled during the first growing season. Poplars are extremely sensitive to herbicide damage (Buhler et al. 1998; Netzer and Hansen 1992; Netzer and Hansen 1994; Netzer et al. 1997; OMNR 1991), but several herbicides have been identified that poplars will tolerate (Table 2). Even labeled herbicides need to be tested by site to insure safe performance. Most herbicides are applied immediately before or after planting while cuttings are dormant. One exception is diuron, which is applied in northwestern Washington the fall prior to spring planting. Herbicides requiring soil incorporation are usually applied prior to planting. Other herbicides are sprayed directly over newly planted dormant stock. These herbicides usually do not provide complete control throughout the growing season.

Grass herbicides such as sethoxydim and fluazifop-p-butyl can be used directly over actively growing trees without damage. Clopyralid, imazaquin, and oxyfluorfen are used to control broadleaf weeds while poplars are growing, although leaf injury has been observed in several instances. Local trials need to be performed to insure tree clone tolerance to application timing and chemical rates.

Several types of cultivators including rototillers, discs, and various shovel and spring cultivators are used to control invading weeds during the growing season (Fig. 8). Cultivation equipment must be kept shallow enough to avoid root damage to the poplars, usually no deeper than 5 cm. Cultivators with guide wheels can control the depth of cultivation accurately. Care must also be taken to avoid damage from tool bars or other equipment to the bark and buds of young trees. Shields have been used in the Midwest to protect young trees from covering by displaced soil during cultivation.

Tending

At the end of the first growing season dormant hybrid poplars may be treated after leaf fall and prior to ground freeze up with herbicides such as azafenidin, low rates of sulfometuron, and others to control weed growth the following spring and part way through the succeeding growing season (Table 2). Care must be taken to ensure the trees are completely dormant to avoid herbicide injury. These applications can be reapplied at the end of the second growing season and beyond as needed, As trees grow taller, directed or shielded spray of low rates of glyphosate may effectively control weeds and grasses near the trees during the growing season. In northwest Washington, a shielded application of glyphosate and diuron (tank-mixed) is made between the plant rows during mid October of the first and second year. Fall applications keep the cultivated portion between tree rows free of weeds during the winter in areas without soil frost and avoid having to bring in equipment too early in spring when soils are wet.

Fig. 8. Disc cultivation of a cottonwood plantation in the Lower Mississippi Alluvial Valley during the second growing season. Photo by Jeff Portwood.

Other competitors

Mammals

Poplars are a preferred browse for most cervid species (deer, elk, and moose) and may cause establishment failure, especially of smaller plantations subject to high browsing pressure. Deterrents such as electric fences and repellants may reduce browsing to tolerable levels. Trees may grow out of the reach of deer if browsing pressure is low, by the end of the second growing season (Netzer 1984), but will remain susceptible for several years to bucks rubbing during the rutting season. Large mammal browsing can be so serious that the landowner is left with only two options: fence or forget growing poplar. In cutover forest stands, slash can be bulldozed into brush fences 3 m or higher (McKnight 1970). Electric fencing is another option, but requires continual maintenance while plants are susceptible. A five-strand fence, with the lowest strand 25 cm off the ground and the other strands 30 cm apart above it, has worked in the northeast (Brenneman 1982). Other options are available, including a more expensive woven wire fence (Dickman and Lantagne 1997). To be effective, at least two tiers of 1.2-m woven wire are required. Stay wires (no wider than 15 cm apart), a third tier of fencing, or a strand or two of barbed wire will be needed to keep deer from penetrating.

Periodically high vole (*Microtus* spp.) populations can be a problem. Grass cover in 3- and 4-year-old plantations provide protection from predators, allowing voles to feed on roots and lower stems, which can lead to heavy tree mortality. Serious damage has occurred to plantations in the Pacific Northwest, the Midwest, and southwestern British Columbia. Grass control can prevent this problem, although mice and voles can still cause trouble under snow cover.

Insects and diseases

Major pests of cottonwood plantations include defoliating insects such as cottonwood leaf beetle, poplar tent maker (*Clostera inclusa*); borers such as the cottonwood twig borer ***(Gypsonoma haimbachiana),*** cottonwood clearwing borer ***(Paranthrene dollii),*** and cottonwood borer ***(Plectrodera scalator)***; and aphids, mites, and leafhoppers (Morris et al. 1975; Solomon 1985). A frequent monitoring schedule should be used to control these insects prior to large infestations. Labeled general-purpose insecticides such as carbaryl or ***Bacillus thuringiensis*** (Bt) may be applied to control these pests (see Chap. 7).

Fertilization

The objective of a nutrient management program is to maximize plantation growth by minimizing nutrient limitations. Nutrient limitations are related to high inherent requirements due to high productivity of poplars, limited availability of native soil nutrients, and imbalance among essential nutrients. Understanding how these factors interact to affect poplar productivity focuses on nitrogen (N) as the main element limiting poplar growth in all regions. Although growth on some sites has been shown to respond to other nutrients, it is most important to provide adequate N supply and keep other nutrients balanced with N to avoid relative deficiencies.

Nitrogen requirements

The amount of N required to support optimum growth is shown in Table 4. These estimates demonstrate the very high N requirement of rapidly growing poplar, especially hybrid poplars, compared with other forest types. The high nutrient demand is due to the young age of intensively managed poplar plantations and

Table 4. Amount of nutrients required to sustain growth of poplar species and their hybrids compared with an average of temperate deciduous and conifer forest types.

Genotype	Age (years)	NPP[a] (tons ha-' year-')	Requirement (kg ha^{-1} $year^{-1}$) N	P	K	Ca	Mg	Reference
	4-6	17	102	11.5	88	151	17.9	Cited by Bemier 1984
P. delroides	7	17	107	11	91	157	18	Nelson et al. 1987
P. trichocarpo	4	7-18	95–159					Heilman and Stettler 1986
P. trichocorpa P. × delroides	4	27-28	27 1-276					Heilman and Stettler 1986
P. x conadensis	4	11	168					Heilman and Stettler 1986
P. x canadensis	1-2	12-24	182-246	20-36	113-171	121-237	38	Cited by Bemier 1984
Temperate deciduous	30–120	1 0	98	7.2	48	56	10.4	Cited by Bemier 1984
Temperate conifers	15–450	8 . 3	46	5.5	28	20	4.6	Cited by Bemier 1984

[a]Net Primary Productivity (NPP) includes belowground and aboveground biomass, including foliar mass,

their high productivity. The variation in nutrient requirements among genotypes may be related to efficiency of N use (Blackmon et al. 1979), which has important ramifications for protecting surface and ground water from nitratecontamination.

Nitrogen to meet plant needs is supplied from various sources including internal cycling and N mineralized from soil organic matter and litter decomposition. We are uncertain how much of the annual N requirement is met by these sources, which limits our ability to accurately prescribe cost-effective nutrient additions. We know that the relative importance of internal cycling increases as the stand develops. Many sites with high native soil fertility do not respond to fertilization, indicating the site supply capacity is adequate to meet even the high nutrient requirements of poplar. Nonetheless, nutrients not adequately supplied by the site must be supplemented ihrough fertilization if optimum growth rates are to be maintained. Peak demand occurs by age 5 or 6 years (Nelson et al. 1987).

Diagnosing nutrient deficiencies

Agricultural crop nutrient requirements and common nutrient deficiencies in a region provide some hints to the poplar grower. Even with practical knowledge, however, diagnostic techniques are needed to evaluate nutrient deficiencies and identify imbalances among essential plant nutrients. The effectiveness of both nutrient management approaches must be monitored to achieve maximum growth potential and avoid negative environmental effects caused by over-fertilization. Diagnostic techniques are especially necessary where variation in site and climate may affect nutrient demand, as in the Midwest and eastern North America. Although there is critical need for diagnostic and prescription techniques, few accurate tests are available.

Leaf analysis is the most common diagnostic technique for determining poplar nutrient deficiency. Nutrient concentrations are analyzed on leaves collected from the upper canopy during midsummer. Consistency in timing and canopy position of sample collection is important because variation in either will affect results. Fertilizer recommendations typically focus on N — critical levels below which fertilization is recommended are between 2 and 3% foliar N (Dickmann and Stuart 1983; Hansen 1993). Growth rates are known to increase at higher foliar concentrations (Jia and Ingestad 1984; Coleman et al. 1998), but these levels are difficult to achieve operationally. The critical foliar concentration level may vary with genotype because of differences in N use efficiency (Heilman 1985). More rapid diagnostic techniques such as the SPAD meter (Spectrum Technologies, Plainfield, IL) hold promise because of the good relationship between leaf N and SPAD value ($r^2 > 0.7$) when foliar N levels are greater than about 2.0% (Young and Berguson 2000). The SPAD meter utilizes the absorbance peak of chlorophyll in the red region (400-500 nm) with the lack of transmittance in the near-infrared (500-600 nm) region to calculate a SPAD value, which is proportional to leaf chlorophyll. Chlorophyll and nitrogen contents are highly correlated in many plant leaves. Standardized leaf sampling location or collecting weight per unit. area information is especially important with such light transmittance meters because leaf thickness influence values.

Maintaining balance between N and other essential nutrients is critical for achieving optimum production. For example, many poplar stands·do not respond to N additions unless accompanied by additions of P, K, or other nutrients (Blackmon 1976). Two diagnostic techniques based on foliar ratios between nutrients are available for evaluating the balance among nutrients — Ingestad's and DRIS. The ratios of several essential plant nutrients to N can be very consistent for high productivity plantations, leading to the use of Ingestad ratios for diagnostic purposes (Ericsson et al. 1992). Recommended ratios for poplar, based on laboratory-grown plants, are 100 N : 11 P : 48 K : 7 Ca : 7 Mg. Luxury consumption of N, however, affects the accuracy of ratios and interpretation of multiple nutrient ratios, making it difficult for plantation managers to determine which nutrient is actually deficient.

Another technique is called DRIS (Diagnostic and Recommendation Integrated System), adapted by Leech and Kim (1981) for use in poplar. DRIS uses all combinations of nutrient ratio means and deviations to calculate balance indices for each nutrient element in the analysis. These indices are easily interpreted and provide a method of identifying which nutrient is deficient relative to the others. For example, fertilization with N alone may result in deficiency of other nutrients and thereby limit growth. DRIS analysis is capable of diagnosing such an imbalance.

Soil testing

Soil testing has been used in forestry for characterizing major differences between soil types and landscapes. In general, routine testing for specific nutrient deficiencies has not been successful, for several reasons. Tree roots access nutrients from multiple layers and often at considerable depth; sampling the total volume utilized by the tree would be prohibitively costly. Further, interpretation of soil test results in terms of tree requirements is difficult because what is extracted by chemical tests may bear little relationship to what the tree can extract. Unless considerable effort is made to calibrate soil test results against tree nutrient status or fertilizer response, interpretation is impossible. Nevertheless, soil testing can play an important role when establishing new plantations on former agricultural land. Rough guidance for tree crops can be obtained from soil test results correlated with the previous row crops; the nutrient-demanding poplars grown on short rotation are not that different from agricultural crops. In areas where severe macro- or micro-nutrient deficiencies of trees have been demonstrated and can be correlated with soil test results, critical levels can be established to guide preventive fertilization. Over time, relationships within a fixed area between soil test results and fertilizer response can be established.

Approaches to fertilizing poplar

The amount of fertilizer to be applied depends not only on the crop nutrient requirement, but also on the application system. Two distinct approaches are used: (1) the dryland approach involves fertilizing the site as little as once per rotation or as often as once per year; (2) the fertigation approach seeks to constantly maintain optimal concentrations in the soil solution during the active growing season (Fig. 9). The dryland approach is suited (1) to non-irrigated plantations where stand entry or over-flights are the only alternatives, and (2) for supplementing micronutrients or relatively immobile nutrients that need to be applied once per rotation (e.g., lime). The dryland approach is economically

Fig. 9. Hybrid cottonwood planting in the first year of growth in western Oregon. Note lead for the fertigation system at the beginning of the row. Photo by John Stanturf.

attractive because of low capital requirements and suitability for contracting out application.

Fertilizing the site with high rates of N (150-500 kg ha-r) only once per rotation assumes that applied nutrients are quickly immobilized in the soil and slowly released to supply tree growth. High rates are expected to produce a long-term fertilizer effect and may not increase growth the first year more than low rates. Nutrients not captured by vegetation or immobilized in soil may contaminate ground and surface water with nitrates.

More frequent fertilization with lower rates (50-150 kg N ha^{-1}) can sustain maximum production and avoid water quality degradation, but application costs increase. The amount of N applied annually can be adjusted to the developmental stage of the stand by ramping the rate up during establishment, reaching a maximum rate at canopy closure, and then either maintaining the maximum rate throughout the rotation or backing down as cycling on the site supplies more of the annual N requirement. Matching developmental requirements involves matching application rates to stand growth patterns and requires more sophisticated diagnostic methods than currently are available. Fertilization prior to canopy closure also risks enhancing growth of competing vegetation. Therefore, a practical approximation of an optimal nutrient regime is annual or biennial applications of constant low fertilizer rates (e.g., 50-100 kg N ha^{-1} $year^{-1}$), beginning when the canopy has closed. This less intensive approach avoids increasing weed control needs during establishment, but it risks missing maximum growth potential by under-fertilizing, or nitrate leaching by over-fertilizing (Table 5).

The fertigation approach provides the greatest flexibility in supplying nutrient uptake requirements but requires high capital costs initially and constant attention to the delivery system. This approach assumes that applied nutrients are available for uptake by poplar roots from soil solution. Nutrients removed from solution through uptake or immobilization are incrementally replenished as often as several times per week so that relatively constant nutrient concentrations are maintained in the soil solution. Such frequent incremental additions are of low concentrations but adequately supply annual growth requirements and minimize risk of nitrate leaching losses. This approach is well suited to drip irrigated plantations for applying mobile or easily fixed nutrients that are required in large quantities such as N, P, or K.

Other nutrients

Nutrients besides N may improve poplar growth, including phosphorus (P), potassium (K), calcium (Ca), and micronutrients such as boron (B), molybdenum (Mo), and zinc (Zn). Other micronutrients may be required to maintain optimum balance on certain sites. These nutrients can be applied separately or with N in fertilizer blends, using the dryland approach or using appropriate concentrates in fertigation systems.

Phosphorous may be limiting on sites such as the coarse-textured well-drained soils used for fertigation systems, highly weathered soils of the southeast U.S., or upland marine and some alluvial soils in the Pacific Northwest. Phosphorus applied at planting will encourage root development. It will persist and become slowly available for several years (possibly even through the rotation) because of mineral fixation with iron, aluminum, and calcium, as well as immobilization in organic matter. Super-phosphate can be broadcast along with N, but fertilizer use efficiency can be low if roots have not fully exploited the site, and soluble P exposed to a large reaction surface on soil particles is easily fixed. Granular super-phosphate, alone or in a mixture with N, may be banded and incorporated along planting rows or placed in a patch directly below the cutting at establishment

Table 5. Typical fertilizer rates applied in various poplar growing regions of North America.

Region	Cropping system	Nutrients applied	Application frequency	Application rate (elemental) (kg ha-‘)	Chemical formulations
Lake States	Non-irrigated	N	Every 2nd year after canopy closure	85–185	Urea 4.5-O-O
Eastern Canada and Northeast U.S.	Non-irrigated	N	Annually	60-100	Urea 45-O-O
		N	Biosolids 55 tons ha^{-1} applied at planting	1008	1.8% N
	Irrigated	N	Every irrigation cycle during 1st year	60	Ammonium polyphosphate 10-34-O
		N	Every irrigation cycle after 1st year	125	Urea - ammonium nitrate solution 28-O-O
Pacific Northwest					
Vancouver Island	Non-irrigated	N	At planting and canopy closure	25-200	Urea 45-O-O
		P	At planting and canopy closure	25–200	Monoammonium phosphate 11-48-o
		S	At planting	8	Copper and zinc sulfate
Lower Columbia River	Non-irrigated	N, P, K	Not required		
Eastside	Irrigated	P	**First** month of establishment, every irrigation cycle (at least once daily)	12	Ammonium polyphosphate solution 10-34-o
		N	May through July, every irrigation cycle	60 first year, increased by 30 every year to 150 by 4th	Urea - ammonium nitrate solution 32-O-O

Table 5 (concluded).

Region	Cropping system	Nutrients appiied	Application frequency	Application rate (elemental) (kg ha-‘)	Chemical formulations
		Zn	1st year	30 (see text)	Zn chelate for rapid response, $ZnSO_4$ for long term
			4th year	2	
Southeast U.S.					
Lower Mississippi Valley	Non-irrigated	N	Subsoil injection at planting	100–120	Urea - ammonium nitrate solution 32-O-O
Coastal Plain	Irrigated	N	Every irrigation cycle, April through October	60-250	8-2-8 or 12-2-8
		Lime	At planting	Achieve pH 6.5	

(van den Driessche 1999). This decreases the contact between fertilizer and soil and improves efficiency of use. Another approach is to inject a mixture of N and P where the base of the cutting will be during the subsoiling / row marking operation. This places the nutrients at an optimal location for tree roots and out of the reach for shallow-rooted competing vegetation.

Fertigation systems can take advantage of slow P availability by adding one or more pulses during the rotation. Much of this pulsed P will become immobilized and slowly mineralized at rates sufficient to meet uptake requirements. Alternatively, fertigation can supply small amounts of P constantly to maintain soil solution concentrations of P adequate to meet requirements. This supplies nutrients directly to waiting roots so there is less opportunity for fixation or immobilization.

Potassium can also increase growth of poplar, usually only if supplied along with N and P (Blackmon 1976). This element can be supplied at planting by broadcast application or banding. On sandy soils, K is easily leached and may require several applications over a rotation. Soils containing expanding lattice (2: 1) clay minerals such as smectite are common on slackwater deposits in the southern U.S. and are capable of fixing large quantities of K. On these soils, K should be applied in bands.

Calcium amendments by liming may be needed to raise soil pH. Poplars prefer pH levels of 6.0-6.5, but do well between 5.5 and 7.5. Black cottonwood and its hybrids perform best between pH 5.0 and 6.0. Acid soils may require heavy lime additions, but individual clones may vary in their preference. Lime additions are required for calcium supply if exchangeable Ca is less than 1000 mg kg-r; levels between 3400 and 3800 mg kg^{-1} are optimal. Calcium and Mg deficiencies are rarely observed, probably because poplars occur naturally, and grow in plantations, on good sites. Attempts to grow poplars on sands and other less fertile sites using fertigation may demonstrate the need for calcium fertilization, especially on old, highly weathered parent materials as found in the southern U.S.

Sulfur and micronutrients such as zinc are also known to be limiting on some sites, but a single addition of these nutrient elements will last throughout the rotation. Because of the small amounts of micronutrients required, surface banding along the planting rows or spot treatments at each tree location are adequate. Excess amounts of these micronutrients can become toxic, so care should be taken to add only required amounts.

Regional distinctions

Poplar nutrient management programs in all regjons include N addjtjons, although the rates, timing, formulations, and methods of applying amendments vary widely.

Table 5 provides examples of the nutrient amendments used in North America. Dryland approaches to fertilizing poplar occur in regions with sufficient precipitation during the growing season or access to ground water. This area includes much of the eastern continent, as well as the west side of the Cascade Mountains in the Pacific Northwest. Fertjgatjon is used in the arid regions east of the Cascades in the Pacific Northwest and on well-drained sites in the southeastern U.S. where extended periods between summer rains make irrigation necessary.

North Central

Sites in the North Central region range from organic peat soils to coarse glacial tills. Climate varies from moist summers and extreme winter temperatures jn Canada to drier summers and milder winters in the Great Plains. Such variation requires diagnostic tools for evaluating fertilizer needs. Productivity is correlated with N levels and response to fertilization is certain when leaf N levels are at or below 2%. Fertilizer response is less certain with leaf N above 2.5%. Typically, urea is applied (85–185 kg N ha-r) after canopy closure in the third or fourth growing season. Applications may continue as often as every second year thereafter, but the effectiveness of multiple applications has not been thoroughly evaluated. Although difficult to predict, growth response to blended NPK fertilizer over N only has been observed but depends on clone and site.

Northeast

Surprisingly few commercial plantations of cottonwood or balsam poplars occur in the Northeast region. Fertilization in eastern Canada consists almost exclusively of mill biosolids applied by Domtar Forest Products. Favorable response is obtained with mill residue mixed from primary and secondary clarifiers. Trees are planted through a biosolids layer applied at 55 Mg ha^{-1}, which contains 1.8% N, 0.26% P; and 0.98% K plus a full complement of micronutrients.

Both dryland and fertigation approaches are used by Mead Fiber Board in Maine. Leaf N concentrations above 3% are maintained by supplying 61 kg ha^{-1} during the first year and then 125 kg ha^{-1} annually, beginning in the second season. These rates provide increased growth over unfertilized plots, but no further effect is seen with greater rates.

Hybrid poplar clones NM-5 and NM-6 are included in the New York coppice system where 100 kg N ha^{-1} of sulfur coated urea is applied at the start of every coppice cycle. Significant productivity increases due to fertilizer application are seen compared with unfertilized controls.

Pacific Northwest — westside

No response has been seen to N application rates up to 370 kg ha^{-1} on the rich alluvial soils along the lower Columbia River even though productivity is high (Fig. 10). Some stands growing on heavy clay soils can be chlorotic and have low Mg, Zn, or Mo concentrations. Such deficiencies are rare and easily remedied by aerial applications of a micronutrient mix. In contrast, marine and alluvial soils on east Vancouver Island respond to N, P, and perhaps S at planting, and at mid-rotation. Significant growth response to N and P is obtained by banding 100–200 kg ha^{-1} of each nutrient with incorporation along the planting row, or by placing fertilizer below the surface at the base of the cutting (25–50 kg ha^{-1}). Poplars growing on marine and alluvial soils on Vancouver Island respond to fertilization just before canopy closure (3–4 years), at rates up to 200 kg N ha^{-1} and 100 kg P ha^{-1}.

Pacific Northwest — eastside

Poplar production using the fertigation approach has reached operational scale east of the Cascade Mountains in the Columbia River basin. This production system depends on fertilizer applied through the irrigation system to meet N, P, and Zn requirements, and all other essential nutrients are supplied by the coarse alluvial soils. Under this regime at the Potlatch Corporation fiber farm in Boardman, Oregon, all nutrients are applied through the irrigation system. During the first month after planting, a 10-34-0 concentrate (12 kg P ha^{-1}) is applied during each irrigation cycle. The high P concentration in the fertigation is used to encourage root growth while at the same time supplying trees with some N for establishment. The P solution is applied until mid May, then N is supplied using a 32-0-0 concentrate starting at a rate of 60 kg ha^{-1} for the first year. This rate is increased by 30 kg ha^{-1} each year until 150 kg ha^{-1} is reached in the fourth year. The N solution is applied during each irrigation cycle, and the total annual treatment is completed by the beginning of August. Zinc chelate is applied (12 kg ha^{-1})

Fig. 10. High-yielding hybrid cottonwood plantation in its fourth year of growth on an alluvial soil in western Oregon. Photo by Don Dickmann.

once trees are 0.75-I m tall during establishment. An additional 6 kg ha^{-1} is applied mid season; in September Zn is applied as a sulfate. The chelate gives quick response during the growing season, and the sulfate form supplies long-term Zn requirements. An additional 2.5 kg Zn ha^{-1} is applied as zinc sulfate in the fourth growing season.

Foliar samples are collected monthly and analyzed for all essential nutrients. This regular monitoring program provides information on the adequacy of the fertilizer rates as well as a check on the operation of the fertigation system.

Southeast Coastal Plain, irrigated

Although the southeast U.S. has a humid climate, evaporation deficits during the growing season and the possibility of drought years lead to productivity gains for irrigated stands and present an opportunity for the fertigation approach to apply mineral nutrients. Typically, 60-250 kg N ha^{-1} are applied using an 8-2-8 or 12-2-8 liquid fertilizer concentrate. Nutrients are added during every irrigation cycle between April and October. Broadcast additions of lime, micronutrients, and P are common prior to planting. Good response is seen to irrigation, but fertilizer response depends on the site.

Lower Mississippi River Valley, non-irrigated

The Lower Mississippi River Valley contains important commercial poplar plantations on sites within the present active floodplain and on sites protected by levees (Fig. 11). Crown Vantage is the predominate grower in this region, managing company lands as well as providing landowner assistance for small private growers. Alluvial sites are periodically recharged with flood deposits and do not respond to fertilizer amendments. Old-field sites have been in cotton or soybean production for more than 20 years while protected from flooding by levees. Cottonwood on old-field sites responds to N, but not other nutrients. In this case, urea – ammonium nitrate solution (98 kg N ha-r, 32-O-O) is injected at a depth of 45 cm during fall subsoiling. Cuttings are planted the following winter or early spring in the slit produced by the blade. This deep placement of N has proved more effective than side dressing because it is placed within reach of the tree roots, but beyond the reach of competing vegetation.

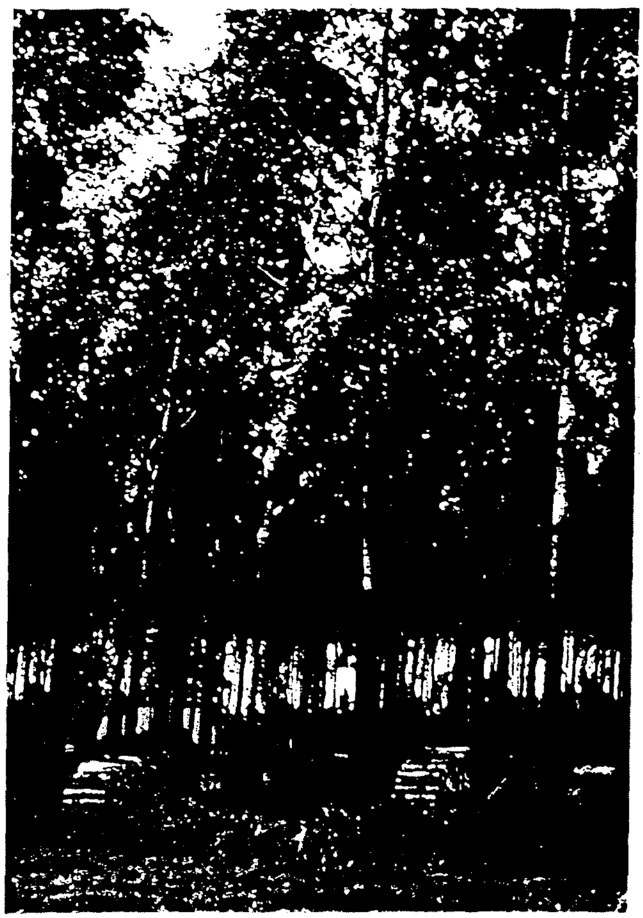
Fig. 11. Three-year-old eastern cottonwood plantation on a Commerce soil in the Lower Mississippi Alluvial Valley. Photo by US Forest Service.

Thinning

Poplar plantations offer an opportunity to produce sawlogs and veneer within 20-30 years of planting. Systematic and selective thinning regimes must be included in management for these products (Fig. 12). Timing of thinning treatments will be determined largely by initial spacing, which is affected by site quality, establishment practices, and survival.

Spacing and thinning studies on eastern cottonwood illustrate the complexity of managing plantations for sawlogs. Cottonwood is characterized by very rapid diameter and height growth in the early years, and plantations must be managed aggressively to maintain this rapid growth and avoid stagnation. Initial spacing has no affect on the rate at which diameter growth peaks, generally by the third or

Fig. 12. Thinning a hybrid poplar plantation to maximize the yield of useful products and maintain the diameter growth of residual trees. This stand will produce high quality sawtimber and veneer. Photo by Don Dickmann.



fourth year (Krinard and Johnson 1984). Because cottonwood cannot tolerate side competition, it responds poorly to release, following crowding. Wide spacing with pruning of the lower branches or closer spacing accompanied by early thinnings is necessary to maintain rapid growth of individual trees.

Anderson and Krinard (1985) summarized experience from experimental and operational plantings of five spacing intervals on two sites (medium and good), shown in Table 6. Generally dbh increases as spacing increases, from 3.7 x 3.7 m to 7.4 x 7.4 m. All spacing intervals were thinned at least once except the two widest. Sawtimber yields were greatest for stands spaced 7.4 x 7.4 m. Wider spacing, however, requires intensive pruning to maintain quality and more weed control to successfully establish plantations. A compromise adopted in the Lower Mississippi River Valley of 3.7 x 3.7 m is suitable both for pulpwood and sawlog production (Gascon and Krinard 1976). Stands established at this spacing on good sites can be systematically thinned, beginning at ages 3-5 years, removing half the trees. Stands should be selectively thinned thereafter to maintain growth.

Spacing trials of black cottonwood indicate that the 3.7 × 3.7 m spacing is best for this species as well (DeBell 1990). Black cottonwood also responds well to thinning. Hybrid poplars are grown at a variety of spacings, including a rectangular spacing of 3.05 x 2.1 m used by Fort James in western Washington. Although they use rectangular spacing for mechanical efficiency, indications are

Table 6. Total wood volume and lumber volume yields of eastern cottonwood plantations on a good site by spacing interval and thinning regime" (source: Anderson and Krinard 1985).

Spacing (m)	Age (years)	Residual stand stocking (stems ha^{-1})	Residual stand dbh (cm)	Total volume cut per hectare (m^3 ha^{-1})	Sawtimber volume cut per hectare (m^3 ha^{-1})
3.47 x 3.41	5	296	15.5	44.1	
	12	188	30	53.2	
	20	124	42	30.0	19.9
	30	0	55	292.3	179.6
4.88 x 5.49	8	168	24	72.8	
	18	111	43	27.4	18
	30	0	58	308.4	187.7
7.32 x 7.32	15	99	42	41.0	26.7
	30	0	63	328.2	196.3
9.75 x 9.75	30	0	63	334.4	200.0
11 x 11	30	0	64	275.1	164.5

"All stands were thinned once except the two widest spaced stands, 9.75 x 9.75 m and 11 x 11 m. The first thinnings in the stands spaced 3.47 x 3.47 m and 4.88 x 5.49 m were row thinnings in which every other row was removed.

that rectangular spacing may produce higher yields. This could be due to more rapid crown differentiation, and a shorter time growth is checked by competition (DeBell et al. 19976).

Coppicing

The ability of poplars to sprout readily from stump or root collar provides an opportunity to regenerate and manage coppice stands in the second rotation. The coppice system of natural regeneration is an inexpensive alternative to replanting. Coppice management is currently used in eastern cottonwood plantations grown for pulpwood in the southern U.S. (Fig. 13), but it is not used elsewhere in North America. Most poplar growers continually replace old planting stock with genetically improved stock; thus, coppice is unattractive even for pulpwood production. If sawlogs or veneer logs are the product goal, replanting is the best option because of poor stem form in coppice, and stumps of larger trees sprout less vigorously.

Coppice rotations are economically attractive to non-industrial private landowners because of lower establishment costs. Clearing and site preparation following harvest of a plantation is complex and expensive. The two most important factors for coppice regeneration are age of stand and time of harvesting. Harvest should begin no later than age 10 in the rotation to insure vigorous sprouting. The time of harvest should be during the dormant season, usually between the months of

Fig. 13. Coppice regrowth of an eastern cottonwood plantation in the Lower Mississippi Alluvial Valley. Photo by Don Dickmann.

October and April, depending on region and weather patterns. Plantations harvested during the winter months are typically those that may be targeted for coppicing. Often there is a proliferation of shoots that arise from a single stump, and how these shoots are treated can potentially affect growth, yield, and average tree size through rotation. If coppice is undesirable, harvesting should begin after trees have fully flushed in the spring and can continue until trees begin dormancy.

Because of multiple sprouting, it has been customary to thin stumps back to two sprouts in the winter after the third growing season, removing up to 10 sprouts from each stump. Without this cleaning step, yields of the coppice rotation will be half or less than the first rotation because of small stem size. Recently, Crown Vantage has harvested every other row in a plantation in the winter, which encourages sprouting. After it is clear that sprouting has been successful, usually after one or two growing seasons, the residual trees are harvested in the summer to discourage sprouting. In this way, even multiple sprouts on a stump will have sufficient growing space to develop to merchantable size. For small landowners, however, this may not be cost effective, as the stand must be entered twice.

Growth and yield

Many factors influence the growth of poplars in plantations, including species or clone, site quality, climate, and spacing. After establishment, the amount of growing space available to an individual tree dominates stand yield and significantly influences the average size stem attained by harvest age. DeBell and others (1997b) concluded that optimal spacing and rotation length would be wider and longer, respectively, than was presented in earlier biomass research (Ranney et al. 1987). DeBell et al. (1997*a*, *b*) concluded that hybrid poplar plantations needed a minimum of 6.2 m^2 growing space per tree to yield a stand with mean tree diameter at harvest of 15 cm, regarded as the economic minimum.

Tree growth is not uniform, however, even when individuals are all from the same clone. Poplars are extremely intolerant of shading, such that crowns of eastern cottonwood do not touch even in densely spaced plantations. Belowground competition probably occurs before crown closure. Francis (1985) found that by age 8, average root length of eastern cottonwood stabilized at slightly more than half the distance between individual stems, indicating significant belowground competition. Clones of eastern cottonwood and hybrid poplar vary in their tolerance of shading; some can be planted closer together than others, a concept expressed as “stockability” (DeBell et al. 1989). Before reviewing the scant data available on growth and yield of poplar plantations, it is instructive to compare patterns of stand development in natural stands to plantations.

Switzer et al. (1976) compared patterns of biomass accumulation in eastern cottonwood natural stands to closely spaced thinned plantations and widely spaced unthinned plantations. Dry matter accumulation in the closely spaced thinned plantations was greater than natural stands early on, until age **10.** The pattern of dry matter accumulation was similar in natural stands and widely spaced plantations until about age 15. Periodic and mean annual biomass increments followed similar trends. The maximum mean annual biomass increment was about the same for all three cultural regimes, between 10 and 11 tons ha^{-1} $year^{-1}$. The potential of a site to produce biomass appears to be relatively fixed, at least under a given management intensity. The time required to achieve culmination of mean annual biomass increment, however, can be influenced by manipulating growing space available to individual stems. Even more importantly, the time required to reach a minimum or average stem size can be influenced by manipulating growing space, nutrients, and water.

Growth of natural stands of eastern cottonwood (Table 7) and black **cottonwood** (Table 8) provide a baseline for comparing growth and yield potential of poplar plantations (Table 9). The highest values for operational plantation culture are generally for eastern cottonwood, although T×D hybrids **in the Pacific Northwest** rival yields from southern bottomland sites. Evidence from experiments with improved genetic stock and more intensive management practices **promise** significantly higher yields in the future. Directly extrapolating from small research plots to operational yield expectations,, however, is dangerous. For example, Heilman and Stettler (1985) determined mean production values at age 4 for a hybrid poplar clone 11-011 (T×D) to be 28 tons ha-t $year^{-1}$. DeBell et al. (19976) used larger plots, attained growth equal to or better than other studies with the same clone, but estimated yield to be 18 tons ha^{-1} $year^{-1}$, similar to the

Table 7. Yields of natural cottonwood stands in the Lower Mississippi River Valley (source: Williamson 19 13).

Age (years)	Volume (m^3 ha-‘)	Stocking (stems ha-‘)	dbh (cm)	Height (m)	Mean annual diameter increment (cm)	Mean annual height increment (m)	Mean annual volume increment (m^3 ha-t)
5	46		5.1	6.7	1 .0	1.3	9.1
10	126	1727	14.5	17.1	0.6	1.7	12.6
15	269	682	23.4	24.7	0.6	1.6	18.0
20	343	403	31.2	29.6	0.6	1.5	17.1
25	381	282	38.1	32.9	0.6	1.3	15.3
30	408	198	44.2	35.1	0.6	1.2	13.6
35	430	146	50.0	36.9	0.6	1.1	12.3
40	450	121	55.9	38.7	0.6	1.0	11.2
45	467	104	61.5	40.2	0.5	0.9	10.4
50	483	79	67.3	41.5	0.5	0.8	9.7

Table 8. Yields of natural black cottonwood (*Populus trichocarpa*) stands by site class (source: Smith 1980, cited by DeBell 1990).

Site class	Stand age (years)	Average dbh (cm)	Stocking Stems (ha-‘)	Height (m)	Net volume (m^3 ha^{-1})	Maximum mean annual volume increment (m^3 ha-‘)
I	112	46	294	41	302	5.5
II	101	33	415	30	220	2.8
III	87	28	474	21	123	1.7

Table 9. Growth and yield potentials of intensively managed poplar plantations (source: Dickmann and Stuart 1983).

Parameter	Growth or yield”
First-year height growth	l-3.4 m
Mean annual height growth after IO-20 years	0.8-2.0 m
Mean annual diameter growth after IO-20 years[b]	1–2.5 cm
Mean annual volume increment after IO-20 years	7-25 m^3 ha^{-1}
Mean annual biomass increment after 5-20 years[c]	5–20 tons ha^{-1}

“Growth and yield will vary appreciably, depending upon geographic location, site quality, clone or cultivar used, and silvicultural conditions. Highest values generally are for cottonwood on southern bottomland sites.

[b]Diameter growth of individual trees depends on stocking density. Wide spacing or frequent thinnings promote rapid diameter growth.

[c]Oven-dry, leafless stems, and branches. Attainment of maximum annual increment will occur only if stands are heavily fertilized and irrigated and will occur much sooner at tree spacing of 2 m or less.

operational yields obtained at the James River Lower Columbia Fiber Farm near Camas, WA (Fig. 14). Nevertheless, clonal trials do indicate biological potential.

Diameter and height growth

Eastern cottonwood is one of the tallest hardwood species. Heights in natural stands of 53–58 m and diameters of 120-180 cm have been reported (Putnam et al. 1960; Johnson and Burkhardt 1976). Cao and Durand (199 1 a) reported mean annual height increments of 1.9-2.4 m $year^{-1}$ at age 10 for plantation stands of eastern cottonwood growing on different soil series in the Lower Mississippi Alluvial Valley, with mean annual increments on the very best sites exceeding 3 m. Heights of 13 m at age 3 and more than 30 m at age 9 have been observed for individual trees. Trees planted at wide spacing can average 29 cm dbh at age 5 (Krinard 1979).

Fig. 14. The payoff — final harvest of a short-rotation hybrid cottonwood plantation on an industrial site in western Oregon. Photo by Don Dickmann.

Annual increment of dominant and co-dominant trees in black cottonwood plantations in British Columbia and Washington can average 1.6 m in height and 1.9 cm in dbh (Silen 1947). In the lower Fraser Valley, annual increment of dbh was 2 cm and height was 1.7 m in a lo-year-old plantation (Smith and Blom 1966); growth is less on sites in the interior and at locations that are more northerly.

Hybrid poplars in the Pacific Northwest can achieve height growth of 2-3 m year' and up to 2.3 cm $year^{-1}$ annual dbh growth (Heilman and Stettler 1985). Ceulemans et al. (1992) reported height growth up to 3.4 m $year^{-1}$ and dbh growth of up to 2.55 cm $year^{-1}$ for hybrids. Both reports are for 4-year old plantations including parents and hybrids.

Hybrid poplars growing under favorable conditions in the Northeast averaged 1–3 cm in annual dbh increment and height increased l-2 m annually (Zsuffa et al. 1977). Hybrid poplars growing on silty clay loam soils in southern Ontario varied in annual height growth from 0.7 to 1.3 m and from 0.6 to 1.3 cm in annual diameter growth after 18-22 years (Marshall 1979). Clones of eastern cottonwood and its hybrid with *P. balsamifera* grew as well as natural aspen *(P. tremuloides* Michx.) root suckers on good sites in northern Ontario, well beyond the range of cottonwood (Farmer et al. 1991). Growth after 9 years for the best clones was 80 cm $year^{-1}$ in height and over 1 cm dbh. Hybrid aspen in northern Wisconsin have grown in excess of 1 m in height and 1 cm in dbh annually (Benson 1972).

. Volume growth[1]

Data on volume of managed poplar plantations are scarce, and the best data available are for pulpwood rotations of eastern cottonwood in the South. A compatible growth and yield model is available (Cao and Durand 1991*a*), which uses the individual tree volume equations developed by Krinard (1988):

[1] $TVOB = 0.06 + 0.002221D^2H$

and

[2] $MVIB = -0.86 + 0.001904D^2H$

where

TVOB = total tree volume outside bark in ft^3 from a 30-cm stump to the tree tip,

MVIB = merchantable tree volume inside bark in ft^3 from a 30-cm stump to a 7.6-cm top,

D = diameter at breast height in in., and

H = total tree height in ft.

Total and merchantable volumes can be converted from ft^3 to m^3 by multiplying by 0.02832.

The equations for total tree volume and merchantable tree volume per acre (1 acre = 0.404 ha) are:

[3] $\ln TV_i = 2.64098 + 0.00868S - 3.27063/A_i + 1.09103 \ln B_i$

and

[4] $\ln MV_i = 2.12838 + 0.01411S - 5.04889/A_i + 1.08576 \ln B_i$

where

$\ln x$ = natural logarithm of x,

TV_i = total outside-bark volume in $ft^3\ acre^{-1}$ at time i,

MV_i = total merchantable inside-bark volume in $ft^3\ acre^{-1}$ at time i,

S = site index in ft at base age 10 years,

[1] Volume equations presented in this section are given in English rather than metric units because the original data sets from which the equations were derived were not available to make the conversions. English-metric conversion factors for dependent variables, however, are given in each case (see Appendix for English-metric conversions).

B_i = stand basal area in ft^2 $acre^{-1}$ at time i, and

A_i = stand age in years at time i.

Total and merchantable volumes can be converted from ft^3 $acre^{-1}$ to m^3 ha^{-1} by multiplying by 0.06998.

Site index often is used in growth and yield models and must be estimated from stand data. Cao and Durand (1991*b*) developed polymorphic site index curves for eastern cottonwood plantations in the Lower Mississippi Alluvial Valley. Their site index curve for any base age up to 10 years is:

$$[5] \qquad \ln(H) = 5.83564 + [\ln(S) - 5.83564](I/A)^{0.41576}$$

where

$\ln(H)$ = natural logarithm of average height in ft of the dominants and co-dominants,

S = site index in ft,

I = base age in years, and

A = stand age in years. Feet can be converted to m by multiplying by 0.3048.

Stanturf and Portwood (1999) used data from three stands of different productivity classes to evaluate the economics of afforestation with eastern cottonwood. They used the Cao and Durand (1991 a) model to estimate merchantable yield to a

Table 10. Characteristics of the stands selected to represent soil/site productivity classes and their estimated merchantable yields[a] at rotations of 10 years; stands were age 3 years when measured (source: Stanturf and Portwood 1999).

	Commerce[a]	Tunica–Bowdre[b]	Sharkey[b]
Site index (base age 10), m	24.4	22.3	20.1
Basal area, m^2 ha^{-1}	6.7	3.9	3.4
Stems ha^{-1}	682	622	642
Survival, %	91	83	86
Tons ha^{-1} age 10	7.6.7	56.3	47.1
Mean annual increment, OD tons ha^{-1} at age 10	7.7	5.6	4.7
Cumulative annual increments, OD tons ha^{-1} at age 10	8.4	7.0	6.0

[a]Merchantable yields are estimated by eq. [4] (inside bark, to a 7.6-cm top). These stands are all on old field sites, protected by the river levee, with good survival. All were planted with the technology described in Table 11.
[b]Soils are Commerce (Aeric Fluvaquents), Tunica-Bowdre (Vertic Haplaquepts - Fluvaquentic Hapludolls), and Sharkey (Chromic Epiaquerts).

Table 11. Schedule of operations for cottonwood cultural practices in the southern U.S.

Dates	Activity
October year 0	Two-pass site preparation disking Row establishment and liquid nitrogen applied in trenches @ 112 kg N ha^{-1}
March year I	Plant cottonwood
March year 1	Spray herbicide in band over dormant cuttings (oxyfluorfen @ 0.26 kg ha^{-1} + glyphosate @ 1.4 kg ha-‘)
May year 1	One-pass disking, followed 2 weeks later by second pass at right angle to first
June and July year I	Basal application of oxyfluorfen @ 0.7 kg ha-’
August year 1	One-pass disking, followed 2 weeks later by second pass at right angle to first
Summer year 1	insect control for cottonwood leaf beetles (carbaryl @ 0.92 kg ha^{-1})
June year 2	Insect control for cottonwood leaf beetles (carbaryl @ 0.92 kg ha-‘)
June and July year 2	One-pass disking
Winter year 10	Cottonwood pulpwood harvest

7.6 cm top (Table 10). The silvicultural system used operationally in the Lower Mississippi Alluvial Valley is detailed in Table 11, and the system in the Lake States in Table 12.

Black cottonwood plantations in the Fraser River Valley in British Columbia yielded mean annual volume increments ranging from 10.5 to 15.4 m^3 ha^{-1} (Smith 1980), much higher than the values for natural stands shown in Table 8. Even greater mean annual volume increment was obtained in a plantation growing on deep alluvial soils in coastal Washington, 20.8 m^3 ha^{-1} over 24 years (Murray and Harrington 1983).

Hybrid poplars in Ontario have been reported to yield as much as 29 m^3 ha^{-1} $year^{-1}$ after 12 years (Zsuffa et al. 1977), and from IO to 27 m^3 ha^{-1} $year^{-1}$ after 18-22 years (Marshall 1979). Elsewhere in the Northeast, mean annual volume increment of *P.* x *canadensis* cv. Eugenei in Indiana was 7 m^3 ha^{-1} $year^{-1}$ (Merritt and Bramble 1966). Recent work in the Lake States with several disease resistant clones of hybrid poplar (D×N crosses) showed estimated yields of up to 9.4 oven-dry (OD) tons ha^{-1} year-^{1} (Hansen 1992; Netzer and Tolsted 1999), with adjacent small plot trials of the best new clones yielding up to 13.4 OD tons ha^{-1} $year^{-1}$ (Hansen et al. 1994).

Biomass growth

Leafless biomass increment is usually measured in research studies of poplar growth, Yield of eastern cottonwood in the southern U.S. and hybrid poplar in the Pacific Northwest is measured in terms of dry or green tons per ha, but where tree weight is oven-dry in kg and DBH is in cm.

They used this equation to estimate mean yields from plantations of improved hybrid poplar in the Lake States to be more than 6.7 OD tons ha-r year-‘, with yields in better sites averaging 9.4 OD tons ha-’ $year^{-1}$. Peak yields at 2.4 x 2.4 m spacing occurred between year 7 and 10, provided weed control was adequate.

Environmental effects

Public perceptions of plantations are often negative, although poplar plantations provide many environmental benefits. The value of poplar plantations to wildlife has been documented (Twedt et al. 1999; Wesley et al. 198 1). Where poplar plantations replace row cropping, additional benefits are improved water quality and greater floral diversity.

Eastern cottonwood plantations in the lower Mississippi River valley produce understory biomass exceeding 1200 kg ha^{-1} annually (Wesley et al. 1981). This luxuriant undergrowth is excellent habitat for whitetail deer and rabbits year-round. Spring nesting and brood habitat is available for wild turkey and quail. There is little difference between older cottonwood plantations and the surrounding bottomland hardwood forest for Neotropical migratory bird territory, except that there are fewer cavity nesters in the plantations (Twedt et al. 1999).

Afforestation of cropland with eastern cottonwood in conjunction with slower growing oak species is practiced in the lower Mississippi Valley (Schweitzer and Stanturf 1999). Besides early financial returns to the landowner, this interplanting system benefits forest-breeding Neotropical migratory birds (Twedt and Portwood 1997). Cottonwood also increases plant species diversity by providing perches for fruit-eating birds, thereby facilitating spread of other species into the afforestation stands (Twedt and Portwood 1997).

Despite the intensive site preparation and early weed control needed to successfully establish poplars, plantations can improve water quality as compared to continuous row cropping. The simplest effect is that soil disturbance in poplar plantations is limited to at most 3 years out of the 7–10-year rotation, while soils supporting row crops are continuously disturbed. Poplar culture can significantly improve water quality by reducing sediment loss as well as lower pesticide and nutrient movement. Surprisingly, the improvement can occur even in the first year. Thornton et al. (1998) reported on a side-by-side comparison of eastern cottonwood with cotton. Sediment loss from the cottonwood was 2.3 tons ha^{-1} the first year, significantly less than the 16 tons ha^{-1} from cotton. The tree canopy developed nearly complete cover over the 3.7 m interval between rows by late spring and probably decreased raindrop impacts on the soil surface because interception lowered runoff.

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References

Anderson, W.C., and Krinard. R.M. 1985. The investment potential of cottonwood sawtimber plantations. *In* Proceedings of the Third Biennial Southern Silvicultural Research Conference, Atlanta, Georgia, November 7-8, 1984. *Edited by* Eugene Shoulders. USDA For. Serv. Gen. Tech. Rep. SO-54. pp. 190-197.

Baker, J.B., and Broadfoot, W.M. 1979. A practical field method of site evaluation for commercially important hardwoods. USDA For. Serv. Gen. Tech. Rep. SO-36.

Benson, M.K. 1972. Breeding and establishment — and promising hybrids. *In* Proceedings of the Aspen Symposium. USDA For. Serv. Gen. Tech. Rep. NC- 1. pp. 88-96.

Bemier, B. 1984. Nutrient cycling in *Populus*: a literature review with implications in intensively-managed plantations. Canadian Forestry Service, Ottawa. IEA/ENFOR Rep. 6.

Blackmon, B.G. 1976. Response of *Aigeiros* poplars to soil amelioration. *In* Proceedings of the Symposium on Eastern Cottonwood and Related Species, Greenville, Mississippi, September 28 - October 2, 1976. *Edired by* B.A. Thielges and S.B. Land, Jr. Louisiana State University, Division of Continuing Education, Baton Rouge. pp. 344-358.

Blackmon, B.G., Baker, J.B., and Cooper, D.T. 1979. Nutrient use efficiency by three geographic sources of eastern cottonwood. Can. J. For. Res. 9: 532-534.

Brenneman, R. 1982. Electric fencing to prevent deer browsing on hardwood clearcuts. J. For. 80: 660–661.

Buhler, D., Netzer, D.A., Riemenschneider, D.E., and Hartzler, R.G. 1998. Weed management in short-rotation poplar and herbaceous crops grown for biofuel production. Biomass Bioenergy. 14: 385-394.

Cannell, M.G.R., and Smith, R.I. 1980. Yields of minirotation closely spaced hardwoods in temperate regions: review and appraisal. For. Sci. 26: 415-428.

Cao, Q.V., and Durand, K.M. 1991*a*. A growth and yield model for improved eastern cottonwood plantations in the lower Mississippi Delta. So. J. Appl. For. 15: 213-216.

Cao, Q.V., and Durand, K.M. 1991*b*. Site index curves for eastern cottonwood plantations in the lower Mississippi Delta. So. J. Appl. For. IS: 28-30.

Ceulemans, R., Scarascia-Mugnozza, G., Wiard, B.M., Braatne, J.H., Hinckley. T.M., Stettler, R.F., lsebrands, J.G., and Heilman, P.E. 1992. Production physiology and morphology of *Populus* species and their hybrids grown under short rotation. I. Clonal comparisons of I-year growth and phenology. Can. J. For. Res. 22: 1937-1948.

Coleman, M.D., Dickson, R.E., and lsebrands, J.G. 1998. Growth and physiology of aspen sup plied with different fertilizer addition rates. Physiol. Plant. 103: 513–526.

DeBell, D.S. 1990. *Populus trichocarpa* Torr. & Gray. *In* Silvics of North America. Vol. 2. Hardwoods. Edited *by* R.M. Bums and B.H Honkala. USDA For. Serv. Agric. Handb. 654. pp. 570–576.

DeBell, D.S., Harms, W.R., and Whitesell, C.D. 1989. Stockability: a major factor in productivity differences between *Pinus taeda* plantations in Hawaii and the southeastern United States. For. Sci. 35: 708-7 19.

DeBell, D.S., Harrington, C.A., Clendenen, G.W., and Zasada, J.C. 1997*a*. Tree growth and stand development in four *Populus* clones in large monoclonal plots. New For. 14: l-18.

DeBell, D.S., Harrington, C.A., Clendenen, G.W., Radwan, M.A., and Zasada, J.C. 19976. Increasing the productivity of short-rotation Populus plantations. Final Report to the Bioenergy Feedstock Development Program, Oak Ridge National Lab, Oak Ridge. Report ORNL/M-5943. (Available at <http://bioenergy.ornl.gov/reports/debell/contents.html>).

Demeritt, M.E. 1990. Poplar hybrids. *In* Siivics of North America. Vol. 2. Hardwoods. *Edited by* R.M. Bums and B.H. Honkala. USDA For. Serv. Agric. Handb. 654. pp. 577-582.

Dickmann, D.I., and Lantagne, D. 1997. Planting oaks for timber and other uses. North Central Regional Extension Publication No. 605. Michigan State University Extension, East Lansing. 12 pp.

Dickmann, D.I., and Stuart, K.W. 1983. The culture of poplars in eastern North America. Michigan State University Press, East Lansing. 168 pp.

Ericsson, T., Rytter. L., and Linder, S. 1992. Nutritional dynamics and requirements of short rotation forests. *In* Ecophysiology *of* short rotation forest crops. *Edited* by C.P. Mitchell, J.B. Ford-Robertson, T. Hinckley, and L. Sennerby-Forsse. Elsevier Applied Science, London. pp. 35-65.

Farmer, R.E., Palmer, C.L., Anderson, H.W., Zsuffa, L., and O'Reilly, G. 1991. Nine-year outplanting test of cottonwood and hybrid poplar clones in northwestern Ontario. Tree Planters Notes, 42: 49-5 1.

Francis, J.E. 1985. The roots of plantation cottonwood: their characteristics and properties. USDA FOJ. Serv. Res. Note SO-314.

Gascon, R.J., Jr., and Krinard, R.M. 1976. Biological response of plantation cottonwood to spacing, pruning, thinning. *In* Proceedings of the Symposium on Eastern Cottonwood and Related Species, Greenville, Mississippi, September 28 – October *2,* 1976. *Edited by* B.A. Thielges and S.B. Land, Jr. Louisiana State University, Division of Continuing Education, Baton Rouge. pp. 385-391.

Hansen, E.A. 1992. Mid-rotation yields of biomass plantations in the north central United States. USDA For. Serv. Res. Pap. NC-309.

Hansen, E.A. 1993. A guide for determining when to fertilize hybrid poplar plantations. USDA For. Serv. Res. Pap. NC-319.

Hansen, E.A., and Netzer, D.A. 1985. Weed control in short-rotation intensively cultured poplar plantations. USDA For. Serv. Res. Pap. NC-260.

Hansen, E.A., Netzer, D.A., and Tolsted, D.N. 1993. Guidelines for establishing poplar plantations in the north-central U.S. USDA FOJ. Serv. Res. Pap. NC-363.

Hansen, E.A., Ostry, M.E., Johnson, W.D., Tolsted, D.N., Netzer, D.A., Berguson, W.E., and Hall, R.B. 1994. Field performance of *Populus* in short-rotation intensive culture plantations in north-central U.S. USDA For. Serv. Res. Pap. NC-320.

Heilman, P.E. 1985. Sampling and genetic variation of foliar nitrogen in black cottonwood and its hybrids in short rotation. Can. J. FOJ. Res. 15: 1137-I 141.

Heilman, P.E., and Stettler, R.F. 1985. Genetic variation and productivity of *Populus trichocarpa* and its hybrids. II. Biomass production in a 4-year plantation. Can. J. For. Res. 15: 384-388.

Heilman, P.E., and Stettler, R.F. 1986. Nutritional concerns in selection of black cottonwood and hybrid clones for short rotation. Can. J. FOJ. Res. 16: 860-863.

Heilman, P.E., Ekuan, G., and Fogle, D. 1994. Above- and below-ground biomass and fine roots of 4-year-old hybrids of *Populus rrichocarpa x Populus delroides* and parental species in short-rotation culture. Can. J. For. Res. 24: 1186-l 192.

Heilman, P.E., Stettler, R.F., Hartley, D.P., and Carkner, R.W. 1995. High yield hybrid poplar plantations in the Pacific Northwest. Pac. Northwest Coop. Ext. Bull. PNW 356. 39 pp.

Jia, H., and Ingestad, T. 1984. Nutrient requirement and stress response of *Populus simonii* and *Paulownia tomentosa.* Physiol. Plant. 62: 117–124.

Johnson, R.L., and Burkhardt, E.C. 1976. Natural cottonwood stands — past management and implications for plantations. *In* Proceedings of the Symposium on Eastern Cottonwood and Related Species, Greenville, Mississippi, September 28 - October 2, 1976. *Edited by* B.A. Thielges and S.B. Land, Jr. Louisiana State University, Division of Continuing Education, Baton Rouge. pp. 20-30.

Krinard, R.M. 1979. Five years' growth of pruned and unpruned cottonwood planted at 40- by 40-foot spacing. USDA For. Serv. Res. Note SO-252.

Krinard, R.M. 1988. Volume equations for plantation cottonwood trees (*Populus deltoides*). USDA For. Serv. Res. Note SO-347.

Krinard, R.M., and Johnson, R.L. 1984. Cottonwood plantation growth through 20 years. USDA For. Serv. Res. Pap. SO-2 12.

Leech, R.H., and Kim, Y.T. 1981. Foliar analysis and DRIS as a guide to fertilizer amendment in poplar plantations. For. Chron. 57: 17-21.

Marshall, P.L. 1979. Growth and yield of two young poplar plantations in Ontario. *In* Poplar research, management and utilization in Canada. For. Res. Info. Pap. No. 102. Ontario Ministry of Natural Resources, Toronto.

McKnight, J.S. 1970. Planting cottonwood cuttings for timber production in the south. USDA For. Serv. Res. Pap. SO-60.

Merritt, C., and Bramble, W.C. 1966. Poplar plantation research in Indiana — a five-year report. Res. Bull. No. 818. Purdue University Agricultural Experiment Station, West Lafayette.

Morris, R.C., Filer, T.H., Solomon, J.D., McCracken, F.I., Overgaard, N.A., and Weiss, M.J. 1975. Insects and diseases of cottonwood. USDA For. Serv. Res. Gen. Tech. Rep. SO-8.

Murray, M.D., and Harrington, C.A. 1983. Growth and yield of a 24-year-old black cottonwood plantation in western Washington. Tree Planters' Notes, 34(2): 3-S.

Nelson, L.E., Switzer, G.L., and Lockaby, B.G. 1987. Nutrition of *Populus delroides* plantations during maximum production. For. Ecol. Manage. 20: 25–41.

Netzer, D.A. 1984. Hybrid poplar plantations outgrow deer browsing effects, USDA For. Serv. Res. Note NC-325.

Netzer, D.A., and Hansen, E.A. 1992. Seasonal variation in hybrid poplar tolerance to giyphosate. USDA For. Serv. Res. Pap. NC-3 11.

Netzer, D.A., and Hansen, E.A. 1994. Establishment and tending of poplar plantations in north-central U.S. *In* IEA/BA Task IX Activity I. Short rotation intensive culture forestry. Mechanization in SRJC Forestry, March l-3, 1994, Mobile, Alabama. *Edited by* B.J. Stokes and T.P. McDonald. USDA Forest Service, Auburn, AL. pp. 79-87.

Netzer, D.A., and Noste, N.V. 1978. Herbicide trials in intensively cultured *Populus* plantations in northern Wisconsin. USDA For. Serv. Res. Note NC-235.

Netzer, D.A., and Tolsted, D.E. 1999. Yields of ten and eleven year-old hybrid poplars in the North Central United States. Final Report to the U.S. Department of Energy, Biofuels Feedstock Development Program. USDA Forestry Services, North Central Research Station, Forestry Sciences Laboratory, Rhinelander. 9 pp.

Netzer, D.A., Riemenschneider, D.E., Bauer, E.O., and Spatcher, D. 1997. Effect of clopyralid on the growth and morphology of hybrid poplars. In Proceedings of the North Central Weed Science Society, Louisville, Kentucky, December 9-l 1, 1997. North Central Weed Science Society, Champaign, IL. Vol. 51. pp. I 14–1 18.

OMNR. 1991. A grower's guide to hybrid poplar. Ontario Ministry of Natural Resources, Toronto.

Ostry, M.E., Wilson, L.F., McNabb, H.S., Jr., and Moore, L.M. 1989. A guide to insect, disease, and animal pests of poplars. USDA For. Serv. Agric. Handb. 677.

Putnam, J., McKnight, J.S., and Fumival, G. 1960. Inventory and management of southern hardwoods. USDA For. Serv. Agric. Handb. 181.

Ranney, J.W., Wright, L.L., and Layton, P.A. 1987. Hardwood energy crops: the technology of intensive culture. J. For. 85: 17-28.

Schuette, B., and Kaiser, C. 1996. Weed control strategies for SRIC hybrid poplars: farmer's perspective. In Proceedings of the Short Rotation Woody Crops Working Group Meeting, Paducah, Kentucky, September 23–25, 1996. 9 pp.

Schweitzer, C.J., and Stanturf, J.A. 1999. A comparison of large-scale reforestation techniques commonly used on abandoned fields in the Lower Mississippi Alluvial Valley. In Proceedings of the Tenth Biennial Southern Silvicultural Research Conference, Shreveport, Louisiana, February 16-18, 1999. by I.D. Haywood. USDA For. Serv. Gen. Tech. Rep. SRS-30. pp. 136-141.

Silen, R.R. 1947. Comparative growth of hybrid poplars and native northern black cottonwoods. USDA For. Serv. Res. Note PNW-35.

Smith, J.H.G. 1980. Growth and yield of poplar in British Columbia. Paper presented at the 1980 meeting of the Poplar Council of Canada. *Cited in* Debell, D.S. ***Populus tricocarpa*** Torr. & Gray. ***In*** Silvics of North America. Vol. 2. Hardwoods. ***Edited by*** R.M. Bums and B.H. Honkala. USDA For. Serv. Agric. Handb. 654. pp. 570-576.

Smith, J.H.G., and Blom, G. 1966. Decade of intensive cultivation of poplars in British Columbia shows need for long-term research to reduce risks. For. Chron. 42(4): 359-376.

Solomon, J.D. 1985. Impact of insects on growth and development of young cottonwood plantations. USDA For. Serv. Res. Pap. SO-217.

Stanturf, J.A., and Portwood, C.J. 1999. Economics of afforestation with eastern cottonwood ***(Populus delroides)*** on agricultural land in the Lower Mississippi Alluvial Valley. In Proceedings of the Tenth Biennial Southern Silvicultural Research Conference, Shreveport, Louisiana, February 16–18, 1999. ***Edited*** by J.D. Haywood. USDA For. Serv. Gen. Tech. Rep. SRS-30. pp. 66-72.

Strauss, C.H., and Wright, L.L. 1990. Woody biomass production costs in the United States: an economic summary of commercial ***Populus*** plantation systems. Sol. Energy, 45: 105-I 10.

Switzer, G.L., Nelson, L.E., and Baker, J.B. 1976. Accumulation and distribution of dry matter and nutrients in ***Aigeiros*** poplar plantations. In Proceedings of the Symposium on Eastern Cottonwood and Related Species, Greenville, Mississippi, September 28 - October ***2,*** 1976. ***Edired*** by B.A. Thielges and S.B. Land, Jr. Louisiana State University, Division of Continuing Education, Baton Rouge. pp. 359-369.

Thornton, EC., Joslin, I.D., Bock, B.R., Houston, A., Green, T.H., Schoenholtz, S.H., Pettry, D., and Tyler, D.D. 1998. Environmental effects of growing woody crops on agricultural land: first year effects on ***erosion*** and water quality. Biomass Bioenergy, 15: 57-69.

Twedt, D.J., and Portwood, C.J. 1997. Bottomland hardwood reforestation for Neotropical migratory birds: are we missing the forest for the trees ? Wildl. Soc. Bull. 25(3): 647-652.

Twedt, D.J., Wilson, R.R., Henne-Kerr, J.L., and Hamilton, R.B. 1999. Impact of forest type and management strategy on avian densities in the Mississippi Alluvial Valley, USA. For. Ecol. Manage. 123(2–3): 261-274.

van den Driessche, R. 1999. First-year growth response of four ***Populus trichocarpa* x *Populus deltoides*** clones to fertilizer placement and level. Can. J. For. Res. 29: 554-562.

Von Althen, F.W. 1981. Site preparation and postplanting weed control in hardwood afforestation: white ash, black walnut, basswood, silver maple, hybrid poplar. Rep. O-X-325. Great Lakes Forest Research Centre, Sault Ste. Marie. 17 pp.

Wesley, D.E., Perkins, C.J., and Sullivan, A.D. 1981. Wildlife in cottonwood plantations. So. J. Appl. For. 5: 37-42.

Williamson, A.W. 1913. Cottonwood in the Mississippi Valley. USDA Bull. 24. 62 pp.

Young, M., and Berguson. W. 2000. In-situ foliar nitrogen determination in hybrid poplar using a Minolta SPAD-502 chlorophyll meter. Research Note, Lake States Region 00-02, Champion International Corp., Norway, MI. 6 pp.

Zsuffa, L., Anderson, H.W., and Jaciw, P. 1977. Trends and prospects in Ontario's poplar plantation management. For. Chron. 53: 195-200.