

5 Operational Poplar and Willow Culture

John A. Stanturf^{1*} and Cees van Oosten²

¹Center for Forest Disturbance Science, USDA Forest Service, Athens, Georgia, USA;

²SilviConsult Woody Crops Technology Inc., Nanaimo, British Columbia, Canada

5.1 Introduction

The fast-growing species of poplars and willows have been cultivated for millennia for commodity uses, generally for their wood (FAO, 1980; Dickmann, 2006). Poplars and willows were economically important in rural areas because of their ease of propagation and adaptation to areas generally too wet for farming, e.g. flood plains and along watercourses. They provided wood for many rural uses and were particularly important for basketry. Poplar was widely used for industrial and commercial packaging, especially fresh agricultural products and foodstuffs, before development and widespread adoption of corrugated paperboard. For example, before powdered eggs were available for the bakery industry, cottonwood boxes were preferred for shipping raw eggs because the wood was non-aromatic and did not impart an odour to the eggs. The wood of poplar and willow continues to have many commodity and specialized uses, from matchsticks, paper pulp, plywood and other composite boards, to willow cricket bats (Table 5.1; Chapter 10, this volume).

Exploitation of natural poplar stands to meet heavy demands for wood during wartime in the 20th century, as well as demand from post-

war industrialization, spurred the development of industrial plantations in Europe, initially in Italy and France (FAO, 1980; Castro and Zanuttini, 2008). This plantation development in the 1950s was facilitated by the intentional introduction of North American clones into European breeding programmes (FAO, 1980; Zsuffa *et al.*, 1996), although introductions were made much earlier (Pourtet, 1976). Depletion of natural stands of aspen and cottonwood in the USA through exploitation, conversion to agricultural land and alteration of natural river flows (Sternitzke, 1976), combined with the energy crisis of the 1970s, generated interest in poplar plantations for both roundwood and bioenergy. Interest in bioenergy waned as oil prices subsided, but current concerns for climate change caused by the release of fossil carbon into the atmosphere has renewed interest in short-rotation poplars and willows for bioenergy production (Berndes *et al.*, 2001; Zerbe, 2006; Christersson, 2008; Bergante and Faccioto, 2011; Volk *et al.*, 2011a, b; Zalesny *et al.*, 2011; Tullus *et al.*, 2012) and integrated systems for producing energy and commodities (Kelley, 2006).

Although poplars and willows occur as natural stands, this chapter is limited to the production and utilization of these species in plantations

*Corresponding author: drdirt48@gmail.com

(Plate 21A). Forest plantations are forests comprised of at least 40% planted trees that have ongoing management to maintain a composition of almost exclusively planted trees. Plantations are often characterized by few species planted at regular spacing and growing in straight rows, although there are many variations (Zhang and Stanturf, 2008). As discussed later, in several jurisdictions in Canada and the USA, poplar plantations are considered agricultural crops. Industrial uses refer to production plantations of poplars and willows managed primarily to produce commodities such as roundwood or fuelwood, as opposed to primarily environmental benefits (Isebrands and Karnosky, 2001). Environmental or conservation plantations differ from production plantations by virtue of their primary purpose;

they may still be characterized as regularly spaced and a single age-class, although more complex plantations (mixed species, multiple age-classes) have been advocated for conservation purposes. Many plantings such as windbreaks serve a double purpose: they protect crops but are also used to manufacture goods. For example, in the Patagonia region of Argentina, when windbreaks are replaced, the harvested wood is used to manufacture boxes for fruit and vegetables, as well as other incidental uses. The techniques used to establish plantations, whether for production or conservation purposes, are based on the same technology.

Poplars and willows grow rapidly, propagate readily and lend themselves to improvement by conventional tree breeding

Table 5.1. Reported industrial uses of poplars and willows.

Use	Products	Poplar	Willow
Bioenergy	Firewood, chips, pellets, charcoal	India, Italy, Serbia, Montenegro, Turkey, China, Canada, USA	Sweden, Russia, China, USA, Canada, New Zealand
Pulpwood	Paper, rayon	India, USA, Canada, Argentina, Sweden, Estonia, Finland, Italy, France, Serbia, Montenegro, Iran, China, Korea, New Zealand	Russia, China, Argentina
Panels	Plywood, oriented strand board (OSB), medium-density fibreboard (MDF), particleboard, basin board, laminated wood	India, USA, Canada, Chile, Argentina, Serbia, Montenegro, Turkey, Korea, Italy	
Sawn wood	Lumber, rough construction, veneer	India, USA, Canada, Argentina, Chile, Sweden, Russia, Italy, France, Serbia, Montenegro, Turkey, Iran, Uzbekistan, China, Italy	
Veneer (light packaging and matches)	Packing cases, crates, fruit and vegetable boxes, wood wool, basketry, matches	India, Argentina, Brazil, Chile, France, Serbia, Montenegro, Iran, Uzbekistan, New Zealand, Italy	Chile, Russia
Specialty products	Ice-cream spoons, chopsticks, toothpicks, sporting goods, pencils, furniture, moulding, tool handles, tannins	India, USA, Chile, Turkey, Iran, Uzbekistan, China, Korea, New Zealand	India
Agriculture Poles, posts and other products	Fodder, vermi-compost Fence posts, supports for agricultural crops, roof rafters	India, Turkey, China, Chile, Argentina	New Zealand

as well as biotechnology (Stettler *et al.*, 1996a; Dickmann *et al.*, 2001; see also Chapter 4, this volume); these characteristics make poplars and willows attractive for cultivation in shorter rotations than is feasible for other species. Various terms have been used to differentiate short-rotation forests from other planted forests, including short-rotation forestry, SRF; short-rotation woody crops, SRWC; short-rotation intensive culture, SRIC (considered an agronomic crop in Canada); and fast-wood. Short-rotation forests typically use high-density, single-species plantings that may include coppicing, with rotation lengths of less than 10–30 years (Mitchell, 1992; Zsuffa *et al.*, 1993; Makeschin, 1999; Cossalter and Pye-Smith, 2003; Weih, 2004). In some countries, a distinction is made between forest plantations of poplars and short-rotation plantings because of land ownership, for example, in Canada, SRIC is applied to hybrid poplar and willow plantings on farmland, or because of preferential tax or regulatory treatment for an agricultural, as opposed to a forestry land use, for example, in Oregon in the USA and in some Canadian provinces, rotations of 12 years or less qualify as a farm use; in Washington state, USA, it is 15 years or less. In some European countries, herbicides are permitted on farmland but not on forests. Such terminology distinctions are largely ignored in this chapter.

The objective of this chapter is to provide a global overview of poplar and willow culture, pointing out commonalities as well as differences. After a brief overview, the chapter is divided between *Populus* species and *Salix* species and follows the sequence of establishment, tending and production. The countries with the largest area of poplar plantations are China (7.6 million ha), France (236,000 ha), Turkey (125,000 ha), Hungary (109,000 ha), Spain (105,000 ha), Italy (101,000 ha), Sweden (49,000 ha) and Romania (48,000 ha). Seven other countries have significant areas of poplar plantations (Table 5.2). The countries with the most planted willow are China (438,000 ha), Argentina (56,400 ha), Romania (19,500 ha), New Zealand (20,000 ha) and Sweden (11,000 ha). Russia and Estonia also have sizeable willow plantings (Table 5.2). Other

Table 5.2. Countries with significant areas of planted poplar and willow (FAO, 2008, 2012).

Country	Poplar (1000 ha)	Willow (1000 ha)
<i>Europe</i>		
Belgium	33	0.02
Bulgaria	18.9	0.1
Croatia	13	3.6
Estonia	1	<1
France	236	
Germany	10	
Hungary	109.3	
Italy	101.4	20
The Netherlands	31	
Romania	47.9	19.5
Russia	31	1
Serbia ^a	33 ^a	6.9 ^a
Spain	105	0.7
Sweden	49.3	11.1
Switzerland	5.4	
UK	1.3	2
<i>Asia/Africa</i>		
China	7570	437.6
India ^b	0.7	1
Iran	150	10
Turkey	125	
Uzbekistan	3	
Egypt	7	
Morocco	4.3	
<i>Australia/New Zealand</i>		20
<i>North America</i>		
Canada	44.1	
USA	45	0.3
<i>South America</i>		
Argentina	40.5	56.4
Brazil	5.5	
Chile	5	3

^aSerbia and Montenegro statistics are combined totals (prior to 2006).

^bIndia's agroforestry area of poplars is over 300,000 ha.

countries known to cultivate poplars and willows are listed, although data are unavailable.

5.2 Poplar

5.2.1 Stand establishment

Planting material

The naturally occurring poplars in riverine environments provided wood for rural economies

in antiquity, specifically *P. euphratica*, *P. tremula*, *P. nigra* and *P. alba*. With the advent of industrial plantations, poplar species have been established in countries beyond their natural range. Often, plantations were developed using the limited number of genotypes that were available. For example, China has relied on a limited number of clones including six *P. ×canadensis* cultivars and two *P. deltoides* cultivars (Q.-W. Zhang and J.-H. Li, 2005, unpublished report); in India, the main poplars grown for industrial purposes cover approximately two dozen clones of *P. deltoides* (R.C. Dhiman, 2005, unpublished report). Nevertheless, many countries today have active breeding programmes (Fig. 5.1) to produce material for industrial plantations (Chapter 4, this volume). These programmes rely on 12 species that include North American (*P. balsamifera*, *P. deltoides*, *P. trichocarpa* and *P. tremuloides*) and Eurasian species (*P. alba*, *P. cathayana*, *P. ciliata*, *P. euphratica*, *P. maximowiczii*, *P. nigra*, *P. simonii* and *P. tremula*) and hybrids of these species (Chapter 4, this volume). Introduction of the

North American *P. deltoides* and *P. trichocarpa* into European domestication programmes spurred development of many of the hybrids in current use worldwide (FAO, 1980; Bisoffi and Gullberg, 1996).

The ability of poplars in the sections *Aigeiros* and *Tacamahaca* for vegetative propagation has facilitated the selection and breeding of superior poplar genotypes. Despite some barriers to hybridization among sections (Stettler *et al.*, 1996b), intersectional hybrids between *Aigeiros* and *Tacamahaca* have been economically important (Eckenwalder, 2001; Zalesny *et al.*, 2011). Although hybrids are common within and among species of the section *Populus*, they do not hybridize readily with other sections (Eckenwalder, 1984). Species of the *Aigeiros* and *Tacamahaca* sections are easy to propagate through asexual means, usually by vegetative propagation of unrooted dormant stem cuttings or sets (also called whips), but poor rooting ability may disqualify some genotypes (Zalesny and Zalesny, 2009). Eastern cottonwood (*P. deltoides*, *Aigeiros* section) displays great variability in



Fig. 5.1. A clonal production nursery of elite *Populus × canadensis* genotypes in Shandong Province, China. Photo courtesy of Greenwood Resources.

rooting ability. Interspecific hybrids within and between the *Aigeiros* and *Tacamahaca* sections usually root well (Eckenwalder, 2001). Poplars in section *Populus* (the white poplars and aspens) are difficult to propagate from stem cuttings, as are the interspecific hybrids between *P. tremuloides* and *P. tremula*, and planting stock is generally produced from seed or root cuttings (Stanturf *et al.*, 2001; Stenvall *et al.*, 2006).

Traits targeted for selection are agronomic (or silvicultural, depending on your perspective), wood quality and disease resistance (Chapter 4, this volume). Silvicultural traits of importance include stem form, yield and rooting ability, generally; for particular locations, cold tolerance, wind firmness and salt tolerance have been desirable traits. For industrial purposes, wood quality traits such as specific gravity, fibre length, cell wall thickness and lignin content have been critical traits depending on use requirements (for pulping or veneer, generally). Disease resistance has been of great importance and sometimes insufficiently regarded in the introduction of new genotypes to an area, leading to plantation failures. The pathogens of greatest economic importance are *Melampsora* leaf rust and *Septoria* stem canker (Chapter 8, this volume). Other serious pathogens include *Discosporium* canker, *Hypoxylon* canker, *Marssonina* leaf spot, *Venturia* shoot blight and *Xanthomonas* bacterial canker (Cellerino, 1999; Newcombe *et al.*, 2001; Giorcelli *et al.*, 2008). Details on poplar breeding strategies can be found in Chapter 4, this volume.

Establishing plantations

Plantation establishment requires the production of appropriate planting material that is adapted to the conditions of the available sites. Sites must be prepared and some adverse conditions may require amelioration prior to planting. Management objectives, markets, costs and regulation may all factor into decisions made in the process of establishing poplar plantations. Because these factors vary among poplar growing regions and over time, there is no single method of poplar culture (Stanturf *et al.*, 2001), but one commonality is

the criticality of controlling competing vegetation during establishment.

Planting stock types

The aspen and *P. alba* (section *Populus*) stock type is a rooted plant, either bare root or container. It can be produced from seed or root cuttings. Poplars in the other sections are propagated easily from unrooted stem or branch cuttings. Poplar planting stock can be produced as several different types that can be differentiated between rooted and unrooted material. Length of the outplanted material is another distinguishing characteristic; cuttings tend to be 1 m or less, sets (also called whips or stakes) vary in length from 1.5 m to as long as 5 or 6 m. Thicker tall material may be called a pole. Rooted cuttings are also called barbatelles and rooted sets are called stecklings. In India, rooted sets are called entire transplants (ETPs). Choice of planting stock is a function of what material is available, its quality (how well nurseries can produce the material) and ease of planting, as well as management objectives and site conditions (Table 5.3). The ease of planting is a factor not only as a cost consideration but also how well material will be planted operationally; large material may be difficult to handle or require extra effort to prepare an adequate planting hole, thus poorly supervised planting operations may impact survival. Site conditions of importance are soil moisture and temperature, competing vegetation and threat of browsers (both wild ungulates and domestic livestock).

Unrooted dormant cuttings of poplars (other than the aspens and *P. alba* in the section *Populus*, which do not root readily) are produced from 1-year-old stem material, varying in length 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; usually, it is recommended that viable buds 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 1-year-old material. Unrooted sets also require buds for new stems to develop. In Italy and France, plantations are established mostly with 2-year-old unrooted poles 6–8 m long, sometimes with 1-year-old poles (A. Berthelot, 2005, unpublished

Table 5.3. Conditions under which certain poplar stock types can be used.

	Unrooted stock				Rooted stock		
	Cuttings	Sets	Poles		Bare root		
					Small	Sets	Container
Density of plantation	>1500 stems ha ⁻¹	700–1500 stems ha ⁻¹	<400 stems ha ⁻¹	<700 stems ha ⁻¹	>700 stems ha ⁻¹	<400 stems ha ⁻¹	>700 stems ha ⁻¹
Plantation purpose	Biomass	Fibre and solid wood	Solid wood	Solid wood	Fibre and solid wood	Solid wood	Research trials; new stoolbeds; extreme drought conditions at planting
Soil moisture conditions	Good	Good	Excellent	Excellent	Good	Good	Needs irrigation if planted in full leaf
Weed control	Excellent	Excellent	Reasonable	None to reasonable	Excellent	Reasonable	Excellent
Threat of browsers	Variable	High to low	High	None to high	Low	High	Low

report; G. Picchi, 2005, unpublished report). Poles are unbranched and if roots are present, they are removed. In Argentina and Chile, 1-year-old unrooted poles 3–4 m long are planted to allow earlier introduction of cattle into the plantation (Fig. 5.2), which also controls competing vegetation (S. Cortizo and R. Suarez, 2005, unpublished report).

Rooted stock is produced by planting unrooted dormant cuttings or sets in a nursery bed and allowing them to grow a viable root system. Rooted stock can be either bare root or container (in Canada, they may be called plug or PSB).¹ Container plants are produced from seed, stem or root cuttings (aspen) or small, single-bud hardwood or greenwood cuttings (Fig. 5.3). These plants are usually dormant 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 (van Oosten, 2006).

Stock production systems

Most poplar planting stock is produced in nurseries; a stoolbed nursery is common for



Fig. 5.2. Hand-planting 2-year-old whips in Chile. Whips are planted 80 cm deep in auger-drilled holes at 6 × 6 m spacing. Note the stumps from the previous stand. Photo courtesy of J. Stanturf.

producing unrooted material (FAO, 1980; Stanturf *et al.*, 2001). A stool is a stump from which new sprouts emerge. Stools may be started from any stock type, but normally dormant cuttings are used. Stoolbed nurseries usually are established on very good sites and may have irrigation. Stoolbed structure and layout vary regionally. For the best production of the healthiest stock, the lifespan of a stoolbed should be limited to 3–7 years. Dormant material harvested from branches of young plantations instead of stoolbeds is known as serial cuttings. Rooted cuttings and sets can be grown from unrooted dormant cuttings in a nursery bed. They are lifted after a year and outplanted as dormant rooted sets; sometimes, they may be transplanted and grown an additional year to develop a larger caliper. Container stock is often begun in a greenhouse and finished outdoors (van Oosten, 2006).



Fig. 5.3. A single-bud cutting about 2 months old, designated PSB 415, produced by the plug-Styroblock® system developed in Canada. This tree was started in the greenhouse and meets the target standard of 5–7 mm caliper and 50 cm height. Photo courtesy of C. van Oosten.

Unrooted dormant cuttings, sets and poles

Unrooted material is most commonly produced in a stoolbed. Cuttings may be planted manually or mechanically. For cuttings, stools are cut back annually to a height of 5–15 cm in the dormant season, thus producing 1-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 pole. Harvested sprouts are sawn into cuttings or sets while dormant and must be refrigerated and remain dormant while waiting outplanting. Storage is in coolers or freezers, depending on the length of storage. The density of the stools in beds varies among regions and determines the caliper of the sprouts and controls the number of viable buds. Each cutting or set must have dormant viable buds. In North America, spacing is typically 0.3 m × 0.3 m, or slightly less than 0.1 m² per stool (Stanturf *et al.*, 2001). In Argentina, cuttings are planted 0.4–0.5 m apart within the row and rows are 0.7–0.8 m apart (S. Cortizo and R. Suarez, 2005, unpublished report). When the stools are planted too widely, the sunlight that penetrates the canopy stimulates buds to develop into sylleptic branches, rendering the sprouts useless for cuttings.

Poles as produced in France and Italy are planted as cuttings at different spacing to produce 1- or 2-year-old material (Frison, 1997; A. Berthelot, 2005, unpublished report). For 1-year-old poles, cuttings are planted at 1.8 m × 0.6 m spacing, or wider for low vigour clones. After one growing season, the poles are pruned and harvested by sawing at the base (for unrooted poles) or by extracting them with the root system. For 2-year-old poles, a wider spacing is used, for example 2.6 m × 0.5 m, and pruning is done annually. Poles are harvested during the dormant season and generally planted within a few days. Poles can be stored under refrigeration for a few months but must be handled carefully to avoid damaging the bark. Poles are also planted in Chile (Ulloa and Villacura, 2005) and recently also in the western USA (Fig. 5.4).

Weed control strategies

Competition from weeds is a serious threat during the establishment of new stoolbeds. Herbicides provide the most effective control of weeds (Stanturf *et al.*, 2001). Mulching can be

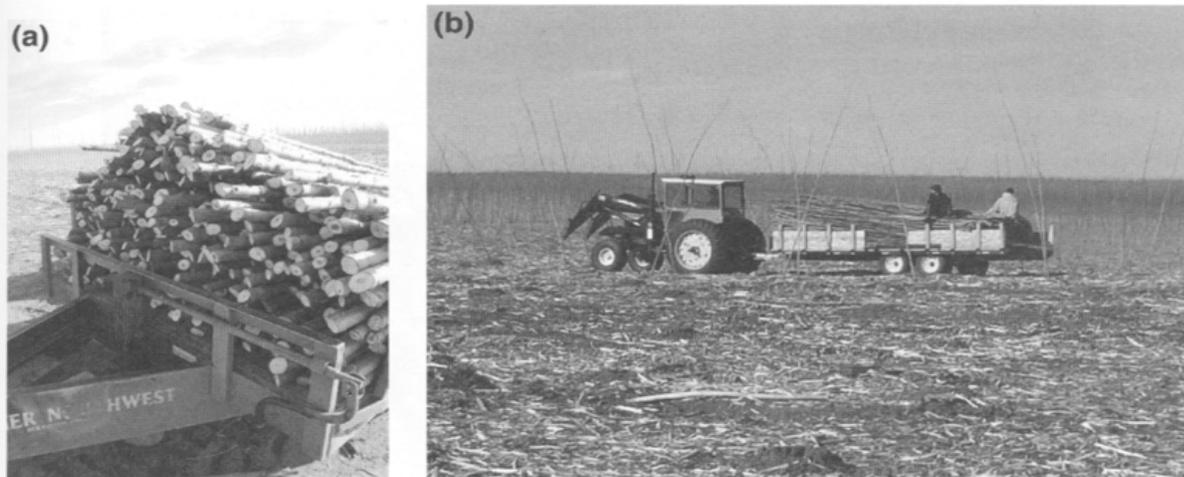


Fig. 5.4. (a) Poles (2 years old) are freshly cut from donor fields and (b) planted at 540 stems ha⁻¹ (approximately 6.1 × 3 m spacing) on a hybrid poplar farm near Boardman, Oregon, USA. Photo courtesy of C. van Oosten.

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. A nursery may be included in a crop rotation with cereals, allowing use of broadleaved-specific herbicides and thereby reducing the weed load for the poplar rotation. During site preparation for a stoolbed, grasses and broadleaved weeds can be controlled effectively with herbicides that would damage the poplars. After cuttings are planted, a pre-emergent or pre-bud break herbicide application may be used. Choice of herbicides will vary by location, soil texture and pH, weed species and local regulations. Some specific practices can be found in regional guides, e.g. Stanturf *et al.* (2001), DEFRA (2002) and van Oosten (2006).

Mechanical methods may be practical when spacing is sufficiently wide, for example in the production of poles (Fig. 5.5). Up to four passes with cultivators is common in France, along with pre-emergent and growing-season herbicides (A. Berthelot, 2005, unpublished report). In closely spaced stoolbeds, manual labour is common to hand-weed portions of stoolbeds. Weeding needs decline rapidly when the stock fully occupies the stoolbed and shades out the weeds. Later leaf litter forms a layer of mulch, which suppresses weeds effectively (Scarcella *et al.*, 2011).

Fertilization and irrigation

Fertilization and irrigation schedules are very specific to local conditions and aim to avoid nutrient deficiencies and moisture stress in stoolbeds. Often, 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. Excess nitrogen is to be avoided because an oversupply can cause increased weed competition, promote formation of sylleptic branches and can delay the onset of dormancy. The same principles apply to irrigation, where the aim is to provide just enough water to maintain even growth. Over-irrigation can also promote sylleptic branch formation. Water should be withheld late in the growing season to promote hardening off and to avoid frost damage.

Crop health, protection and hygiene

Even though poplars are susceptible to a myriad of insects and pathogens (Ostry *et al.*, 1989; Mattson *et al.*, 2001; Duplessis *et al.*, 2009; Chapters 8 and 9, this volume), there is great variability among clones in their resistance (Robison and Raffa, 1998; Nordmann *et al.*, 2005). The most serious disease and pest problems facing the nursery grower are leaf rusts, blackstem diseases, cottonwood leaf beetle and



Fig. 5.5. A stoolbed of poles in Chile in their second growing season, grown in tight spacing (approximately 1.5×0.6 m), one pole per stool, is of *Populus deltoides* \times *Populus nigra* hybrids. Photo courtesy of C. van Oosten.

stem borers (Mattson *et al.*, 2001; Newcombe *et al.*, 2001; Stanturf *et al.*, 2001). High stoolbed densities favour foliage diseases such as *Melampsora* rusts, especially with overhead irrigation. Clones with normally low susceptibility in plantations may develop serious problems in stoolbeds. Protection strategies are a combination of chemical control, cultural practices and use of resistant clones. If *Melampsora* rust causes early defoliation, cuttings in this physiologically weakened state are more vulnerable to blackstem disease and high levels of mortality. Blackstem diseases are caused by a number of organisms (*Cytospora chrysosperma*, *Phomopsis oblonga*, *Cryptodiaporthe populea* (*Dothichiza populea*) 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 *Melampsora* rust. 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. Removing suppressed stems at or prior to harvest is the most effective control. The stressed stem usually is lighter in colour and smaller than its neighbours (van Oosten, 2006).

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. Successful control has been achieved in the USA with several commercial insecticides, including several Bt (*Bacillus thuringiensis*) products (Stanturf *et al.*, 2001), but there may not be registered products in other countries (van Oosten, 2006).

Stem borers native to North America include the poplar borer (*Saperda calcarata*). It is a large beetle that bores into the stems of young trees with a diameter around 10 cm (Newcombe *et al.*, 2001; van Oosten, 2006). The larvae bore into the wood and create galleries that weaken the stem, often leading to breakage. Pesticides

registered in Canada and the USA can control this pest (Stanturf *et al.*, 2001; van Oosten, 2006), and it is important to remove dead infected stems as they provide a habitat for the borer.

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. Riparian cottonwoods, i.e. *P. deltoides*, naturally reproduce asexually by branch breakage and crown damage. In plantations of *P. trichocarpa* × *P. deltoides* hybrids, sylleptic branches can be used for small-diameter cuttings to establish stoolbeds. Sylleptic branches from the previous year grow to a reasonable size the second year, but only the 1-year-old portion of these branches is used. 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. This system of plant production is expensive and labour-intensive. Plants usually begin with unrooted cuttings planted in the nursery; after growing 1 year, bareroot plants with the root systems intact are excavated for outplanting. 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 and avoid planting stress (Grossnickle, 2005; DesRochers and Tremblay, 2009). Bareroot stock is lifted while the trees are dormant. Large stock (especially if kept in the nursery bed for 2 years) can be several metres tall with large caliper; it cannot be stored easily and must be transported and planted immediately.

In India, the most common method for establishing poplar plantations uses ETPs that are bareroot saplings 4–6 m tall with 5–10 cm caliper (R.C. Dhiman, 2005, unpublished report). Material is collected from previously lifted ETPs and cuttings of at least 20–25 cm with five active buds are stored until planted in the nursery bed at 80 × 60 cm spacing. Cuttings are

treated with fungicide and insecticide and irrigated weekly until the monsoon rains arrive. During the growing season, the nursery is hoed manually at least twice and shoots are singled at least once. Earth is mounded 15–20 cm around the base of the shoot to provide anchoring during the rainy (monsoon) season. Because of the warm Indian climate, the apical bud on very tall plants may not develop and will retard the growth of the plant; thus, the practice is to remove 30–40 cm of the stem above a healthy bud (Chandra, 2011).

Container stock

Materials that can be produced in a container nursery may be grown from single-bud or small stem cuttings, seed, or root cuttings. Dormant single-bud hardwood cuttings are used for clones that are difficult to propagate or if only a limited amount of material is available, such as from a breeding programme. This method is expensive and labour-intensive but can be used to multiply a single mother plant quickly into thousands of identical plants. Uses include establishing a new stoolbed with an improved genotype or for experimental purposes (Stanturf *et al.*, 2001). In the Prairie region of Canada, unrooted single-bud or small cuttings are placed in PSB containers in late spring. They start off in a greenhouse and are placed outside later in the summer under full sunlight prior to lifting, packaging and storing (van Oosten, 2006).

For the hard-to-propagate aspens (section *Populus*) and their hybrids, only rooted plants, either bareroot or container, can be used to establish plantations. Micropropagated hybrid aspen (*P. ×wettsteinii*) has been used in Estonia after developing in the nursery bed for 1 year (K. Jürgens, K. Heinsoo and A. Tullus, 2005, unpublished report). Rooted container stock is widely used in Canada and Finland (E. Beuker, 2005, unpublished report), although bareroot stock is beginning to gain acceptance in parts of Canada. Container stock is produced from dormant root cuttings or seed and grown in containers in a greenhouse in order to produce fully rooted plants with soil for outplanting. 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. The containers are

placed outdoors during the summer and overwintered in a cooler or freezer (Stanturf *et al.*, 2001; van Oosten, 2006).

Site requirements

Poplars generally grow best under high light intensity and warm temperatures during the growing season. Soil texture and drainage are two of the most important site factors for a successful plantation (Baker and Broadfoot, 1979). The influence of soil texture and drainage condition on site quality for poplar is summarized in Table 5.4. They prefer alluvial soils that are well aerated, have sufficient moisture and nutrients, are sufficiently deep (>1 m to the water table), have a medium texture (sand/loam) and have a soil pH in the 5.0–7.5 range (Baker and Broadfoot, 1979). While droughty soils should be avoided, supplemental irrigation has been successful even on deep sands (Gallagher *et al.*, 2006; Robison *et al.*, 2006). In northern climates, sandy soils warm earlier in the spring and favour

growth of hybrid aspen, but this advantage may be offset by the risk of drought conditions later in the growing season (Bergante *et al.*, 2010; Scotti *et al.*, 2010; Tullus *et al.*, 2012).

Saturation and waterlogging during the growing season cause anaerobic conditions to develop in soils that starve the root systems of oxygen, leading to drought-like symptoms. Most poplar clones cannot tolerate anaerobic conditions for very long into the spring months and must have well-aerated soils by the beginning of summer to survive and thrive. Younger trees are more vulnerable. Some clones do not tolerate saturated soil conditions in the winter very well either.

Heavy soils (clay, clay loam and silty clay loam textures) are considered less favourable for poplar growth than soils with lower clay content (Stanturf *et al.*, 2001). 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

Table 5.4. The influence of soil texture and drainage condition on site quality (very good to poor) for poplar. Shaded fields indicate potential to improve suitability through ditching, installing drain tile, subsoiling, or some combination. (Sources: Baker and Broadfoot, 1979; Dickmann and Stuart, 1983; Stanturf *et al.*, 2001.)

Dominant profile textures	Natural drainage class		
	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 to very good	Fair	Poor
Loam and silt loam 25–50 cm over well-decomposed peat	Good to very good	Poor	Poor
Loam and silt loam marbled with well-decomposed peat	Good to very good	Fair to good	Poor
Sandy loam	Very good	Fair to good	Poor
Loamy sand	Very good	Fair to good	Poor
Sand	Poor	Fair	Poor
Sandy loam 35–100 cm over clay	Very good	Fair	Poor
Sandy loam 50–100 cm over loam to 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 to loamy sand 50–100 cm over loam to clay loam	Very good	Very good	Poor
Sand to loamy sand 100–150 cm over loam to clay	Good	Very good	Poor
Organic (muck, peat)	N/A	N/A	Poor to fair

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 sites with as much as 90% clay (Stanturf *et al.*, 2001).

Poplars generally are intolerant of saline conditions; the North American species *P. trichocarpa* is extremely intolerant of salt and so are its hybrids; *P. deltoides* is slightly less intolerant (Stanturf *et al.*, 2001). 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 salinity 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. In countries with Mediterranean or semi-arid climates, soils tend to have higher pH and may develop salinity problems under impeded drainage. In Italy, for example, growth limitations develop when soil conductivity is $>1.5 \text{ dS m}^{-1}$, and $>4 \text{ dS m}^{-1}$ is considered a severe limitation (G. Picchi, 2005, unpublished report; Scotti *et al.*, 2010). Similar recommendations are made for the Prairie Provinces of Canada (van Oosten, 2006). Breeding for salt tolerance is important for use of poplars in phytoremediation but not for industrial plantations (Chapter 4, this volume).

Poplars can perform well on shallow soils, although better sites generally are preferred. During extended drought, shallow soils may have insufficient moisture storage, leading to reduced growth or mortality. Shallow soils also may present a windthrow 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. Various clones may show differential resistance to windthrow (Chapter 4, this volume), and fertigation practices may affect root development that is maladapted to the prevailing winds (Coleman, 2007).

Peat soils are commonly thought to be poor sites for poplars. Even in Finland, where many

conifer plantations are established on peaty mineral soils, truly peat (organic) soils are avoided (Stanturf *et al.*, 2001). 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 the northwestern USA are reasonably well drained and support good growth of hybrid poplar (Stanturf *et al.*, 2001). Windthrow damage is a real threat, especially if water tables are shallow, but some poplar clones are well suited to these conditions and hardly pose a serious windthrow problem.

Site preparation

Poplars are very intolerant of shading, thus it is essential to get a poplar plantation off to a faster start than competing vegetation (Stanturf *et al.*, 2001). Proper site preparation for planting is essential to the successful establishment of poplar plantations and to provide easy access for essential weed control. Without adequate site preparation, the survival and growth of poplars may be diminished drastically (FAO, 1980; Dickmann and Stuart, 1983; Facciotto, 1998; Stanturf *et al.*, 2001). A thorough evaluation of soil and site conditions will aid in the selection of appropriate treatments that will result in reduced planting costs, more effective herbaceous weed control and reduced damage to young poplars in mechanical cultivation. Some sites will have impervious soil layers; mechanical disruption of these layers will improve internal drainage and aeration. Plantations may be established on open pasture or agricultural land, cutover natural stands or prior plantations. On prior pasture or farmland, site preparation can be very simple. On cutover forest or prior plantations, site preparation becomes complex and very expensive due to stumps, logging debris and heavy vegetation.

Agricultural sites

Agricultural land may have supported a cover of crops before conversion to poplar plantations, and often these sites have a history of good weed

control and adequate fertilization. Former pasture or grass hay sites may require herbicide treatments to kill grasses and tillage to break up sod. Open agricultural land is commonly prepared using combinations of conventional and minimum tillage methods, such as disking, chisel ploughing, subsoiling and mowing (Fig. 5.6). Many poplar growers have added herbicide treatments to their arsenal of site preparation tools in order to reduce early weed competition, and in the process have reduced mechanical weed control. In Sweden, herbicides are applied in the autumn before ploughing and again in the spring after harrowing, before or just at planting (M. Ramstedt, 2005, unpublished report). In the Canadian province of Quebec, herbicides are not allowed, requiring tall, rooted whips ('stecklings') to be planted. In the delta region of Argentina, weeds are crushed with a heavy iron or wooden cylinder, or simply burned (S. Cortizo and R. Suarez, 2005, unpublished report). Where mechanical planting or irrigation is practised, as in Italy, land levelling may be used (ISP, 2002; G. Picchi, 2005, unpublished report). Raised beds or bedding is relatively new to poplar culture in North America but has a long history

of success in pine plantation culture on poorly drained sites. Bedding has been used extensively in Washington State but may have contributed to instability during windstorms, although this seems to depend on the clone. In China, bedding and surface drainage ditches may be used on poorly drained sites (Q.-W. Zhang and J.-H. Li, 2005, unpublished report). In countries where poplars are grown with agricultural crops, including India and China, there is no separate preparation for the poplar (R.C. Dhiman, 2005, unpublished report; Q.-W. Zhang and J.-H. Li, 2005, unpublished report).

Deep ploughing or subsoiling is recommended under some conditions, especially for soils with higher clay content or impermeable subsoil layers. Ripping or subsoiling along the planting row is common in the USA, often using modified conventional farm equipment (Stanturf *et al.*, 2001). In Italy, both deep ploughing and ripping (70–100 cm) are practised, but ripping is preferred because it does not turn under the fertile topsoil (Colorio *et al.*, 1996; Facciotto, 1998; G. Picchi, 2005, unpublished report). Ripping is usually followed by ploughing to 30 or 40 cm depth. In France, deep



Fig. 5.6. Site preparation by agricultural tractor in India; the operator is cross-disking the site. Older plantations are in the background. Photo courtesy of R.C. Dhiman.

ploughing and herbicides are recommended but seldom used (A. Berthelot, 2005, unpublished report). Where poles are planted, only individual planting spots may be prepared using an auger or hydraulic excavator (mechanical digger).

Forestry sites

Preparation of sites after timber harvest is generally 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. Site preparation after harvest seeks to facilitate planting by removing debris or reducing its size and incorporating it into the soil. 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 USA (Stanturf *et al.*, 2001). After shorter-rotation poplar plantations, less intensive, more cost-effective means of clearing sites are possible. In many countries, planting is between the rows of the previous stand. Site preparation between existing stumps has been successful, using an orchard flail to reduce woody debris, followed by a rototiller or a modified pavement grinder to grind and incorporate debris further into the soil. This leaves stumps intact and sprouts are controlled with herbicides or mowing. Alternatively, stumps may be treated with herbicide such as glyphosate immediately after harvest.

Stumps may also be removed along with other logging debris and competing vegetation using an excavator. This was the practice in the Canadian province of British Columbia on lands that previously supported a poplar plantation or a mixed stand of conifers and black cottonwood. Due to its expense, this has been replaced by leaving stumps in the ground and preparing individual planting spots using a small excavator with a modified brush rake (Fig. 5.7). The humus layer and mineral soil are mixed in this process. On poorly drained land, planting mounds are created. In Italy and China, agricultural crops commonly follow poplar plantations so that stumps and other debris must be removed. In Italy, branches and tops are concentrated and burned, comminuted

and incorporated, or chipped and sold for bio-energy (ISP, 2002; G. Picchi, 2005, unpublished report). Stumps are removed with a special machine (levaceppi) or destroyed with a grinder. Fine roots are removed by harrowing. In China, stumps and large roots are removed and an agricultural crop or green manure grown for 1 or 2 years before replanting with poplar (Q.-W. Zhang and J.-H. Li, 2005, unpublished report).

Planting

Planting is a crucial phase of plantation establishment, and only quality planting stock should be used. Hand planting of unrooted dormant cuttings is common in many poplar growing regions where adequate weed control is possible. Although either seedlings or cuttings can be used, cuttings are preferred because they survive and grow as well as seedlings and cost less to produce and plant. Additionally, genetically superior clones can be expanded more rapidly through vegetative propagation. The desired length for cuttings for planting varies from 15 to 45 cm. Optimum cutting size is from 1 to 2 cm in top diameter. Cuttings with a top diameter larger than 2 cm are excellent planting stock but are hard to handle. Cuttings may be planted by inserting them directly into moist soil using a narrow planting spade or a dibble (Fig. 5.8) or by pushing them directly into soft, well-prepared soil. Planting depth varies by conditions; as a general rule, more of the cutting is below ground than above, so that roots have adequate moisture to develop. In most countries, at least one bud is above ground; more than one bud will develop into unwanted sprouts, necessitating expensive removal. In Russia, where planting unrooted cuttings follows immediately after frozen soil thaws, it may be necessary to use a Kolesov sword, a type of planting spade (A. Tsarev, 2005, unpublished report).

In coastal areas in the Canadian province of British Columbia, long cuttings (up to 1 m) are inserted at least 30 cm into the soil. The remainder is above ground and prevents immediate shading by small weeds, and the cuttings are visible during subsequent maintenance. This method may require singling to a single leader in the first or second growing season. In Argentina, one corporate plantation operation

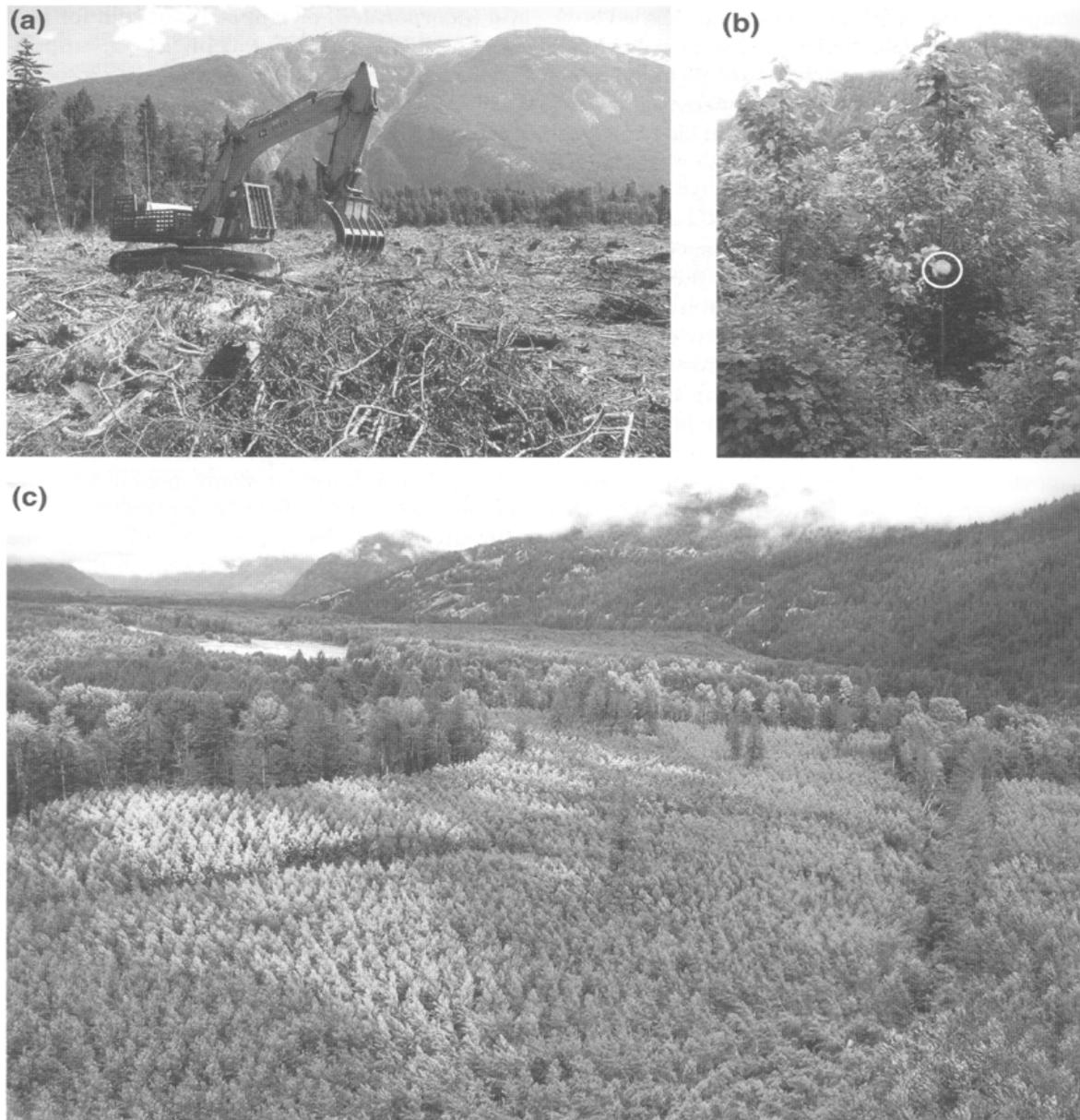


Fig. 5.7. (a) Reforestation site preparation using spot mounding with hydraulic excavator, Kingcome Island, British Columbia, Canada. The harvested stand was a mix of cottonwood (*Populus trichocarpa*), red alder (*Alnus rubra*), western hemlock (*Tsuga heterophylla*) and red cedar (*Thuja plicata*). Low-intensity management of hybrid poplar, planted with unrooted whips approximately 1.5–1.8 m long. (b) Second year after planting (note whip next to hardhat, circled). (c) Aerial view of stand when approximately 5 years old. Residual trees are red cedar. Photos courtesy of Kruger Products LP (a), C. van Oosten (b and c).

in the humid pampas region of the province of Buenos Aires uses unrooted dormant cuttings with a length of 1.2–1.3 m. These are deep-planted 1 m below ground, with 0.2–0.3 m above ground. Planting is achieved with a hollow dibble

connected to a water supply that squirts water at high pressure to form the planting hole. This method also delivers sufficient water for immediate growth in this rain-uncertain but very fertile region of deep loess soils.



Fig. 5.8. Planting dibble with step used for hand-planting bare-root *Populus* cuttings. The string on the ground marks the row. Photo courtesy of J. Stanturf.

Planting rooted material requires greater effort than unrooted cuttings. If rooted cuttings are small enough, they can be planted with a narrow tree-planting spade (van Oosten, 2006). Planting spades and dibbles are also suitable for planting container stock. Dibbles may have a foot-step to help drive it into the soil and also serve as a guide to planting depth. The shape and size of the dibbles are close to the dimensions of the root plug of the container stock (van Oosten, 2006).

Machine planting requires a well-prepared site that may be harrowed or cultivated prior to planting (DEFRA, 2002). Machine planting methods are not widespread and vary by country. In Italy, for short-rotation coppice plantings for biomass, a specially designed machine cuts and drives cuttings into the soil for their entire length (Balsari *et al.*, 2003a, b; G. Picchi, 2005, unpublished report). In Canada, mechanical tree planters pull a knife or rolling coulter blade through the soil, followed by a trencher. The planting trench produced is deep enough to accommodate the root system (van Oosten, 2006). Larger material such as whips and poles may require an auger that can be hand-held or machine mounted (Fig. 5.9).



Fig. 5.9. Auger planting poplar poles in China. Photo courtesy of J.G. Isebrands.

Poles are planted in Italy into augered holes about 30 cm in diameter, to a depth of 70 cm for 1-year-old poles and 120 cm for 2-year-old poles (ISP, 2002; G. Picchi, 2005, unpublished report). In India, ETP planting holes are 10 cm in diameter and augered to a depth of 1 m (Fig. 5.10). In western Argentina, bareroot sets are planted by shovel or with an auger (S. Cortizo and R. Suarez, 2005, unpublished report).

Season

Poplars are usually planted during the dormant season. In North America, this means when soil temperatures have warmed to 10–15°C, which varies from March to late April and extends to late May or mid-June (Zalesny *et al.*, 2004). At this temperature, roots are initiated in unrooted cuttings. In Sweden, soil temperatures above 5°C are recommended for planting (M. Ramstedt, 2005, unpublished report). In southern hemisphere countries such as Argentina and Chile, the corresponding winter months are June–September



Fig. 5.10. Hand-augering a planting hole for an entire transplant (ETP), as used in India; ETP are rooted sets. Photo courtesy of R.C. Dhiman.

(S. Cortizo and R. Suarez, 2005, unpublished report; Ulloa and Villacura, 2005). Although later planting is possible in some years, it is generally not recommended. In Finland, however, planting in summer and even into autumn has been successful in experiments (E. Beuker, 2005, unpublished report). 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 but should not be used on drier ridges unless irrigation is available.

Cuttings should remain in freezer storage until planting (Stanturf *et al.*, 2001). In drier regions, harvested poplar whips and 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 whips should not be exposed to drying conditions during transport to planting sites. Exposure to light for extended periods before planting is also harmful. When planting will be delayed until after the start of the normal growing season, cuttings must be kept in freezer storage at –2 to –4°C.

Proper spacing is needed to achieve maximum production in industrial plantations and marking planting spots is considered part of the planting process, even though marking may be done in autumn before planting in late winter. Cross-marking is common whether planting is by hand or machine. The planting row may be ripped in the autumn prior to planting or in the spring. In the southern USA, a slow-release nitrogenous fertilizer is placed at the bottom of the rip (Stanturf *et al.*, 2001). Cross-marking can be accomplished by various methods, including painting (van Oosten, 2006) or the planting crew using spacing guides. In fertigated hybrid poplar plantations in the western USA, planting spots are determined by the placement of the emitters; the cutting is planted at a wet spot (J. Eaton, 2005, unpublished report).

Espacement and planting density

Three considerations guide the choice of spacing in industrial poplar plantations: (i) product objective; (ii) weed control; and (iii) cost of planting

material (Weih, 2004). Because survival is generally 90% or better, seldom is fill-in planting required. Where pulpwood is the objective, most plantations are established with spacing from 2.1×3.0 m to 4×4 m; most cottonwood and aspen plantations in the USA, for example, have been planted at something close to 3×3 m spacing (Stanturf *et al.*, 2001; J. Eaton, 2005, unpublished report; Zalesny *et al.*, 2011). Early spacing trials with both *P. deltoides* in the south (Gascon and Krinard, 1976; Anderson and Krinard, 1985) and *P. trichocarpa* in the west (DeBell, 1990) established that 3.7×3.7 m spacing was a good compromise for pulpwood and sawlog management. Spacing rows at least 3 m apart allows access by commercial farm equipment, which is essential for mechanical or chemical weed control (Stanturf *et al.*, 2001). Regular spacing, usually square, allows space for cross-cultivation, but indications are that rectangular spacing may produce higher yields, at least in very high-density biomass plantings. This could be due to more rapid crown differentiation, and a shorter time growth is checked by competition (DeBell *et al.*, 1996).

Wider spacing is common for sawlog rotations (Fig. 5.11). In Italy, for example, wide spacing was common until recently, with as few as 200 plants ha^{-1} , or about 7 m square (Frison and Facciotto, 1993; G. Picchi, 2005, unpublished report; Castro and Zanuttini, 2008). In Argentina, where livestock grazing in plantations is common, spacing ranges from 4×4 m to 6×6 m (S. Cortizo and R. Suarez, 2005, unpublished report). In the irrigated hybrid poplar plantations on the Columbia River plateau of eastern Washington and Oregon, pulpwood spacing was 3.05×2.29 m or 1450 stems ha^{-1} , but this spacing was found to be too narrow and the distance between trees in the row was widened to 4.58 m for sawlog management (J. Eaton, 2005, unpublished report), while maintaining the between-row spacing at 3.05 m to facilitate the existing irrigation dripline spacing. Recently, planting has included between-row spacing of 6.10 m and in-row spacing of 3.05 m for approximately 540 stems ha^{-1} ; this allows two irrigation driplines per tree row. Economic analysis of stand densities suggests that even wider spacing may be warranted.



Fig. 5.11. Sawlog-size stand of poplar in Chile, ready for manual felling. Trees have been pruned to 8 m, beginning in the second growing season, to increase value. Photo courtesy of J. Stanturf.

The tendency of some cultivars to develop sylleptic branches, especially in the lower bole, dictates caution in using wider spacing, unless pruning is feasible. Experience from experimental and operational plantings of *P. deltoides* in the southern USA illustrates the effect of spacing (Anderson and Krinard, 1985). Generally, diameter increased as spacing increased, from 3.7×3.7 m to 7.4×7.4 m. All spacing intervals were thinned at least once, except the two widest. Initial spacing has no effect on the rate at which diameter growth peaks, generally by the third or fourth year (Krinard and Johnson, 1984). Sawtimber yields were greatest for stands spaced 7.4×7.4 m. Wider spacing, however, required intensive pruning to maintain quality and more weed control to establish plantations successfully (Stanturf *et al.*, 2001).

Interest in bioenergy production has spurred research on spacing to achieve maximum biomass production, generally at narrower spacing than pulpwood plantations. Spacing may be as close as 0.5–1.5 m to increase biomass production per unit area and reduce weed competition (Weih, 2004). For operational bioenergy plantations in Italy, for example, densities depend on cutting cycles (Bisoffi and Facciotto, 2000; G. Picchi, 2005, unpublished report). For a 1-year cycle, a double-row design is used, with 0.75 m within the twin rows, 2.8 m between the sets of twins and 0.4 m between the twin rows, resulting in 14,000 stems ha^{-1} . For longer cutting cycles, spacing varies between 2.8×0.6 m (2-year cycle) and 3×2 m (5-year cycle). The double-row system of planting cuttings that has been used so successfully with willows has received only limited attention with *Populus* in North America (Zalesny *et al.*, 2011), but is widely used in short-rotation coppice systems for bioenergy (DEFRA, 2002). Other planting designs incorporating row crops (both food and bioenergy) are under investigation. In Russia, in the forest-steppe zone, wide spacing is the norm (6×6 m) with agricultural crops raised between the rows until canopy closure (A. Tsarev, 2005, unpublished report).

Coppice

The coppice system of natural regeneration offers an inexpensive alternative to replanting a second rotation stand by utilizing the ability of

poplars to sprout readily from stump or root collar. Coppice management, however, is uncommon in industrial poplar plantations. 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 remains the best option because of poor stem form in coppice, and stumps of larger trees sprout less vigorously. Coppice may, however, be economically attractive for bioenergy production and for non-industrial private landowners because of lower establishment costs, although poplars do not coppice as well as willow (Tubby and Armstrong, 2002). In bioenergy plantations, cutting after the first growing season to stimulate profuse sprouting has the advantage of capturing the site even if first year survival is low (Tullus *et al.*, 2012). This is standard practice in willow bioenergy plantations (Danfors *et al.*, 1997; Abrahamson *et al.*, 2002; DEFRA, 2002).

Coppicing works best when cutting occurs during the dormant season, when root reserves of carbohydrate are greatest, but this may also be the season when soil strength is lowest, limiting the weight of harvesting machinery (Verani *et al.*, 2008). Machinery limitations currently favour short cutting cycles, for example 1–2 years in Italy, for bioenergy plantations (Spinelli *et al.*, 2009).

Some non-industrial landowners in the southern USA have used coppicing for pulpwood production (Stanturf *et al.*, 2001). Plantations harvested during the winter months are typically those that may be targeted for coppicing. Harvest should begin no later than age 10 in the rotation to ensure vigorous sprouting. Often, there is a proliferation of shoots that arises from a single stump, and how these shoots are treated can potentially affect growth, yield and average tree size through the second rotation. 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 ten 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. Another coppice approach that has been tested is to fell every other row in the first-rotation harvest. 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.

Clonal deployment and risk management

Disease and pest resistance are critical concerns in poplar breeding programmes, and clonal deployment strategies to minimize the risk of plantation failure should be the norm in industrial plantations (Ramstedt, 1999; Mattson *et al.*, 2001; Zalesny *et al.*, 2011). However, the practice is monoclonal plantings to facilitate cultivation, health monitoring, inventory and harvest scheduling (Zalesny *et al.*, 2011). The standard practice is to plant a mixture of monoclonal blocks, with some growers taking care to plant different genotypes in adjacent blocks and others paying little attention to diversity among adjacent clones (Zalesny *et al.*, 2011). Monoclonal blocks are easier to manage and, as yet, polyclonal mixes have not shown any sustained yield benefit (DeBell and Harrington, 1997; Knowe *et al.*, 1998). Mixtures require clones with similar growth characteristics at a given site to avoid some clones out-competing the other clones (Verwijst, 2001).

In many countries, poplar plantations are stocked with material from a limited number of clones. Often, this was due to limitations on the number of clones available, with even fewer performing successfully (R.C. Dhiman, 2005, unpublished report). Breeding programmes have expanded the genetic diversity of planting stock (Chapter 4, this volume), and multiple clones may be deployed yearly after testing under local conditions (e.g. Rédei, 2000; Coyle *et al.*, 2006). In the USA, for example, 3–16 different clones may be deployed annually; block size ranges from 2 to 45 ha (J. Eaton, 2005, unpublished report). In Canada, forest management regulations vary among provinces and according to land ownership (public or Crown lands versus private (Plate 21B)). In general, there are few restrictions on the deployment of hybrid poplars, except monoclonal blocks cannot exceed 10 ha in size on publicly owned forestland in the province of British Columbia; there are no such restrictions on private farmland. Several other provinces have restrictions on the deployment of hybrid poplars on public forestland. The limited number of clones suitable

for the Prairie Provinces underscores the risk of planting only the 'best' performers; guidelines based on common sense suggest monoclonal blocks should be 20 ha or smaller on private land (van Oosten, 2006).

5.2.2 Stand tending

Competition control

Competition in any form will affect poplar plantation survival and growth. Control of competing vegetation is critical to establish poplar plantations successfully (Von Althen, 1981; Hansen and Netzer, 1985; Schuette and Kaiser, 1996) and poplars require full sunlight, adequate water and nutrients to realize their maximum growth potential (Demeritt, 1990). Substandard weed control in the first several years of plantation establishment can lower production at rotation significantly. For these reasons, aggressive weed control must begin by controlling perennial grasses and broadleaved weeds in the site preparation phase. Ignoring this important aspect increases costs and leads to unpredictable results once the plantation is established. Aggressive weed control continues during establishment and may continue longer in sawlog rotations with wider spacing that require more time for crowns to close and shade out weeds. Different strategies for controlling competing vegetation are used in industrial plantations, depending on local conditions and traditions. Herbicides and mechanical methods, in combination and alone, are common. Hand hoeing or tall planting stock (whips or poles) are preferred alternatives where labour is inexpensive, herbicides are unavailable (or too expensive), or both. Livestock grazing after successful establishment is also used to control weeds (Fig. 5.12). Any or all of these methods may be used at various developmental stages of the poplar plantation. Because the methods and timing of application are so varied, only representative examples will be given.

In China and India, poplars are often grown in combination with agricultural crops and benefit from weed control for the companion crop (Fig. 5.13). In China, mowing or scything is common on wetter sites; disk cultivation is common on drier sites (Q.-W. Zhang and J.-H. Li, 2005, unpublished report). Ploughing at least twice a year is common in India (R.C. Dhiman,



Fig. 5.12. Cattle grazing in a hybrid poplar stand in Chile. Grazing controls weeds and the stand provides thermal cover as well as forage. Livestock are excluded from young plantations to avoid damage. Photo courtesy of J. Stanturf.



Fig. 5.13. Poplars planted on a farm in China; poplars are integrated into smallholder farms in many Asian countries. Photo courtesy of J. Stanturf.

2005, unpublished report). In Italy and France, where spacing is relatively wide, two to four passes of a disk cultivator annually for 4–5 years is alternated by shallow ploughing in the winter (Facciotto, 1998; A. Berthelot, 2005, unpublished report; G. Picchi, 2005, unpublished report). Directed spraying of glyphosate during the first 2–3 years is followed by disking between the rows.

The practice in North America is more intensive, although fewer herbicides are available for poplar plantations in Canada than in the USA (Thomas *et al.*, 2000). Competition control strategies vary by region and depend on annual rainfall, soils and herbicide registration (Stanturf *et al.*, 2001). 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. Nearly all regions use a pre-emergent herbicide prior to or immediately following planting. In the southern USA, newly planted eastern cottonwoods are sprayed in bands 0.9 m in width as needed directly over the dormant tree rows with oxyfluorfen alone or in combination with herbicides such as imazaquin (Stanturf *et al.*, 2001). The strategy in the Midwest is to broadcast apply herbicides such as imazaquin and pendimethalin over entire plantations of dormant, newly planted hybrid poplar cuttings (Stanturf *et al.*, 2001). One industrial plantation owner in the state of Minnesota successfully uses flumioxazin as a pre-emergent herbicide at the time of planting, followed by broadcasting a tank mix of pendimethalin and imazaquin at the start of the second growing season when the trees are still dormant. 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, although this is more difficult in the second rotation where stumps limit working the soil. West of the Cascades, glyphosate and metsulfuron methyl in tank mix are applied for site preparation as a post-emergent the season before planting, a tank mix of glyphosate and sulfometuron methyl as a pre-emergent in a band directly before planting and as a pre-emergent

in a directed basal spray prior to bud break in young plantations (J. Eaton, 2005, unpublished report). As companies seek certification, however, use of herbicides may become more limited.

Poplars typically are grown on sites that have recently been in agriculture and the weed complex is herbaceous broadleaves and grasses, although persistent woody vines are a problem in the southern USA (Stanturf *et al.*, 2001). Control of 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. After planting, options are more limited because poplars are generally sensitive to herbicides and mechanical damage. Certain herbicides, however, can still be applied effectively while poplars are still dormant. Several other herbicides are registered in the USA and Canada to control grasses (Canada: sethoxydim and fluazifop-P-butyl; USA: quizalofop P-ethyl) and some broadleaved weeds when trees are actively growing (Canada and the USA: clopyralid). Generally, these herbicides can be applied either directed to the base of the trees or right over the actively growing trees. Some equipment used after planting includes various hooded (shielded) and broadcast sprayers, backpack sprayers, cultivators and hand weeding. 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.

In Canada, where fewer herbicides have been approved for poplar plantations than in the USA, the general strategy in forest plantations is to plant unrooted or rooted whips (stecklings) to gain an advantage over competing vegetation. For short-rotation, intensively managed hybrid poplar plantations, integrated weed control using a few recently labelled pre-emergent herbicides (oxyfluorfen and flumioxazin) and mechanical cultivation can be used, except in the province of Quebec, where herbicides are not allowed. In Quebec, rooted whips (stecklings) are used to improve plantation success in the absence of herbicide use.

Mulches have been tested and may have some use in smaller intensive plantings for bioenergy and fertigated sites near mills or power plants (DEFRA, 2002; Robison *et al.*, 2006). Synthetic and paper mulches have been tested (Thomas *et al.*, 2001; Shogren and Rousseau, 2005; Geyer *et al.*, 2006), primarily to avoid using herbicides. In agroforestry systems, intercropping has a weed control effect (Delate *et al.*, 2005) and is widely used in India (R.C. Dhiman, 2005, unpublished report) and China (Q.-W. Zhang and J.-H. Li, 2005, unpublished report).

Nutrition

Poplars are demanding of high nutrient levels and generally are established on relatively fertile sites. In some places, municipal effluent and biosolids have been used; biosolids have been beneficial especially on marginal soils. Use of treated wastewater is more common in willow bioenergy plantations (see below). Nevertheless, nutrient limitations may occur as related to high inherent requirements due to high productivity of poplars, limited availability of native soil nutrients and imbalance among essential nutrients (Stanturf *et al.*, 2001). The commonest form of fertilization is at planting, in the planting hole or trench. Applications of potassium and phosphorus are common in India (R.C. Dhiman, 2005, unpublished report), limited applications of NPK in Canada (Thomas *et al.*, 2000; DesRochers *et al.*, 2006; van Oosten, 2006), and nitrogen in the southern USA (Stanturf *et al.*, 2001) and east of the Cascade Mountains in the west (J. Eaton, 2005, unpublished report). Phosphorus fertilization enhances early growth of aspen and hybrid aspen in Canada (van den Driessche *et al.*, 2003, 2005; Liang and Chang, 2004). The benefit generally comes from rapid height growth above competing vegetation. The application of nitrogen may continue throughout the rotation, especially on coarser textured soils or those with low organic matter content (Einspahr and Wycoff, 1978). The highest levels of poplar productivity have been obtained when N supply is adequate and other nutrients are kept in balance with N to avoid relative deficiencies (Stanturf *et al.*, 2001). Although growth on some sites has been shown to respond to other nutrients, it is most important to provide nitrogen as the main element limiting poplar growth.

Fertilizer recommendations focused on N generally consider foliar N levels of 2 and 3% as critical; in other words, levels below this suggest that N should be added (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 amount of N and other nutrients required to support optimum growth is shown in Table 5.5. The critical foliar concentration level may vary with genotype because of differences in N use efficiency (Blackmon *et al.*, 1979; Heilman, 1985). These estimates demonstrate the very high N requirement of rapidly growing poplar, especially hybrid poplars, compared with other forest types (Heilman and Xie, 1993). The high nutrient demand is due to the young age of intensively managed poplar plantations and their high productivity. Peak demand occurs by age 5 or 6 years (Nelson *et al.*, 1987). 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. None the less, nutrients not adequately supplied by the site must be supplemented through fertilization if optimum growth rates are to be maintained. Maintaining balance between N and other essential nutrients is critical for achieving optimum production. For example, poplar stands may not respond to N additions unless accompanied by additions of P, K or other nutrients (Blackmon, 1976).

Nutrients besides N may improve poplar growth (Stanturf *et al.*, 2001), 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, and not all sites will respond even to added N (Stanturf *et al.*, 2001). Nutrients can be applied separately or with N in fertilizer blends. Phosphorus may be limiting on sites such as the coarse-textured, well-drained soils used for fertigation systems, highly weathered soils or upland marine and some alluvial soils. 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

Table 5.5. Amount of nutrients required for sustained growth of poplar species and their hybrids compared with an average of temperate deciduous and conifer forest types.

Genotype	Age (year)	NPP ^a (Mg ha ⁻¹ year ⁻¹)	Requirement (kg ha ⁻¹ year ⁻¹)					Reference
			N	P	K	Ca	Mg	
<i>P. deltoides</i>	4–6	17	102	11.5	88	151	17.9	Cited by Bernier, 1984
<i>P. deltoides</i>	7	17	107	11	91	157	18	Nelson <i>et al.</i> , 1987 Heilman and Stettler, 1985
<i>P. trichocarpa</i>	4	7–18	95–159					
<i>P. trichocarpa</i> × <i>deltoides</i>	4	27–28	271–276					Heilman and Stettler, 1985
<i>P. × canadensis</i> ^b	4	11	168					Heilman and Stettler, 1985
<i>P. × canadensis</i> ^b	1–2	12–24	182–246	20–36	113–171	121–237	38	Cited by Bernier, 1984
Temperate deciduous	30–120	10	98	7.2	48	56	10.4	Cited by Bernier, 1984
Temperate conifers	15–450	8.3	46	5.5	28	20	4.6	Cited by Bernier, 1984

^aNet primary productivity (NPP) includes belowground and aboveground biomass, including foliar mass.

^bSynonym *P. xeuramericana*.

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 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 (Fig. 5.14). This places the nutrients at an optimal location for tree roots and out of the reach for shallow-rooted competing vegetation.

Poplars grown on farms often benefit from fertilizing with animal manure. For example, in Iran a green manure cover crop is grown and ploughed under with 30–40 t of decayed animal manure before planting (P. Nejad, B. Reza, H. Hasan, H. Sabeti and A. Babaipour, 2005, unpublished report). Additional manure may be added to the planting hole and around the base of the plant. Later, compost with added inorganic N may be incorporated. In Argentina and other countries where livestock are grazed in poplar plantations, it is believed that animal manure contributes nutrients to the trees (S. Cortizo and R. Suarez, 2005, unpublished report).

Irrigation and drainage

Poplar requires adequate moisture throughout the growing season and even on the best sites may experience periodic dry conditions. The capital expenditure necessary for irrigation usually is not justified, however. The exceptions are fibre farms established on coarse soils to provide all-weather wood supply to pulp mills (Stanturf *et al.*, 2001; Stanton *et al.*, 2002; J. Eaton, 2005, unpublished report; Gallagher *et al.*, 2006; Robison *et al.*, 2006) and semi-arid and Mediterranean environments such as east of the Cascade Mountains in the western USA (Stanton *et al.*, 2002; J. Eaton, 2005, unpublished report), the steppes of Russia (A. Tsarev, 2005, unpublished report), Uzbekistan (G. Vildanova and K. Tolipov, 2005, unpublished report), India (R.C. Dhiman, 2005, unpublished report), China (Q.-W. Zhang and J.-H. Li, 2005, unpublished report), Mendoza and Rio Negro provinces in western Argentina (S. Cortizo and R. Suarez, 2005, unpublished report), Chile (Ulloa and Villacura, 2005) and Italy (ISP, 2002; G. Picchi, 2005, unpublished report). Irrigation technology varies from gravity-fed ditches to drip systems. For example, the practice in India is to fill



Fig. 5.14. Moulder and fertilizer dispenser pulled by a farm tractor to prepare for planting on former agricultural sites. The fertilizer dispenser is mounted behind a subsoiler shank, which is followed by mounding. Fertilizer is fed by gravity continuously at the bottom of the rip. The disks pull soil into a mound that serves to mark the planting row. Cuttings (45 cm in length) are planted by hand 30 cm deep, right on to the fertilizer. The fertilizer was mono-ammonium phosphate (11-52-0) applied at 220–340 kg ha⁻¹ to supply between 50 and 75 kg P ha⁻¹. Photo courtesy of Alberta-Pacific Forest Industries Inc.

planting holes partially with soil and then flood irrigate the field; water accumulates in the planting holes, which are later filled with soil. Irrigation continues as needed, every 15 days during the first growing season or according to the needs of the companion agricultural crop. Irrigation is less frequent from the second growing season through to the end of the rotation (R.C. Dhiman, 2005, unpublished report). In Italy, both gravity-fed and sprinkler irrigation are used in intensively cultured plantations but not in biomass plantings. Gravity-fed systems (Fig. 5.15) require essentially level fields and require large amounts of water even with careful monitoring of plant needs (ISP, 2002; G. Picchi, 2005, unpublished report). Sprinkler systems can be used on any kind of site and use less water. In Russia, poplar is irrigated every 14–15 days in the summer and monthly in spring and autumn. The amount of water is lower in the first 2 years of stand development (3500 m³ ha⁻¹ year⁻¹) and increases in later years (up to 5000 m³ ha⁻¹ year⁻¹). Irrigation may be gravity-fed or sprinkler (A. Tsarev, 2005, unpublished report).

The drip irrigation systems used in the desert regions east of the Cascade Mountains in the western USA (Fig. 5.16) require a major capital investment and careful monitoring and control (J. Eaton, 2005, unpublished report). Annual precipitation is only 20 cm and falls mostly during the dormant season, so virtually all crop needs must be supplied by irrigation. Water is drawn from the Columbia River and its tributaries and pumped through buried pipe to the drip distribution system. Water demand is predicted from transpiration models using data from soil moisture sensors. Emitters at each plant deliver metered applications of water and fertilizer, and sometimes insecticide (J. Eaton, 2005, unpublished report). Demand by young plants is low (15–25 cm ha⁻¹ for 1-year-old trees), but increases rapidly until levelling off at canopy closure (80–100 cm ha⁻¹ annually).

Poplar plantations are often established on alluvial sites and excess water may affect management activities and growth. Drainage or levee systems in some cases may have been established for agricultural purposes. In the southern USA in the flood plain of the Mississippi



Fig. 5.15. Gravity-fed irrigation of hybrid poplar in Chile. Gravity-fed systems require essentially level fields and large amounts of water. Photo courtesy of J. Stanturf.



Fig. 5.16. A new plantation of dripline-irrigated hybrid poplar at the start of the first growing season at Boardman, Oregon, USA, against a backdrop of an older irrigated plantation. Photo courtesy of C. van Oosten.

River, eastern cottonwood (*P. deltoides*) plantations have been established both in the protected area behind levees and within the unprotected area flood plain (Stanturf *et al.*, 2001). Similarly in the Paraná River delta region of Argentina, channels and ditches are constructed to remove excess water from plantings on higher ground and behind levees (S. Cortizo and R. Suarez, 2005, unpublished report). In many countries such as France, wetlands are now protected and drainage consists of cleaning existing ditches prior to planting (A. Berthelot, 2005, unpublished report). In Iran where flash flooding threatens agricultural crops, water diversion channels funnel floodwaters to poplar plantations (Sagheb-Talebi, 2005).

Protection

Poplar plantations are susceptible to a host of pests and diseases and the best strategy is prevention rather than correction. Literally hundreds of diseases and insects affect poplars (Giorcelli *et al.*, 2008; see also Chapters 8 and 9, this volume), and disease and insect resistance are key components of breeding programmes. The main emphasis in breeding programmes is for disease resistance (van Oosten, 2006; Chapter 4, this volume) and screening especially for *Melampsora* rust resistance should be carried out before a newly introduced clone is deployed in a region. Nevertheless, disease and insect pests likely will adapt and overcome resistance or tolerance, hence the importance of a clonal deployment strategy. Other protection needs include animal pests and fire.

Diseases

The first line of defence against diseases is breeding for resistance (Duplessis *et al.*, 2009; Chapters 4 and 8, this volume). Planting resistant clones that are otherwise adapted to the site and maintaining healthy trees is essential to obtain the benefit of breeding programmes. *Melampsora* leaf rust is the most serious foliar disease in North and South America and Europe, but seems to be of only minor importance in India. The rust causes premature defoliation and decreased growth and may weaken young plants, leading to mortality (Cellerino, 1999). There are several species of *Melampsora* rusts, and poplar clones differ greatly in their susceptibility. While the best defence is to plant resistant

clones, low-density plantings afford some protection, as is done in European plantations (van Oosten, 2006). *Melampsora* rust can be problematic in stoolbeds and can seriously affect many hybrid clones that are normally considered tolerant in plantation settings. In Canada, one fungicide (tebuconazole) was recently approved to control this rust in stoolbeds and intensively managed plantations. Protection strategies in Russia against *Melampsora* and other leaf diseases is to gather leaf litter at the end of the growing season and burn it, followed by ground application of 3–5% Bordeaux mixture in May (A. Tsarev, 2005, unpublished report).

The most serious disease of hybrid poplars in North America is *Septoria* leaf spot and canker caused by the fungus *Septoria musiva*, which is also present in Argentina and southern Brazil (van Oosten, 2006; Isebrands, 2007). High densities (greater than 800 stems ha⁻¹) are conducive to spread of this disease that begins as circular necrotic spots on the leaves and progresses to cankers at the base of branches (Isebrands, 2007). Several formulations of one registered fungicide are available in Canada (thiophanate-methyl) (van Oosten, 2006) to control *Septoria* leaf spot but not in the USA (Isebrands, 2007). *P. deltoides* is not susceptible to this *Septoria* damage, but many of its hybrids are. In Canada, susceptible native *P. balsamifera* in a plantation setting was reported in the province of Alberta, and in 2006 *Septoria musiva* stem cankers were reported in the province of British Columbia (Callan *et al.*, 2007) on several hybrids of *P. trichocarpa* × *P. maximowiczii* grown in a stoolbed; this was the canker's first occurrence west of the Rocky Mountains in North America. Subsequent surveys found several hybrids of *P. trichocarpa* × *P. deltoides* to be affected in stoolbeds and nearby stands. The canker disease has now also been confirmed as present on the native *P. trichocarpa* in south-western British Columbia, although many phenotypes appear to be resistant. *Marssonina* leaf spot, however, can be a serious problem in nurseries, stoolbeds and dense plantings of the North American poplar species, including trembling aspen (*P. tremuloides*). Selection and breeding of hybrid poplar clones with diverse parentage and planting resistant clones is one defence; another is to disk between tree rows after leaf fall to decrease inoculum (Isebrands, 2007). Early spring (April) application with a systemic pesticide is used in Italy

for non-resistant clones (ISP, 2002; G. Picchi, 2005, unpublished report), and in Canada several formulations of one registered fungicide (thiophanate-methyl) are available to control this disease.

The most significant disease of poplar in India is the southern leaf blight, *Bipolaris maydis*, that also attacks some strains of maize (R.C. Dhiman, 2005, unpublished report). The disease is a problem during the monsoon season; leaves of infected trees dry and crumble. The *P. deltoides* 'G3' clone, once widely planted, is especially susceptible and no longer planted (Chandra, 2001). Breeding and screening for resistance is the main form of defence (R.C. Dhiman, 2005, unpublished report).

Insects

The major insect pests of North American poplar plantations (Chapter 9, this volume) include defoliating insects such as cottonwood leaf beetle, or CLB (*Chrysomela scripta*), poplar tent maker (*Clostera inclusa*); borers such as the cottonwood twig borer (*Gypsonoma haimbachiana*), cottonwood clearwing borer (*Paranthrene dollii*), cottonwood borer (*Plectrodera scalator*) and exotics (Haack, 2006), and poplar borer (*Saperda calcarata*) and poplar-willow borer, or PWB (*Cryptorhynchus lapathi*) (van Oosten, 2006); and aphids, mites and leafhoppers (Morris *et al.*, 1975; Solomon, 1985; Coyle *et al.*, 2005). Grasshoppers (various species) and sawflies (*Nematus* spp.) have been recent and recurrent problems in the province of Alberta, Canada, in new and young plantations. A frequent monitoring schedule should be used to control these insects prior to large infestations (Coyle *et al.*, 2002, 2008). Labelled general-purpose insecticides such as carbaryl or *Bacillus thuringiensis* (*Bt*) may be applied to control some of these pests. In addition, the CLB is controlled in irrigated hybrid poplar plantations with a nicotine-based systemic insecticide, imidacloprid (J. Eaton, 2005, unpublished report).

Stem borers have taken on greater importance in western North America in recent years, as poplar management has focused on producing sawlogs. The three most important pests are the western poplar clearwing moth (*Paranthrene tabaniformis*), PWB (*Cryptorhynchus lapathi*) and the carpenterworm moth (*Prionoxystus robiniae*). All form galleries that severely degrade the

lumber produced. Experience suggests that hybrids with *P. deltoides* × *P. nigra* parentage are more resistant than *P. trichocarpa* × *P. deltoides* or *P. trichocarpa* × *P. nigra* parentage (J. Eaton, 2005, unpublished report). In Italy, the PWB is treated by spraying the tree trunk for the first 3 years with pyrethroid or organophosphorus insecticides (ISP, 2002; G. Picchi, 2005, unpublished report). These insecticides are also used to treat the poplar borer, *Saperda carcharias*.

The large-scale afforestation effort of drylands in northern China has resulted in novel pest outbreaks (Chapter 7, this volume). Large monocultures, limited genetic material and sub-optimal growing conditions have been implicated in outbreaks of Asian longhorn beetle (*Anoplophora glabripennis*) since 1998 (Chapter 7, this volume). The beetle is not native to most of the affected areas, hence lacking in natural enemies. It has spread to 13 provinces in northern China (Pan, 2005), with widespread mortality of thousands of hectares of poplar plantations (see Chapter 7, this volume).

In South America, east of the Andes, the ambrosia beetle, *Megaplatypus mutatus* (also identified as *Platypus mutatus*) causes serious damage, resulting in major degrade of the wood and often stem breakage. The economic damage is in the outer shell of the stemwood, which contains the most valuable veneer and lumber grades. It is associated with a blue stain that degrades the wood and is reported to affect many hardwood trees, including *Salix*. This insect was recently found in Italy. In Argentina, this ambrosia beetle causes serious damage to poplar plantations due to breakage and reduced vigour (Alfaro, 2003; Giménez and Etiennot, 2003).

Animals

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 repellents 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 for several years will remain susceptible 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 north-eastern USA in forest clearcuts (Brenneman, 1982). Other options are available, including a more expensive woven wire fence (Dickmann 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.

Small mammals are also localized problems. Periodically high vole (*Microtus* spp.) populations can be a problem even in older (3- and 4-year-old) plantations with grass or snow cover that provides protection from predators. Voles feed on roots and lower stems, which can lead to heavy tree mortality. In the north-western USA (west of the Cascades) and coastal south-western British Columbia (Canada), the main problem with voles occurs after canopy closure, when shading reduces alternate food sources such as grasses. Grass control can prevent this problem, although mice and voles can still cause trouble under snow cover. Beaver (*Castor canadensis*), porcupine (*Erethizon dorsatum*), squirrels (*Sciuridae* spp.), hare (*Lepus* spp.) and rabbits (*Sylvilagus* spp.) are occasional problems in North American plantations, especially by stripping bark from young trees. Damage can be minimized by effective weed control and by planting large stock (Stanturf *et al.*, 2001). In France, plantations are planted with individual tree protection against roe deer (*Capreolus capreolus*), coypus (*Myocastor coypus*, an introduced rodent species from South America also known as river rat) and rabbits (A. Berthelot, 2005, unpublished report). In the UK, fencing must be buried and turned outward to deter rabbits (DEFRA, 2002). In northern Europe, damage to hybrid aspen stands from deer and moose is controlled by fencing, at least during the first rotation in coppice stands (Tullus *et al.*, 2012).

Livestock grazing in plantations must be controlled to prevent damage to young plants. In Argentina, this is accomplished by planting large material (poles) and excluding livestock for

the first year or two (S. Cortizo and R. Suarez, 2005, unpublished report). Blue bull or nilgai (*Boselaphus tragocamelus*) is an indigenous antelope of central and northern India that damages nurseries and newly planted areas by trampling and breaking (Dhiman, 2004). They are controlled by watchmen and scarecrows and by pungent repellents.

Stand improvement

Three stand improvement treatments are practised in poplar plantations: singling, thinning and pruning. By far the most common practice is pruning in sawlog and veneer management systems.

Singling

Removing multiple stems in order to concentrate growth on a single stem is a common practice in many poplar growing regions where pulpwood, veneer or sawlogs are the management objective. Generally, singling is done at the beginning of the second growing season, allowing one stem to express dominance or other desirable characteristics (R.C. Dhiman, 2005, unpublished report). Because the singling treatment is labour-intensive, growers in many regions seek to avoid it by planting cuttings deeply enough that only a single bud develops (Stanturf *et al.*, 2001). On the other hand, in drier regions, development of multiple buds is an insurance that a stem will develop and singling is less expensive than fill-in planting (P. Nejad, B. Reza, H. Hasan, H. Sabeti and A. Babaipour, 2005, unpublished report). In biomass plantations, multiple stem development is often an objective (DEFRA, 2002).

Thinning

Thinning is uncommon in industrial plantations; initial planting density is generally the target harvest density. Limited thinning has been used to convert stands from pulpwood to sawlog management or other situations where rotations have been lengthened (Stanton *et al.*, 2002; J. Eaton, 2005, unpublished report). Early plantations of native eastern cottonwood (*P. deltoides*) in the southern USA envisioned opportunities to produce sawlogs and veneer within

20–30 years of planting, and thinning trials were conducted (Stanturf *et al.*, 2001). 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. Timing of thinning treatments will be determined largely by initial spacing, which is affected by site quality, establishment practices and survival. Initial spacing has no effect on the rate at which diameter growth peaks, generally by the third or 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 thinning is necessary to maintain rapid growth of individual trees.

Thinning has become popular in Argentina as the demand for solid wood has increased (S. Cortizo and R. Suarez, 2005, unpublished report). Initial stand density of 625 stems ha^{-1} is reduced to between 278 and 430 stems ha^{-1} (Borodowski and Suárez, 1999; Borodowski *et al.*, 2005). While thinning is often pre-commercial, some Indian growers will harvest the largest stems and allow unmerchantable stems to grow another year or two to reach merchantable diameter (R.C. Dhiman, 2005, unpublished report). Rising pulpwood demand in India has prompted some farmer-growers to increase initial density above 400–500 stems ha^{-1} in hopes of commercial thinning for pulpwood after 3 or 4 years.

Pruning

Pruning to reduce knots and increase wood quality is common in veneer and sawlog management systems, especially where initial planting density is low. Pruning usually begins early and no later than the third growing season. The goal in Italy is 5 m of branch-free stem at harvest, thus pruning to a height of 6–7 m is needed (Facciotto, 1999; G. Picchi, 2005, unpublished report). The lower 3 m is veneer quality and the upper 2 m of the log is taken for solid wood products. Pruning is progressive and every year all branches are removed below the point where bole diameter reaches 10 cm. Initial pruning (education pruning) begins in the dormant season after the second year, to shape the stem and eliminate double apex

shoots and large branches. Cleaning pruning begins at the same time and continues for 5 years, gradually removing all branches less than 60 mm in diameter. Hydraulic shears and small chainsaws on long poles are used (Fig. 5.17); workers may be raised to the higher levels on hydraulic lifts mounted on agricultural tractors (Fig. 5.18). Because planting stock may be 1- or 2-year-old poles, different strategies are followed. For 1-year-old poles, more shaping may be required since branches develop on the upper two-thirds of the pole (3–4 m tall). The taller 2-year-old poles (6–8 m) develop branches in the upper half of the stem and require mostly cleaning pruning. Such intensive pruning may reduce growth rates but is more than offset by the higher value of the final assortment. Similar regimes are followed in France (A. Berthelot, 2005, unpublished report), Argentina (S. Cortizo and R. Suarez, 2005, unpublished report) and Chile (Ulloa and Villacura, 2005; Baettig *et al.*, 2010): pruning to 7–8 m, beginning in the second year.



Fig. 5.17. Pruning lower limbs with a small chainsaw mounted on a pole. Pruning to reduce knots and increase wood quality is common in sawlog management systems, especially where initial planting density is low. Pruning usually begins early and no later than the third growing season. Photo courtesy of J. Stanturf.



Fig. 5.18. Two workers in tandem, pruning taller trees from hydraulic lifts mounted on an agricultural tractor. Initial pruning was accomplished from the ground using hydraulic shears or small chainsaws on long poles. Photo courtesy of J. Stanturf.

Pruning in North America is limited to pruning of lower branches in Canadian plantations to allow equipment access and in sawlog management of irrigated hybrid poplar plantations east of the Cascade Mountains in the USA (J. Eaton, 2005, unpublished report). Pruning in the eastside plantations uses a three-lift system that prunes up the stem to approximately 8 m. Pruning begins at the start of the third growing season and is completed within 3 years. Pruning during the growing season reduces epicormic branching. All pruning is by hand; lower levels with lopping shears and upper lifts with pruning poles. Generally, 50–60% of live crown remains after pruning in order to avoid growth loss, although this may differ among clones (J. Eaton, 2005, unpublished report).

5.2.3 Production

Rotation length

Rotation lengths vary according to the time needed for trees to meet product requirements,

with sawlog and veneer rotations the longest and pulpwood and bioenergy the shortest. Pulpwood and chip-and-saw rotations are determined by the time needed to reach minimum piece size for economical harvesting and handling. While rotation lengths generally are longer for sawlogs and veneer production, in the western USA a maximum rotation length of 12–15 years is due partly to local (state) regulations on maximum rotation length to qualify as an agricultural tree crop, and therefore exempt from more restrictive forest practice regulations (J. Eaton, 2005, unpublished report). Bioenergy rotations are fixed by limits on the size of material that can be harvested economically by available equipment (Weih, 2004; Verani *et al.*, 2008). The very short-rotation poplar coppice bioenergy systems using modified silage harvesters typically are on 2- or 3-year cutting cycles (Verani *et al.*, 2008; Spinelli *et al.*, 2009). Rotation lengths vary by poplar growing region because of different management regimes, climate and growing conditions and product objectives (Table 5.6). Markets for poplar wood in Serbia and Montenegro are unstable and plantations are carried longer, from 22 years on optimal growing sites along the Danube River to 32 years on suboptimal sites along the Sava River (S. Orlovic, B. Klasnja, Z. Galic, L.P. Pajnik and P. Pap, 2005, unpublished report).

Survival

Industrial poplar plantations typically have high survival rates when properly managed. This requires that clones are adapted to the site and competing vegetation is controlled, especially in the first 2 years (Stanturf *et al.*, 2001; Weih, 2004). Contributing factors are adequate site preparation and quality planting stock. Expected survival in many countries is greater than 90%, unless a major disturbance occurs such as windstorms or growing-season flooding. If poles are planted at wide spacing, there is an opportunity to replant if initial survival falls below 90%. In Argentina, the threshold is greater than 15% mortality in the first year (S. Cortizo and R. Suarez, 2005, unpublished report). In France, dead trees may be replaced in the first 2 or 3 years (A. Berthelot, 2005, unpublished report). In countries where greater planting density is the practice, it is uncommon to replant dead cuttings.

Table 5.6. Poplar yield, stand density and rotation length.

	Stand density (stems ha ⁻¹)	Rotation length (years)	Mean annual increment (m ³ ha ⁻¹ year ⁻¹)	Diameter at harvest (cm)	Height at harvest (m)	Basal area at harvest (m ² ha ⁻¹)	Yield (m ³ ha ⁻¹)	Yield, green (Mg ha ⁻¹)	Source
<i>Canada</i>									
British Columbia	280-450	33	15						van Oosten, 2008
Quebec	550	15	25						van Oosten, 2008
Alberta	1111	15	12-20						van Oosten, 2008
Ontario	816-1111	18	16-18						C. van Oosten, 2005 (unpublished)
	1111	15	12-15						
<i>USA</i>									
Westside PNW	750-768	6-8	25-30						J. Eaton, 2005 (unpublished)
Eastside PNW	1450	6-8	42	17-22	22-25	40-45			J. Eaton, 2005 (unpublished)
South	725	10-15	32						J. Eaton, 2005 (unpublished)
Midwest	745	8-10		25-30	30	30-34	250-350		J. Eaton, 2005 (unpublished)
	1100	12		20-25	18-20			270	J. Eaton, 2005 (unpublished)
<i>South America</i>									
Chile	278	12	23						Ulloa and Villacura, 2005
Argentina	278-625	10-16	20-21	35-45	28-30				S. Cortizo and R. Suarez, 2005 (unpublished)
<i>Europe</i>									
Italy	291	10.7	19	28	24	18			Coalao, 1999; G. Picchi, 2005 (unpublished)
France	200	15-25	15	40	30-35	20-30			A. Berthelot, 2005 (unpublished)
	2000	7-9	26	12-15	15-18	27-31			
Spain	250-505	13	16					136	Barrio-Anta <i>et al.</i> , 2008
Sweden	5000	15-20							M. Ramstedt, 2005 (unpublished)
Finland	1000	20-30	12		20				E. Beuker, 2005 (unpublished)
Russia	500	21	20	27	36				A. Tsarev, 2005 (unpublished)
Serbia	278-555	22-32					200-500		S. Orlovic <i>et al.</i> , 2005 (unpublished)
Montenegro	278-555	22-32					200-500		S. Orlovic <i>et al.</i> , 2005 (unpublished)
<i>Asia</i>									
India	400-500	6-8	20-30						R.C. Dhiman, 2005 (unpublished)
China	277-333	12-13	18-27						Q.W. Zhang and J.H. Li, 2005 (unpublished)
(south)	833-1111	6-7	22.5-27						

Growth and yield

Many factors influence the growth of poplars in plantations, including species or clone (Zabek and Prescott, 2006), site quality (Baker and Broadfoot, 1979), climate (Chandra, 2011) and spacing. 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 (*P. deltoides*) do not touch even in densely spaced plantations. Poplar clones vary in their tolerance of shading; some can be planted closer together than others, a concept expressed as 'stockability' (DeBell *et al.*, 1989). 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 (Ranney *et al.*, 1987; DeBell *et al.*, 1997a, b). Although site potential is relatively fixed, at least under a given management intensity, the time required to achieve culmination of mean annual biomass increment can be influenced by manipulating growing space available to individual stems (Stanturf *et al.*, 2001). Even more importantly, the time required to reach a minimum or average stem size can be influenced by manipulating growing space, nutrients and water (Stanturf *et al.*, 2001).

Growth rates of poplar in industrial plantations are among the highest in the world (Dickmann and Stuart, 1983; Boysen and Strobl, 1991; Christie, 1994; Stanturf *et al.*, 2001; Stanton *et al.*, 2002; Weih, 2004; Dickmann, 2006; Zalesny *et al.*, 2011; Tullus *et al.*, 2012), and even higher growth rates can be obtained in experimental and bioenergy plantings. Directly extrapolating from small research plots to operational yield expectations, however, is dangerous. For example, an experiment with a hybrid poplar clone in small plots determined mean production values at age 4 to be 28 Mg ha⁻¹ year⁻¹ (Heilman and Stettler, 1985). Another experiment using larger plots (DeBell *et al.*, 1996) attained growth equal to or better than other studies with the same clone, but estimated yield to be 18 Mg ha⁻¹ year⁻¹. Yield predictions have been published for individual trees or for stands (e.g. Christie, 1994), but should be used with caution outside of the region in which they were developed (Zabek and Prescott, 2006).

Individual-tree and stand-level regression equations have been published for poplars (Krinard, 1988; Tuskan and Rensema, 1992; Clendenen, 1996; Lodhiyal and Lodhiyal, 1997; Scarascia-Mugnozza *et al.*, 1997; Kort and Tornock, 1999; Netzer and Tolsted, 1999; Stanturf *et al.*, 2001; Aylott *et al.*, 2008). A stand-level equation for *P. deltoides* in the southern USA (Cao and Durand, 1991a) uses site index equations (Cao and Durand, 1991b) to scale up the individual-tree volume equations of Krinard (1988) and assumes that yields reflect planting site-adapted clones.

Improved genetic material and advances in establishment, tending and protection of poplar has produced significant gains over time. Growth of natural stands of eastern cottonwood (*P. deltoides*), black cottonwood (*P. trichocarpa*) and aspen (*P. tremula*, *P. tremuloides*) and representative yields from industrial plantations (Table 5.7) provide a baseline for comparing growth and yield currently achieved in industrial poplar plantations (see Table 5.6). The highest values reported for operational plantation culture are from hybrid poplar in the western USA under irrigation with mean annual increment of 42 m³ ha⁻¹ (Stanton *et al.*, 2002; J. Eaton, 2005, unpublished report). Clonal trials generally provide estimates of aboveground dry matter, including branches but not leaves, expressed as Mg ha⁻¹ year⁻¹. This indicates biological potential (Table 5.8) but must be interpreted with regard to species, length of growing season, density and rotation length. Industrial plantations in the USA have achieved sustainable yields of from 10 to 20 Mg ha⁻¹ year⁻¹ on an oven-dry basis, and potential yields have been estimated as 18, 27 and 40 Mg ha⁻¹ year⁻¹ for the Midwest, South and Northwest regions, respectively (Volk *et al.*, 2011a, b). Doubling yields will require advanced breeding and appropriate silvicultural techniques.

Harvesting and processing

Harvesting methods vary from fully mechanized in some regions of North America and Europe to fully hand labour in India (R.C. Dhiman, 2005, unpublished report) and combinations such as hand-felling and motorized skidding. In the western USA, mechanized equipment with hydraulic shears or hot saws fell, accumulate

Table 5.7. Growth and yield estimates of natural and managed poplar stands.

Stand type	Stand age	Mean annual volume increment (m ³ ha ⁻¹)	Reference
Natural <i>P. deltoides</i> , southern USA, 1900	10	12.6	Williamson, 1913
Natural <i>P. trichocarpa</i> , north-west USA, best site	20	17.1	Williamson, 1913
Planted <i>P. tremuloides</i>	112	5.5	Smith, 1980
<i>P. tremula</i> forest stand	15	6.4–7.4	Einspahr, 1984 ^a
Italian poplar plantations (clone 'I-214'), good sites, medium spacing, 1960s	80	14.8	Opdahl, 1992
Italian poplar plantations (clone 'I-214', 'Neva', 'Dvina', 'Lena'; 278–320 stems ha ⁻¹)	12	36	Prevosto, 1965
<i>P. trichocarpa</i> plantations, 1970s	7–13	7.9–35	Facciotto <i>et al.</i> , 2003
Intensively managed poplar plantations, USA, 1980s	24	15–20	Smith, 1980; Murray and Harrington, 1983
Irrigated hybrid poplar plantations, USA, 2005	10–20	7–25	Dickmann and Stuart, 1983
	6	42	J. Eaton, 2005 (unpublished)

^aRepresentative yields; from Tullus *et al.*, 2012.

and bunch the trees that are then skidded or forwarded to the roadside for loading or processing (J. Eaton, 2005, unpublished report). One location east of the Cascade Mountains has a central processing site; after whole trees are felled and skidded to the roadside, they are loaded and transported to the processing site. Stems are then scanned and merchandized; sawlogs are sent to a sawmill and the rest of the stem is debarked and ground into chips. Residual material is consolidated and then shipped for composting or bioenergy production. In some other plantations, portable debarking and chipping machines process stems at the roadside (Fig. 5.19) to minimize skidding to a central chipper (J. Eaton, 2005, unpublished report). In south-western British Columbia, Canada, similar methods are used, including mechanical harvesters with directional felling heads (Thomas *et al.*, 2000). In some cases, material is moved with hydraulic excavators equipped with a loading grapple that picks up the wood and swings it in the direction of the road. This method is called 'hoe-chucking'. Logs are transported to the mill for debarking and chipping; some merchandizing of veneer grade logs occurs. Although hoe-chucking is sometimes used in short-rotation plantations, it is expensive and

causes unwanted stem breakage with smaller diameter material.

Felling and delimiting are manual processes in Argentina (S. Cortizo and R. Suarez, 2005, unpublished report), France (A. Berthelot, 2005, unpublished report) and Italy (G. Picchi, 2005, unpublished report; Castro and Zanuttini, 2008). In France, logs are extracted by skidders or forwarders (A. Berthelot, 2005, unpublished report); in Argentina, they are loaded on to trailers by a crane and transported (Fig. 5.20). Debarking is done at the wood yard or mill. In Italy, logs are concentrated using skidders or loaders with a hydraulic boom (G. Picchi, 2005, unpublished report). If the buyer is a large company, each log is scaled in the woods and delimited and bucked (sectioned). Branches, tops and unmerchantable logs are chipped and loaded directly into trucks or piled on-site for later transport. Use of feller-bunchers or processors is increasing in France and Italy; the reduction in cost achieved with mechanization offsets the less efficient selection of assortments (Spinelli *et al.*, 2004). Harvesting in bioenergy coppice plantations uses modified silage harvesters (Spinelli *et al.*, 2009).

Harvesting is a fully manual process in India (R.C. Dhiman, 2005, unpublished

Table 5.8. Yields achieved in experimental plantings.

Location	Clone/ species ^a	Age (years)	Density (stems ha ⁻¹)	Productivity (Mg ha ⁻¹ year ⁻¹)	Reference
West USA	T	2	111,111	13.4–20.9	Heilman <i>et al.</i> , 1972
West USA/ Canada	T	Multiple	6,944–111,111	9.0–11	Smith and DeBell, 1973
West USA	T	8	6,944–111,111	5.8–9.7	Heilman and Peabody, 1981
UK	T	5	40,000	9–10	Cannell and Smith, 1980
West USA	T, TD	4	6,944	5.2–27.8	Heilman and Stettler, 1985
West USA	T, TD	4	6,944	11.3–12.6	Heilman and Stettler, 1990
West USA	T, TD	7	10,000	11–18	DeBell <i>et al.</i> , 1996
West USA	T, TD	4	10,000	14–35	Scarascia-Mugoza <i>et al.</i> , 1997
UK	T, TD	4	2,500–10,000	13.6	Armstrong <i>et al.</i> , 1999
Sweden	T, TD	13	6,944	8.0	Christersson, 2006
West USA	TD	5	5,917–308,642	6.4 (high density) – 30 (low density)	DeBell <i>et al.</i> , 1993
West USA	TD	7	2,500–40,000	10.1–18.2	DeBell <i>et al.</i> , 1996
West Canada	TD	4–13	1,111	9.2–13.6	Zabek and Prescott, 2006
France	TD	2–3	Multiple	0.6–3.5	Auclair and Bouvarel, 1992
Belgium	TD	Multiple	15,625	30	Pontailier <i>et al.</i> , 1999
South USA	D	5–20	1,111	10–11	Switzer <i>et al.</i> , 1976
South USA	D	5	10,000	13.3	Dowell <i>et al.</i> , 2009
India	D	5–8	400	9–14	Lodhiyal <i>et al.</i> , 1995
China	D, DN	4	Multiple	17.4–23.4	Fang <i>et al.</i> , 2007
South USA	DN	5	10,000	7.4	Dowell <i>et al.</i> , 2009
North-east USA	DN	4	17,313–694,444	7.7	Bowersox and Ward, 1976
North-central USA	DN	4	26,875–189,036	11.3–13.8	Ek and Dawson, 1976
East Canada	DN	Multiple	Multiple	5–19	Anderson, 1979
North-central USA	DN	7–12	1,736	4.7–10	Netzer <i>et al.</i> , 2002
North-central USA	DN, B	Multiple	Multiple	4.9–12.8	Strong and Hansen, 1993
North-central USA	B	5	6,944	4.2	Isebrands <i>et al.</i> , 1982
Finland	B	6	5,102–20,408	4.2	Ferm <i>et al.</i> , 1989
UK	B	5	4,444	10.2–16.2	Proe <i>et al.</i> , 2002
Czech Republic	N, MT	4–7	2,268	7.6–9.4	Benetka <i>et al.</i> , 2007
Canada	MN	4	18,146	16.62–18.05	Labrecque and Teodorescu, 2005
Belgium	Multiple	6	4,444–17,778	10.8	Laureysens <i>et al.</i> , 2003
Belgium	Multiple	4	10,000	2.8–11.4	Laureysens <i>et al.</i> , 2004
Belgium	Multiple	Multiple	10,000	9.7	Laureysens <i>et al.</i> , 2005
Belgium	Multiple	3	4,444–17,778	2.8–9.7	Al Afas <i>et al.</i> , 2007
Belgium	Multiple	11	4,444–17,778	13.3–14.6	Al Afas <i>et al.</i> , 2008
Chile	Multiple	6	7,500	4–8	Baettig <i>et al.</i> , 2010
Italy	Multiple	4	5,917	6.5–17.75	Paris <i>et al.</i> , 2011
Italy	D, DN	9	10,000	2.7–14.4	Bergante and Facciotto, 2011

Continued

Table 5.8. Continued.

Location	Clone/ species ^a	Age (years)	Density (stems ha ⁻¹)	Productivity (Mg ha ⁻¹ year ⁻¹)	Reference
Italy	Multiple	5	1,143–1,667	7.9–25.0	Facciotto and Bergante, 2011
Czech Republic	Multiple	6	5,495	8.1–13.9	Trnka <i>et al.</i> , 2008
Europe	Multiple	Multiple	Multiple	10–15	Dillen <i>et al.</i> , 2007
Sweden	Multiple	Multiple	410–2,500	3–10	Christersson, 2010
Germany	Aspens and hybrids	10	4,167–5,556	4.7–12.4	Liesebach <i>et al.</i> , 1999
Germany	HA	23	830–6,900	9.0	Johansson, 1976
Sweden	HA	9	5000	7.9	Karačić <i>et al.</i> , 2003
Estonia	HA	10	1,100–1,300	1.6–3.8	Tullus <i>et al.</i> , 2012

^aSpecies and clone designations as follows: T, *Populus trichocarpa*; D, *Populus deltoides*; N, *Populus nigra*; B, *Populus balsamifera*; M, *Populus maximowiczii*; letters together are hybrids, e.g. TD = *P. trichocarpa* × *P. deltoides*; HA = hybrid aspen, *Populus xwettsteinii*.



Fig. 5.19. A portable debarking and chipping machine is processing stems at the roadside to minimize skidding to a central chipper. Residual material is consolidated and then shipped for composting or bioenergy production. Photo courtesy of BoiseCascade.

report). The base of each tree is excavated slightly and side roots are severed by axe. As the tree falls, the supporting roots are cut. The fallen stem is sectioned into standard-length logs (2.5 m) and delimbed by axe. Logs are

sorted by girth (oversize are >60 cm in the middle of the log, undersize are <50 cm). Debarked wood with a 20–50 cm girth may be sold as pulpwood. Roots, bark and branches are sold for firewood.



Fig. 5.20. Poplar logs are loaded on to trailers by a crane and transported to the mill. Felling, delimiting and bucking are done manually, by chainsaw crews. Photo courtesy of J. Stanturf.

Transportation

Truck transportation is the main transportation mode in industrial operations. Where plantations are located close to a major river system, barges may be used to transport chips or logs to the mill, for example in the USA (J. Eaton, 2005, unpublished report), Serbia and Montenegro (S. Orlovic, B. Klasnja, Z. Galic, L.P. Pajnik and P. Pap, 2005, unpublished). In the Delta region of eastern Argentina, most transport is by barge (Fig. 5.21). Short-distance hauling of chips by farm tractor occurs in Italy (G. Picchi, 2005, unpublished report); long-distance hauling by rail is used somewhat in France, India and China (A. Berthelot, 2005, unpublished report; R.C. Dhiman, 2005, unpublished report; Q.-W. Zhang and J.-H. Li, 2005, unpublished report). Short logs may be transported by truck. Farmers in India may transport wood by bullock carts or, rarely, by bicycle-rickshaw (R.C. Dhiman, 2005, unpublished report).

Storage

Poplar is generally used within a few days of harvesting. The fibre oxidizes and discolours on exposure to the air; the discoloration lessens the brightness advantage for pulping as compared to other species. Higher-quality lumber can be

produced from processing fresh logs because drying tends to cause checking on the log ends. Dry logs also take longer to cut, slowing throughput and raising operating costs. Match factories in India may store poplar logs under sprinklers for 3 months or longer to soften them for easier peeling.

5.3 Willow

Willows (*Salix* spp.) have long been cultivated for wickerwork, stakes, specialty products and fuelwood (FAO, 1980). Industrial cultivation of willows was concentrated in the Danube basin in Europe (Marković, 1986) and the Paraná delta in South America (FAO, 1980). Today, the primary industrial uses are for wicker furniture and baskets, and interest has renewed in willow for biofuels, particularly in northern Europe and North America. Cultivation of willow for the manufacture of cricket bats continues as a specialty product in India. Willows have been planted in many countries for soil conservation, especially stream bank stabilization. Recently in New Zealand, willows have been planted in browsing blocks for livestock fodder and managed as a grazing system, using *S. matsudana* × *S. alba* 'Tangoio' (I. McIvor and



Fig. 5.21. Where plantations are located close to a major river system, barges may be used to transport chips or logs to the mill. Most transport is by barge in the Paraná delta of Argentina; here poplar logs are being loaded on to a barge. Photo courtesy of J. Stanturf.

I. Nicholas, 2005, unpublished report). Many of the techniques used in poplar culture apply to willow, especially coppice methods. Willow, especially the species with shrub growth forms, has very high juvenile growth rates and the fastest growth rates under boreal conditions (Christersson *et al.*, 1993; Labrecque and Teodorescu, 2003) and vigorous sprouting from stumps (Ceulemans *et al.*, 1996). These characteristics have made them attractive for bioenergy and phytoremediation applications (Kuzovkina and Quigley, 2005) and in combination (Mirck *et al.*, 2005; Ruttens *et al.*, 2011).

5.3.1 Stand establishment

Planting material

Industrial plantings of willow are predominantly species of shrub willows. Clones of *S. viminalis*, *S. schwerinii* and *S. gmelinii* and hybrids predominate in northern Europe (Larsson, 1998). A nascent willow bioenergy industry in the northern USA relies on the

native *S. eriocephala* and the widespread *S. purpurea* that was introduced by European settlers to New York State for basket making in the 1700s (Smart *et al.*, 2005). European clones are not planted in the USA because they are very susceptible to the potato leafhopper (*Empoasca fabae* Harris), a pest of lucerne. Clones with *S. viminalis* pedigree are especially susceptible; resistance to this pest can be bred by crossing with Asian clones (Keoleian and Volk, 2005). An active breeding programme incorporates many clones of these species as well as Eurasian species (Smart and Cameron, 2008). Efforts to revive the Chilean basket willow sector rely on the naturalized *S. viminalis* (Abalos Romero, 2005).

Commercial willow bioenergy plantations in Europe rely on material produced by specialist growers in nursery beds and supplied as 1-year-old whips (rods) for mechanical planting. Because these improved clones are protected by European plant breeders' rights, producing material for self-use or sale is illegal (DEFRA, 2002), except that filling gaps with material cut from an existing crop is allowed (Caslin *et al.*, 2010). Sweden is the leader in

willow bioenergy cultivation in Europe (Wright, 2006) and many of the commercially available clones come from a Swedish breeding programme,² including 'Tora', 'Sven', 'Torhild', 'Tordis', 'Olof', 'Gudrun' and 'Inger' (Table 5.9). Older Swedish clones such as 'Jorr' and 'Joruun' are less productive and have poorer disease resistance (Caslin *et al.*, 2010). A European breeding programme based at Rothamsted Research in the UK has released commercial clones 'Nimrod', 'Resolution', 'Discovery', 'Endeavour', 'Beagle' and 'Terra Nova'. The Swedish programme has focused on *S. viminalis* and its hybrids with *S. schwerinii* (Table 5.9), but the European programme encompasses more species (Caslin *et al.*, 2010).

In northern Europe, willows are planted as cuttings or whips (rods), depending on the type of machinery available. Cuttings are 18–20 cm long and cut fresh from whips procured from a licensed producer; planting whips are cut and trimmed willow stems 1.5–3 m long. Whips are harvested from 1-year-old material while dormant and either planted immediately or stored at -2° to -4°C (DEFRA, 2002). In the USA, unrooted dormant stem cuttings 20–25 cm long or whips greater than 1.3–2 m long (Abrahamson *et al.*, 2002) are used, with size limitations dictated by the planting machinery used. In New Zealand where plantings may be in small areas on farms, 25 cm unrooted dormant cuttings or 1 m stakes are used (I. McIvor and I. Nicholas, 2005, unpublished report).

Site requirements

Willow plantations grow mostly on marginal agricultural soils and are often integrated into farms. Site requirements for willows are similar to those for poplars (Table 5.10), although native willows are adapted to wetter sites than native poplars, growth on poorly drained soils may be non-economic (Abrahamson *et al.*, 2002). Nevertheless, when plantings are for both wastewater treatment and other environmental purposes in combination with bioenergy production, site requirements may be less restrictive. Clay soils with good aeration may be suitable, although establishment may be slower and early growth lower, but once established they may be highly productive (Abrahamson *et al.*, 2002; DEFRA, 2002). Traffickability may be a concern on clay soils, especially if the site is prone to flooding in winter. Growth on organic soils in Sweden has been acceptable, but difficulty in controlling weeds and frost-prone landscape positions render them less suited for commercial plantations (Lantmännen Agroenergi, no date).

Site preparation

Effective weed control is just as critical for willow plantings as it is for poplars. If good weed control until canopy closure (1–2 years) is absent, failure is a likely prospect (Abrahamson *et al.*, 2002). Both mechanical and chemical treatments are used, beginning at the end of the growing season prior to planting. Mowing

Table 5.9. Commercially available *Salix* clones in Northern Europe in 2006^a (<http://pohjonen.org/veli/vpapps/2006-agrob-salix-clones.pdf>).

Willow clone name	Parentage
'Doris'	<i>S. dasyclados</i>
'Gudrun'	<i>S. dasyclados</i>
'Inger'	<i>S. triandra</i> × <i>S. viminalis</i>
'Jorr'	<i>S. viminalis</i> × <i>S. viminalis</i>
'Karin'	(<i>S. schwerinii</i> × <i>S. viminalis</i>) × <i>S. viminalis</i> × <i>S. burjatica</i>
'Olof'	(<i>S. viminalis</i> × (<i>S. schwerinii</i> × <i>S. viminalis</i>))
'Tora'	<i>S. viminalis</i> × <i>S. schwerinii</i>
'Sherwood'	(<i>S. viminalis</i> × <i>S. eriocephala</i>) × (<i>S. schwerinii</i> × <i>S. viminalis</i>)
'Sven'	<i>S. viminalis</i> × (<i>S. schwerinii</i> × <i>S. viminalis</i>)
'Tordis'	(<i>S. schwerinii</i> × <i>S. viminalis</i>) × <i>S. viminalis</i>
'Torhild'	(<i>S. schwerinii</i> × <i>S. viminalis</i>) × <i>S. viminalis</i>

^aSalixEnergi Europa (<http://www.salixenergi.se/>) is the current owner of rights/royalty for willow cuttings from the Swedish programme in the whole of Europe.

Table 5.10. Soil characteristics suitable for willow bioenergy crops (adapted from Abrahamson *et al.*, 2002).

Soil characteristic	Suitable	Unsuitable
Texture	Loams, sandy loams, loamy sands, clay loams and silt loams; clay soils with adequate aeration ^a	Coarse sand, heavy clay soils without adequate aeration
Structure	Well developed to single grain	Massive or structureless
Drainage	Imperfectly to moderately well drained	Excessively well or very poorly drained
pH	5.5–8.0	More acid than 5.5 or more basic than 8.0
Depth (of rooting)	Greater than or equal to 46 cm	Less than 46 cm

^aEstablishment may be more difficult and early growth slower on these soils.

to remove hay or brush, including baling, and removal of excessive vegetation may be necessary prior to herbicide application (Abrahamson *et al.*, 2002). Depending on the weed complex, one or two applications of a glyphosate-based herbicide are needed beginning in late summer or early autumn (DEFRA, 2002). To control perennial broadleaved weeds, a tank mix with 2,4-D and glyphosate may be necessary (Abrahamson *et al.*, 2002). Aggressive weed control must therefore start with controlling perennial grasses and broadleaved weeds in the site preparation phase; ignoring this important aspect leads to increased costs and unpredictable results once the plantation is established.

Subsoiling to a depth of 40 cm followed by ploughing to a depth of 25 cm is the next step (Abrahamson *et al.*, 2002; DEFRA, 2002), followed by cross-disking (Abrahamson *et al.*, 2002). Soils prone to erosion can be protected by sowing an annual cover crop such as winter rye (*Secale cereale* L.) that must be killed prior to planting (Abrahamson *et al.*, 2002). In the USA, cultivation (cultimulching) just before planting is recommended (Abrahamson *et al.*, 2002). In the UK and Ireland, suitable sites can be ploughed and power-harrowed in mid-March, 6 weeks before planting. A second or third application of glyphosate kills any germinated weeds. This approach is not practical on heavy clay soils, and these sites should be power-harrowed just before planting (DEFRA, 2002; Caslin *et al.*, 2010). Protruding rocks (more than 5 cm) should be removed from the site to avoid interference with mechanical planters and damage to expensive saw blades on harvesting equipment.

Planting

Bioenergy plantings generally follow the method developed in Sweden that uses a double or twin-row system. Planting density in Sweden has decreased from 20,000 cuttings ha⁻¹ in the early 1990s to around 12,000 stems ha⁻¹ today. Spacing between individual rows in each set of double rows is 0.75 m; the sets of double rows are 1.5 m apart. The in-row plant spacing is 0.75 m. Commercial plantings in Northern Ireland and the USA retain the earlier practice of planting 18,000 stems ha⁻¹ to attain a final density of 15,000 stems ha⁻¹; row spacing remains the same, but spacing between plants is reduced to 0.6 m (Abrahamson *et al.*, 2002; Caslin *et al.*, 2010). The lower planting density produces thicker stems and thus larger material when chipped (DEFRA, 2002). Biomass yield is highly correlated with planting density; studies have shown that yield plateaus above 20,000 or 25,000 stems ha⁻¹ (depending on the clone) and there is a sharp decline below 10,000 stems ha⁻¹ (Bergkvist and Ledin, 1998).

These row spacings accommodate the use of step planters (Fig. 5.22) such as the Swedish machine designed by Salix Maskiner (Caslin *et al.*, 2010). Step planters plant two double rows in a single pass and automatically cut whips 1.5–2.5 m in length into cuttings 18–20 cm long. Whips are fed into the machine manually and guided by two belts. In the planting mechanism, the whip is cut to the desired length and the cutting is inserted vertically into a slit in the soil made by a coulter; the machine firms the soil around the cuttings (Abrahamson *et al.*, 2002; DEFRA, 2002; Caslin *et al.*, 2010). Another Swedish machine,



Fig. 5.22. The double-row planting system accommodates use of step planters that can plant two double rows in a single pass. Whips are fed into the machine manually and cut automatically by the planting mechanism into cuttings 18–20 cm long, which are inserted vertically into a slit in the soil made by a coulter; the machine firms the soil around the cuttings. Photo courtesy of N. Thevathasan.

the Fröebbesta planter, uses 25-cm-long cuttings that are fed into a planting tube manually and driven by hydraulic-powered rubber wheels into an open slit made by the machine. The slit is closed around the cutting by two packing wheels (Abrahamson *et al.*, 2002). The smaller, more manoeuvrable Fröebbesta planter can be used for planting small areas or riparian buffers (Abrahamson *et al.*, 2002) and modified cabbage planters have been used in the UK for small areas (DEFRA, 2002). Application of a pre-emergent herbicide immediately after planting is recommended (Abrahamson *et al.*, 2002; DEFRA, 2002; Caslin *et al.*, 2010). Oxyfluorfen and simazine have been used, but others are being tested (Abrahamson *et al.*, 2002). In Canada, the herbicide, flumioxazin, was recently approved for use as a pre-emergent in willow crops.

Clonal deployment and risk management

Similar to poplars, willows are susceptible to rust pathogens and only resistant clones should be planted. In the UK, where the moist maritime climate favours the pathogen, planting at least six clones from different breeding programmes is recommended. Planting should be in intimate mixtures (DEFRA, 2002; Tubby and Armstrong, 2002; Caslin *et al.*, 2010; Wickham *et al.*, 2010). This is accomplished using the step planter by planting short runs (10–15 cuttings) of a single clone, followed by a short run of another, randomly selected clone out of the six or more (Caslin *et al.*, 2010). In the north-eastern USA where rust has not yet become a major problem, planting clones in small blocks of a few double rows to 1 ha in size has been recommended (Abrahamson *et al.*, 2002).

5.3.2 Stand tending

Competition control

Typically, 90% survival is obtained as long as weed control is effective (Abrahamson *et al.*, 2002). If herbicide treatments are not totally effective, some mechanical cultivation may be needed (Abrahamson *et al.*, 2002; Lantmännen Agroenergi, no date), but may not be effective under moister climatic conditions (Caslin *et al.*, 2010). Grasses may be controlled with suitable post-emergent herbicides without harming the willow (Abrahamson *et al.*, 2002). Some broad-leaved weeds (such as Canada or creeping thistle – *Cirsium arvense*) can be controlled effectively with minimal or no injury to the willow with the post-emergent herbicide, clopyralid. Growth during the first season will vary by clone, rainfall and site conditions, but willow should be at least 1 m tall at the end of the season and may reach 4 m, with 1–3 sprouts per cutting (Abrahamson *et al.*, 2002; DEFRA, 2002).

Cutback

During the first dormant season following planting, the willow should be cut back to within 3–10 cm of ground level to encourage sprouting (Abrahamson *et al.*, 2002; DEFRA, 2002; Caslin *et al.*, 2010). Cutting needs to be accomplished before bud break using a modified, reciprocating-type mower that gives a clean cut, without tearing or pulling the cutting from the soil (Abrahamson *et al.*, 2002; DEFRA, 2002; Caslin *et al.*, 2010). Multiple stems will emerge, up to 5–20, depending on the clone. Canopy closure should be achieved within a few months of active growth. Under some conditions, a contact herbicide may be needed to control weeds that have established during the previous year (DEFRA, 2002).

Nutrition

Willow has higher demand for nutrients than many tree or shrub species, yet lower than most agricultural crops. On most sites where willow plantations will be established, sufficient nutrients are available that no fertilization is required during the first establishment year. Indeed, fertilization may simply stimulate competing vegetation and hinder effective weed control

(Abrahamson *et al.*, 2002; DEFRA, 2002; Caslin *et al.*, 2010). Most published work on willow nutrition is based on early clones and may underestimate nutrient requirements of the higher-yielding clones now in commercial use (Caslin *et al.*, 2010). Estimates of crop requirements based on nutrient removals in harvested material are in the range of 150–400 kg N ha⁻¹, 180–250 kg P ha⁻¹ and 24–48 kg K ha⁻¹ over a 3-year rotation (Caslin *et al.*, 2010).

Nitrogen fertilization has been shown to increase yields significantly under experimental conditions (Adegbidi *et al.*, 2001; Mola-Yudego and Aronsson, 2008). In Sweden, sewage biosolids applications are common in commercial willow plantations, but it is doubtful that nitrogen requirements are being met (Aronsson *et al.*, 2002; Lantmännen Agroenergi, no date). One complicating factor is the difficulty of applying fertilizer beyond the first year without damaging the crop (Abrahamson *et al.*, 2002). Sewage biosolids applied in liquid form through a dribble bar can be applied until the coppice reaches 2.5 m in height, or possibly in the second year of a rotation (DEFRA, 2002). Slow-release fertilizers (mineral as well as composted sewage biosolids) applied after cutback to meet total rotational demand may be a solution (DEFRA, 2002). Fertilizer recommendations for the UK are based on the site nutrients available in the soil (Table 5.11).

Protection

In northern Europe, *Melampsora* rust is the most important disease of willow coppice systems (DEFRA, 2002; Toome *et al.*, 2006; Caslin *et al.*, 2010; Chapter 8, this volume). Climatic conditions favour rapid infection that leads to premature defoliation and entry of secondary pathogens through unprotected leaf scars (Caslin *et al.*, 2010). In addition to lowering yields directly from the defoliation, the secondary infections from dieback organisms (*Fusarium* spp. or *Glomerella* spp.) can cause sufficient damage to shoots and stools that mortality ensues. Control with fungicides is possible, but in some countries may be deemed economically unfeasible or environmentally undesirable (Caslin *et al.*, 2010). In Canada, the fungicide, tebuconazole, was recently approved for *Melampsora* rust control in willow crops; use of this fungicide is primarily foreseen for stoolbed production.

Table 5.11. Fertilization recommendations (kg ha^{-1}) for short-rotation willow in the UK; soil index refers to amount of site nutrient availability. Soil index = 1 is low site nutrients and responsive to fertilization (adapted from Wickham *et al.*, 2010.)

Soil index	Nitrogen (N)	Phosphorus (P)	Potassium (K)
1	130	34	155
2	100	24	135
3	75	0	120
4	40	0	0

Although little to no rust has been reported, the expectation is that *Melampsora* rust will eventually gain a foothold in expanding willow crops. Where rust is well entrenched and resistant clones are available, they should be deployed. Since new rust races will appear over time, even clones considered resistant will fall victim and need to be replaced with new clones.

Willow beetles (Chrysomelids) are the major economic pest problem in northern European plantations (Caslin *et al.*, 2010; Chapter 9, this volume). Both adults and larvae feed on the leaves and can reduce yield by as much as 40% (DEFRA, 2002). Even though damage may appear visually to be severe, defoliation experiments have shown that effect on yield is minimal if <30% of the leaf surfaces are damaged (Caslin *et al.*, 2010). There can be two generations per year but there is significant year-to-year variation in populations. The adults overwinter in rotting wood and under the bark of trees in forest areas around the coppice. Although it is not feasible to treat established plantations, some control is possible by spraying insecticides around the border of a plantation when the beetles are re-colonizing the coppice in the spring. Because some clones are more resistant to beetle damage than others, planting mixtures has been effective in limiting economic effects (DEFRA, 2002; Caslin *et al.*, 2010).

5.3.3 Production

Harvest cycle

Coppice growth is rapid after cutback, particularly in the third and fourth growing season (2 and 3 years after coppice). Thus, a 4-year harvest cycle is common in commercial plantations. Harvest may be delayed, however, if initial

establishment is poor or growth is slower than average due to the high cost of the harvest operation (Abrahamson *et al.*, 2002; DEFRA, 2002; Caslin *et al.*, 2010). Swedish practice is to stage the initial harvest after growth has accumulated to 25 Mg ha^{-1} (oven dry) or until the largest shoots exceed 6 cm in basal diameter. This usually requires 3–4 years (Lantmännen Agroenergi, no date). In Chilean basket willow plantations, rotations may be 9–11 years with annual harvesting (Abalos Romero, 2005).

One advantage of coppice systems is that several crops can be harvested from the same root system, thereby avoiding several repeats of site preparation and establishment costs. Yields will plateau after the second harvest cycle but can be maintained for up to 7–10 harvest cycles (Abrahamson *et al.*, 2002; Caslin *et al.*, 2010). Similarly, in basket willow plantations in Chile, plantings are expected to produce for 10–12 years (Abalos Romero, 2005). On the other hand, improved planting material with greater productivity and disease resistance may justify more frequent replanting (Wickham *et al.*, 2010).

Growth and yield

Yield is usually given on the basis of oven dry, aboveground matter to standardize comparisons. Harvesting occurs in the dormant season after leaf fall, and the harvested material accounts for about 60% of total annual net productivity (Caslin *et al.*, 2010). Average annual growth of $10\text{--}20 \text{ Mg ha}^{-1} \text{ year}^{-1}$ has been reported from experiments with even higher growth rates ($30 \text{ Mg ha}^{-1} \text{ year}^{-1}$) recorded from irrigated and fertilized research plots (Labrecque and Teodorescu, 2003, 2005; Larsson *et al.*, 2003; Szczukowski *et al.*, 2005; Arevalo *et al.*, 2007; Stolarski *et al.*, 2007; Aylott *et al.*, 2008; Cerrillo *et al.*, 2008; Mola-Yudego and

Aronsson, 2008; Fillion *et al.*, 2009; Mola-Yudego, 2010; Tullus *et al.*, 2012). Commercial yields of 10–12 Mg ha⁻¹ year⁻¹ are probably a good benchmark for current levels of production (Mola-Yudego, 2010; Volk *et al.*, 2011a), and advances in breeding and optimization of management systems, including matching clones to sites, should increase commercial yields closer to what is attainable in experimental plantings. For example, in New York State in the USA, second harvest cycle yields of experimental trials increased by 18–62% compared to the first harvest cycle yields. More recent trials with advanced material are yielding 20–40% more than unimproved standard clones (Volk *et al.*, 2011a).

Further analysis of yield data from four consecutive harvest cycles from the US trial, combined with yield data from the first harvest cycle from a network of trials across the USA and Canada, provided a comparison of old versus new willow clones (Volk *et al.*, 2011b). The overall yield increase from the first to the second harvest cycle was 23% for four commercial clones. By the fourth harvest cycle, these same clones showed an overall increase of 30.8% over the first harvest cycle with a yield of 23.4–32.4 Mg ha⁻¹ year⁻¹ (oven dry). In the network's first harvest cycle trials, the top three new clones had a 13.9% greater yield (11.5 Mg ha⁻¹ year⁻¹ oven dry) than the older three reference clones. Increases in yield are not all due to improved genotypes. Some of these increases can be attributed to improved crop management practices, especially weed control and site factors. The impact on yield from factors such as disease and insect pressure, winter dieback, predation by various animals, for example deer, rabbits, etc., are still poorly understood and require better quantification.

Harvesting and processing

Harvesting methods vary according to available machinery and end-user requirements. Willow may be harvested as whips (rods), billets, chips or round bales. Whips up to 8 m long are produced loose and must be collected; they are often bundled if transported some distance. In Chile, whips (called switches) are sorted by size and colour and bundled; bundles may weigh as much as 50 kg (Abalos Romero, 2005). Bundler harvesters in bioenergy plantations cut whole

stems, bind them and re-cut them into 2.5-m-long bundles (DEFRA, 2002).

Direct-chip harvesting is preferred for bioenergy production because chip quality is better if fresh material is chipped, as opposed to dried rods or bundles (DEFRA, 2002). Silage harvesters with specially designed cutting heads cut, chip and blow material into wagons in one continuous operation (Fig. 5.23). Most direct-chip harvesters have been designed to cut a double row in a single pass (Caslin *et al.*, 2010), but at least one machine cuts a single row and can be used to cut across rows, if necessary (Abrahamson *et al.*, 2002). While direct-chip harvesters are the most efficient harvesting system, drying the fresh chips poses some difficulty and chip quality is degraded unless moisture is removed soon after harvest (DEFRA, 2002; Caslin *et al.*, 2010). Chips are optimally 5 × 5 × 5 cm in size and moisture content must be lowered from 45–60% at harvest to below 30% (DEFRA, 2002). Billets are cut stems 5–10 cm long; they are produced by harvesters that cut the stems whole, re-cut into billets and blow the material into accompanying trailers (DEFRA, 2002; Caslin *et al.*, 2010). They are modified from sugarcane harvesters and the larger the size of the billets as compared to chips, the more air space there is between the pieces, which improves circulation and promotes natural drying. As with whip harvesters, chipping dry material reduces quality.

A relatively new development is to cut and bale willow biomass into round bales (Fig. 5.24). Willow shoots are cut and shredded into smaller pieces and baled in one operation by a modified agricultural hay baler. The main advantages of this system are lower capital costs and greater flexibility. The baler method harvests biomass as a stand-alone operation without the immediate need for transport capability. Storing bales until they are needed for processing increases flexibility in scheduling harvests. Bales can be stored either on site or at the processing plant; standard farm equipment can handle the bales.

Drying and storage are the weak links in the willow bioenergy supply chain (Caslin *et al.*, 2010; Wickham *et al.*, 2010), except when produced as round bales. Chips require immediate use or drying to avoid decomposition and degradation of quality, i.e. caloric value. Some agricultural facilities such as ventilated grain floors



Fig. 5.23. Silage or maize harvesters with specially designed cutting heads cut, chip and blow willow material into wagons in one continuous operation. Direct-chip harvesting is preferred for bioenergy production because chip quality is better if fresh material is chipped, as opposed to dried whips or bundles. Shown here is a Claas Jaguar direct-chip harvester. Photo courtesy of Claas Group.

with heated air can reduce moisture levels in fresh chips to acceptable moisture content, and low-cost methods with forced ventilation drying have been demonstrated (Caslin *et al.*, 2010). Whips and billets can be stored for several months under ambient air conditions and chipped at lower moisture contents than fresh stems (Wickham *et al.*, 2010). Round bales dry down naturally in the field or at the processing plant. When stored on site, the benefits are lower transport weights and thus decreased transportation costs

Processing whips for basket willow production can be done by the grower or an intermediary (Abalos Romero, 2005). Stems are harvested beginning after one growing season, although initial yield is low, and commercial production begins after two growing seasons. Cut shoots are referred to as switches and range from 0.6 m to 6 m in length; diameters (at the thick end) range from 0.4 to 3 cm. Bark stripping, drying and sorting are the postharvest treatments. Traditional bark stripping consists of standing

the switches in water until shoots emerge in the spring and then stripping the bark off by hand, with knives. Large-scale processing consists of boiling the switches and then stripping them with machines (Fig. 5.25). After air-drying, switches are sorted and bundled according to length, diameter and defects (Abalos Romero, 2005).

At some point, a final harvest will be made and it will be necessary to prepare the site for replanting with willow or another crop. The older the plantation at final harvest, the larger the root system and the more difficult it will be to prepare the site. In the UK and Ireland, willow plantations are expected to be followed by a return to grass or row crops (DEFRA, 2002; Caslin *et al.*, 2010). After the final winter harvest, the stools are allowed to re-sprout. After the sprouts have reached 30–50 cm in height, they are sprayed with a translocated herbicide such as glyphosate to kill the stool. After sufficient time for the herbicide to be absorbed and translocated (usually a minimum of 2 weeks), the stool and sprouts are mulched and incorporated into



Fig. 5.24. Willow bale produced by the 'Willow Harvester' (a), a prototype bale harvester developed through Université Laval, Agriculture and AgriFood Canada (AAFC) and Natural Resources Canada. These bales are typically 1.20 m in width. The 'Willow Harvester' is a prototype; other balers have been produced commercially and several have been used to bundle biomass from harvest residue in the southern pine region of the USA. 'Biobaler' harvesting 3-year-old coppice willow at Conestota, New York (b). Photos courtesy of C. van Oosten (a) and J. Richardson (b).

the surface layer of the soil. The majority of the root system is left in place to decompose and soil structure is not disrupted. Grass is sown into the soil and grown for a year or two before the field is

placed back into production (DEFRA, 2002; Caslin *et al.*, 2010). In Sweden, the stools remain in place until the spring after the final harvest. The actively growing sprouts are sprayed with



Fig. 5.25. Large-scale processing of basket willow; switches are stripped using specialized machines. Fresh material has been boiled, giving it uniform colour. The next stage is air-drying. Photo courtesy of J. Stanturf.

herbicide such as glyphosate. After the sprouts die, the land is worked with a heavy disk that breaks up the stools and severs the large roots without raking them to the surface. The stand can be replanted to another willow rotation or converted back to agriculture (Lantmännen Agroenergi, no date).

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Notes

¹ PSB stands for 'plug Styroblock®'; most container stock in Canada uses the Styroblock® tray system (van Oosten, 2006).

² SalixEnergi Europa (<http://www.salixenergi.se/>) is the current owner of rights/royalty for willow cuttings from the Swedish programme in the whole of Europe.

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