Growing Hybrid Poplar for Bioenergy in the PNW

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CHAPTER 1 | POPLARS FOR BIOENERGY

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Introduction

This manual is intended for growers who are interested in the production of **hybrid** poplar trees (genus *Populus*) on short **coppice rotations** as **feedstock** for **biorefineries**. Although there are other methods for growing and harvesting hybrid poplar trees for other product markets, this manual is intended to specifically describe the feedstock production portion of the supply chain for biofuel and bio-based product industries. When grown as a **coppice**, hybrid poplar trees produce a consistent and readily available **biomass** feedstock for bio-based industries. Using the methods described in this manual, poplar growers can produce a reliable, high-quality, renewable feedstock with uniform chemical properties for ease of conversion that is free of dirt and debris and that can be delivered to the biorefinery at a consistent price.

Hybrid Poplar as a Biorefinery Feedstock

Hybrid poplar grown on three-year rotations is a viable feedstock for biofuel and biochemical industries in the Pacific Northwest (PNW). Hybrid poplar trees are adapted to produce high biomass **yields** across the diverse regions of the PNW (figure 1.1). At harvest, poplar wood chips can be converted into a variety of renewable fuels and chemicals, with poplar becoming a dependable source of biomass feedstock for biorefineries (figure 1.2). Biorefineries will likely rely on contracts with local poplar growers to produce a significant percentage of the facility's feedstock demand (Hart et al. 2015).

As a **bioenergy** feedstock, hybrid poplar trees are established and intensely managed as a **short-rotation woody crop** (SRWC).

Figure 1.1. Coppiced poplar trees with two years of biomass growth after the initial harvest at a demonstration poplar bioenergy farm in Clarksburg, California. Photo: R. Shuren.

Figure 1.2. When grown as a bioenergy crop, poplar trees are cut and chipped in the field. The chips are then converted to biofuels and bio-based chemicals. Photo: N. Haider.

Across the United States, SRWCs are identified as a key part of the national effort to replace up to 30% of U.S. petroleum consumption with biofuels by 2030 (U.S. Department of Energy 2011). SRWCs are fast-growing species that include *Populus* (poplar), *Salix* (willow), and *Eucalyptus* species that are harvested after growing periods of up to 15 years. In addition to biomass for bioenergy production, SRWCs are grown for conventional wood products and to provide environmental services, such as shelterbelts that offer protection from wind, buffer zones to protect riparian areas from erosion and nutrient runoff, and to treat wastewater effluent (figure 1.3) (see Chapter 16).

A poplar-based biofuel industry in the PNW could utilize **marginal farmlands** for growing dedicated energy crops for locally produced, renewable, bio-based chemicals and transportation fuels. This local- and renewable-material based industry could reduce net greenhouse gas emissions, reduce dependence on petroleum products, and spur economic development opportunities in rural communities (U.S. Environmental Protection Agency 2018).

Production Overview

Poplar grown for bioenergy is managed as a perennial row crop. From one planting growers can harvest a poplar crop six to seven times before it is necessary to remove the trees and plant again (figure 1.4).

Planting—After preparing the field for the poplar crop, growers plant poplar trees using unrooted **cuttings** in the early spring.

Establishment cycle—During the initial two years of growth, the poplar's root system develops, creating a strong foundation for future growth. Yields from the establishment cycle are expected to be less than subsequent cycles since the plant is expending energy on establishing its root system.

Initial coppice harvest—The initial harvest occurs in the late fall after the second growing season (i.e., approximately 1.5 years from initial spring planting). A harvest involves cutting the poplar near the ground and allowing it to resprout (coppice) from the cut stump for subsequent rotations (figure 1.5).

Coppice regeneration—Utilizing the existing root structure, biomass regrowth after the initial harvest will be significantly greater than the initial establishment cycle. Growers can expect yields of five to ten **bone dry tons** (BDT) per acre per year after the initial coppice harvest depending on the productivity of the site. Sites with exceptional productivity might be harvested on two-year rotations, while less productive sites might have longer rotations.

Subsequent harvests—To optimize biomass production for consistent deliveries to the biorefinery, the second harvest will typically occur three years after the first harvest and will continue on three-year harvest rotations for around 20 years.

Figure 1.3. In Chehalis, Washington, poplar trees are irrigated with treated wastewater effluent rather than discharging the effluent into the Chehalis River. This practice is done to protect the water quality of the river. Temperature is the primary water quality concern. Photo: N. Haider.

Replant/restoration—It is expected that after six or seven harvests biomass yields will decrease, necessitating new establishment. Continuing research may also produce new varieties of poplar that have improved traits of economic importance and growers will want to replace the initial poplar crop with new **hybrid varieties**. Growers that wish to cease poplar production will need to incorporate the stumps into the soil and restore the land.

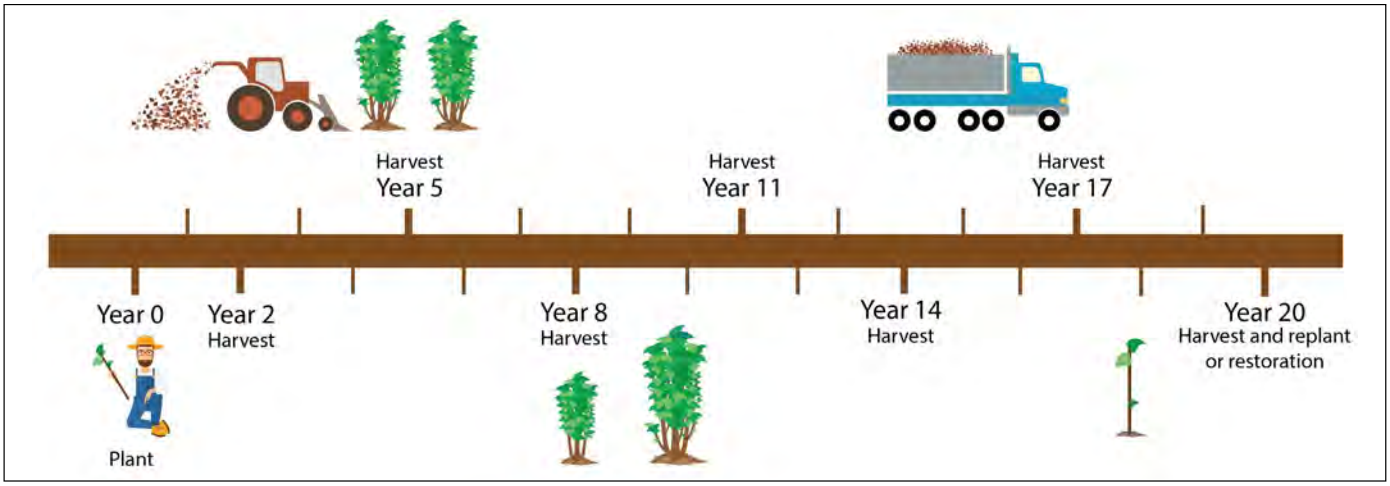

Figure 1.4. As a bioenergy feedstock, poplar trees are grown on coppice rotations and are harvested every three years.

Short-Rotation Coppice Culture

Coppicing is a **silvicultural** method in which certain tree species, after being cut, resprout from the **stool** and regrow (figure 1.5). Farmers have coppiced poplar for millennia to produce firewood, fence posts, and other small-diameter wood products (Dickmann et al. 2001). When growing poplar as a bioenergy feedstock, coppice management is advantageous because of the tree's ability to rapidly regrow from an already-established root system. It does not require replanting after each harvest, and the tree's structure allows for a **single-pass harvest system** (figure 1.6). Coppicing produces multiple small-diameter stems rather than a single trunk. Harvesting is done using a **forage harvester** with a **biomass head** that cuts and chips the poplars in a single pass (figure 1.6).

Figure 1.5. Coppice management describes a cultivation technique where trees are cut near the ground to encourage multiple stems of new growth to emerge from the cut stump for subsequent rotations. Photo: K. Zobrist.

Figure 1.6. Poplar grown as a bioenergy crop is harvested using a single-pass system that cuts and chips the trees as the harvester moves down the crop row. Photo: N. Haider.

A Brief History of Short-Rotation Poplar in the PNW

In the PNW, hybrid poplar trees were first commercialized by the pulp and paper industry in the 1970s and '80s. By the late 1990s, numerous pulp and paper companies had established hybrid poplar plantations throughout the PNW, covering over 65,500 acres (Stanton 2014). Paper companies chose to invest in poplar plantations to secure a new fiber supply. During this time, forest harvest operations were curtailed on federal lands in response to diminishing northern spotted owl populations. The forest products industry forecasted a shortage of red alder, a traditional hardwood fiber source, prompting investment in commercial poplar plantations (Berguson et al. 2010).

By the time poplar plantations were ready to harvest, it was evident that the anticipated shortage of tradition fiber sources had not materialized. Pulp and paper facilities were closing down across the region, reducing demand for wood fiber. As a result, paper companies began to shed their poplar holdings (Stanton 2014). In addition, some poplar growers lost many trees to wind and ice storms and were unwilling to replant (Velush 2005). Across the PNW, poplar plantations were slowly converted back to traditional farmland, often with considerable effort and expense (Keary 2013).

Figure 1.7. Poplar grown for wood markets are harvested with traditional forestry harvesting equipment. Photo: WSU Hybrid Poplar Research Program.

Some poplar plantations remained in production, such as a 42,000-acre tree farm managed by GreenWood Resources near Boardman, Oregon. These managed tree farms were focused on solid wood production (lumber and veneer) as well as chip markets. Unlike the poplar system described in this manual for biorefinery feedstock, these poplar systems have rotation lengths of eight or more years and use conventional forestry harvesting techniques (figure 1.7).

From Tree to Fuel

Bioenergy is energy derived from biomass—organic material that can include the leaves, roots, branches, and stems of trees and plants, as well as animal waste. In addition to heat and electricity, bioenergy can include biofuels for use in motor vehicles, ships, and aircraft. Currently, biofuels such as **ethanol** and **biodiesel** are blended with gasoline or diesel fuel to increase **octane** and reduce vehicle emissions. Almost all gasoline and diesel sold in the United States is blended with 10% ethanol (E10) and 5% biodiesel (B5), respectively. While higher blends of the fuel are available, only specialized engines can use these blends, and higher-blend fuel availability is limited.

Biorefining processes convert biomass, such as poplar trees, to ethanol. This product is indistinguishable from the mostly Midwest-produced corn ethanol currently blended with gasoline in North America. Known as **cellulosic ethanol**, this biofuel will likely be one of the first products commercially produced from poplars grown for bioenergy in the PNW (Budsberg et al. 2015).

Cellulosic ethanol can also be further processed to create **drop-in biofuels**, which are hydrocarbon fuels having the same chemical structure and performance as petroleum-derived gasoline, diesel, and jet fuel. As a drop-in fuel, blending is not necessary for use in existing engines. Drop-in fuels can also be stored and transported in existing fuel infrastructure that is used for petroleum-derived products. Drop-in biofuels are still being researched and developed, but potential exists for these biofuels to significantly reduce greenhouse gas emissions compared to fuel derived from petroleum (Advanced Hardwood Biofuels Northwest 2014).

During the process of converting poplar wood chips into liquid fuels, the biorefinery can also produce intermediate chemicals (table 1.1). These chemicals can replace the petroleum-based products that are currently used to make many everyday products such as plastics, paints, and textiles. Bio-based chemicals can be sold by biorefineries as profitable commodities.

Advanced Hardwood Biofuels Northwest

Advanced Hardwood Biofuels Northwest (AHB) is one of seven biofuel research projects funded by the United States Department of Agriculture (USDA) National Institute of Food and Agriculture (NIFA) to explore the development of sustainable bioenergy systems based on locally produced feedstocks. AHB is working to establish a framework for a poplar-based biofuel and bioproduct industry in the PNW using hybrid poplar as the primary feedstock. Much of the poplar management strategies discussed in this manual are based on the research conducted in conjunction with the AHB project. Led by the University of Washington, AHB also includes researchers at Washington State University, the University of Idaho, the University of California, Davis, Oregon State University, the Rocky Mountain Wildlife Institute, GreenWood Resources, Inc., and ZeaChem.

A major initiative of AHB is the establishment of four hybrid poplar demonstration sites located across the PNW (figure 1.8). These sites, located in the Idaho Panhandle, Oregon's Willamette Valley, the Sacramento River Delta in northern California, and the north Puget Sound region of Washington, highlight hybrid poplar production techniques for bioenergy crops. AHB's demonstration sites feature commercial production trials as well as research plots investigating alternative spacing, alder intercropping, and new hybrid varieties, among other studies. More information on AHB can be found on the project website at https://hardwoodbiofuels.org.

Table 1.1. One ton of poplar chips can yield 80 gallons (302 L) of bio-jet fuel.

One ton (2,000 pounds [907 kg]) of poplar feedstock will yield[1]:		
Conversion Step	Product	Yield
Pretreatment and hydrolysis	Sugars	1,270 lb (576 kg)
Fermentation	Acetic acid	1,170 lb (530 kg)
Reactive distillation	Ethyl acetate	860 lb (390 kg)
Hydrogenation	Ethanol	900 lb (408 kg)
Dehydration	Ethylene	520 lb (236 kg)
Polymerization and hydrogenation	Jet fuel	500 lb (80 gallons) (227 kg [302 L])

[1] Yields are approximate.

Figure 1.8. AHB "Poplar for Biofuels" demonstration site in Hayden, Idaho. Photo: N. Haider.

Why Hybrid Poplar?

- Poplar can be economically competitive with other agricultural crops.
- Poplars are the fastest growing trees in temperate regions of North America.
- Poplar plantations require fewer inputs (chemical, nutrient, and water) than many other agricultural and bioenergy crops.
- Poplar trees regrow from their cut stump after harvest, eliminating the need to replant for up to 20 years.
- Poplars are adaptable to a wide range of sites.
- There is a long history of poplar production and research in the PNW.
- The chemical composition of hybrid poplar makes for relatively easy conversion to biofuels.
- High genetic variation presents opportunities to breed poplars for economically important traits, such as pest and **disease** resistance, rapid growth, improved conversion attributes, and drought tolerance.
- Poplar's ability to reproduce through vegetative propagation is ideal for genetic improvement and plantation uniformity.
- Poplar plantations offer more habitats for wildlife than annual agricultural crops.

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CHAPTER 2 | ESSENTIALS OF POPLAR BIOLOGY

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Introduction

Poplars are **deciduous** trees in the *Populus* genus that are native to the northern hemisphere. Poplar trees tend to grow tall and straight. Black cottonwood (*Populus trichocarpa*) is the most common type of poplar tree native to the Pacific Northwest (PNW). Black cottonwood is typically found in flood plains, riparian areas, and wetlands, and it is common to see them at higher elevations in mountainous regions (Dickmann et al. 2001). Black cottonwoods are known for their cottony seeds that fill the springtime air in the PNW. Poplars are often pioneering species, being one of the first trees to occupy recently disturbed areas. Poplars are **dioecious**, which means that female and male flowers develop on separate trees.

Poplar Taxonomy

Poplar species (*Populus* spp.) belong to the willow (Salicaceae) family. The poplar genus is divided into six groups according to leaf and flower morphology. Only two groups, balsam poplars (*Tacamahaca*) and cottonwoods (*Aigeiros*), contain species that are commonly used in the breeding of **hybrids** for energy plantations (table 2.1). Poplar trees differ in size, leaf shape and color, bark color, and growing range throughout the northern hemisphere. In the PNW, native poplar species include the western black cottonwood (*Populus trichocarpa*) (figure 2.1) and quaking or trembling aspen (*Populus tremuloides*) (figure 2.2*)*.

There is considerable genetic diversity within the poplar genus, and hybrids are readily produced. Hybrid poplars, the cross of two different poplar species, occur in nature where the range of native species overlap and as the result of **selective breeding** programs. Due to hybrid vigor, or **heterosis**, hybrid poplars usually outgrow and outperform the parent species in some way. In hybrid poplar, heterosis produces enhanced traits, such as pest resistance and fast growth, as a result of mixing the genetic contributions of the plant's parents.

Trees from the genus *Populus* should not be confused with other trees with poplar in their common name. *Liriodendron tulipifera* is known as the yellow poplar, tulip tree, or tulip poplar. It is a valuable timber tree native to the eastern United States that is commonly used to make cabinets and furniture. Although this tree has a long history of genetic improvements and commercial deployment, it is in the Magnoliaceae family and is distinct from species recognized in the Salicaceae family.

Figure 2.1. Black cottonwood (*Populus trichocarpa*). Photo: K. Zobrist.

Figure 2.2. Quaking or trembling aspen (*Populus tremuloides*). Photo: K. Zobrist.

Hybrid Poplar

Hybrid poplar breeding programs have a long history in the PNW. Poplars were originally envisioned as a biofuel **feedstock** during the petroleum crisis in the 1970s, but they were first commercialized in the mid-1980s for the pulp and paper industry (Stanton et al. 2002). Today there are thousands of acres of poplar trees growing in the PNW for lumber and engineered wood products as well as pulp and paper. Research into the use of hybrid poplars as an energy crop was revived in the 2010s through the USDA-NIFA-funded project Advanced Hardwood Biofuels Northwest (AHB) to explore the use of hybrid poplar as a feedstock for a renewable biofuel and bio-based chemical industry.

Hybrid varieties are the trees of choice for poplar plantations in the PNW. The majority of commercially grown hybrids are derived from eastern cottonwood (*P. deltoides*) selections that have been bred with the following species: European black poplar (*P. nigra*), black cottonwood (*P. trichocarpa*), and Japanese poplar (*P. maximowiczii*). Other species crosses may also appear in the commercial nursery trade (Heilman 1999) (table 2.2). Because considerable variation exists within the different poplar species, hybridized varieties vary considerably in most commercial traits. To select the most economically important hybrids, breeding programs continually evaluate hybrid poplar varieties based on both the quantity and quality of the **biomass** produced. Examples of agronomic traits that affect quantity include productivity, survival, **disease** and pest resistance, growth, resprouting vigor from **coppice**, and drought tolerance. The quality of the wood is assessed by measuring specific gravity, fiber length, and **cellulose** and **lignin** content (Stanton et al. 2014).

Currently, the hybrid varieties being researched for **bioenergy** applications in the PNW were developed for other markets (pulp and sawlogs), and poplar with preferred traits for bioenergy markets are currently being developed. These traits would include increased coppicing and higher biomass **yields**, rather than traits for growing tall, straight trees. Breeding programs require years of monitoring and selection before the varieties are ready for deployment at a commercial scale. Poplars bred specifically for deployment in the PNW for bioenergy application are not yet available. Despite this limitation, biomass yields from older varieties are meeting expectations at research sites. New varieties bred specifically for bioenergy applications are being developed, and growers should look for them when purchasing their **planting stock** in the future. For bioenergy applications, high-quality feedstock will have high sugar content and low lignin content, which will make the conversion process more efficient (Dou et al. 2018).

Hybrid poplars grown as a bioenergy crop are planted as **cuttings**, grown on three-year harvest rotations, and harvested with a **forage harvester** with a **biomass head**. After harvest, the stand regenerates by coppice (resprouting from the cut **stool**). This harvesting and resprouting cycle may be repeated as many as five to seven times before biomass production begins to decrease, requiring the stand to be replanted.

Table 2.1. Common species used for hybridization.

Species	Common Name	Native Range
Populus deltoides	Eastern cottonwood	Southeastern North America to the Great Plains
Populus nigra	European black poplar	Europe through central Asia
Populus trichocarpa	Black or western cottonwood	Pacific Northwest to southern Alaska
Populus maximowiczii	Japanese poplar	Eastern Russia, China, Korea, and northern Japan

Table 2.2. Common hybrid crosses.

Any Cross Between:			Hybrid Binomial
P. deltoides	×	*P. trichocarpa*	*P. ×generosa*
P. deltoides	×	*P. nigra*	*P. ×canadensis*
P. deltoides	×	*P. maximowiczii*	*No hybrid binomial assigned*

Poplar Varieties and Suitable Hybrids for the PNW

Matching a hybrid poplar variety to the environment in which it will be grown is one of the most fundamentally important principles of poplar culture (Dickmann and Isebrands 1999). Prospective growers should select varieties that have been proven to be successful for a given geographic area. Examples of productive hybrid poplar varieties by region are listed in table 2.3. Growers should only purchase poplar cuttings from reputable nurseries, preferably near the planting location (Dickmann and Isebrands 1999). Information on where to get poplar cuttings and how to plant them is available in Chapter 5. Hybrid poplar varieties that do well in one area may react differently when planted in different environments. Some poplar varieties, such as white poplar (*Populus alba*) and its hybrid gray poplar, are prone to **root suckering** and may not be suitable for many plantation settings due to this species' tendency to become invasive (Eckenwalder 2001).

General Characteristics of Poplar Trees

Leaves

The leaves of poplar trees are distinct but highly variable between varieties. They are commonly triangular in shape but may be rounded with an elongated or pointed tip. Leaves are simple and are arranged in an alternate pattern along the shoot (figure 2.3). Poplar leaves are known to be highly reactive to the wind. Even with a gentle breeze, ruffling poplar leaves mimic the sound of flowing water. In the fall, hybrid poplar leaves tend to turn yellow in color before falling.

Stems, Branches, and Bark

The bark of young poplars varies, but it is often light in color and smooth. The bark on older trees will darken and may furrow. Branches grow upright in a spreading fashion. After the first harvest, hybrid poplars grown on **coppice rotations** have many stems branching from the stump near the ground (figure 2.4).

Table 2.3. Growing regions, suitable taxa, and examples of productive varieties of hybrid poplar bioenergy feedstock.

Production Region	Suitable Poplar Crosses	Example of Productive Hybrid Poplar Varieties[1]
North Puget Sound, Washington	*P. ×generosa*	UW 49-177[2]; UW 15-29; GWR 20-88-183; GWR 346-94-10403
	P. deltoides × P. maximowiczii	GWR 284-93-6294; GWR 386-95-11567; GWR 605-97-19163
Lower Columbia River, Oregon, and Washington	*P. ×generosa*	GWR 20-88-183; GWR 346-94-10403
	P. deltoides × P. maximowiczii	GWR 284-93-6294; GWR 386-95-11567; GWR 605-97-19163
Willamette Valley, Oregon	*P. ×generosa*	UW 49-177; UW 15-29; GWR 20-88-183; GWR 346-94-10403
	P. deltoides × P. maximowiczii	GWR 284-93-6294; GWR 386-95-11567; GWR 605-97-19163
Sacramento Delta, Central and Northern California	*P. ×canadensis*	OP-367[3]; BC-79; Simplot Alkaline[4]; I-65A; Tripolo; R270
Idaho Panhandle	*P. ×canadensis*	OP-367; BC-79; Simplot Alkaline; I-65A; Tripolo; R270
Mid-Columbia River Basin, Oregon, and Washington	*P. ×canadensis*	OP-367; BC-79; Simplot Alkaline; I-65A; Tripolo[5]

[1] Hybrid varieties starting with GWR were developed by GreenWood Resources. Varieties starting with OP were developed by Oxford Paper. Varieties starting with BC were developed by Boise Cascade. Varieties starting with UW were developed by the University of Washington.

[2] UW 49-177 is a female T×D hybrid whose mother came from Orting, WA. The male pollen came from Texas. This hybrid has been planted extensively in western and eastern OR and WA. The variety tends to break bud early in the spring and can remain active late into the fall. For this reason, it is susceptible to cold injury (Boswell 2008).

[3] OP-367 is a male D×N hybrid that was bred by Oxford Paper in the 1930s. In many ways, it is an industry standard with wide site adaptability throughout the western United States. The parents are unknown but thought to be an eastern cottonwood mother from the midsouth and a black poplar male from Europe. It is very windfirm, insect resistant, and drought tolerant (Boswell 2008).

[4] Simplot Alkaline is a D×N hybrid developed by the Oxford Paper Company and commercialized by Simplot Corp.

[5] Tripolo was developed in Italy.

Figure 2.3. The leaves on this hybrid poplar are simple and arranged in an alternate pattern along the shoot. Photo: D. Kilgore.

Figure 2.4. Regenerating poplar by coppicing produces several stems from the cut stump, instead of a single trunk. Photo: N. Haider.

Figure 2.5. A few weeks after planting, leaves and roots appear from the poplar cutting. Photo: R. Stonex.

Roots

Fast-growing poplar trees are quick to expand their root systems underground. When planted as a cutting, poplar roots will vigorously expand into the soil as the first leaves on the plant flush out (figure 2.5). Poplars form roots from preformed **root primordia** that are present on the inner bark of the poplar cutting. The roots grow rapidly, taking up water and dissolved nutrients. Roots that survive the first growing season will undergo thickening in subsequent years, forming the structural architecture of the root system. At first, the root system develops within the upper layer of the soil, but then vertical sinker roots will elongate and thicken, forming one or more taproots that can reach depths of nine feet (three meters) or more. Fine roots are rapidly produced during the juvenile phase of growth and in the spring. Root formation is highly dependent on the soil drainage, texture, and profile characteristics (Dickmann et al. 2001).

Poplar will develop symbiotic relationships with microorganisms present in their root zones. **Endophytes**, bacteria and fungi that live inside plants, are plant-associated microbes that stimulate plant growth and improve nutrition, increasing the stress tolerance of poplar trees. Although the interaction between endophytes and their host plant is not fully understood, several studies have demonstrated the positive effects of endophyte inoculation to increase plant growth and enhance drought tolerance (Khan et al. 2016). Growers should investigate the use and availability of endophytes when they purchase their poplar cuttings for planting.

Propagating Poplars

Sexual Reproduction

Poplars are dioecious with individual trees bearing either male (pollen-producing) or female (seed-producing) flowers. Poplar flowers appear early in the spring before the leaves appear. Both male and female flowers form catkins that hang down from the branches. Once spent, the male catkins fall to the ground. After pollination, female catkins mature to capsules containing large quantities of seeds. Each seed is covered with white, fluffy, cotton-like hairs that facilitate dispersal by wind and water (figure 2.6).

Flowering is unlikely on hybrid poplars grown on short rotations as a bioenergy crop. Poplars typically take seven years to mature to the reproduction stage. Because hybrid poplar grown for bioenergy would be harvested on three-year rotations, the trees do not have a chance to reach reproductive maturity. However, in the case of unforeseen management interruptions, the escape of viable hybrid seeds is possible and should be considered when the plantation is established (see Chapter 16 for more information on invasive poplars).

Figure 2.6. Cottonwoods like *Populus trichocarpa* (pictured) get their name from the fluffy, white, cotton-like fibers attached to their seeds. Photo: K. Zobrist.

Asexual Reproduction

Poplars can reproduce both sexually, through the dispersal of seed, and asexually, through **vegetative propagation**. In nature, vegetative propagation occurs through root suckering or when a poplar stem or branch falls off a parent tree and takes root in the ground. The resulting tree is genetically identical to the parent tree and may be referred to as a **clone**. Poplar growers can take advantage of this feature to create varietal poplar plantations where each tree is genetically identical and features the same preferred traits.

Hybrid Poplar Varietal Development

Poplar trees are bred within a greenhouse to create superior hybrid varieties. Hybrid varieties of poplar can express hybrid vigor, outperforming both parents in terms of growth, pest and disease resistance, or other preferred traits. This allows breeders to quickly improve several traits of economic importance. Poplar growers can take advantage of poplar's ability to propagate vegetatively by using cuttings to replicate superior varieties.

Figure 2.7. Using controlled pollination techniques, pollen is extracted from a male plant, then used to fertilize female poplar catkins on branches that are isolated in a greenhouse. The controlled-pollinated seeds then germinate and are planted in a nursery, beginning a multi-stage selection process where progeny performance is evaluated. Photos: N. Haider.

Hybrid poplar breeders create poplar varieties using time-tested methods of controlled pollination in which two pure parent species are crossed. To accomplish this, male and female breeding branches are collected from orchards and transferred to a greenhouse at a breeding facility. Male flowers are forced to mature using horticultural techniques involving lights and heat, and the pollen is collected and stored in small jars. Female branches are isolated to preclude unwanted pollinations and are either rooted in soil or maintained in water. Once open, the female flowers are artificially pollinated using an instrument that sprays the stored pollen onto the isolated female floral catkins (figure 2.7). The flowers are then allowed to mature to seeds.

To begin the varietal selection process, the resulting hybrid seeds are sown as a family in a greenhouse. As the poplar seedlings grow over the spring and summer, they are monitored and evaluated for survival and growth to initiate the selection process.

In the second growing season, select seedlings are transferred to field trials for further evaluation. The field trials reveal trees with preferred traits, such as survival, disease and pest resistance, growth, and wood composition. Trees featuring desired traits are replicated when cuttings, a short length of a stem, are taken from the trees. The cuttings are then established in a nursery as exact genetic copies (clones) of the original tree the cutting was taken from.

Once established in the nursery, cuttings are taken from the nursery stock annually to supply planting stock for new poplar plantations. These cuttings are collected as **whips** from one-year-old growth and then cut into suitable lengths for the site at which they will be planted.

Since hybrid poplar varieties are replicated through vegetative propagation methods, the poplar cuttings are clones of their parent tree. The terms *hybrid variety* and *clone* are often used interchangeably when referring to poplar cuttings that are deployed commercially. The advantage of vegetative propagation is that all of the hybrid vigor and genetic traits that are captured in the processes of hybrid breeding are replicated in every cutting that is placed in the field (Johnson 1999). On a hybrid poplar plantation, growing poplar trees from cuttings assures a uniform crop of genetically identical trees that display the same traits as the parent tree.

Using cuttings to establish a poplar plantation for bioenergy is far less costly than establishment using containerized seedlings or cuttings that are transported to the field after roots have been established. There will also be uniformity in the varietal stands, improving the ease of management (Stanton 1999).

Variety vs. Clones

Hybrid variety and *clone* are terms that are used interchangeably in regard to hybrid poplar that is deployed for commercial production. Once a suitable hybrid variety is identified, cuttings are taken from the parent tree. The cuttings grow to be individual trees with the same genetic makeup of the parent. Thus, commercially deployed trees are clones of select hybrid varieties.

Poplar Wood Chemistry

The chemical makeup of poplar makes it a prime feedstock for bioenergy production. Wood is primarily composed of cellulose, **hemicellulose**, and lignin, which are important components of plant cell walls. Biofuels and bio-based chemicals are derived specifically from the cellulose and hemicellulose, which are sugar polymers, hence the name cellulosic biofuels. Poplar wood is high in cellulose and hemicellulose and low in lignin, making it an efficient choice for biofuels and bio-based chemical production (Sannigrahi et al. 2009).

In the conversion process, when poplar wood is converted to biofuels and bio-based chemicals, the lignin molecules that make plants rigid are broken down, and the sugar polymers are released. Once exposed, the long cellulosic sugar chains are broken down into individual sugar molecules (glucose) that can be fermented by yeast or bacteria and further processed to the desired bio-based chemical or biofuel (figure 2.8). The lignin, which would otherwise be a waste product, can then be burned to produce heat and steam for the conversion process.

Getting to the Sugar in Poplar Bioenergy Crops

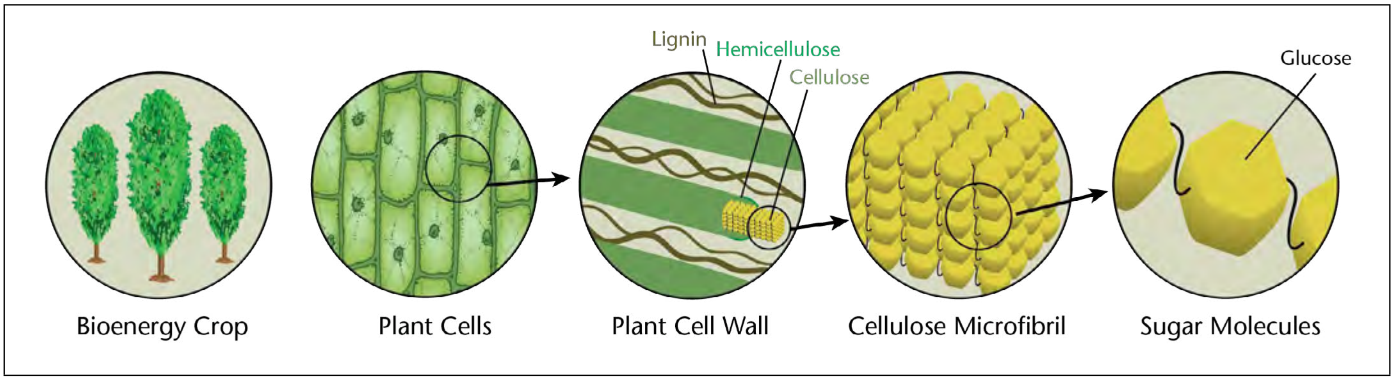

Figure 2.8. In the conversion process to biofuels, the sugars in the cell walls of the poplar tree are broken down to individual sugar molecules. The sugar molecules are then fermented and further processed to make a suite of biofuels and bioproducts. Image: B. Nordaker, adapted from Sannigrahi et al. (2010).

Hybrid vs. Genetically Engineered Poplars

To create poplar with superior traits and high biomass yields, hybrid crosses and genetically modified varieties of poplar are researched for their potential as a bioenergy crop. Hybrid poplars are the result of selective breeding in which two distinct poplar species are crossed using time-tested methods of controlled pollination. Although hybridization is common in nature, the concern regarding hybrid poplar as a bioenergy crop is that it could introduce non-native species and genes into native poplar populations through **transgene flow**. This is a natural process that can cause dilution or alterations of a native poplar species' genetic diversity and locally adapted traits.

In contrast, **genetically engineered** (GE) poplars are the result of modifying a tree's DNA using genetic engineering techniques. Currently, the use of GE poplars in commercial plantations needs approval from the USDA. To date, no commercial plantations of GE poplar have been given this approval. GE poplars are confined to field trials and subjected to regulatory oversite. Some poplar breeders are interested in GE poplars because they could help in refining wood characteristics to address specific problems and improve growth (Strauss et al. 2015). Genetic engineering could also provide a method for containing non-native tree species: trees could be engineered to be sterile and thus would not be able to reproduce (Strauss et al. 2010).

Using the lignin as energy can further reduce the net greenhouse gas emissions from a poplar-based biofuel system. Low-lignin wood, such as poplar, is ideal for biofuel production, because it is relatively easy to remove the sugars locked inside the biomass (figure 2.9).

Typical Wood Properties of Poplar

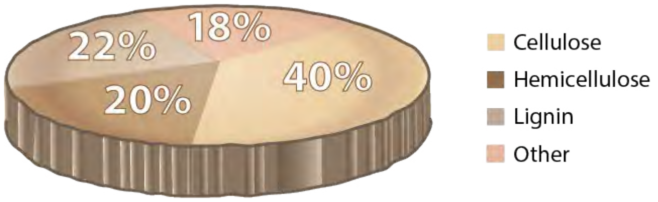

Figure 2.9. Poplar contains relatively low amounts of lignin compared to other forms of biomass, which allows for efficient conversion to biofuels and other products (Townsend et al. 2014). Image adapted by B. Nordaker from original art by G. Steffen.

Future Research

Research on improving hybrid poplar varieties for bioenergy is continuing. Growers will want to seek out newer, improved poplar varieties with higher sugar content and reduced lignin content. While growers will be interested in planting high-yielding varieties, **biorefineries** will be looking for feedstock with high sugar content (Dou et al. 2018; Sannigrahi et al. 2009). Growers are advised to select varieties where these traits overlap.

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CHAPTER 3 | SITE SELECTION

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Introduction

For poplar plantations to be successful, growers should carefully consider the suitability of the site. **Hybrid** poplars grow well on productive farmland with deep, fertile soils that possess both good nutrient and moisture availability. However, as a low-value crop, poplar is not likely to be economically competitive with other crops on productive farmland. Growers may choose to adopt **bioenergy** crops, such as poplar, if their poplar plantation profits exceed those from food production (Bandaru et al. 2015; Kang et al. 2013). Poplar could be an attractive option for farmers of **marginal farmland**, as long as there is sufficient water and soil nutrients available. More information on the economics of poplar production is available in Chapter 14.

Marginal farmland is characterized by lower productivity and reduced economic returns with limited plant growth resources for agricultural use, compared to land that is considered prime farmland. Marginal farmland could include ecologically sensitive areas, such as land with erodible soil and land in floodplains (Blanco-Canqui 2016). In some situations, poplar **cultivation** can be used to enhance ecosystem services on marginal lands by improving wildlife habitat, **sequestering** carbon, and improving soil and water quality (Blanco-Canqui 2016). Marginal farmland could be favorable for poplar production using the guidelines and practices described in this manual. In addition, poplar cultivation can restore degraded land using **phytoremediation** techniques.

The site characteristics described in this chapter are features that should be considered when identifying potential locations for poplar plantations in the Pacific Northwest (PNW). These site features are incorporated in a site suitability model that is available online as a web application. The model uses these site features to assess the suitability of a specific land parcel for poplar production.

Climate

Native poplars have evolved over time to adapt to local climatic conditions, allowing poplars to thrive from the tropic to arctic latitudes of North America (Dickmann et al. 2001). In the PNW, growers should select poplar varieties that will grow well in their region's climate, while making sure that preferred soil, nutrients, and moisture conditions are also at the appropriate levels. Suitable growing season temperatures and length are categorized in tables 3.1 and 3.2. The presence of native poplar trees in the vicinity should be included in the initial site assessment, since this is a good indicator of a site's suitability for plantation establishment (Johnson 1999).

Table 3.1. Range of suitable average monthly high temperatures from April to September.

Marginal Suitability—Too Cool	Ideal Temperatures	Marginal Suitability—Too Hot
< 60°F (16°C)	60°–85°F (16°–29°C)	85°–95°F (29°–35°C)

Table 3.2. Range of suitable number of days between the first frost-free day in spring and the last frost-free day in autumn.

Unsuitable—Too Short of Season	Marginal Season Length	Ideal Season Length
< 90 days	90–120 days	> 120 days

Water Availability

Lack of water will limit the growth of the poplar trees more than any other environmental variable (Dickmann et al. 2001). Establishing a poplar plantation in close proximity to a water resource is best to provide sub-irrigation from the water table to the trees throughout the growing season, but this is not a crop requirement (figure 3.1). In places where the water table is too shallow, there could be a negative influence on root growth and aboveground **yields**. In areas where the water table is too deep, the soil will become too dry to support the crop (table 3.3). Poplar plantations established in areas with adequate precipitation, such as the west side of the Cascade Range, will thrive if management practices like those described in this manual are used that meet the needs of the plant (table 3.4). In drier regions, poplars can adequately perform with minimal amounts of water available. In these conditions, poplar varieties that are adapted to drier climates should be used (see Chapter 2). More information on water requirements can be found in Chapter 10.

Figure 3.1. Adequate water availability is an important feature of productive poplar plantations and should be considered in the site selection process. Photo: N. Haider.

Irrigation

If irrigation can be provided to poplar crops, the range of acceptable sites is far greater (Bandaru et al. 2015; Cooke et al. 2014). However, irrigation will increase the cost of cultivation, making the production of poplar **biomass** for bioenergy applications uneconomical for the grower. Decisions by growers on how to utilize their land and water in regard to poplar bioenergy crops will be based primarily on economics. Growers will most likely reserve irrigated farmland for high-value food crops such as fruits and vegetables. Energy crops, such as poplars, may be able to compete with crops of lower value, such as hay and small grains. However, unless the value of biomass greatly increases, irrigation will probably not be used on most poplar biomass production operations. More information on production economics is available in Chapter 14.

With the proper permits, irrigating with wastewater from wastewater treatment facilities, food processing plants, mining, or other industries may be feasible (Townsend et al. 2018). For fields in proximity to wastewater treatment plants, poplar trees can utilize the recycled water while removing excess nutrients from the water (Haider and Parker 2018).

Soil

For best performance, soils should be well-aerated with sufficient moisture and nutrients. Poplars perform best in medium-textured soils (sandy loam to clay loam), but other soils may be acceptable if the site is well-drained (Stanturf at al. 2001). Sites with saturated and waterlogged soils are generally considered unfavorable, but occasional flooding during the **dormant season** may be tolerable especially beyond the establishment phase (Dickmann et al. 2001; Isebrands 2007). Soil compaction or the presence of **hardpans** in the soil profile can inhibit root penetration, reducing the tree's ability to acquire water and nutrients. However, deep ripping can improve growing conditions by providing channels for roots to penetrate (see Chapter 5). Soils should have a sufficient depth of at least three feet (one meter) (Stanturf and van Oosten 2014). Poplars prefer a soil site **pH** of 5.5 to 7.5 (Stanturf et al. 2001). Sites with saline conditions should not be considered, as poplar is not salt-tolerant (table 3.5) (Stanturf et al. 2001).

Table 3.3. Range of suitable depth to water table (based on Schuette, n.d.)

Unsuitable—Too Shallow	Marginal Shallow	Ideal Depth	Marginal Deep
< 20 inches (0.5 m)	20–40 inches (0.5–1 m)	40–100 inches (1–2.5 m)	> 100 inches (2.5 m)

Table 3.4. Range of suitable average monthly precipitation throughout the growing season from April to September.

Unsuitable—Too Dry	Marginal Dry	Ideal Precipitation
< 1 inch (2.5 cm)	1–2 inches (2.5–5 cm)	≥ 2 inches (5 cm)

Table 3.5. Classification of soil characteristic for poplar bioenergy crops.

Soil Quality	Unsuitable	Marginal	Optimal
Texture[1]		Coarse- or sandy- to fine-textured; clayey	Medium-textured; silty or loamy
pH	< 4.5 > 8.0	4.5–5.5 7.5–8.0	5.5–7.5
Salinity (dS/m)	> 5	2–4	0–2
Depth (inches)	< 20 (50 cm)	20–40 (50–100 cm)	> 40 (100 cm)

[1] Assuming adequate drainage.

Nutrients

Nitrogen is the most important element for optimizing poplar productivity. However, soil nutrient levels alone should not exclude sites from poplar production. A comprehensive list of nutrient requirements is summarized in Chapter 10. Nitrogen and other elements can be applied when necessary to avoid deficiencies. Even sites with adequate soil nutrients at planting may require fertilizer inputs after repeated harvests (see Chapter 10).

Soil analyses can be performed prior to planting to establish a baseline for correcting gross nutrient deficiencies and repeated after each harvest to ensure soil fertility and health is maintained. The nutrient demands of poplar are fairly similar to other agricultural crops. Nutrient recommendations for other row crops can give a rough estimation of nutrient recommendations for new stands of short-rotation poplars. Routine soil testing can continue into the production years. However, analysis of the poplar foliage is more accurate in identifying nutrient deficiencies in established plantations (see Chapter 10).

Figure 3.2. The slopes of the rolling hills on this hay field are acceptable for effective commercial poplar production. Photo: N. Haider.

Site Features

Slopes

Flat or gently sloping sites are best, with slopes no greater than 10% to allow management without erosion risks (figure 3.2). Moderately steep slopes might inhibit tractor operations required for plantation establishment and maintenance (Schuette, n.d.). Harvesting on steep-sloped fields might also be problematic.

Surface Rocks

Hybrid poplars can adequately perform in rocky soils, but surface rocks should be removed from the field to avoid damaging farming and harvesting equipment (figure 3.3).

Figure 3.3. This large rock was removed from the soil to prevent damage to farming equipment. Photo: N. Haider.

Size Requirements

The availability of harvesting equipment will affect the minimum acreage a grower would want to plant in poplars. It is not likely to be economically viable to plant fewer than 25 acres (10 ha) with poplar unless there are additional poplar plantations nearby that could share in the cost of transporting the harvester to the field. Neighboring growers could form a growers' cooperative that could share in the harvesting costs and work jointly to negotiate with the biomass buyer. Economy of scale must be considered for field size, orientation, and location within a management area.

Location

Growers should consider plantation sites that are relatively close to a **biorefinery** or other markets. A marginal site close to a biorefinery may be more economical than a better site farther away. Transportation costs should be considered when making site selection decisions. Typically, sites within 50 miles (80 km) of the delivery location are ideal. Relatively easy access to highways is also important for reducing transportation costs. Poplar plantations should be concentrated within a management area that will supply a biorefinery. An estimated 100,000 acres (40,469 ha) of poplar is required to supply **feedstock** to a 50-million-gallons-a-year (189-million-liters-a-year) **bio-jet fuel** refinery. Additional feedstock supply options should also be available in the area, such as wheat straw, corn **stover**, and other residual and waste products (Bandaru et al. 2015).

Land Suitability Study for Poplar

University of Washington researchers undertook a land suitability study to identify the potential for growing poplar over the four-state region of the PNW, including Washington, Oregon, Idaho, and northern California (Cooke et al. 2014). The researchers used the suitability factors described in this chapter and in table 3.6 to rank land into four suitability classes. They used normalizing functions that converted values for each factor into a score from zero to one. The suitability score for each factor was then multiplied by weights and summed to calculate the final overall suitability score. The results from the suitability model summarize the number of potential acres for poplar production into four suitability classes.

- Highly suitable: suitability score greater than .80
- Moderately suitable: suitability score between .60 and .80
- Marginally suitable: suitability score between .40 and .60
- Currently unsuitable: suitability score less than .40

Table 3.6. Site suitability factors.

Suitability Factors	Suitability Scores			Weights	
	0	0–1	1	Without irrigation	With irrigation
Growing season precipitation	0–1 inches	1–2 inches	≥ 2 inches	0.33	0.0
Average monthly temperature during the growing season	0–32 degrees ≥ 95 degrees	32–60 degrees 85–95 degrees	60–85 degrees	0.17	0.26
Growing season length	0–89 days	90–210 days		0.17	0.26
Soil texture and drainage	-	All soil types and drainage classes	-	0.07	0.10
Soil pH	0–4.5 pH ≥ 8.0	4.5–5.5 pH 7.5–8.0 pH	5.5–7.5 pH	0.07	0.10
Soil salinity[1]	-	2–4 dS/m	0–2 dS/m	0.07	0.10
Soil depth	0–20 inches	20–40 inches	≥ 40 inches	0.07	0.10
Water table depth	0–20 inches	20–40 inches ≥ 100 inches	40–100 inches	0.03	0.04
Slope[2]	-	10–15%	0–10%	0.02	0.02

[1] Soils with salinity greater than 4 dS/m were excluded from the analysis.
[2] Land with slopes greater than 15% were excluded from the analysis.

Land identified as permanently unsuitable was removed from the model, including land under federal ownership, urban areas, land with slopes greater than 15%, and areas with high soil salinity. Although these lands might have the physical capabilities for growing poplar, lands with these characteristics are generally not used for farmland and thus would not be suitable for poplar production. The model shows there are 2.9 million acres (1.2 million ha) of highly suitable, non-irrigated land and an additional 26.9 million acres (10.9 million ha) of highly suitable, irrigated land across Washington, Oregon, Idaho, and northern California.

The land suitability model was further enhanced with county parcel data where available. The parcel-level suitability analysis integrates the suitability model with topography, size of ownership, and land use to identify the most likely lands that could be available for commercial poplar production. Growers can use the Advanced Hardwood Biofuels Northwest Suitability Model Data Viewer to determine how their parcel ranks in the hybrid poplar suitability classes. An overview of land suitability for Washington, Oregon, Idaho, and northern California is shown in figures 3.4 to 3.11 and summarized in tables 3.7 to 3.10.

The Suitability Model Data Viewer is available online at: http://nrsig.org/apps/ahbnw/suitability/.

Directions for using the Suitability Model Data Viewer are available in Appendix A of *A Poplar Suitability and Parcel Land Use Study* (Rogers et al. 2016).

Overall Suitability Classification for Poplar Bioenergy Crops with and without Irrigation

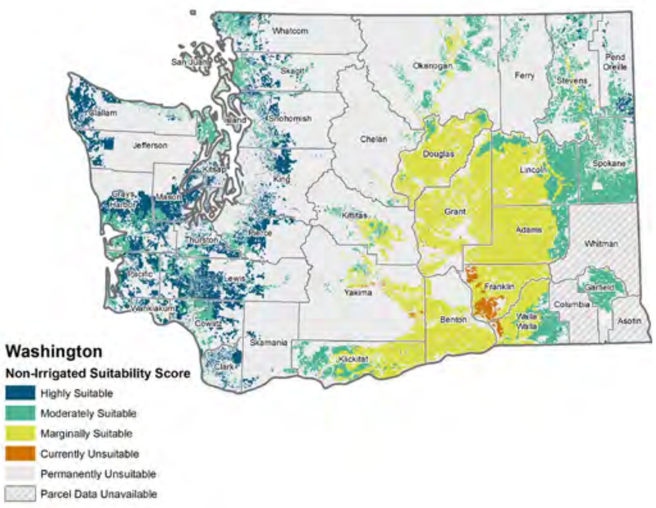

Figure 3.4. Washington parcel suitability for growing hybrid poplar without irrigation. Counties where parcel data was not available are shown with a grey crosshatch.

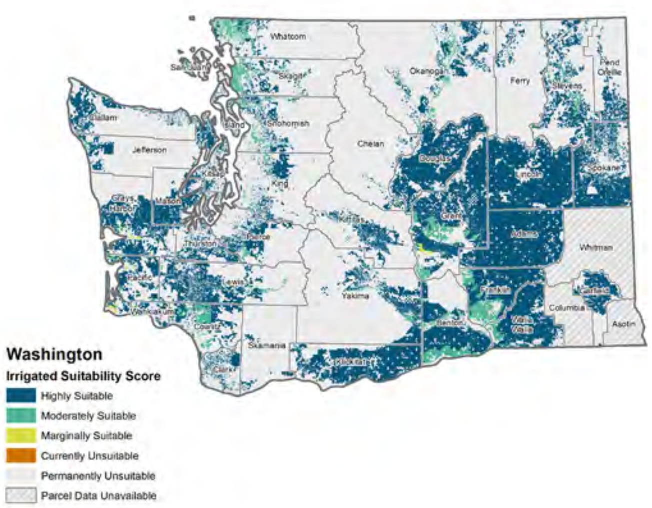

Figure 3.5. Washington parcel suitability for growing hybrid poplar with irrigation. Counties where parcel data was not available are shown with a grey crosshatch.

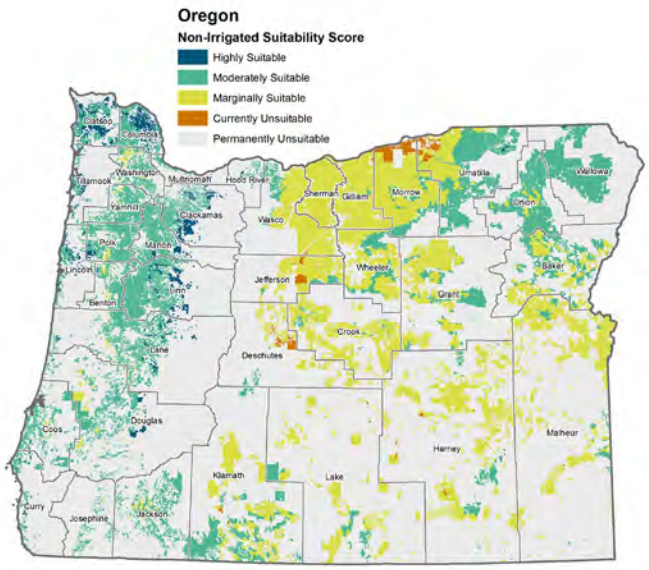

Figure 3.6. Oregon parcel suitability for growing hybrid poplar without irrigation.

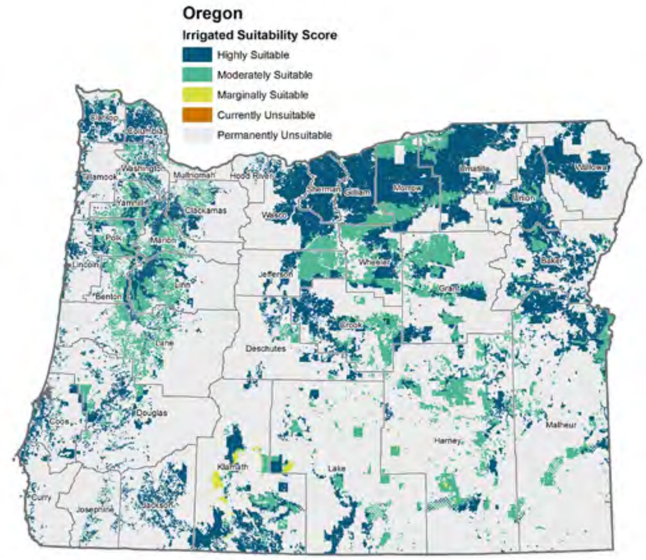

Figure 3.7. Oregon parcel suitability for growing hybrid poplar with irrigation.

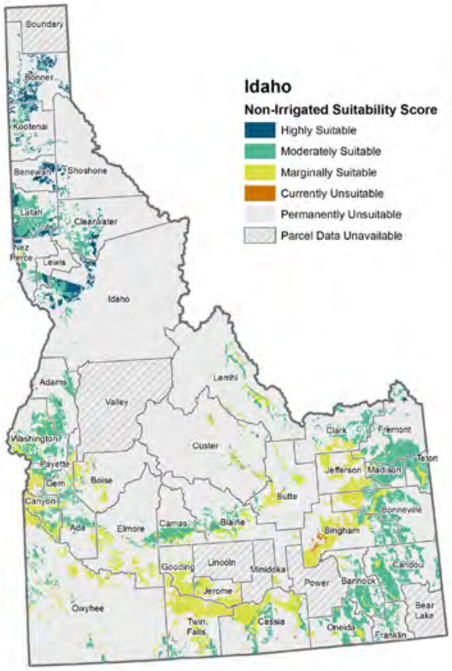

Figure 3.8. Idaho parcel suitability for growing hybrid poplar without irrigation. Counties where parcel data was not available are shown with a grey crosshatch.

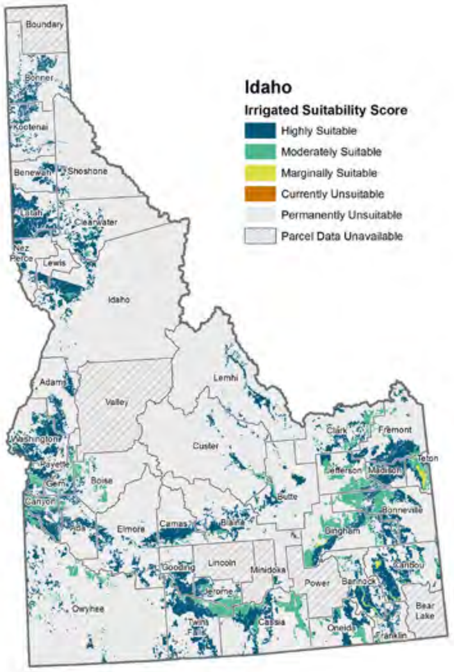

Figure 3.9. Idaho parcel suitability for growing hybrid poplar with irrigation. Counties where parcel data was not available are shown with a grey crosshatch.

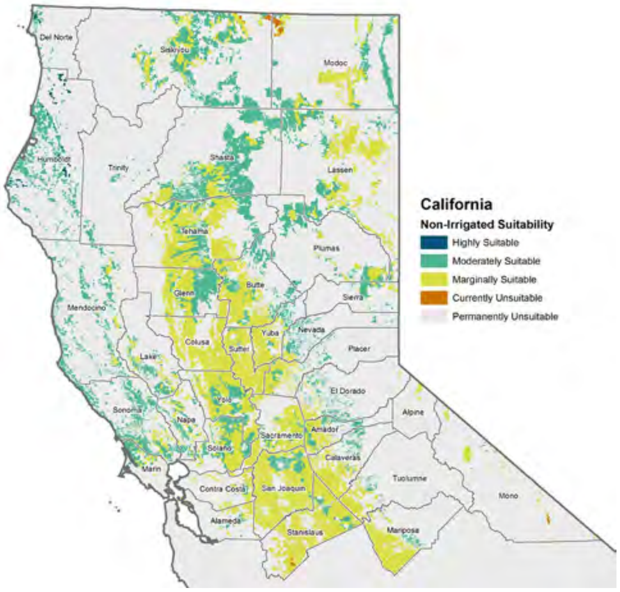

Figure 3.10. California parcel suitability for growing hybrid poplar without irrigation.

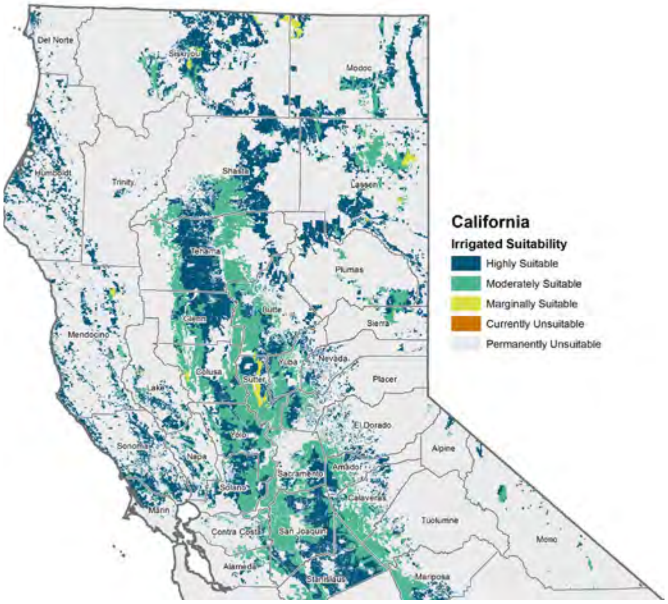

Figure 3.11. California parcel suitability for growing hybrid poplar with irrigation.

Table 3.7. Number of acres suitable for growing hybrid poplar for bioenergy in Washington.

	Highly Suitable	Moderately Suitable	Marginally Suitable	Not Suitable
Non-irrigated	1,764,036	3,337,909	5,185,301	41,398
Irrigated	9,520,915	908,921	39,965	0

Table 3.8. Number of acres suitable for growing hybrid poplar for bioenergy in Oregon.

	Highly Suitable	Moderately Suitable	Marginally Suitable	Not Suitable
Non-irrigated	563,855	4,640,425	5,152,636	23,615
Irrigated	7,295,443	2,948,810	141,492	13

Table 3.9. Number of acres suitable for growing hybrid poplar for bioenergy in Idaho.

	Highly Suitable	Moderately Suitable	Marginally Suitable	Not Suitable
Non-irrigated	578,402	3,483,316	2,908,695	22,108
Irrigated	5,418,011	1,515,950	58,562	0

Table 3.10. Number of acres suitable for growing hybrid poplar for bioenergy in California.

	Highly Suitable	Moderately Suitable	Marginally Suitable	Not Suitable
Non-irrigated	27,026	3,304,373	4,524,693	41,398
Irrigated	4,697,355	3,056,441	146,131	0

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CHAPTER 4 | PREPARING TO PLANT

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Preparation and Planning

Detailed preparation and precise planning are essential to the success of a **hybrid** poplar plantation, and growers should carefully consider field layout before the poplars are planted. With a good field layout, a hybrid poplar plantation can be a productive crop for six or seven harvests, spanning 20 years or more. Poor planning of field layout could affect crop management activities for years to come.

Field layout will affect the efficiency of **site preparation**, planting, crop care, fire control, and harvesting activities. For efficient crop care and harvesting, the crop rows should be as long as possible. **Headland** space at each end of the rows should be wide enough to allow space for the harvester and other farm machinery to make smooth turns and to accommodate support vehicles that are waiting to enter the field. The spacing between rows should be consistent and wide enough for the harvester and accessory vehicles to operate without damaging poplar stumps or equipment tires. It is wise to contact local trucking contractors during the planning stage to see what equipment they offer and plan the site layout accordingly. A **landing area** is necessary where the chips can be stored, then transferred to highway trucks. There also needs to be relatively easy access to roads and highways to get the chips to market. More information on harvesting, including equipment requirements, is available in Chapter 11.

Weed control is also an essential consideration in establishing a poplar plantation. Weeds will rapidly outcompete the poplar if preventive measures are not taken to control weed growth (Eaton 1999). Growers should not plant poplar unless they are fully committed to the necessary cultural practices, especially at early stages (Stanturf et al. 2001). Effective site preparation results in essentially bare ground. Failure to obtain this level of site preparedness will likely result in a marginal crop or outright failure of the poplar plantation (Dickmann 2006). See Chapter 6 for more information on weed management.

The quantity of poplar **cuttings** that need to be ordered from the nursery will depend on planting density and planned field layout. Depending on availability, orders for cuttings may need to be placed up to one year before planting. Information on suitable hybrid poplar varieties is available in Chapter 2.

Plantation Design

Density

Planting density is a key factor in influencing poplar stem diameter at harvest. Stem diameter is important for the **single-pass harvesting system** used for **coppiced** production, where trees are cut and chipped in the field (Eisenbies et al. 2017). Maximizing stem diameter for optimal **yields** of **biomass** must be balanced with the need to limit stem growth to no more than five inches (12.7 cm) in diameter, which is the maximum amount the harvester can handle effectively.

For most **bioenergy** plantings, a density of 1,452 trees per acre (3,588/ha) is adequate to produce biomass with acceptable bark and leaf content, minimize weed control efforts, and produce stems with optimal diameters to maximize harvesting efficiency (figure 4.1). Planting at greater densities will likely only produce taller trees with thinner stems, lowering wood yield and generating too much leaf and bark matter. Although coppice management techniques produce relatively small diameter stems, the high planting density and frequent (three-year) harvests may achieve yields comparable to traditional short-rotation poplar grown on eight-to-twelve-year rotations at 300–660 stems per acre (750–1,650/ha) in terms of **mean annual increment** (MAI).

On sites where water and nutrient resources are at the boundary of suitability relative to the site selection criteria listed in Chapter 3, a reduced planting density should be considered to reduce competition for these scarce resources. Lower densities of 1,200–1,400 trees per acre (2,695–3,459/ha) will reduce competition between the trees for light, nutrients, and water, giving the trees more room to grow and producing higher wood yields at harvest. However, more aggressive weed control may be necessary on lower density sites, as there will be more open spaces in which weeds can establish.

When determining field design, the grower should look to the future to anticipate any and all scenarios that could be made more efficient by a thoughtfully laid out field design. Crop care, irrigation, harvesting, and the layout of future poplar plantings will be impacted by the decisions made at the beginning of a poplar operation.

Figure 4.1. Planted at 1,452 trees per acre (3,588/ha) at this poplar plantation in Jefferson, Oregon, this crop captures the site in the second year, eliminating weed competition by shading. Photo: D. Kilgore.

Row Spacing

Spacing within and between rows will depend on the desired density of the poplar plantation. At 1,452 trees per acre (3,588/ha), ten-foot (3 m) between-row tree spacing is recommended (figure 4.2), with three feet (0.9 m) of separation between the individual trees within the crop row (figure 4.3). Using this rectangular design rather than a square layout is not detrimental to poplar growth (Ritters et al. 1989). The between-row spacing must also consider the axle width of the tractor to be used for crop care. At harvest, the **forage harvester** and supporting vehicles (trailers and 10-wheel trucks) straddle the crop row, with the vehicles' axles passing over the cut poplar **stools**. Care needs to be taken to ensure that the tires of the equipment will have room to avoid the sharp stumps of the harvested poplars. If larger equipment is to be used, increase the row spacing to twelve feet (3.7 m) and reduce the tree spacing to 2.5 feet (0.8 m) to allow room to maneuver the equipment while maintaining the target density.

Figure 4.2. Ten-foot spacing between the poplar rows allows for easy access for crop maintenance and harvesting. Photo: N. Haider.

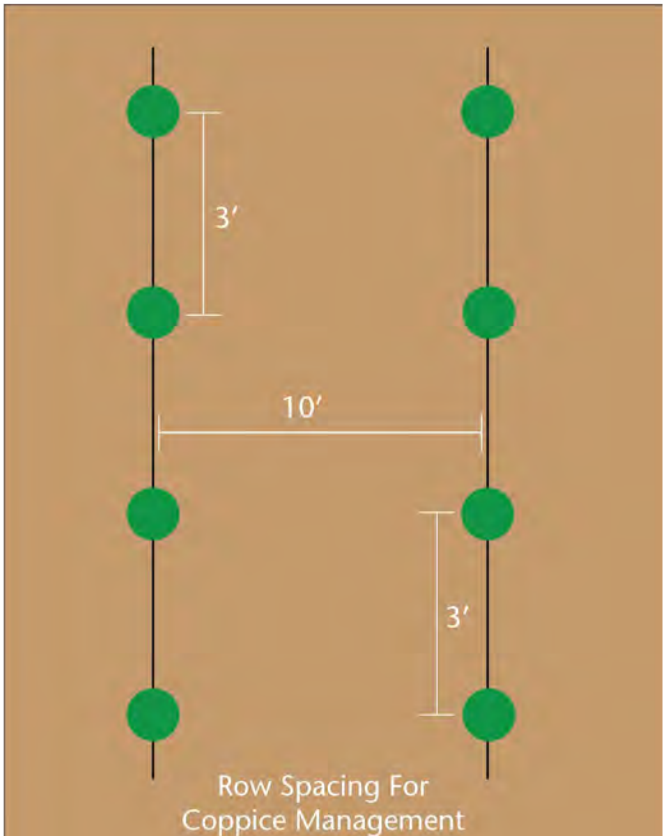

Figure 4.3. Within the crop row, trees (shown as green circles) are planted in a single row. To reach a target density of 1,452 tree per acre (3,588/ha), rows should be situated ten feet (3 m) apart with three feet (0.9 m) between trees within the row. Image: B. Nordaker.

Row Length

The row length will depend on the size and shape of the field. Rows should be as long as possible to maximize harvesting efficiency, minimizing the harvester's idle time as it turns at the end of each row. Adequate headland space of at least 30 to 40 feet (9.1 to 12.2 m) must be maintained at each end of the rows for the harvesting equipment to make smooth turns (figure 4.4).

On exceptionally long fields, a **row break** may be necessary. Row breaks can increase harvesting efficiency if the crop row produces enough biomass to fill the truck/trailer collecting the poplar chips before the end of the row. Switching the collector truck mid-row could potentially cause damage to the crop if the driver is unable to avoid the cut stumps left in the field. However, a row break will take some land out of production and create additional space for weed growth. Row breaks should be carefully considered before incorporating them into field design. If row breaks are incorporated into the field design, a 30- to 40-foot (9.1 to 12.2 m) break should be adequate. More information on harvesting efficiency can be found in Chapter 11.

Figure 4.4. At this poplar plantation in Clarksburg, California, the headland space allows for just enough room for the harvesting equipment to make a smooth turn during harvest. Photo: N. Haider.

Figure 4.5. In the landing area, poplar chips are temporarily stored in piles until they can be transported to the biorefinery. Photo: N. Haider.

Landing Area

Depending on the size of the plantation, one or more landing areas should be included in the field layout with adequate space for storing material until it can be transferred to the **biorefinery** (figure 4.5). The landing area should be located in an area where it is easy for highway trucks to enter and exit the field. A landing area of 1%–2% of the total field area should be adequate for temporary chip storage. If the poplar plantation is less than five miles (8 km) from the biorefinery, a landing area may not be needed as the chips can be directly transferred to their final destination without delaying the harvesting crew.

Varietal Blocks

The use of multiple hybrid poplar varieties in a single plantation reduces the risk of losses from **disease**, insects, or adverse weather, which have variety-specific impacts (Libby 1982; Park 2002). Ideally, the poplar trees should be planted in a mosaic of **varietal blocks** that are 20–70 acres (8–28 ha) in size, depending on the magnitude of the project, with each block containing a different poplar variety (figure 4.6). The number of blocks on a given plantation will depend on a variety of factors including the risk preference of the grower, the number of high-performing poplar varieties for the region, and plantation size, among

Figure 4.6. Seen from above, the subtle variations in color differentiate varietal blocks of hybrid poplar at an 85-acre demonstration site in Jefferson, Oregon. Photo: D. Kilgore.

other variables. Twelve varieties are typically appropriate for a large planting covering several hundred acres. For smaller plantations, planting five or six different varieties may be adequate.

Planting each variety within its own block increases crop uniformity within the stands, which greatly improves stand manageability. For example, by grouping trees in varietal blocks, the grower will find it easier to treat pests and diseases that affect only certain varieties. If an entire block fails, the block can be replanted in another variety without significant impact on adjacent blocks. Harvesting will also be more efficient as the equipment can be adjusted for each block to accommodate the different biomass loads of each variety and maintain overall consistency in cutting and chipping.

Conclusion

Ultimately, field design will vary depending on the features present at your field site. The most important aspect of field design is to anticipate future activities and plan the layout accordingly.

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CHAPTER 5 | PLANTATION ESTABLISHMENT AND PLANTING

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Preparing a New Poplar Plantation

The practices used for preparing a site for planting will depend on several factors, including soil type, soil texture, soil compaction, slope, drainage, precipitation, existing vegetation, and previous land use. **Site preparation** techniques for **hybrid** poplars were adapted from conventional agriculture and forestry techniques. Although site preparation activities can be quite extensive, these activities will only be required for the initial crop establishment, which is only necessary once every twenty years or so as **coppice** regeneration eliminates the need for site preparation between cutting cycles.

The elimination of weeds and control of residual **weed seed banks** is critical during the site preparation stage. Weeds will compete with newly planted poplar **cuttings** for resources such as light, water, and nutrients. The goal is to reduce the weed competition so that adequate resources and growing space are available to the poplar crop. On sites where it is not possible to obtain complete elimination of weeds (figure 5.1), weed control can be limited to the crop rows, with sod **alleyways** in between (figure 5.2). A secondary goal is to improve soil **tilth**.

On fields transitioning from annual row crops, site preparation can begin in midsummer to fall of the year prior to planting, immediately after the existing field crop is removed. For pasture or hay fields, beginning site preparation activities one year in advance is optimal. To begin, weeds should be first controlled through mowing, herbicides, and tilling (refer to Chapter 6 for weed management recommendations). In most instances, mowing and herbicide applications should be adequate to control weeds, but care must be exercised to ensure herbicide carryover will not harm the newly established poplar stands the following year. **Tillage** (disking) can be used to control weeds that are resistant to herbicides. In addition, tilling the soil can optimize soil structure within the rooting zone by loosening the soil to allow for rapid and prolific establishment of the poplar tree's roots (figure 5.3). Broadcast spraying of herbicides or tilling within the crop row may continue until the week prior to planting, depending on weed regrowth. Detailed steps for weed control activities for both site preparation and after establishment are outlined in Chapter 6.

Figure 5.1. Weed free site preparation for poplar plantation. Photo: N. Haider.

Figure 5.2. Prepared crop rows with sod alleyways. Photo: N. Haider.

If the soil is heavily compacted or there is a **restrictive layer** (e.g., **hardpan**) that inhibits root growth and water movement, it may need to be **subsoiled** (ripped) to break it up. At planting, the poplar cuttings are placed directly into the rip lines. The depth of the subsoiling will depend on the depth of the restrictive layer. Subsoiling is done with a vertically mounted **rock-ripping shank** on a tractor (figure 5.4). Subsoiling increases the depth and volume of rooting soil, dramatically increasing the amount of water and nutrients available to the crop trees (Espinoza 2004; Kees 2008).

Figure 5.3. Prepare and loosen the soil within the rooting zone by tilling. At a minimum, this should be done at least within the crop row, if not the entire field. Photo: N. Haider.

It is best to do the subsoiling when the soil is dry to avoid compacting the soil further and to ensure that the restrictive layer is adequately broken up. On sites where soil compaction or a restrictive soil layer is present, subsoiling is typically done 15–30 days before planting. However, in some cases there might not be enough time to get the subsoiling done this far in advance, particularly if soil moisture levels are high and field access is restricted. If time is limited, up to a week prior to planting should be sufficient.

Figure 5.4. This tractor is equipped with double shanks 18 inches (46 cm) apart to create offset rows where the poplars are planted 9 inches (23 cm) off the row center. Photo: N. Haider.

If the site is susceptible to flooding, raised planting beds should be made. **Bedding** is the formation of a continuous mound of soil down the planting row using a **bedding plow**. Bedding is used on poorly drained, oxygen-deprived soils. Elevating the tree's rooting zone above the water table loosens and moves air into the soil. In addition, bedding improves the tree's nutrition supply by concentrating organic and mineral rich surface soil in the poplar's rooting zone. It also helps control competing vegetation by eliminating existing ground cover (Espinoza 2004). Beds should be formed about six weeks before the anticipated planting date. This way the bedded soil has time to settle but not enough time to slump and lose its shape. If your site also requires subsoiling, bedding and subsoiling can be completed at the same time using a **combination plow**. A poplar bed should be approximately two to three feet (0.6–0.9 m) high and two to three feet wide for the length of the planting row (figure 5.5).

Figure 5.5. Bedding can be done at wet sites to elevate the surface soil to improve nutrition and increase soil oxygen levels. Photo: J. Espinoza.

Poplar Planting Stock

Planting stock for high-density poplar plantings is commonly unrooted sections of poplar stems or branches, referred to as cuttings. Poplar cuttings are collected in the **dormant season** from one-year-old stems taken from nursery plants. Ideally the poplar cuttings should be 9 to 22 inches (22 to 56 cm) long and 3/8 to 3/4 inches (1 to 2 cm) in diameter. Cuttings smaller than 3/8 inch (1 cm) in diameter are not ideal as they would likely bend and snap when placed into the ground, while cuttings larger than 3/4 inch (2 cm) would be more difficult to push into the ground. Longer cuttings cost more but are more vigorous in growth (Johnson 1999). Longer cuttings would be used in areas with dry soils, as they hold more water and are less likely to dry out before roots are formed (Desrochers and Thomas 2003). Shorter cuttings are adequate for higher-quality sites.

Cuttings could be collected from a nursery and directly planted, but more typically they will require storage prior to planting. Cutting suppliers harvest and process the poplar cuttings at a nursery in winter and place them in **cold storage** until planting occurs in the spring. The cuttings are stored in plastic bags (figure 5.6) to maintain high moisture content at temperatures between 10°F and 28°F (-12°C to -2°C) . Poplar cuttings will arrive refrigerated from the nursery and should remain in cold storage until ready to plant. The cuttings should never be allowed to dry out, even for a short amount of time. The poplar cuttings should be kept cool and out of the sunlight so that the cuttings do not overheat. Keeping the cuttings cool can be challenging as they will be sealed in plastic bags.

To speed up the rooting process and to hydrate the cuttings, soak them in cold water just before planting (Johnson 1999). Two days of soaking is adequate for most varieties, refreshing the water daily (Desrochers and Thomas 2003).

Figure 5.6. Cuttings will arrive wrapped in plastic to maintain moisture. Photo: N. Haider.

Planting Poplar Cuttings

Poplar cuttings can be planted from late January to early May when soil temperatures approach 50°F (10°C) at 8 inches (20 cm). Poplars can be planted by machine or hand, but hand-planting is more common. An experienced farm labor crew can hand-plant two acres (0.8 ha) of poplar cuttings per person per day. Care should be taken to ensure that the cuttings are planted with the buds pointing up.

A **dibble bar** is a useful tool on the poplar plantation. It can be used in all types of soil, especially rocky soils where the insertion of the cuttings into the soil may be difficult. A dibble bar is made of strong metal. It has a horizontal handle at the top and a foot step to assist with driving the tool into the soil and to guide planting depth (figure 5.7).

Figure 5.7. A dibble bar is used to create holes in the soil where the poplar cuttings will be placed. Photo: N. Haider.

Soil Temperature Guides

Soil temperature can be found using a soil thermometer probe at your field site or by consulting data from local weather stations. Washington State University maintains soil temperature data from each county in Washington and select counties of Oregon and Idaho. The U.S. Bureau of Reclamation is another source for soil temperature data.

Washington State University— https://weather.wsu.edu/

Bureau of Reclamation AgriMet— https://www.usbr.gov/pn/agrimet/location.html

Dibble bars can be used to create a uniform planting pattern by maintaining the correct spacing for the poplar cuttings. Place a dibble bar at each end of the planting row and connect them with a thin cable. Premark the cable at specific intervals to achieve the required density. This allows the planting crew to easily identify the correct spacing for the cuttings (figure 5.8). Once the correct spacing is identified, another dibble bar is used to make a hole in the soil for the poplar cutting at each interval mark (figure 5.9). The planting crew will place one foot on the foot step and plunge the dibble bar into the soil to the desired depth, which should match the length of the cutting's uppermost bud. Since the location of the upper bud will not be uniform across all cuttings, the planting crew will need to make sure the hole's depth is the proper length for the cutting. On loose, well-prepared soils, the planting crew may be able to plunge the poplar cutting into the soil without the use of a dibble bar (figure 5.10).

Figure 5.8. Dibble bars that are connected by a thin cable that is stretched down the crop row. The cable is marked at three-foot (0.9 m) intervals so the planting crew can easily identify where to place the poplar cuttings. Photo: N. Haider.

Figure 5.9. Near Stanwood, WA, a dibble bar is used to make a hole in the soil for the poplar cutting. Photo: N. Haider.

Figure 5.10. At this well-prepared site in Clarksburg, CA, the poplar cuttings are easily pushed into the ground by hand. Photo: N. Haider.

To plant, insert the cutting to a depth that leaves a single bud exposed (figure 5.11). Gently step around the cutting to ensure the cutting makes good contact with the soil. This removes air gaps that could dry out the roots once they begin to sprout. Once the cutting is in place, it should be firm enough so that it does not wiggle or come out when pulled with two fingers.

Approximately six weeks after planting, leaves should be sprouting from the poplar cuttings (figure 5.12). The field should be checked for failed cuttings and replanted where necessary.

Figure 5.11. Cuttings should be planted at a depth that leaves only the uppermost bud exposed. Cuttings must be planted with the buds pointing up or they will not survive. Photo: N. Haider.

Figure 5.12. Eight weeks after planting, multiple shoots are sprouting on this hybrid poplar cutting. The lower shoots emerged from buds below the soil surface. Photo: N. Haider.

Timetable for Site Establishment and Planting

The following timetables represent activities and estimated dates for establishing a poplar plantation (figures 5.13 and 5.14). These timetables assume that planting will occur during the last week of March. Figure 5.13 provides time estimates for sites that were formerly hay fields, whereas figure 5.14 provides time estimates for sites that were formerly row crops. Some of the activities may not be necessary on all sites. Specific activities and timing will vary between farms and sites within a farm. For example, subsoiling may only be required if the field has a restrictive soil layer, forming planting beds is only necessary on wet sites, herbicide applications may vary, and all tilling activities should occur prior to subsoiling and bedding activities.

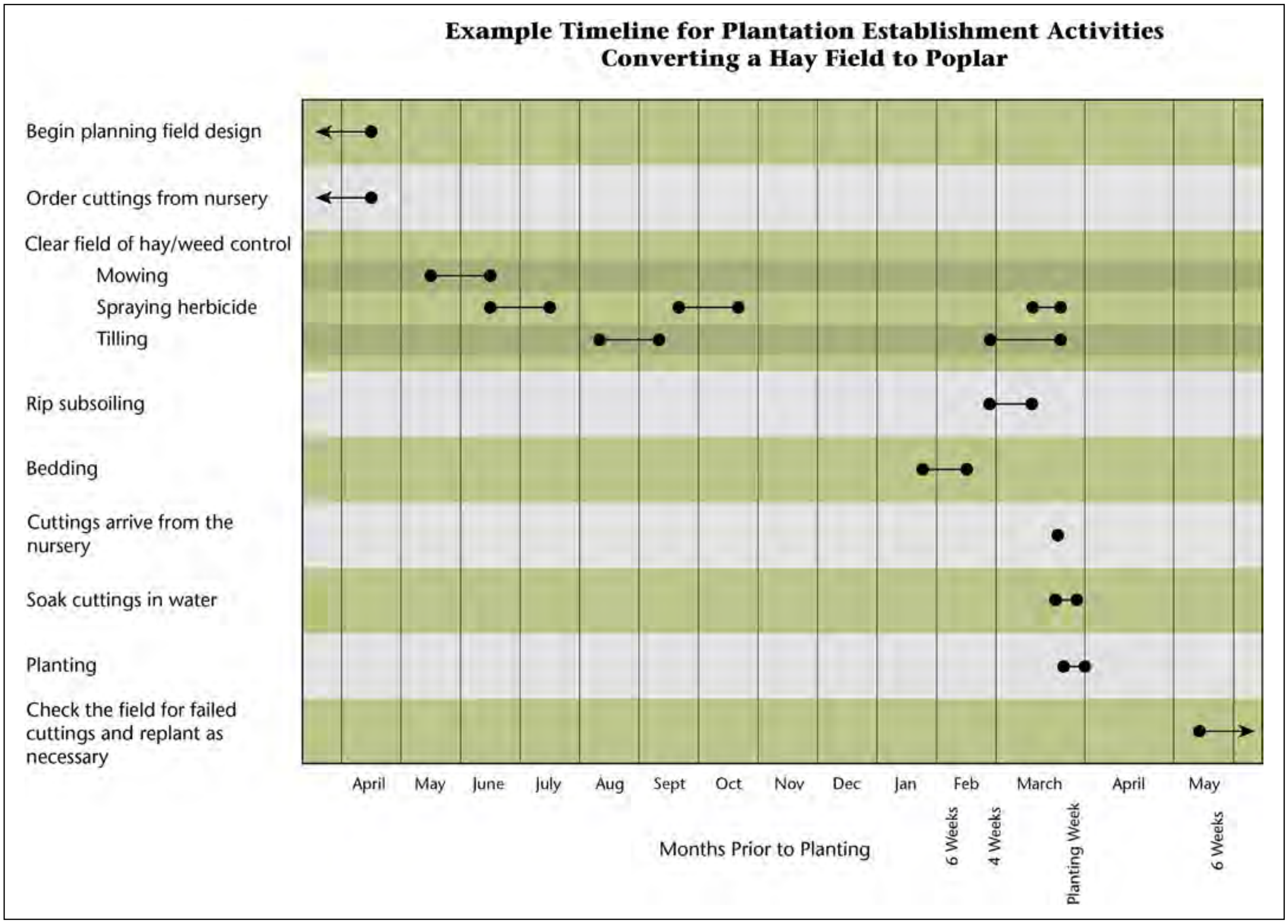

Figure 5.13. This is an estimated timeline for plantation establishment activities on sites that are being converted from a hay field to a poplar plantation. The given dates and order of activities are only an approximation and should only be considered as a general guideline for planning activities. Image: B. Nordaker.

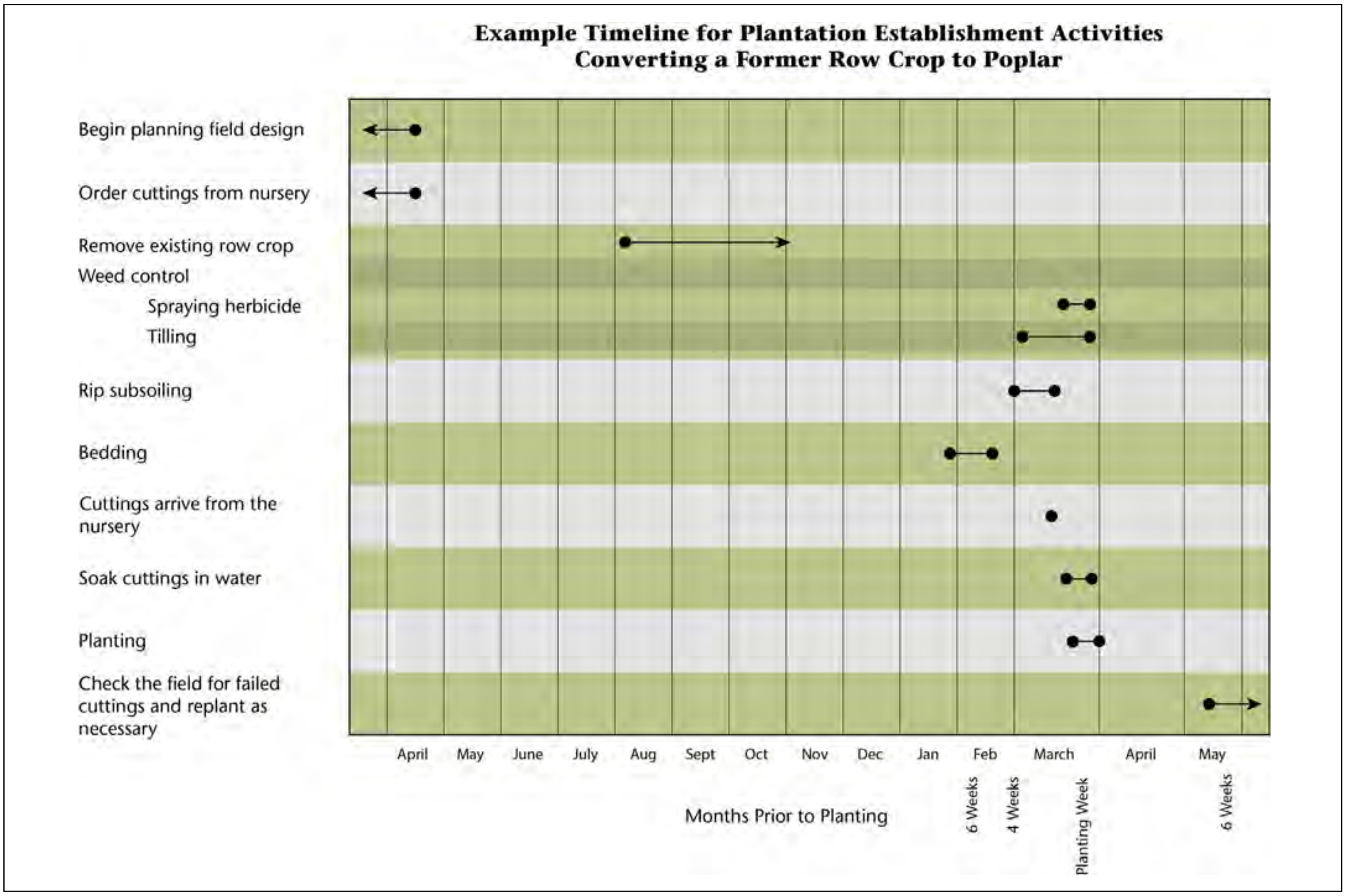

Figure 5.14. This timeline estimates plantation establishment activities on a site that was previously in a row crop. Directions for removing existing crops is beyond the scope of this manual but might include tilling, disking, and plowing as required to remove any debris and vegetation. The given dates and order of activities are only an approximation and should only be considered as a general guideline for planning activities. Image: B. Nordaker.

Preparing for a Second-Rotation Poplar Plantation

After six or seven coppice cutting cycles, around twenty years after the initial planting, the poplars should be completely removed as their **stools** may have declined to a point where stool mortality becomes an issue. Growers can then replant new cuttings using newer, higher-yielding poplar varieties. To begin preparing for the second planting, herbicide should be used to kill off the existing poplar crop and any other competing vegetation as described in Chapter 13. A single pass with a **mulching implement** should clear the site of any protruding woody debris. The majority of the root systems from the former crop can be left in place to decompose so that the soil structure is not disturbed. The field layout described in Chapter 4 should be adjusted so that the new poplar rows are planted in the former alleyways. By avoiding the former rows and leaving the roots of the older poplar intact, the land can be prepared by tilling and ripping the soil within the new crop rows as described earlier in the chapter. Tilling and ripping the existing rows would expose the roots of the former poplar crop and litter the field with excess debris.

Where to Find Farm Labor Contractors

WASHINGTON—Washington State Department of Labor & Industries
https://lni.wa.gov/workers-rights/farm-labor-contractors/farm-labor-contractor-licensing

OREGON—Oregon Bureau of Labor and Industries
https://www.oregon.gov/boli/employers/Pages/labor-contractor-licensing.aspx

IDAHO—Idaho Department of Labor
https://www.labor.idaho.gov/businesses/idaho-labor-laws/flc-registry/

CALIFORNIA—State of California Department of Industrial Relations
https://www.dir.ca.gov/dlse/dlse-databases.htm

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CHAPTER 6 | VEGETATION CONTROL

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Introduction

Vegetation control is among the largest cost factors in managing **hybrid** poplar plantations. A poplar planting will suffer poor growth or even widespread mortality due to its inability to compete for water, sunlight, and nutrients without carefully applied, complete, and timely control of competing vegetation. Effective vegetation management strategies typically comprise a combination of **mechanical** and **chemical controls**, which vary depending on climate, soil type, and the predominant species and extent of the vegetation to be controlled.

Site preparation and the **establishment period** are the most critical times for vegetation control, as competing vegetation will stifle hybrid poplar growth during the first two years after planting. After **canopy closure**, when the poplar **crowns** expand to the point of overlapping across the rows, the need for weed control is minimized due to shading.

Site Preparation

Site preparation consists of clearing debris from the planting site, eliminating residual vegetation, and improving soil **tilth** for **adventitious rooting** and growth. The field should be completely cleared of vegetation (figure 6.1) or cleared in planting strips (figure 6.2) before planting. Not only is site preparation crucial for reducing competing vegetation during the ensuing two years but it will also reduce soil compaction and increase the availability of nutrients and water by improving the quality or quantity of soil volume exploited by tree roots (Espinoza 2004).

The more time and preparation invested into controlling and preventing vegetation before planting, the easier and less expensive the vegetation control is the year following planting. When converting from pastureland or where there is perennial vegetation it is preferable to begin vegetation control the year prior to planting. In these cases, the recommended sequence of activities is to mow, apply herbicide appropriately, and then conduct mechanical **cultivation**. Additional herbicide or cultivation activity may be required to address persistent weeds. A **preemergent herbicide** application (see sidebar Sequence of Vegetation Control Activities for Converting Pasture or Hay Fields to Poplar) is the final activity prior to planting. If the field is coming out of

Figure 6.1. Recently established poplar in a weed-free environment near Clarksburg, CA, four months after being planted in March. Photo: N. Haider.

Figure 6.2. Establishment near Stanwood, WA, was done with a combination of mechanical and chemical vegetation control in the tree rows only, leaving the preexisting sod in the **alleyways**. Activities occurred in the fall and winter with planting following in late March. Photo: N. Haider.

grain or row cropping, a fall soil preparation followed by a preemergent herbicide will usually be adequate. If the time between harvest of the preceding crop and preparation for the poplar crop allows green-up of the field, an additional herbicide application may be needed.

Table 6.1 lists some recommended pesticide products for use on a poplar plantation. Always review labels and consult with local agronomy experts prior to herbicide applications. Knowledge of herbicides applied to the field in the years prior to poplar establishment is suggested as some herbicides can damage poplar through residual effects.

Sequence of Vegetation Control Activities for Converting Pasture or Hay Fields to Poplar

1. Mow the vegetation to stimulate active regrowth and deplete energy reserves in the roots (May or June the year before planting).
2. Allow vegetation to regrow for about two weeks, then apply a **postemergence herbicide** to kill the vegetation and discourage seed production (June or July). Herbicide is more effective when sprayed on actively growing vegetation.
3. Disk the field once the vegetation is dead (August or September).
4. Allow any subsequent vegetation to regrow and apply another round of postemergence, contact herbicide (September or October).
5. The following spring (March), disk the field to incorporate debris and remove any remaining vegetation from the winter.
6. Apply a preemergent herbicide, wait until the herbicide takes effect, and then plant (follow instructions on the label regarding the safe plant-back restriction) at the end of March or the beginning of April.

(See Chapter 5 for timeline of site preparation activities.)

Controlling vegetation in strips is common in Pacific Northwest (PNW) orchards and can be suitable for poplar plantations as well. In this method, a three- to eight-foot row is sprayed and disked in preparation for planting, as described previously. Alleyways, the areas between rows, are left in sod and are maintained through mowing (figure 6.2). If controlling vegetation in strips is chosen, it is important to regularly mow the alleyways so that sod cover does not disperse seed into the tree row. Figure 6.3 is an example of poor vegetation management using strips where reed canary grass overtook the site. Minimizing the tilled area will reduce erosion as well as the cost of site preparation. Controlling weeds in strips is especially beneficial on sites where it is difficult to maintain a completely clear field due to the presence of rocks, low-lying or poorly drained areas, or steep slopes with increased risk of soil erosion.

In some cases, strips may not adequately control competing vegetation and the entire field should be cleared. For example, ladysthumb (a.k.a. smartweed) (*Polygonum persicaria*), bull thistle (*Cirsium vulgare*), Himalayan blackberry (*Rubus armeniacus*), reed canary grass (*Phalaris arundinacea*), and field bindweed (a.k.a. morning glory) (*Convolvulus arvensis*) are particularly aggressive weed species that should be eliminated before planting poplars.

Figure 6.3. At this new poplar plantation near Stanwood, WA, the crop rows were sprayed with herbicide but were not tilled. Reed canary grass overtook the site by June. Photo: N. Haider.

Sequence of Vegetation Control Activities for Converting a Grain or Row Crop Field to Poplar

1. Disk the field after the previous crop is harvested (September–February).
2. Wait one to two weeks and apply a preemergent herbicide (September–February).
3. If any unwanted vegetation emerges in the spring, a postemergence herbicide may be necessary one to two weeks before planting (end of March or beginning of April).

Vegetation Control in Year One

Keeping the field clear of competing vegetation during the establishment year (figure 6.4) is important, as young trees are more sensitive to competition than trees that are more established. Spending more time to prepare a clean field is a much better option than having to resort to expensive and time-consuming vegetation control methods later. For example, after the trees are planted and still very small, weeds can grow as tall if not taller than the young trees (figure 6.5). Spraying herbicide around small trees engulfed by weeds is not a viable option because the trees may be damaged by inadvertent spray contact. Instead, the crop row must be cleared around each tree with a hoe (figure 6.6). This becomes very labor intensive and expensive.

Chemical Control

Herbicide, either alone or in conjunction with mechanical methods, is one of the most effective means to control unwanted vegetation. After planting, extreme care must be taken to prevent exposure to the trees when applying herbicide. Spot applications with backpack sprayers (figure 6.7) and tree shields should be used for vegetation control within the tree rows to protect the trees from herbicide damage. A tractor-mounted shielded sprayer is very efficient for alleyway vegetation control. It is important to continue monitoring competing vegetation to avoid competition during the growing season. If persistent weed growth reaches a height where spraying may cause damage to the trees, then the field should be mowed first. After mowing, wait until the vegetation is actively growing again, then apply herbicide according to the instructions provided on the product label.

Figure 6.4. Young poplar field with good vegetation control in July. Photo: R. Shuren.

Figure 6.5. Weeds within the crop row prior to mechanical control. Photo: R. Shuren.

Figure 6.6. To address weed pressure within the crop row, a labor crew manually cleared vegetation around the poplar trees. Photo: R. Shuren.

Figure 6.7. A backpack sprayer with a shield. Photo: N. Haider.

Herbicide selection depends on the type of vegetation, site conditions, and environmental risks. Examples of chemical products used for vegetation control in hybrid poplar are shown in table 6.1. Glyphosate is often a good choice as it is a **broad-spectrum herbicide** and a **systemic herbicide** that has little activity in the soil. The type and application rates of herbicides will vary from site to site based on the vegetation type and level of coverage. The Hybrid Poplar chapter of the *Pacific Northwest Weed Management Handbook* (Peachey 2021) is available online and offers recommendations for chemical weed control in hybrid poplar plantations.

Contact your local Extension agent or herbicide dealer for a technical recommendation appropriate for your site. *Always consult herbicide labels before application and adhere to all label instructions.*

Mowing

Mowing the alleyways between the tree rows is an important mechanical method for vegetation control, especially post-establishment. Although mowing will not eliminate competing vegetation, mowing makes it more manageable. In general, mowing between rows every four to six weeks during the growing season (if the soil is not too wet) will keep competing vegetation at a manageable height. To keep persistent weeds under control, herbicides can be applied to actively growing vegetation in the alleyways and within the rows using a tractor-mounted sprayer or backpack sprayers as described above. The postemergence herbicides listed in table 6.1 are suitable for this management strategy, but users must adhere to all label instructions.

Site conditions (e.g., slope, soil moisture, and soil texture) also dictate whether mowing is a viable option. If compaction is a concern, such as on wet, clay soils, mowing with heavy equipment is not recommended. In these conditions, chemical control applied with a backpack sprayer may be the only viable option.

Cultivation

Cultivation with small equipment can also be effective when used in combination with other vegetation control methods. Disking consists of using a series of small- to medium-diameter, saucer-shaped steel blades joined at the center of an axle that allows them to roll when the equipment is pulled by a tractor. A chisel is a frame with shanks that is dragged through the surface of the soil in the alleyways. Extreme care must be given when cultivating post-establishment, because the young poplar trees have very shallow roots that can be damaged. As the canopy closes, alleyway travel becomes difficult or nearly impossible with machinery (figure 6.8).

Table 6.1. Partial list of herbicides for use in poplar plantations in the PNW.

Common Name	Trade Name Example	Application
Dimethenamid-P	Tower	Preemergent
Dichlobenil	Casoron 4G	Preemergent
Sulfometuron methyl	SFM 751	Preemergent and postemergence
Glyphosate	Roundup Pro Concentrate and various others	Postemergence
Clopyralid	Clean Slate, Spur, Stinger	Postemergence

[1] Product labelled for use on poplars in the state of Washington west of the Cascades.

Weed Control after Canopy Closure

After the poplar canopy closes, usually in the second growing season, the resulting shade slows the growth of shade intolerant vegetation and competition declines. The canopy-closure shading is even more effective in the subsequent **coppice rotations** due to the multiple stems of the tree (figure 6.8). There may also be poplar leaf litter buildup that acts as a mulch to suppress other vegetation. Even if some non-crop vegetation does persist after **canopy closure**, the trees will have established root systems that have captured the site, and resource competition from other vegetation is minimal or nonexistent. Continued monitoring for competing vegetation is an ongoing activity after canopy closure, but vegetation control will be minimal, especially in the coppice rotations.

Postharvest Vegetation Control

After coppicing, the soil will be exposed to light again and competing vegetation should be managed similarly to years one and two. The competing vegetation will vary based on the chemical and mechanical control done during the previous years. To minimize damage to the trees, wait at least a month after harvest before applying herbicides. This allows the stump to heal over and become more impervious to herbicide uptake.

Figure 6.8. After canopy closure, filtered sunlight reduces ground-level vegetation and alleyway travel with machinery becomes difficult. Photo: N. Haider.

References

Espinoza, J. 2004. Site Selection, Site Preparation, and Weed Control for *Gmelina arborea* in Western Venezuela. *New Forests* 28 (2–3): 217–226.

Peachey, E., ed. 2021. Hybrid Cottonwood (Hybrid Poplar) Grown for Pulp. In *Pacific Northwest Weed Management Handbook* [online]. Corvallis, OR: Oregon State University. https://pnwhandbooks.org/weed/forestry-hybrid-cottonwoods/hybrid-cottonwood-hybrid-poplar-grown-pulp

CHAPTER 7 | INSECT DAMAGE IDENTIFICATION AND MANAGEMENT

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The Importance of Understanding Pests

Pest management requires accurate information on the biology and **life cycles** of pests that damage a resource at a specific location and time of the year. Not all **insects** and **mites** found on poplars are pests, and the abundance of some pests may never reach an **economic injury** level. This chapter is organized by injury type, focusing on injuries that impede maximum growth of poplars used for biofuels, pulp, and nonstructural lumber products. Injury from **abiotic** factors (e.g., mechanical injury or frost), **diseases**, and **vertebrate** pests should not be confused with insect damage. See Chapter 8 for more information on herbivory, especially **browse** damage from deer, and see Chapter 9 for information on diseases.

The purpose of this chapter is to provide basic diagnostic information to monitor and identify some of the most important insect pests of poplars. Once an insect pest is identified, growers should determine the potential of that pest to cause significant damage to their crops. Management control strategies are suggested for situations where a response is deemed necessary.

Additional resources are available for readers interested in more in-depth study of hybrid poplar pests. The WSU Extension Publications Store (https://pubs.extension.wsu.edu/extension-publications) carries a publication that covers poplar insect pests in the Pacific Northwest (PNW) in greater detail as well as additional resources related to individual PNW hybrid poplar insect pests.

Leaf-Damaging Insects

Fall Webworm

(*Hyphantria cunea* Drury; Lepidoptera: Arctiidae)

Webbing (figure 7.1) is indicative of fall webworm infestation (Rodstrom and Brown 2017a). This gregarious herbivore remains within the webbing during daylight hours to avoid bird predation, venturing out of the protective web at night to feed. Left untreated, webworm populations can cause extensive **defoliation**, significantly decreasing biomass yield. Initial infestations can be physically removed by pruning the branch containing the web and either burning the infested branch or shredding it and disposing of the shredding waste off-site. If chemical control efforts are needed, the developmental stage of the **larvae** must be determined. See *Fall Webworm: Insect Pest Management in Hybrid Poplars* (Rodstrom and Brown 2017a) for more information (https://pubs.extension.wsu.edu/search?q=FS275E).

Figure 7.1. A poplar tree with webbing associated with fall webworm infestation. Photo: R.A. Rodstrom.

Sawflies

(Various spp.; Hymenoptera: Tenthredinidae)

Shot hole and edge-of-leaf damage (figure 7.2) is often caused by sawfly larvae feeding. Four different sawfly genera attack poplars in the PNW; *Nematus* spp. and *Pontania* spp. are the most common, but *Fenusa* spp. and *Halidamia* spp. are equal in their potential to cause damage. Entire stands can be defoliated. Sawfly larvae can be identified by a dark **eyespot** on the head (figure 7.3) and the lack of **crochets** on their **prolegs** compared to Lepidoptera larvae.

Figure 7.2. Shot hole and edge-of-leaf damage from sawfly larvae feeding. Photo: J. Brown and R.A. Rodstrom.

Figure 7.3. Close-up of the simple eye spot on the lateral side of the head of a sawfly larva. Photo: J. Brown and R.A. Rodstrom.

Cottonwood Leaf Beetle

(*Chrysomela scripta* F.; Coleoptera: Chrysomelidae)

Cottonwood leaf beetles deposit their yellow egg masses on the undersides of new leaves (figure 7.4). Early **instar** larvae are dark in color, feed in aggregations, and skeletonize the leaf. Larger cottonwood leaf beetle larvae move upward and outward on the branch, feeding and defoliating (figure 7.5). Pupation occurs on the stem, close to where larvae have fed (Carlson et al. 2017). Adults **eclose**, mate, and disperse to new growth on nearby trees. See *Cottonwood Leaf Beetle: Insect Pest Management in Hybrid Poplars* (Carlson et al. 2017) for more information (https://pubs.extension.wsu.edu/search?q=FS278E).

Figure 7.4. Cottonwood leaf beetle egg mass on the underside of a leaf. Photo: J. Brown.

Figure 7.5. Cottonwood leaf beetle larvae, second and third instars. Larva on right is actively exuding salicylaldehyde as a chemical defense against predators. Photo: J. Brown and R.A. Rodstrom.

Gluphisia

(*Gluphisia septentrionis* Walker; Lepidoptera: Notodontidae)

Initial skeletonization of the leaf surface followed by severe defoliation radiating away from the initial infestation and leaving only the midrib of each leaf is indicative of feeding damage by *Gluphisia* (figure 7.6) (Del Pozo-Valdivia and Brown 2017). *Gluphisia* are gregarious feeders, and large populations can be clumped in their distribution. *Gluphisia* populations can increase to damaging levels after one or two years. Monitoring populations of *Gluphisia* is essential, and control measures should target early instar larvae to avoid unintended harm to beneficial **arthropod** biological control agents. When larvae evade detection and populations grow, large outbreaks occur. At this point in time, *Gluphisia* can be controlled with several broad-spectrum **insecticides**. See *Gluphisia septentrionis Walker: Insect Pest Management in Hybrid Poplars* (Del Pozo-Valdivia and Brown 2017) for more information (https://pubs.extension.wsu.edu/search?q=FS271E).

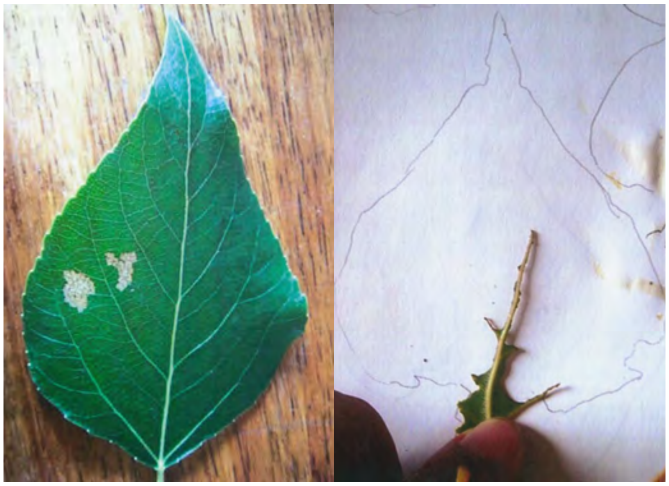

Figure 7.6. First instar *Gluphisia septentrionis* skeletonizing the leaf (left photo), and later instar damage leaving only the midrib of the leaf (right photo). Photos: A. Del Poso-Valdivia.

Lace Bug

(*Corythucha* spp.; Heteroptera: Tingidae)

Lace bug **nymphs** feed in aggregations on the undersides of leaves (figure 7.7), and this pest can seriously damage *Populus* spp. leaves west of the Cascade Mountains (figure 7.8). Growers can recognize lace bug infestations by bronzing of areas on the top of the leaf and areas of brown **necrotic** tissue on the underside of the leaf that is often accompanied by both fecal residue and cast exoskeletons. Infestations may require control efforts in midseason. See *Lace Bugs: Insect Pest Management in Hybrid Poplars* (Rodstrom and Brown 2017b) for more information (https://pubs.extension.wsu.edu/search?q=FS274E).

Figure 7.7. Lace bug nymphs (*Corythucha* spp.) feeding on the underside of a leaf. Photo: R.A. Rodstrom.

Figure 7.8. Individual leaf showing the resulting damage and sign of lace bug nymphal feeding. Photo: R.A. Rodstrom.

Stem-Damaging Insects

Western Poplar Clearwing Moth

(*Paranthrene robiniae* Hy. Edwards; Lepidoptera: Sesiidae)

Gall-like swelling of a small stem (figure 7.9), possibly with an exit hole and small, chunky, sandy-textured **frass** (waste product of the **gallery** boring), is indicative of a western clearwing moth larval gallery (Kittelson and Brown 2017). Large populations of western poplar clearwing moths can girdle or weaken poplar propagation cuttings, making the cuttings susceptible to wind **lodging** (Brown et al. 2006). Control measures are limited to **mating disruption** by saturation of the area with a synthetic sex **pheromone** specific for this moth. See *Western Poplar Clearwing Moth: Insect Pest Management in Hybrid Poplars* (Kittelson and Brown 2017) for more information (https://pubs.extension.wsu.edu/search?q=FS266E).

Figure 7.9. Western poplar clearwing moth larva within a poplar branch. Note the chunky, sandy-like frass in the gallery. Photo: J. Brown and R.A. Rodstrom.

Carpenterworm Moth

(*Prionoxystus robiniae* Peck; Lepidoptera: Cossidae)

A large exit hole and gallery with chunky frass is indicative of a carpenterworm moth infestation (figure 7.10). Generally, these large Cossidae moths preferentially attack trees three years old or older and should not be a concern in short-cycle biofuel feedstock plantings. See *Carpenterworm Moth: Insect Pest Management in Hybrid Poplars* (Hannon et al. 2017) for more information (https://pubs.extension.wsu.edu/search?q=FS256E).

Figure 7.10. Mature carpenterworm larva within gallery. Photo: J. Brown.

Figure 7.11. Poplar-and-willow borer larva within stem with stringy frass. Photo: F. Stergulc, Università di Udine, Bugwood.org.

Poplar-and-Willow Borer

(*Cryptorhynchus lapathi* L.; Coleoptera: Curculionidae)

An exit hole without a gall-like expansion of a small stem and with stringy rather than chunky frass indicates a poplar-and-willow borer larval gallery (figure 7.11) (Hannon and Brown 2017). **Clone** parentage can influence the susceptibility of stems to this borer. Stringy versus chunky frass helps to differentiate this pest from similar pests (see sidebar Frass and Exit Hole Comparison). See *Poplar-and-Willow Borer: Insect Pest Management in Hybrid Poplars* (Hannon and Brown 2017) for more information (https://pubs.extension.wsu.edu/search?q=FS267E).

Figure 7.12. Waxy protective cover of mature oystershell scales on the bark of hybrid poplar. Photo: J. Brown and R.A. Rodstrom.

Oystershell Scale

(*Lepidosaphes ulmi* L.; Hemiptera: Diaspididae)

Gray, mottled bark is the result of waxy secretions that cover mature oystershell scales (figure 7.12). Females lay eggs under the shell-like protective layer. These eggs hatch to a “crawler” stage of individuals less than a millimeter in length that spread the infestation to other parts of the host tree or to other trees. This mobile stage occurs in late May and early June. An application of dormant oil, if registered for use, in the early spring or a registered horticultural oil applied at a growing season (reduced) rate can control scale populations in May and June. An application of an imidacloprid product (e.g., Admire Pro), if registered for use, is another highly effective treatment option. Scale populations can build for several years before tree vitality suffers, but, eventually, the tree may be killed.

Frass and Exit Hole Comparison

Western Poplar Clearwing Moth

Small exit hole; small, chunky frass

Carpenterworm

Large exit hole; chunky frass

Poplar-and-Willow Borer

Small exit hole; stringy frass

Pest Monitoring

Insect development through the stages of egg hatch, larval pupation, and adult emergence is temperature sensitive. A **degree day** model enables the pest manager to predict when the first adults will be observed. Once identified, that date becomes the **biofix** for additional accumulated degree days (ADD) data. The additional ADD information will then predict when various developmental stages of that pest species can be expected during the growing season. For example, western poplar clearwing moths in eastern Oregon can be expected after the accumulation of 123 ± 8 ADD. Carpenterworm moths can be expected after accumulation of 108 ± 6 ADD. This knowledge can be used to time treatments to most effectively lower pest populations. Data on surface and subsurface temperature and moisture content are available through AgriMet, beginning each growing season (https://www.usbr.gov/pn/agrimet/location.html).

Pheromone-Baited Traps

If a synthetic sex pheromone for a pest is available, the use of either baited delta or bucket traps (figure 7.13) provide the easiest method to sample a specific pest population. Traps used to detect male moths can be distributed at a rate of one trap per 160 acres of trees. These traps need to be deployed several weeks before bud break. Traps should be monitored once a week throughout the growing season or until no targeted moths have been captured for three consecutive weeks.

Light Traps and Black Light Traps

Large light traps using a 250 watt clear ED28 mercury vapor bulb can be used to sample nocturnal moths. Smaller commercial black light traps are also effective (figure 7.14). A simpler, less expensive strategy is to hang a light in front of a white fabric sheet (figure 7.15). Moths attracted to the light will land on the sheet and can be collected and identified. This method requires constant monitoring, though, which increases the labor needed compared to the mobile light trap.

Pitfall and Sticky Traps

Pitfall traps are an easy method to sample ground insects. Each is constructed by excavating a hole in which an eight inch (20 cm) section of two inch (5 cm) diameter PVC drainage pipe is placed. This length maintains the integrity of the hole and provides support for the trap cup. Traps are 296 ml cups partially filled with soapy water (figure 7.16). A teaspoon of liquid soap can be used as a surfactant to break down the surface tension of the water such that small individuals are more likely to be caught and retained (Rodstrom 2013). Yellow sticky trap cards (figure 7.17) are another inexpensive means to sample flying insects not attracted to light or pheromone traps.

Figure 7.13. Large delta trap on the left versus a plastic bucket trap on the right. Both are baited with 1 mg of synthetic sex pheromone for a specific pest species. Photo: R.A. Rodstrom.

Figure 7.14. A bucket equipped with a light socket for trapping nocturnally active insects. Photo: R.A. Rodstrom.

Figure 7.15. Hanging a light in front of a white sheet is a simple, inexpensive way to trap nocturnally active insects. Photo: E. Coombs, Oregon Department of Agriculture, Bugwood.org.

Visual Surveys

No monitoring technique is as important as weekly growing-season surveys. Weekly observations should be reviewed to determine where additional surveys are needed the following week. In late autumn after leaf fall, an annual survey should target infestations of stem and bark pests. Poplar-and-willow borer and western poplar clearwing moth populations are best monitored after trees have dropped their leaves in the autumn.

Figure 7.16. A pitfall trap set in the ground as a passive method to sample ground insects. Photo: J. Brown and R.A. Rodstrom.

Figure 7.17. A yellow sticky card used as a passive trap for small flying insects. Photo: R.A. Rodstrom.

Recommended Management Practices

An Integrated Pest Management (IPM) approach requires an understanding of the following:

Economic injury level is where a crop's loss in yield or value would be equal to or exceed the cost associated with management efforts, thus warranting pest control.

Economic threshold represents a pest density where a management effort can prevent an increasing pest population from reaching an economic injury level.

Treatment threshold indicates the approximate density of pests that requires treatment.

The economic threshold of some pests will be lower than the economic threshold for others. A key consideration is the value of the crop. Defoliation of a biofuel stand results in a loss of biomass and should be minimized. In contrast, borer damage to stems after the first year of growth is unlikely to cause wind lodging, and, if populations are small, the value of harvested chips or biomass is not diminished. In general, hybrid poplars grown on short rotations for pulp or biofuel represents a relatively low investment such that less should be spent on protecting the crop yield compared to higher investments in hybrid poplars grown for roundwood.

Prevention

The number one defense against a pest population is to prevent problems by sustaining healthy plant growth. Optimizing planting density, fertilization, soil pH, and adequate water should be a goal for all growers. Optimum conditions for hybrid poplar are described in Chapters 3, 6, and 10. Proper clone selection is also important for preventing pest problems. Different clones have different levels of resistance to specific pests. For example, hybrid poplars with *P. maximowiczii* parentage are less susceptible to *C. lapathi* attack than clones with the highly susceptible *P. trichocarpa* parentage (Broberg and Borden 2005; Hannon et al. 2008). Clones of the *P. deltoides* × *P. nigra* taxon are susceptible to *C. lapathi*, but not as much as those with *P. trichocarpa* parentage (Hannon et al. 2008).

Sanitation

Lodging of trees weakens their resistance to pest invasion. Once infested, these trees increase the chances that proximate healthy trees will be attacked. Thus, removing downed trees for sanitation helps protect the health of the stand. Sanitation needs to occur before pests emerge and infect surrounding trees. Any infestation that occurs during the growing season should be removed before the pest emerges the next growing season. It is best to have this done before April 1.

Biological Control

There are no commercial, pest-specific **biocontrol** agents available for purchase by hybrid poplar growers. However, minimal, or at least judicious, use of insecticides can favor increases of endemic populations or emigrating biocontrol agents.

Pheromone Strategies

Pheromone strategies may be useful for controlling some Lepidopteran insect pests. For instance, preliminary research has shown that a **male confusion** strategy of saturating hybrid poplar plantings with female sex pheromone lowers the overall western poplar clearwing population (Kittelson and Brown 2017). Male confusion works by either delaying or preventing mating such that the females are unable to lay fertile eggs.

Pheromones can also be used for trapping insect pests. For example, bucket traps can be baited with 1 mg of synthetic pheromone to attract male carpenterworm moths. This can delay or prevent mating by reducing the number of males in an area. When using traps to reduce the pest population as part of a control strategy, as opposed to using traps only as a detection tool, some states may require the pheromone bait to have a pesticide registration for that use.

Judicious Use of Pesticides

Always check current registration labels for pesticides that can be used on poplars in the PNW. Currently, Idaho, Oregon, and Washington allow the registered use of several active ingredients to protect tree pulp and wood production. Broad-spectrum insecticides registered for use include three organophosphate insecticides (acephate, chlorpyrifos, and dimethoate), one carbamate (carbaryl), and two synthetic pyrethroids (lambda-cyhalothrin and gamma-cyhalothrin). More selective insecticides include three systemics (two neonicotinoids, imidacloprid and dinotefuran; and emamectin benzoate), two biopesticides (spinosad and *Chromobacterium subtsugae* strain PRAA4-1), two inorganic compounds (kaolin clay and iron phosphate formulated as a bait for slugs and snails), and one sex pheromone (E,Z-3,13-octadecadien-1-ol/Z,Z-3,13-octadecadien-1-ol blend).

Pesticide licenses are required for applying or supervising the application of general use pesticides. **Restricted-use pesticides** (RUP) require a license of the correct type and classification to buy the product. All individuals involved in pesticide application should undertake pesticide safety training and acquire the proper applicator's license.

This publication contains insecticide recommendations that are subject to change at any time. The recommendations herein are provided as a guide. It is always the pesticide applicator's responsibility to read and follow all current label directions for the specific pesticide being used. The label always takes precedence over the recommendations found in this publication.

Summary

A variety of insect pests can cause injury to hybrid poplar plantations in the PNW to the point of economic loss to the grower. It is critical for the grower to be able to correctly identify the damaging agent and be able to assess if and when a pest population should be controlled. Insecticides should be used judiciously and minimized as much as possible. Careful monitoring and cultural practices that focus on prevention are key to an effective pest management strategy.

Additional Recommended Reading

Brown, J.J., and R.A. Rodstrom. 2017. Poplar Satin Moth: Insect Pest Management in Hybrid Poplars Series. *Washington State University Extension Publication* FS277E. Washington State University.

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CHAPTER 8 | DEER AND VOLE HERBIVORY

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Introduction

Poplar plantations can be prime habitat for deer and vole species (figure 8.1). Herbivory by deer and voles can potentially result in economic damage for the grower of short-rotation coppiced poplar and may be one of the greatest impediments to the establishment of a successful plantation (figure 8.2). The extent of damage is dependent on a number of factors, the most important of which is pest population density. The extent of animal movement throughout the plantation is affected by the seasonal availability of other food sources and water, the proximity of refuge, the territory of mates and family members, natural predation pressure, and the animal's assessment of the risk of predation. Before plantation establishment, it is important that the grower make a thorough assessment of wildlife populations in the area based on field observations in order to more knowledgably estimate the capital expenditures that will be required to implement either repellent, poison, harassment, **lure crops**, or exclusion technologies. Regular monitoring of deer and vole populations is important so that a pest management plan can be developed before too much damage is incurred and a response plan is needed. The costs associated with implementing a pest management strategy are typically balanced against estimates of crop loss and the crop's market value. Some technologies such as exclusion fencing can require substantial costs. Given that markets for coppiced poplar chips in the bioproducts and biofuels industries in the Pacific Northwest (PNW) are being developed and prices for delivered chips are not well established, we cannot recommend a particular pest management technology to offset a particular level of crop loss for all plantation sizes. The goal of this chapter is to assist the grower in considering various pest management options.

Deer Damage

Unfenced plantations adjacent to woodlands where deer find refuge can be particularly susceptible to **deer browse**. Consumption of the first tender **shoots** emerging from stick plantings in a new plantation can set back the establishment of a main leader and may severely retard plant development or kill the plant (figure 8.3). During the seedling and stick planting stages, poplar are most susceptible to herbivores; however, newly emerged shoots from a **root collar** are also vulnerable to browse after **coppicing**—and coppicing occurs every second or third year. Deer may feed on shoot tips or leaves lower on the stems depending on the **hybrid** poplar

Figure 8.1. The lush foliage of a poplar plantation provides ample food and cover to deer and vole populations. Photo: N. Hart.

Figure 8.2. Deer consuming foliage at a young poplar plantation near Stanwood, WA. Photo: J. Kallestad.

genotype and tree age. In more mature plantations (second and third year of a three-year rotation), evidence of deer herbivory may be found throughout the tree, such as missing or partially chewed leaves with **petioles** still attached to the stem (figure 8.4) or bare stems with partially browsed leaves. Male deer will also damage stems by rubbing their antlers on them (figure 8.5). Rubbing damages the tree's vascular system, disrupting the pathways that carry water, minerals, and sugars between the roots and the leaves. If the bark damage is all the way around the tree, it will most likely die (Schiess, n.d).

Deer Management

As with all pest management, rarely is there one "silver bullet" approach. Rather, an integrated approach, utilizing all of the management tools available in a cost-effective manner, is usually the best. Cultural techniques are methods that manipulate wildlife habitat in and around the plantation. Lure crops have often been used to reduce deer damage to agricultural crops. The lure crops provide an alternate food source and may lure the deer away from the plantation, at least for a period of time until the trees have grown higher than deer can browse. A perennial crop, such as alfalfa, may be a suitable lure crop that could be planted around a poplar plantation. Another cultural method would be, as much as possible, to strategically position the plantation within the landscape. Establishing plantations adjacent to areas of high deer density, such as a forest or stream where well-worn animal trails are evident, may result in more damage to the plantation.

For **chemical control**, deer repellents can be applied to the trees to reduce browsing damage. Repellents that are protein-based (e.g., blood or egg) seem to be the most effective deterrent for deer. Commercially available products such as Plantskydd have been shown to be effective at minimizing deer browse on hybrid poplar (Moser 2000) and conifer plantations (Trent et al. 2001). Repellents should be applied on a regular basis in response to the tree's fast growth and environmental degradation of the repellent (e.g., repellent getting washed off by rain over time). Repellents do not necessarily keep deer out of an area, but they can keep deer from browsing treated trees. Growers need to make sure the deer repellents they are using are registered in their state and that the product labels are adhered to, as the use of wildlife repellents are governed by state pesticide laws.

Physical control techniques include barriers to keep deer from browsing trees and reduction of the deer population through hunting. Fencing is probably the most effective method to keep deer from browsing plantations (figure 8.6). However, fencing can be costly to install and maintain. Growers also need to

Figure 8.3. Deer browse severely impacted the growth of the main stem of this poplar tree. Photo: N. Haider.

Figure 8.4. Missing shoot tips and missing leaves with leaf petioles still attached to the stem are evidence of deer browse. Photo: J. Kallestad.

Figure 8.5. Male deer will rub their antlers against trees to remove the velvet that has been growing on their antlers over the summer. Photo: N. Haider.

Figure 8.6. Typical deer exclusion fencing at a hybrid poplar plantation in Washington. Photo: N. Haider.

Figure 8.7. Staked nylon mesh tubes can be applied to protect terminal buds from browse. Photo: K.W. Zobrist.

consider the space requirements for operating harvest machinery within a fenced area and plan for appropriate setbacks. A variety of deer fences are commercially available. Growers should consider the longevity and maintenance costs associated with synthetic netting materials versus wire mesh. Fences should be at least seven feet (2.5 m) tall with the bottom next to the soil. Barbed wire should be avoided. Because deer seem to have difficulty seeing fencing, it is recommended that reflective flagging such as bird deterrent Mylar streamers or reflectors be installed to prevent injury by entanglement. The key to preventing deer injury is to make the top wire of the barbless fencing highly visible. Reflectors arranged in patterns described in *A Landowner's Guide to Fences and Wildlife: Practical Tips to Make Your Fences Wildlife Friendly* (Paige 2012) may last longer than plastic flagging and Mylar tape.

Another type of barrier is nylon mesh that can be applied over terminal buds, thus impeding deer from browsing (Moser 2000) (figure 8.7). Mesh barriers need to be checked and adjusted often during the growing season due to rapid tree growth.

Hunting can be an effective way to reduce the local deer population, as browse damage is heavier when deer populations reach high densities. Growers may be able to partner with local sportsman clubs to provide access and encourage seasonal predation.

Genetic control of biochemical factors that affect the palatability of poplar foliage to deer is poorly understood (McArthur et al. 1993). While there have been numerous controlled feeding studies and plantation damage surveys that have demonstrated that deer seem to have preferences or aversion for particular genotypes of hybrid poplar (Christian 1997; Netzer 1984; Verch 1979), the combinations of chemical compounds thought to be responsible for these behaviors do not consistently explain observed herbivory. Complicating matters, the array and concentrations of chemical compounds in leaves potentially responsible for attraction or repulsion change over the growing season and from year to year as the trees age. Deer may browse shoots from young plantings but avoid the leaves of the same variety when the trees are more mature. Deer also change their forage preference throughout the growing season as other foods become seasonally available. Hence, growers may have few options in selecting poplar varieties that are considered less deer-palatable as part of their pest management strategy. While there are research reports that suggest certain hybrid taxa seem to be generally more deer-resistant, a grower's varietal selections should also be based on growth rate parameters, insect resistance (which may not align with deer avoidance), and product characteristics such as low **lignin**, high **hemicellulose**, and high sugar content wood chips.

Vole Damage

Voles (*Microtus* spp.) are small rodent herbivores, larger than mice but smaller than rats, which can give birth to several litters of young per year (figure 8.8). In optimal conditions their population can increase exponentially, but they also exhibit cyclical year-to-year patterns of growth and decline. When their density is high, voles can cause economic damage by girdling the bark and phloem of tree seedlings and shoots at the base. Voles also feed on and damage roots. Vole damage can happen at any stage of the plantation rotation, but the conditions are ideal for population explosion after coppicing, when there are multiple stems emerging from the root collar and an accumulation of leaf litter around the stems. This post-coppicing environment provides ample food, nesting material, and cover from predators. This environment also allows other food sources that voles consume, such as grasses and forbs, to get established between closely spaced trees before they are excluded by shade. Evidence of vole damage can include patches of exposed wood at the base of the stems (figure 8.9) or dead stems due to bark girdling. Partially girdled stems are also susceptible to **lodging** from wind or invasion by fungal **pathogens**.

Figure 8.8. Voles have short legs and tails; stout, compact bodies; coarse brown or gray fur; small, round ears; and are typically 4.5 to 5.5 inches (11.5 to 14 cm) long, including the tail. Photo: J. Kallestad.

Figure 8.9. Rodents, such as voles, will eat the bark at the base of poplar trees. Vole damage can impact tree growth and make the tree susceptible to disease and decay. Photo: B. Moser.

Vole Management

An integrated approach to managing vole damage will usually work the best, utilizing a variety of cultural, physical, chemical, biological, and genetic controls to reduce vole damage to plantations (Moser 1999). The best vole management strategy in the early phase of plantation establishment is cultural control of grass and other vegetation between trees with mowing or by herbicide application (see Chapter 5 for more information and specific recommendations on proper **site preparation**).

Chemical controls include several poisons to decrease populations—for example, anticoagulant rodenticides, which are slow-acting, **restricted-use pesticides**. These products are limited to certain landscapes. Anticoagulants are environmentally toxic to fish and aquatic animals, and they can indirectly kill beneficial vole predators, such as owls, raptors, bobcats, foxes, dogs, coyotes, and weasels, when voles are consumed as prey. Zinc phosphide vole bait, also a restricted-use pesticide for poplar plantations, is more fast-acting and does not accumulate in body tissues, making it safer for vole predators. However, it can affect other non-target wildlife through direct contact. Information on **special local need** (SLN) label restrictions for zinc phosphide and anticoagulant rodenticide use in Oregon and Washington can be found at the Pesticide Information Center Online (PICOL) Database at https://picol.cahnrs.wsu.edu/. For information on rodenticide use restrictions in Idaho or California, contact the Idaho State Department of Agriculture or the California Department of Pesticide Regulation.

An alternative, passive approach might be to support biological control measures by providing vole predator microhabitats, such as the establishment of small forested patches along the northern and western borders of the plantation that would allow hawks, eagles, owls, and kestrels to nest and perch while minimizing shading effects on the plantation (Bottorff and Zobrist 2013). Such microhabitats could be expanded to provide refuge for bobcats, foxes, and coyotes as well. Perch poles (figure 8.10) made from logging debris or scrap wood could be erected temporarily throughout the plantation and removed before harvest.

Similar to deer, studies have shown that voles do have preferences and aversions for particular poplar species and hybrids, but the reasons are poorly understood. Bark palatability results from a complex interplay of plant defensive compounds and nutritional factors that change throughout the growing season and as the trees age year to year. Since there are no verified vole-resistant poplar species or hybrids known at this time, it is difficult to support varietal selection as part of a pest management strategy.

More information on vole management and rodenticides can be found online at https://www.epa.gov/rodenticides/restrictions-rodenticide-products.

Figure 8.10. Perch poles may encourage vole predation by raptors. Photo: K.W. Zobrist.

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CHAPTER 9 | DISEASES OF HYBRID POPLAR PLANTATIONS IN THE PACIFIC NORTHWEST

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Introduction

When it comes to **diseases** that cause significant damage to **hybrid** poplar, most can be mitigated or avoided by choosing disease-resistant **clones**. **Pathogens** native to the Pacific Northwest (PNW) affect the common native host, *Populus trichocarpa* (T). These native, pathogenic diseases can then infect the interspecific hybrids: *P. trichocarpa* × *P. deltoides* (T×D), *P. deltoides* × *P. trichocarpa* (D×T) (T×D and D×T are officially known as *P.* ×*generosa*), *P. trichocarpa* × *P. maximowiczii* (T×M), and *P. trichocarpa* × *P. nigra* (T×N). Disease may be prevented by avoiding T hybrid clones; however, *P. trichocarpa* may bring other desirable traits to hybrids that can outweigh potential disease issues. A grower might also bear in mind that low levels of the spring disease *Venturia* blight or leaf **rust** late in the growing season might be tolerable if they have little to no effect on growth. This chapter will discuss how hybridization and controlled breeding result in disease-resistant clones and describe the common diseases that are easily controlled by selecting appropriate hybrid clones. Recommendations of particular clone types for disease resistance are also suggested.

Hybridization and Disease Resistance

The PNW region has both hybrid poplar plantations and natural, riparian populations of the native black cottonwood, *Populus trichocarpa*. Pathogens cause diseases which have mostly been much less common in hybrid poplar plantations of the region than in natural populations. Hybrid poplar has been present in the region for about four decades, and during this time, three phases can be distinguished with respect to disease: (1) a first phase in which T×D hybrids were the main hybrid type and were more resistant to disease than native black cottonwood, (2) a relatively brief phase in the early 1990s in which T×D hybrids were more susceptible to rust disease than native trees, and (3) a third, and continuing, phase in which hybrids of various types are again more resistant to disease than native cottonwood populations.

Diseases in natural cottonwood populations have remained largely the same over the years. Some spillover of pathogens from hybrid poplar plantations to natural populations has occurred, and the examples of this phenomenon will be noted in the disease descriptions below. To expand on the brief history given above, in the 1980s and 1990s, crosses between female trees of *Populus trichocarpa* and male trees of *Populus deltoides*, the eastern North American cottonwood, allowed poplar breeders in the region to select and multiply highly productive and relatively disease-free clones for hybrid poplar plantations (Newcombe et al. 2001a). Although *Populus trichocarpa* is host to many pathogens in the PNW (Newcombe 1996), for the most part, these pathogens do not affect plantations with T×D hybrids.

It is worth emphasizing again that the T×D and D×T hybrids are sometimes denoted as *Populus* ×*generosa*, particularly in the scientific literature. They are sometimes also called interamerican hybrids since both parental species are native to North America. They are distinguished from their Euramerican counterparts that represent crosses of North American *P. deltoides* and European *P. nigra*.

In the early 1990s, things changed with the arrival of a new rust disease, *Melampsora medusae*. *Melampsora occidentalis* had always been in the region as the native rust fungus on *Populus trichocarpa*. The T×D hybrids had been resistant, though. With the introduction of *Melampsora medusae* (Newcombe and Chastagner 1993b) and subsequent hybridization of it with native *M. occidentalis* (Newcombe et al. 2000), T×D hybrids that had been resistant were suddenly susceptible, and mortality was commonly observed (Newcombe et al. 1994). Pathotypes of the hybrid rust became so varied that resistant clones would lose their resistance in the middle of a rotation (Newcombe et al. 2001b). By the mid-1990s it was clear that hybrids other than the T×D type would have to be used.

Genetic analyses in the 1990s had shown that species of *Populus* from outside the PNW provided genes for resistance to *Melampsora* rust and to other PNW cottonwood diseases (Newcombe and Bradshaw 1996; Newcombe et al. 1996; Newcombe 1998a, 2005). Ever since, new hybrid types such as *Populus deltoides* × *Populus nigra* (i.e., D×N, also known as *Populus* ×*canadensis* and *Populus* ×*euramericana*) and *Populus deltoides* × *Populus maximowiczii* (i.e., D×M) have been of increasing interest to poplar growers. The small-leaved D×N clones also provided more resistance to the wind and temperature extremes found east of the Cascades in the inland PNW.

Today, when choosing clones to plant, hybrid poplar growers should always choose disease-resistant varieties to try to avoid the difficult decisions that need to be made when disease strikes in the middle of a rotation. It should be noted that the "middle-of-a-rotation" problem may vary with rotation length (e.g., the problem may not be evident in mini-rotation designs for **biomass** production). Researchers are also not currently sure whether high density and short harvest cycles will exacerbate or alleviate disease issues. Clones within a hybrid type will vary in disease resistance, so new growers should consult with experienced growers, a local Extension office, or with representatives of GreenWood Resources (GWR). Table 9.1 broadly characterizes poplar hybrid types in relation to prominent diseases in different regions of the PNW. Following table 9.1 are short descriptions and photos of the most common diseases of *Populus trichocarpa* and hybrid poplars in the PNW. These descriptions and photos can help growers diagnose their own disease problems, though confirmation at a plant disease diagnostic clinic is advised as diagnostic characters are often microscopic. Contact information for the clinics of the region is listed following the disease descriptions.

Common Diseases of Hybrid Poplar That Can Be Controlled by Using Disease-Resistant Clones

Leaf Rust Caused by Melampsora *Species*

Rust is the most damaging disease of *Populus trichocarpa* in the PNW. Three *Melampsora* taxa can be found in the region. The first two are common:

1. *Melampsora occidentalis* is common and almost exclusively found on *Populus trichocarpa* and not on hybrids.

2. *Melampsora × columbiana* is also common. This hybrid rust affects poplar hybrids, especially the T×D hybrid. This hybrid rust is also found to some extent on *Populus trichocarpa* and as such is one of two important spillovers from the hybrid plantations to the natural populations.

3. *Melampsora larici-populina* is a Eurasian species that is uncommon in the PNW. It was introduced to North America in the early 1990s and has since been found only sporadically in the PNW (Newcombe and Chastagner 1993a). *Melampsora larici-populina* is more common in California, and it can be found occasionally spreading up into the PNW in fall. This Eurasian rust is more likely to affect D×N and D×M hybrids than *M. × columbiana*. *Melampsora occidentalis* cannot attack D×N or D×M at all.

Leaf rust causes premature defoliation, which can lead to reduced growth, and, in severe cases, mortality (Newcombe et al. 1994). The first two *Melampsora* rusts alternate between Douglas-fir in the spring (figure 9.1) and poplars in the fall (figure 9.2). These rust fungi also spend the winter as black, **telial** crusts on fallen poplar leaves. The disease typically intensifies on poplar in late summer when cooler and more humid conditions promote rust urediniospore germination and new infections. **Signs** of leaf rust on poplar in the fall are the aforementioned dark or even black telia and orange, powdery pustules called **uredinia** that are primarily on the lower leaf surfaces (figure 9.2). **Symptoms** include **chlorosis** (yellowing) and **necrosis** (browning) that are seen surrounding uredinia and telia, respectively. **Cuttings** taken in late winter from trees that were rusted the previous year are more susceptible to black-stem **canker** caused by *Valsa sordida*.

Table 9.1. Disease-resistant hybrid types (T×D, D×M, or D×N) for six PNW poplar-growing regions.

Production Region	Suitable Hybrid Taxa	Prominent Diseases of P. trichocarpa in the Region
North Puget Sound; Washington	T×D, D×M	All diseases described below.
Lower Columbia River; Oregon and Washington	T×D, D×M	All diseases described below.
Willamette Valley; Oregon	T×D, D×M, and D×N	All diseases described below.
Sacramento Delta; Central and Northern California	D×N	All diseases described below.
Idaho Panhandle	D×N	All diseases described below, except leaf bronzing and *Venturia* leaf and shoot blight.
Mid-Columbia River Basin; Eastern Oregon and Washington	D×N	All diseases described below, except leaf bronzing and *Venturia* leaf and shoot blight.

The three rusts of the region can only be distinguished microscopically. Three spore states (the uredinial, telial, and **basidial**) are produced on poplars, and two (**spermogonial** and **aecial**) on Douglas-fir in spring.

Rust damage should not be confused with "leaf bronzing" caused by an eriophyid **mite** endemic to the PNW. This mite is only seen on poplars in the region and appears to be restricted to areas west of the Cascades. It received a formal name (new genus and species) and supporting description relatively recently (Oldfield et al. 1998). This microscopic mite is small enough to enter leaf **stomata** to feed on spongy **mesophyll** cells. Their feeding causes the lower leaf surfaces to start to appear brown or "bronzed" (figure 9.3). The impact of the mite on tree growth is not known, so no specific management is recommended. Interestingly, mites compete with rust fungi for mesophyll cells, so each organism is somewhat of an agent of biological control for the other.

Figure 9.1. Aecia of *Melampsora* on Douglas-fir in spring. Photo: P. Busby.

Figure 9.2. Orange uredinia of *Melampsora* are rust fungal tissues and are easily visible. Photo: G. Newcombe.

Figure 9.3. Mites and rust compete for spongy mesophyll cells on lower leaf surfaces (note the minimal rust in bronzed area). Photo: P. Busby.

Marssonina *Leaf Blight Caused by* Drepanopeziza *Species*

Two species of *Drepanopeziza* affect *Populus trichocarpa* and hybrids in the PNW:

1. *Drepanopeziza populi-albae* is native to the PNW and is quite common on *Populus trichocarpa*, especially east of the Cascades.

2. *Drepanopeziza tremulae* f.sp. *brunnea* is restricted in the region to some T×D hybrids in coastal areas. Its introduction into the PNW was relatively recent (Newcombe and Callan 1997).

Drepanopeziza species cause premature defoliation, reduced growth, and enhanced susceptibility to other environmental stresses (Newcombe et al. 2001a). Symptoms are small, brown to black leaf spots which develop white centers where **asexual** spores accumulate. In some cases, lens-shaped **lesions** develop on midveins (figure 9.4), **petioles**, and new **shoots** (Ostry et al. 2014), and even on seed capsules (figure 9.5). Rough, scabby areas can form.

Figure 9.4. *Drepanopeziza* lesions on midvein of lower side of leaf of *Populus trichocarpa*. Photo: G. Newcombe.

Leaf Spot Caused by Sphaerulina populicola

The fungus that causes this disease also bore two scientific names in the past: *Septoria populicola* (the asexual name) and *Mycosphaerella populicola* (the **sexual** name) (Quaedvlieg et al. 2013). In the case of this important foliar pathogen, in addition to the dual nomenclature issue, modern efforts in **systematics** moved this fungus to a new genus: *Sphaerulina*.

Sphaerulina populicola is a leaf-infecting fungus which causes necrotic spots to form on leaves of its poplar hosts (Thompson 1941). Many T×D clones have been shown to be resistant to *Sphaerulina populicola* (Newcombe 1996). **Ascospores** of *Sphaerulina populicola* infect leaves in the spring, and **conidia** produced on those primary lesions may go on to cause secondary lesions, which may lead to premature defoliation in bad years. Figure 9.6 illustrates the mostly round, brown (or sometimes red or grey) lesions.

Sphaerulina musiva is closely related to *Sphaerulina populicola*. *Sphaerulina musiva* is a more serious pathogen because it causes stem cankers (figure 9.7) in addition to leaf spots. Its leaf spots are indistinguishable macroscopically from those caused by *Sphaerulina populicola*, but microscopically the two fungi can be distinguished. *Sphaerulina musiva* is native to eastern North America but it was recently reported on introduced hybrid poplars in the Fraser River Valley of southwestern British Columbia (Callan et al. 2007). Its occurrence now in natural populations of *Populus trichocarpa* represents a second serious spillover event, in addition to the hybrid rust discussed above. *Populus trichocarpa* and many hybrids are susceptible to *Sphaerulina musiva* when planted in eastern North America, so continued vigilance is advised (Newcombe et al. 2001a).

Figure 9.5. *Drepanopeziza* on seed capsules of *Populus trichocarpa*. Photo: G. Newcombe.

Figure 9.6. Leaf spot of *Populus trichocarpa* due to *Sphaerulina populicola*. Photo: P. Busby.

Figure 9.7. A developing *S. musiva* canker on a young poplar stem. Photo: G. Newcombe.

Figure 9.8. Late spring defoliation. Photo: G. Newcombe.

Leaf and Shoot Blight Caused by Venturia *Species*

Two species of *Venturia* occur in the PNW:

1. *Venturia inopina* causes blight of native *Populus trichocarpa*.
2. *Venturia populina* occurs on introduced *Populus nigra* (Newcombe 2003) which is common in the PNW as 'Lombardy poplar' or *P. nigr*a cv. *'Italica'*.

Venturia leaf and shoot blight is like leaf bronzing in that within the PNW region it is restricted to coastal areas west of the Cascades. The disease can stunt and deform the growth of young trees when defoliation occurs (figure 9.8) in successive wet springs (Newcombe 2003). Symptoms include black leaf lesions similar to those described for *Valsa* leaf blight below and pictured in figure 9.13. In the case of *Venturia*, an olive-green cast develops on the upper leaf surface when the asexual spores are produced. Young shoot tips can be killed by *Venturia* species, forming so-called "shepherd's crooks" (figure 9.9). *Venturia* leaf and shoot blight develops in early spring when new leaves are just emerging from buds. Ascospores are discharged from fungal fruiting bodies that develop on the previous year's dead shoots. Germinating ascospores infect young leaves if the surfaces of the leaves stay wet long enough.

Figure 9.9. The two main symptoms of *Venturia* leaf and shoot blight (spreading lesion of leaf in lower left; shepherd's crook can be seen top center). These symptoms are the same for both *P. tremuloides* (pictured) and *P. trichocarpa*. Photo: G. Newcombe.

Leaf Blister and Leaf Curl Caused by Taphrina *Species*

Taphrina is a foliar disease that warps or distorts leaves by forming blisters that can be up to an inch in diameter (figure 9.10). Although damage to hybrid poplar due to *Taphrina* has never been determined, it is likely that reductions in growth are commensurate with disease severity. Golden yellow layers of **asci** and ascospores develop on the concave sides of the blisters in spring. *Taphrina* is said to be present in its **yeast form** in overwintering buds of poplar, unlike other pathogens that infect the leaves in the spring. Resistance in hybrid T×D and T×M to the *Taphrina* population of the PNW is inherited from *Populus deltoides* and *Populus maximowiczii*, respectively (Newcombe 2005).

Figure 9.10. *Taphrina* blisters on *P. trichocarpa*. Photo: G. Newcombe.

Leaf Blight Caused by Linospora tetraspora

This fungus occurs only in northwestern North America. It is more common in Alaska and British Columbia than Washington and Oregon, and it is likely to be more damaging where it is more common (Newcombe 1998b). An observation of this disease in September 2015 in Corvallis, Oregon, may represent the southern limit of this pathogen. Distinct symptoms of this disease are large, tan-colored lesions that become peppered with black spots at the end of the growing season (figure 9.11).

Figure 9.11. *Linospora* blight of *Populus trichocarpa*. Photo: G. Newcombe.

Blackstem Disease and Valsa *Leaf Blight, Caused by* Valsa sordida

Blackstem is a canker disease that is common in weakened, stressed stems. Commonly called *Cytospora* canker, leaf rust predisposes stems to this disease. Stem cuttings taken in winter and stored improperly may develop blackstem. The fungus is considered opportunistic because it causes blackstem in injured tissues. Cankers appear as slightly sunken, often elongate, discolored areas. Cankers may not always be evident. The bark may at first turn orange or brown before becoming black. However, other microbes might cause similar discoloration of poplar stem cuttings so positive diagnosis requires microscopic examination of conidia that are produced in spore tendrils from the discolored wood. These conidia are colorless, unicellular, slightly curved, and tiny compared to the spores of most other fungi (figure 9.12). Cuttings with blackstem will probably not root and, if they do, the plants will not flourish. Trees with blackstem will develop dead branches, or “flags,” or even **crown** dieback.

Blackstem also develops in T×D **stool** beds if the trees are planted with rust-susceptible clones.

Until recently, *Valsa sordida* was only known as a canker pathogen. In 2014 and 2015, *Valsa sordida* emerged as a foliar pathogen on *P. trichocarpa* along the Yakima River in Washington (Fraser 2016). Partial crown dieback can occur in trees with blighted leaves (figure 9.13). The incidence of this new disease is being monitored.

Figure 9.12. Hundreds of conidia (i.e., sexual spores) of *Valsa sordida* in a highly magnified light micrograph. These unicellular, colorless, slightly curved spores are tiny compared to the one *Alternaria* spore included in this image. These conidia are essential to see for diagnostic purposes. Photo: G. Newcombe.

Figure 9.13. Symptoms of *Valsa* leaf blight on *Populus trichocarpa*. These symptoms resemble those of Venturia leaf blight, but with Venturia leaf blight the conidia are produced all over the lesion surface. In the case of Valsa leaf blight, in contrast, the tiny conidia are produced in discrete, black, fruiting bodies called pycnidia. Photo: G. Newcombe.

Other Control Strategies for Poplar Diseases

Host genetic resistance has been, and continues to be, the ultimate preemptive strategy to control disease in poplar plantations. Several other methods are described below, but these should not be necessary if appropriate disease-resistant clones are planted in the first place.

Biological Controls

Nonpathogenic fungi that cohabit poplar leaves are called **endophytes**. They commonly antagonize rust pathogens and thereby reduce disease severity (Raghavendra and Newcombe 2013). Another endophyte, *Streptomyces,* can decrease severity of *Sphaerulina* leaf spot when applied weekly, bimonthly, or monthly (Gyenis et al. 2003). While promising, this type of biological control requires additional study as some endophytes can increase disease severity (Busby et al. 2013).

Chemical Controls

Recommended fungicides change over time. Therefore, it is best to consult with the plant disease diagnostic clinics listed below for current recommendations. Control of rust in stool beds is needed in order to avoid the development of blackstem.

Cultural Practices

Removal and burning of overwintering **inoculum** in fallen leaves, particularly those between tree rows, might reduce disease the following year. Lower planting density or interplanting with non-poplars might also reduce leaf rust disease severity.

Poplar Damage Diagnoses

If you observe damage in your poplar plantation, it is essential to get a correct diagnosis of the problem. It may be a pest problem rather than a disease problem, especially if you have used disease-resistant clones. See Chapter 7 for more information. To get an accurate diagnosis, it is best to consult with diagnosticians at regional plant disease diagnostic clinics. Before collecting the disease sample, contact the diagnostician to receive instructions on sampling and shipping. Consulting the websites of the following regional disease diagnostic clinics is also a good idea, and these are listed below.

Western Oregon

Oregon State University, OSU Plant Clinic, 1089
Cordley Hall, Corvallis, OR 97331-2903.
Tel.: (541) 737-3472
https://plant-clinic.bpp.oregonstate.edu/

Northeast Oregon

OSU Extension Plant Pathology Laboratory, 2121
South 1st St., Hermiston, OR 97838.
Tel.: (541) 567-8321
https://extension.oregonstate.edu/harec/plant-pathology-diagnostic-laboratory-services

Idaho

University of Idaho, Parma Research and Extension
Center, Plant Samples, 29603 U of I Lane, Parma, ID
83660-6699.
Tel.: (208) 772-6701
https://www.uidaho.edu/cals/plant-diagnostics/parma

Plant Symbiosis Lab, University of Idaho, Department of Forest, Rangeland, and Fire Sciences, 875
Perimeter Drive, Moscow, ID 83844-1133.
Tel.: (208) 885-9158
https://www.uidaho.edu/cnr/faculty/newcombe

Western Washington

WSU Puyallup Plant and Insect Diagnostic Clinic,
WSU Research and Extension Center, 2606 West
Pioneer, Puyallup, WA 98371-4998.
Tel.: (253) 445-4501
https://puyallup.wsu.edu/plantclinic/samples/

Eastern Washington

Plant Pest Diagnostic Clinic, WSU Pullman, Pullman,
WA 99164-64630.
Tel.: (509) 335-0619.
https://plantpath.wsu.edu/diagnostics/

British Columbia

Plant Health Laboratory, British Columbia Ministry
of Agriculture, Abbotsford Agriculture Centre, 1767
Angus Campbell Rd., Abbotsford, BC V3G 2M3
Canada.
Tel: (604) 556-3003 or toll free: 1 (800) 661-9903.
https://www2.gov.bc.ca/gov/content/industry/agriculture-seafood/animals-and-crops/plant-health/plant-health-laboratory

California

UC Cooperative Extension Eskalen Lab, 267
Hutchinson Hall, Department of Plant Pathology,
UC Davis, CA 95616.
https://ucanr.edu/sites/eskalenlab

Conclusion

Choosing disease-resistant clones is the best strategy for avoiding disease problems in hybrid poplar plantations. Other control options are limited and not as effective. If you observe damage in your plantation, it is essential to get an accurate diagnosis to determine if it is a disease, pest, nutrition, or other type of problem. Work with your breeder to select clones that are most appropriate for your location and offer the best disease control.

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CHAPTER 10 | WATER AND NUTRIENT MANAGEMENT

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Water Management

Water is one of the most important growth factors for **hybrid** poplar. If water requirements are not met, **biomass** production will decline. Water requirements for hybrid poplars vary greatly depending on the site, climatic conditions, soil type, hybrid poplar **genotype**, planting density, and the age of the stand. Water demands will be higher in the more arid regions of eastern Washington and eastern Oregon, compared to areas west of the Cascade Mountains, because of the warmer temperatures, lower relative humidity, and increased **evapotranspiration**. In most cases, poplar should be sited in areas where precipitation or access to groundwater will supply adequate water. Though it is often economically unviable to irrigate, irrigation may be economically tenable in cases where hybrid poplars provide an additional economic benefit, such as sewage treatment. Multiple wastewater treatment facilities across the PNW are irrigating nearby poplar fields with pretreated wastewater effluent (see Chapter 16).

Water requirements increase as poplars grow, peaking at **canopy closure** when the leaf coverage is maximized. Water availability is most critical during the growing season (April through September). For **bioenergy** crop stands planted at the recommended density of 1,452 trees per acre (3,588/ha), poplars generally require about 13–21 inches (33–53 cm) of water (precipitation or irrigation) during the growing season before coppice and 18–36 inches (46–91 cm) after coppice (Mike Berk, personal communications, GreenWood Resources, 2015). Table 10.1 presents these water requirements as they relate to the trees' age. Some studies have found even higher water needs for coppiced poplar; up to 28 inches (71 cm) and 43 inches (109 cm) for the first and second growing seasons after coppice (Guidi et al. 2008). This difference may be explained by the much greater planting density of 4,050 stems per acre (11,120/ha) used for this study, as higher planting densities will require more water.

These ranges should be used as a starting estimate as water requirements vary greatly between climates and the age of the trees. Additionally, water use can vary between **clones** by almost twofold (table 10.2) (Dickmann et al. 2001; Bloemen et al. 2017). In some cases, the availability of groundwater can mitigate the need for precipitation as poplar roots can extend 6–15 feet (2–4.5 meters) down to reach the water table (Petzold et al. 2011; Hartwich et al. 2014; Schuette, n.d.). When poplar roots are able to tap into the groundwater, they may increase their water use by twofold (Hartwich et al. 2014). Twice the water availability in eastern Oregon results in double the production rate (Shock et al. 2002).

Table 10.1. Approximate water requirements for hybrid poplar for each growing season.

	Year 1	Year 2	Year 3	Coppice Year 1	Coppice Year 2	Coppice Year 3
Water needs per growing season	13 in. (33 cm)	17.5 in. (43 cm)	21 in. (53 cm)	18 in. (46 cm)	24 in. (61 cm)	36 in. (91 cm)

Source: Mike Berk, GreenWood Resources, 2015.

Table 10.2. Daily water use among hybrid poplar clones for photosynthetically active radiation of 40 mol per m^2 per day.

Clonal Variety	Gal/tree/day (L/tree/day)	Clonal Parentage
Oudenberg	0.68 (2.58)	*P. deltoides* × *P. nigra*
Grimminge	0.65 (2.46)	*P. deltoides* × (*P. trichocarpa* × *P. deltoides*)
Skado	0.32 (1.22)	*P. trichocarpa* × *P. maximowiczii*

Source: Modified from Bloemen et al. (2017).

Irrigation

Poplar water can be supplied through drip or furrow irrigation from surface- or groundwater sources. Overhead irrigation is not recommended due to rapid crop height increases and canopy interception that decreases irrigation effectiveness. Drip irrigation is preferred over furrow irrigation because of greater control over timing and quantity of water applied and lower erosion potential. Greater control decreases erosion and leaching losses caused by drainage below the rooting zone compared with furrow irrigation. Drip irrigation can be costly to install relative to furrow irrigation. An irrigation engineer may be required to determine required drip irrigation zones based on field size, soil texture and topography, drip-tube characteristics, pressure, and filtration requirements. Poplar coppice with high-density, dual-row planting designs commonly use two drip lines per planting row, while wider-spaced poplar use a single drip line per row. Irrigation should be timed to maintain favorable soil moisture without drainage loss. Soil tension sensors or potential evaporation are used to schedule irrigation. Soil tension should be maintained above -25 kPa (Shock et al. 2002), and current potential evaporation is monitored and modified using poplar crop coefficients (USBR 2016) to determine daily or weekly water deficits.

Water in the Columbia Basin and Snake River Plain can be supplied with surface water while other regions may be supplied with groundwater wells. The quality of water, whether from ground or surface water supplies, should be tested for turbidity and nutrient content. Excess suspended solids may require more rigorous filtration to avoid plugging of drip tubes, while dissolved minerals can eliminate the need for **cation** amendments.

Waterlogging

Too much water can be as damaging to hybrid poplar as insufficient water. Waterlogged soils can cause **anaerobic** conditions that deprive the roots of oxygen. If flooding conditions persist into the growing season, the leaves will turn yellowish green, and the trees may eventually die. For trees to thrive, soils must be drained and well aerated by the beginning of June (Stanturf et al. 2001).

Soil and Nutrient Management

As with any crop, nutrient management of poplar is site-specific and depends on soil series, **pH**, and previous land use. Hybrid poplars differ from many traditional row crops in that the need for fertilization is generally minimal on good quality soils (van Oosten 2006). Approximate nutrient requirements for hybrid poplar and nutrients contained in harvested biomass are summarized in table 10.3. These requirements do not always translate to equivalent fertilizer application because much of these needs are fulfilled from soil organic matter and litter decomposition. One study found that about 60–80% of the nutrients removed by the trees are returned to the soil each year from leaf litter decomposition (Berthelot et al. 2000). Harvesting during the **dormant season** (after leaf fall has occurred) will help maintain soil nutrient pools because the nutrient-rich leaves are left on the ground to be recycled back into the soil (figure 10.1).

Figure 10.1. Leaves left on the ground at harvest act as mulch and maintain nutrient pools. Photo: M. Heppenstall.

Depending on the site, fertilizer application may be needed only occasionally, or not at all. For example, poplars do not respond to nitrogen applications on rich **alluvial** soils of the lower Columbia River. On marine and alluvial soils on east Vancouver Island, on the other hand, poplars have responded to nitrogen, phosphorus, potassium, and sometimes sulfur applications at planting and canopy closure (Stanturf et al. 2001).

Table 10.3. Approximate nutrient requirements for hybrid poplar and nutrients removed during harvest of leafless biomass.

	Annual Nutrient Requirements of Hybrid Poplar[1]				
	N	P	K	Ca	Mg
lb/acre (kg/ha)	150–246 (168–276)	18–32 (20–36)	100–153 (113–171)	108–211 (121–237)	34 (38)
	Nutrients Removed during Harvest[2]				
lb/ton (kg/tonne)	1.6–2.7 (0.8–1.35)	0.30–0.46 (0.15–0.23)	1.2–1.9 (0.6–0.95)	4.0–7.1 (2.0–3.55)	0.27 (0.14)

[1] Adapted from Stanturf et al. (2001).
[2] From Ranger and Nys (1996).

Leaf Testing

Leaf analysis is the most common and reliable method of determining nutrient deficiencies in poplar. Because routine testing can be expensive, leaf analysis is only recommended if the trees appear unhealthy. Symptoms include yellowing or brown spots on leaves or leaves with burned edges. Figures 10.2–10.5 show examples of hybrid poplars with symptoms of nutrient deficiencies. The canopy cover can also be an indication of nutrient availability. If the site provides adequate nutrient supplies, the canopy will be dense with much shade underneath. A sparse canopy with excess sunlight reaching the forest floor after the second year suggests that the stand may not be adequately supplied. If these symptoms appear, leaf analysis should be done to determine an appropriate fertilization strategy. Amendments should not be added based on visual cues alone, as many nutrient deficiencies look the same, and similar symptoms can appear from drought, air pollution, or high salinity—leaf analysis is recommended. Target values for leaf nutrient levels are presented in table 10.4. If nutrient levels drop below these values, fertilization is likely needed.

Table 10.4. Target nutrient values for poplar leaf tissue.

Element	Low %	High %
N	2.0	3.0
P	0.2	0.4
K	1.0	2.5
Ca (variable)	2.0	
Mg	0.2	0.4
S	0.2	0.3
Cl	0.5	1.0
	Low ppm	High ppm
Fe	50.0	100.0
Mn	50.0	200.0
Zn	10.0	25.0
Cu	10.0	20.0
Mo	0.5	5.0
B	25.0	100.00

Source: Adapted from Boswell (2008).

Figure 10.2. Yellowing of leaves from nitrogen or iron deficiency. If pH is above 6.5, then the yellowing is more likely from iron deficiency. Photo: K. Wallace.

Figure 10.3. Burnt edges and interveinal **chlorosis** may be signs of a potassium deficiency. Photo: R. Shuren.

Protocol for Collecting and Analyzing Poplar Leaf Nutrient Samples

Leaf nutrient concentrations of **deciduous** trees, including poplar, vary during the growing season and within the position in the canopy. Normal nutrient concentrations listed in table 10.4 are based on recently matured leaves collected mid-growing season from upper sunlit branches of dominant trees. Nutrient concentrations of upper sunlit branches at this stage of the season are stable and most representative of site and soil nutrient statuses. For accurate comparison of nutrient measurements, it is important that leaf samples for nutrient analysis also be collected at this same time and position.

Figure 10.4. Wrinkled leaves and interveinal chlorosis could be a manganese deficiency. Photo: R. Shuren.

Figure 10.5. Leaf **necrosis** (blackening and dying) resulting from a phosphorus, potassium, zinc, or copper deficiency. Photo: R. Shuren.

Upper branches in one-year-old **shoots** can be collected by bending the stem over and clipping by hand. Taller trees will require use of pruning poles capable of reaching upper branches 30–40 feet tall. Collect three recently matured leaves per branch and include a branch taken from three different trees for a total of nine leaves. That number should result in about 0.5 oz (10 g) of dried tissue, which will be adequate for analysis. Collect three leaves from more branches as needed to reach enough dry matter. Select only the three most recently matured leaves for analysis from each branch, taking care not to include immature or overly mature leaves.

Recently matured poplar leaves are typically the longest and largest leaves on the branch, about 5 to 10 leaves back from the branch tip. During this midsummer period of active growth, new immature leaves are still expanding in size and will feel soft and pliable, while recently matured leaves have stopped expanding and will have a leathery texture. The recently matured leaves should be placed in properly labeled paper bags and dried in a convection oven (60°C or 140°F) to a constant weight. Microwave ovens may also be used if used at low settings. Avoid burning the foliage because that will result in carbon loss and inaccurate nutrient concentrations.

Dried samples should be sent to your local agricultural service lab. The full suite of nutrients listed in table 10.4 should be analyzed to identify both macro- and micronutrient deficiencies and any nutrient imbalance. Several laboratories are listed at the following website: http://analyticallabs.puyallup.wsu.edu/analyticallabs/services.

Soil Testing

Soil testing may be useful when establishing a new plantation on agricultural land. More information on how to take soil samples and a list of soil testing labs can be found at http://puyallup.wsu.edu/soils/soils/. Soil tests correlated with other row crops can give a rough estimation of nutrient recommendations for new stands of poplars as the nutrient requirements of short-rotation poplar are fairly similar to other agricultural crops (Stanturf et al. 2001). A diagnostic method to correlate soil fertility with nutrient needs of hybrid poplar has not been established as it has with traditional agricultural crops; at this point, lab recommendations based on soil tests can only provide a rough estimate of nutrient needs (van Oosten 2006). Nutrient management should be based on foliar analysis rather than routine soil testing.

Fertilization

If foliar nutrients are below the critical levels, fertilizer should be applied. Keep in mind that overfertilization of nitrogen, or fertilization before canopy closure, can promote weed competition, so proper weed control is especially important if fertilizer is used (see Chapter 6 for more information on controlling competing vegetation).

Nitrogen

Nitrogen is the most common nutrient limiting poplar growth and development. Other essential nutrients should be managed to maintain a proper ratio with nitrogen. In some cases, nitrogen fertilization alone does not increase **yield** unless accompanied by other nutrients such as phosphorus or potassium (Stanturf et al. 2001; van Oosten 2006). Nitrogen can be applied alone or in combination with other nutrients in granular blends or injected into irrigation drip lines. Because of the wide range of soil types and climates in the PNW, fertilizer needs vary greatly between regions. If soil tests prior to planting indicate that nitrogen is limited, 22–45 pounds per acre (25–50 kg/ha) of elemental nitrogen can be buried in the planting holes with the **cuttings**. Burying fertilizer will discourage weed growth and will place nutrients in an optimal position for tree uptake. Another option is to place fertilizer at a rate of 89–178 pounds of N per acre (100–200 kg/ha) in bands along the planting row (Stanturf et al. 2001). Nitrogen can also be applied at canopy closure in this method using this rate if leaf analysis indicates low nitrogen.

Actual application rates should be guided by lab recommendations and will vary based on soil organic matter content, pH, salinity, and soil texture. Broadcasting fertilizer is an efficient application method if the root system has fully occupied the soil (indicated by canopy closure), because nutrients will be acquired by the full root system that stretches between tree rows. Incorporation of nitrogen fertilizer into the soil once the stand is established is not necessary and could damage the roots.

Phosphorus

Phosphorus can also be a limiting nutrient in some alluvial soils or upland marine soils. Because phosphorus is easily fixed to soil particles, it is most effective to either apply granular mono- or diammonium phosphate in bands along planting rows or place it in the hole in which the cutting is planted. When applied at planting, phosphorus can encourage root development. Recommended phosphorus rates in the Pacific Northwest (PNW) are about 22–45 pounds per acre (25–50 kg/ha) of elemental phosphorus buried in the planting hole or up to 90 pounds per acre (100 kg/ha) banded after canopy closure (Stanturf et al. 2001).

Other Nutrients

In addition to nitrogen and phosphorus, other nutrients including calcium, potassium, sulfur, boron, molybdenum, and zinc may be required to optimize growth. Fertilizer should be considered if leaf nutrients are less than the target values in table 10.4. Calcium nitrate or lime can be used to increase soil calcium availability, with the former applied when concurrent nitrogen deficiencies occur, and the latter used to adjust acidic soil conditions. Attention should be given to monitor potassium when trees are grown in sandy soils, as potassium easily leaches in sand. Deficiencies of micronutrients including sulfur, boron, molybdenum, and zinc can cause chlorosis in heavy clay soils. Deficiencies are simply cured for one or more rotations with banding or spot treatments because only small quantities are required. However, rates should not exceed recommendations, because these metals can become toxic.

Fertigation

In irrigated fields, **fertigation** (injecting fertilizers into an irrigation system) can provide more flexibility in the rate and timing of nutrient applications. Nutrients can be applied in smaller, more frequent doses so that the rates and timing match the changes in nutrient demand throughout the season. However, in many cases, irrigation systems may not be economical for poplar bioenergy crops such that fertigation is not an option.

pH

Monitoring the soil pH is an important part of poplar soil management. Soil pH should be measured before planting and is usually included when soil samples are sent to a lab for nutrient analysis. Poplars do well at pH levels of 5.5–7.5 with 6.0–6.5 being optimal (Stanturf et al. 2001). Not all clones respond similarly to soil conditions. For example, *P.* ×*canadensis* hybrids do much better in **alkaline** soils than the *P.* ×*generosa* hybrids. Matching the needs and adaptability of the clones with site conditions can greatly improve the crop yield (see Chapter 2 for more information on clone selection).

Amending acidic soils with lime or applying sulfur or acidic nitrogen fertilizer to alkaline soils may be necessary to keep the pH within the appropriate range. Monitoring soil pH is important, because pH can influence the bioavailability of some nutrients such as phosphorus, iron, and copper. Alkaline **calcareous** soils (pH greater than 7), which are common in southern Idaho and other arid regions of the west, can also cause severe iron deficiencies. Look for yellowing of the leaves between the veins (figure 10.2), which is a symptom of iron deficiency chlorosis. Decreasing the pH or adding available iron can correct iron chlorosis. If these symptoms appear, confirm that it is an iron deficiency by having the foliage analyzed. Foliar applications of iron sulfate or **chelated** iron compounds are an effective treatment (St. John 2001).

Summary

- Adequate precipitation is necessary for poplar production. Irrigation is economically viable when coupled with other environmental services, such as disposal of treated effluent.
- It is not possible to visually diagnose nutrient deficiencies with enough accuracy to make fertilizer recommendations. Photos of visual symptoms show various nutrient deficiencies and are intended to encourage growers to order leaf analysis. Fertilizer should be applied only after receiving test results indicating deficiencies.
- It is difficult to correlate tree growth with the traditional agronomic soil tests. Within-tree and soil nutrient cycling add considerable variation to the relationship between soil nutrient tests and poplar productivity. Visual symptoms for nutrient deficiencies such as sparse canopies and foliar discoloration should prompt foliar testing.
- Nitrogen is the main nutrient limiting poplar growth. Other macronutrients including phosphorus and base cations should be managed to maintain a proper balance with nitrogen. Slightly acidic soil reaction should be maintained through lime application based on soil pH testing.

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CHAPTER 11 | HARVESTING HYBRID POPLAR FOR BIOENERGY

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Length of Harvest and Production Cycles

Hybrid poplar produced on a three-year harvest cycle permits harvesting with commercially available, single-pass **forage harvesters**. **Single-pass harvesting systems** are considered state of the art currently due to their ability to complete multiple steps of the harvesting process at the same time. These harvesters produce a uniform chip at lower cost than other harvesting systems by cutting and chipping as it moves through the field.

In a **coppice** production system, the purpose of the first harvest is to cut the trees at the base to promote the regrowth of multiple stems, which occurs in poplar and some other tree species. This process is called coppicing. **Yields** of **biomass** are lowest in the first harvest because each poplar tree has only one stem and most biomass allocation goes belowground to the tree roots in the establishment years. The first harvest usually follows the crop's second growing season. It is important that the trees are able to establish a vigorous root system, which helps maximize coppice survival and biomass yield in future rotations. Subsequent harvests of the coppice regrowth can occur on regular cycles, typically every three years.

Deviation from the typical two-year establishment and three-year coppice cycles may be necessary depending on the quality of the site, productivity of planted varieties, annual weather variation, and operational logistics. Biomass yields are expected to remain relatively stable for five to seven harvest cycles (approximately 20 years), after which it is recommend that the **rootstock** be killed, and a new crop established. If hybrid poplar is replanted, the old rootstock may be left in place to decompose, and the new trees planted between the old rows (see Chapter 5). If a different kind of crop or land use is desired, the old root stock can be mulched in place or removed from the field entirely (see Chapter 13).

Determining When to Harvest

An inventory at the end of the second and third growing seasons will help decide the length of harvest cycle for your site (see Chapter 17). A good indication that the trees have reached the target yield is that most **stools** have multiple stems with a two- to three-inch (5.1–7.6 cm) **diameter at breast height** (DBH) and are 30 to 40 feet (9–12 m) tall. Height can be an important visual cue for the health of the tree, but stem diameter at breast height better predicts biomass yield. If more than 10% of the stems are over four inches (10.2 cm) in **diameter at stool height**, or if any of the stems are larger than seven inches (17.8 cm), it can bog down current harvesters. Likewise, trees taller than 40 feet (12.2 m) tend to hang-up and feed poorly into the chipper, causing the harvest to slow down.

A three-year coppice cycle should generally yield 15–30 **bone dry tons** (BDT) per acre at harvest (see Chapter 12 for more on yield). If ground conditions are favorable, the forage harvester will operate most efficiently if the harvest volume is 18 to 40 **green tons** (GT) per acre (9–20 BDT/acre, assuming 50% moisture content). If the harvest volume is less than 18 GT per acre, the machine will be limited by how fast it can move over the terrain, and at over 40 GT per acre, the machine can become mechanically limited by how much wood it processes (Eisenbies et al. 2014a). Actual harvester performance will vary based on machine power, field conditions, and operator behavior. These numbers are provided as general guidelines to provide a sense for capacity and limitations.

Season of Harvest

The **dormant season**, typically November through March in the Pacific Northwest (PNW), is generally the best time for harvesting hybrid poplar for **bioenergy**. Harvesting in the dormant season produces clean, leafless biomass, and trees cut while dormant are more likely to resprout. However, soil saturation at some locations may prevent equipment from entering the field this time of year. Harvest can also be done from late spring to midsummer if the dormant season is not an option due to weather or market demand. However, harvesting during the growing season means there will be leaves on the trees. Harvesting with leaves on causes several problems, such as accelerated decomposition, problems for **biorefineries**, and removal of nutrients and organic matter from the field. Technology to remove the leaves from an active season harvest is currently in development.

Harvesting hybrid poplar in the early fall or early spring can decrease tree survival and should be avoided. During these times trees are transporting energy either to or from roots (fall and spring, respectively), and disrupting the process can harm the trees. On sites with harsh winters, harvesting in the early fall or early spring may also expose sensitive new growth to damaging frost.

Equipment and Logistics

A forage harvester with a coppice header is well suited for cutting and chipping short-rotation hybrid poplar. The most established equipment for single-pass harvesting of poplar in the United States is New Holland's FR 9000 series forage harvester or the newer FR Forage Cruiser series with a New Holland 130FB Coppice Header (see sidebar New Holland 130FB Coppice Header for more information). The maximum stem size recommended for this equipment is about six inches (15 cm) in diameter at a stool height of four to six inches (10–15 cm). This system can harvest up to 100 green tons per hour (upper limit under ideal conditions, excluding turn times, and without being limited by the speed of the collection system) in fields with three years of coppice growth (Summers and Posselius 2015; Eisenbies et al. 2017). As the harvester moves down the row, it straddles the trees, cutting the stems four to six inches (10–15 cm) from the ground and directing them into a cutting drum where they are chipped into three-quarter-inch (2 cm) long pieces. The harvester leaves the remaining stool relatively undisturbed so it can resprout (Summers and Posselius 2015).

The stems in coppice growth flare outward at an angle such that cutting them leaves sharp edges horizontal with the ground (figure 11.3). These sharp-edged sticks can cause flat tires on equipment by jabbing into the sidewalls. Outfitting the harvester and support vehicles with thick, durable, forestry-grade tires will greatly reduce the risk of tire damage.

A support truck or tractor-towed trailer positioned alongside (figure 11.4) or directly behind (figure 11.5) the harvester collects the chips as the harvester moves down the rows. Typically, the support vehicle is positioned alongside the harvester, ex-

New Holland 130FB Coppice Header

This attachment for a forage harvester (figure 11.1), a machine traditionally used to harvest crops for animal feed, cuts down **short-rotation woody crops**, like poplar and willow (figure 11.2).

Figure 11.1. Parts of the New Holland 130FB Coppice Header. Photo: N. Haider.

1. Divider point—guides trees into blades.
2. Sawing blade—cuts tree stems.
3. Push bar—pushes trees forward.
4. Feed rotor—feeds trees into chipper.
5. Gauge wheels—supports header's weight.

Figure 11.2. New Holland 130FB Coppice Header harvesting a row of poplars. Photo: N. Hart.

Figure 11.3. The base of a harvested multistemmed hybrid poplar tree can have sharp sticks jutting outward that can puncture tires (as viewed from above [left] and the side [right]). Photos: N. Hart (left), C. Gowan (right).

cept when opening up the field during the beginning of harvest operations when it follows the harvester. Support equipment will vary depending on local contractors, but they should be self-unloading (figure 11.6) and ideally have the capacity to carry wood chips from an entire row. Trade-offs between various support vehicle options are listed in table 11.1.

If the support vehicle is beside the harvester, it should be spaced two rows apart in order for the harvester spout to maneuver. If the support vehicle is directly behind the harvester, a full vehicle should be replaced by an empty vehicle in the **headlands**. Switching support vehicles in the middle of the row can increase the risk of flat tires, reduce the efficiency of harvesting, and damage the crop (e.g., driving over a crop row if the full vehicle was behind the

Table 11.1. Characteristics and limitations of different support vehicles for collecting poplar chips during harvest.

	Small–Medium Dump Wagons/Carts	Self-Propelled Wagons	Cane Wagons	10-Wheeled Trucks	18-Wheeled Trucks
Capacity	Low	Low	Medium	Medium	High
Operating Cost	Low	Medium	Medium	Medium	High
Local Availability	High	Low	Very Low	Medium	High
Ability to Load into Semitruck	No	No	Yes	No	N/A
Maneuverability	Fair–Excellent	Excellent	Excellent	Fair–Good	Poor
Cycle Time	Good	Poor	Excellent	Good	Poor
Primary Limitations	Capacity; Wheel Spacing	Capacity; Cycle Time	High Center of Gravity	Tire Damage; Sensitivity to Field Layout	Turning Radius; Effective Capacity

Source: Adapted from Eisenbies et al. (2014b).


Figure 11.4. Truck positioned alongside harvester collecting biomass. Photo: N. Haider.


Figure 11.5. Truck positioned behind the harvester collecting biomass. Photo: S. Kar.


Figure 11.6. Live bottom trailer unloading wood chips. Photo: N. Haider.

harvester); therefore, it is better to avoid the need to switch in the middle of the row by planting row lengths based on expected support vehicle capacity and yield of the field. If necessary, a long continuous row may need to be split up with a **row break** in the middle to accommodate harvesting.

If the delivery distance to the biorefinery is greater than five to ten miles (3–6 km), a third support vehicle will be needed to deliver the material to its destination. Three support vehicles reduce the time the harvester spends waiting for an empty support vehicle to collect chips. Alternatively, chips can be unloaded on-site and later reloaded into a highway truck.


Figure 11.7. A full dump wagon is taken to the unloading site as another wagon takes its place beside the harvester. Photo: N. Hart.

Another option is to pull a dump wagon with a tractor (figure 11.7) or behind the harvester itself. The wagon will unload biomass at a central landing site for reloading into highway trucks. In wet conditions, a tractor with floating tires can often navigate fields that trucks cannot enter.

If the ground is wet during harvest, the harvester and support vehicles may leave ruts in the soil. After the harvest, these ruts should be smoothed out using a small bulldozer, a bulldozer with a disk, or a tractor with a disk. You may also need to remove excess debris from the site postharvest.

Optimizing Harvest Costs

Minimizing inefficiencies during harvest is extremely important as harvesting accounts for 50–80% of the overall production costs of short-rotation woody crops (Dimitriou and Rutz 2015). Current cost estimates for harvesting, collecting, and transporting to short-term storage are $30–$40 per BDT (Shuren et al. 2017), or about $450–$1,200 per acre (assuming 15–30 BDT/acre; see Chapter 12). The most expensive piece of equipment to run in a harvest operation is the forage harvester.

When running efficiently, a single-pass forage harvesting system like the Case New Holland 9000 series with an 130FB Coppice Header should produce 60 GT or more of hybrid poplar chips per hour, not including turns and waiting for support vehicles (Eisenbies et al. 2014a; Guerra et al. 2016; Eisenbies et al. 2017). The harvester will run optimally when: (1) the trees are cut at the right size, (2) the field is laid out with harvesting in mind, and (3) an experienced operator runs the machine. Harvester performance will also be influenced by the ground conditions, such as how firm the soil is.

Ideal Tree Size and Biomass Quantity

The harvester is limited by the size of tree it can harvest. The machine should not be used on stems greater than six inches (15 cm) in diameter at the base, and trees taller than 40 feet (12.2 m) will not feed into the machine properly. When harvest yield is greater than about 18 GT of hybrid poplar per acre, the speed of the harvester is limited by its capacity to feed and chip the trees. As the harvest yield increases, the machine will have to move slower and slower, but the amount of wood harvested per distance traveled is also higher. If the trees are too big (more than 10% of the trees having a diameter greater than four inches at the base) or the total yield is too high (greater than approximately 40–55 GT/acre), the harvester is likely to become mechanically limited, which is less efficient and hard on the equipment.

A Well-Planned Field

Harvest logistics must be considered during field layout and planting (see Chapter 4) and will depend on available equipment, proximity to the biorefinery, headland space in the field, and available **landing areas** where collected biomass can be stored until it is transported to the biomass buyer. Unlike an annual crop, once planted, the stools will be in place for 20 or 30 years. Therefore, it is much easier and less expensive to plan thoroughly before planting rather than make changes to accomodate harvesting after the trees are established.

Headlands should be 30–40 feet (9–12 m) wide to allow space for turning the harvester and staging support vehicles. Establishing adequate headlands prevents costly harvesting delays and logistical complications. The harvest efficiency gained with row breaks and comfortable headspace must be weighed against commensurate decreases in productive area.

The importance of field logistics cannot be overemphasized. In a well laid out field with adequate support vehicles, 70–90% of the harvester's time in the field should be spent cutting and chipping biomass. Only 10–30% of the harvester's time should be taken up by turning at row ends and waiting for support vehicles. If the field is poorly laid out or the support vehicles are inadequate, harvesting efficiency will not be maximized.

Operator Experience

Ultimately, it will be the experience of the harvester's operator that determines the consistency and reliability of the harvest operation (Eisenbies et al. 2017). Growers need to know how field layout affects the efficiency of harvest equipment so that they plant appropriately, but an experienced operator is the best person to determine the optimal harvest pattern and best use of collection vehicles (Eisenbies et al. 2014a).

Storing Biomass

Ideally, harvesting should take place at the time the material is needed. This will deliver the best quality material to the biorefinery and avoid the need for storage space on-site. In some cases, wood chips may only need an interim storage space where they are transferred from the collecting truck or trailer to the delivery truck. If wood chips are unloaded at a central landing area, a conveyor system or front-end loader will be necessary to transfer biomass from the ground into highway trucks.

If delivery within a month of use is not possible, wood chips should be stored under cover out of the rain, unless operating in a dry climate. In a dry climate, storing chips in the open with exposure to sun and the predominant wind can expedite drying. Dry chips decompose slower than chips with high moisture content and retain better quality and mass. Generally, fresh wood chips left uncovered can have a 2–4% decrease in biomass per month due to decomposition (Dimitriou and Rutz 2015), so the less storage time, the better. Winter storage with freezing conditions is an exception because decay will not occur when the biomass is frozen (although melted snow cover can destroy the biomass if the biomass is left to sit for long periods).

Safety

Operating and working with harvesting equipment can pose serious safety risks. Equipment vendors provide specific safety instructions for proper use of their particular type of equipment. Operators should comply with vendors' written instructions regarding guarding, lock out, and safe distances from moving equipment. More safety and general information about the New Holland 130FB Coppice Header can be found in the *New Holland Agriculture Operator's Manual*. Some general guidelines to be aware of include, but are not limited to:

1. All workers should wear personal protective gear including protective eye and headwear, and vests for visibility.
2. Be aware of the possible presence of bystanders. Keep people away from the header during harvest. Ask bystanders to leave the field.
3. Do not allow anyone to enter the work area. Make sure the area is clear and the operation is safe before lowering or moving the header attachment.
4. Never attempt to pull material from the header or force material into the header with hands or feet while it is in operation or the harvester engine is running.
5. Never operate equipment under the influence of alcohol or drugs or while otherwise impaired.

Workers should also be alert and careful when walking around cut coppice stems. However, the danger of injury from falling onto the stools is minimal, as the worker would land on the flat top of the stool.

Additional Resource

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CHAPTER 12 | POPLAR BIOMASS GROWTH AND YIELD

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Introduction

Poplar is one of the fastest growing trees in the temperate region. In the Pacific Northwest (PNW), **hybrid** poplar typically grows up to 10–12 feet (3–4 m) in height each year on a high-quality, well-managed site, and 4–5 feet (1–2 m) a year on marginal-quality or poorly managed sites. The **yield** of **biomass** will typically range from five to ten **bone dry tons** (BDT) per acre (11–22 tonnes/ha) per year after the stand has progressed into the **coppice** cycles (i.e., when the trees are regenerating with multiple stems). Biomass yields vary greatly among poplar varieties and are influenced by multiple environmental conditions including climate, nutrient and water availability, competing vegetation, and damage caused by **insects**, **disease**, and wildlife. Achieving the best poplar yield depends on management factors discussed in previous chapters.

Quantifying Biomass Yield

Biomass can be measured as **green tons** (freshly cut material) or BDT (material dried to zero percent moisture). Moisture content will vary by season, **clone**, leaf content, and biomass storage time but is generally around 50% in freshly cut material (e.g., 40 green tons is roughly 20 BDT). Lab testing is used to precisely estimate moisture content and dry weight.

Biomass yields are typically expressed as BDT per acre (BDT/acre) for a specific point in time or as an average across multiple years (BDT/acre/yr). The multiyear average is called the **mean annual increment** (MAI). With yields differing from year to year during growth cycles, MAI serves as a common metric that allows for better yield comparisons among different management options. See the two sidebars Metrics for Stand Growth and Example: Metrics for Coppice Stands for more information about these metrics.

Metrics for Stand Growth

Yield is the volume of biomass available for harvest at a given age.

Mean annual increment is the average stand growth per year, calculated as the current volume divided by the current age.

MAI should not be confused with **current annual increment** (CAI), which is the volume of biomass accumulated since the previous year.

Harvesting at the culmination of MAI (when the CAI curve intersects the MAI curve) maximizes volume production (figure 12.1). After that point, delay in cutting results in less biomass growth compared to cutting and starting a new cycle.

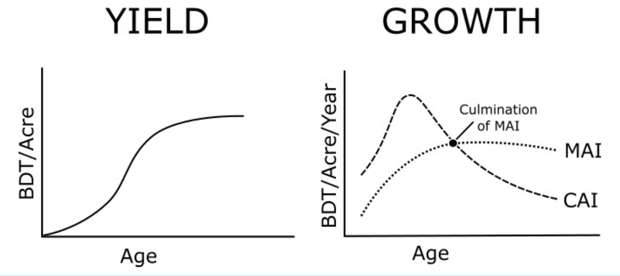

Figure 12.1. Biomass yield curves over time.

For coppice systems, the yield and growth rate curves will be different for the **establishment cycle** and coppice cycles (see sidebar Example: Metrics for Coppice Stands). The establishment cycle (between planting and first harvest) generates lower yields and has slower rates of growth than the multistemmed coppice regrowth cycles that have an established root system. "Age" corresponds to the age of the aboveground biomass during each cycle rather than the age of the roots. Therefore, after harvest the age of the stand goes back to zero.

Example: Metrics for Coppice Stands

Table 12.1 contains hypothetical data and calculations to demonstrate the relationship between yield, MAI, and CAI in a coppice system. These values are for example purposes only and are *not* real data points.

Table 12.1. Example values to demonstrate the relationship between yield, MAI, and CAI in a coppice system.

	Establishment Cycle		Coppice Cycle		
	Age 1	Age 2	Age 1	Age 2	Age 3
Yield (BDT/Acre)	1.2	4.0	3.3	10.2	15.6
MAI (BDT/Acre/Year)	1.2 / 1 = 1.2	4.0 / 2 = 2.0	3.3 / 1 = 3.3	10.2 / 2 = 5.1	15.6 / 3 = 5.2
CAI (BDT/Acre/Year)	1.2 – 0 = 1.2	4.0 – 1.2 = 2.8	3.3 – 0 = 3.3	10.2 – 3.3 = 6.9	15.6 – 12.6 = 3.0

Taking an Inventory to Predict Yields Before Harvest

Conducting an **inventory** of a poplar stand allows an assessment of crop performance. An inventory is recommended at least once before each harvest. This inventory gives a “snapshot” of the biomass quantity at the time of measurement and assists with estimates of projected harvest yield.

An inventory involves establishing a series of measurement plots in the stand and using **yield tables** to convert the measurements to an estimate of biomass yield, expressed as BDT/acre inclusive of stems, branches, and bark. For details on how to conduct an inventory, refer to Chapter 17. It is recommended that a separate inventory for coppice survival and health be conducted. This should occur during the growing season shortly after each harvest.

Yield Examples from Four Locations in the PNW

Advanced Hardwood Biofuels Northwest (AHB) conducted inventories and measured yields at the project’s four demonstration sites located across the PNW (figure 12.2). These sites represent a wide range of environmental conditions as well as irrigated and non-irrigated management, demonstrating the variability of yields depending on site conditions.

The two northern sites included a North Puget Sound site near Stanwood, Washington (a.k.a. the Pilchuck site), and an Idaho Panhandle site near Hayden, Idaho. These sites have young soils derived from volcanic and glacial activity and are both nitrogen-limited. The Stanwood site represents marginal land that does not economically support food crop production but can produce acceptable poplar biomass yields. The southern sites in Jefferson, Oregon (Willamette Valley) (figure 12.3), and Clarksburg, California (Sacramento Delta), are derived from **alluvial** deposits with relatively high nitrogen availability, allowing greater use options including higher-quality agricultural soils. The Hayden and Clarksburg sites were irrigated, while Jefferson and Stanwood were not.

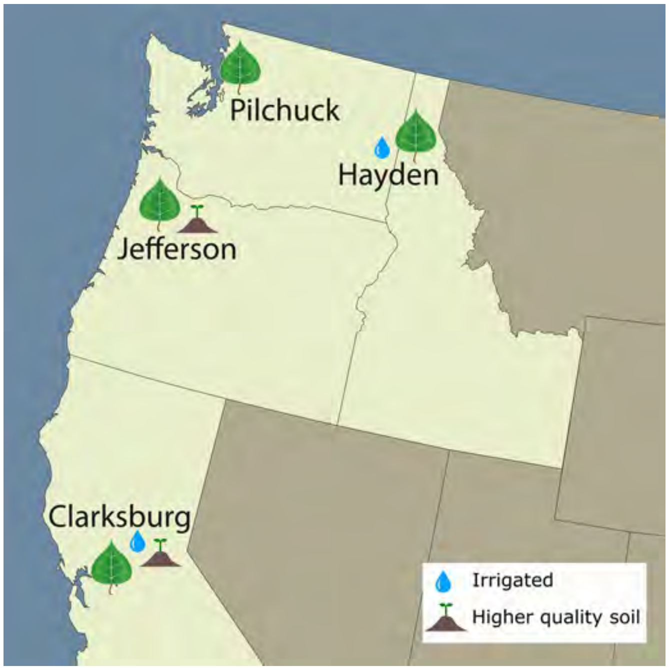

Figure 12.2. Locations of Advanced Hardwood Biofuels Northwest’s four hybrid poplar demonstration sites (leaf symbols), planted in 2012 and 2013 and managed from their respective establishment years through 2017 or 2019 depending on the site. Image: WSU Extension.

Table 12.2 provides estimated mean annual increment (MAI) and yield of biomass at the four sites. Estimates were determined using data from field measurements extrapolated to biomass per acre. Each site tested multiple hybrid poplar clones to help identify the best clones for a region. The site average is calculated across clones and **microsite conditions**. Data for the top-performing clones are likely a better predictor of a prospective landowner's yields. However, **clonal blocks** were not replicated, so results may reflect differences in microsite conditions rather than clonal differences.

Biomass yields from the first cutting after planting are relatively low, as the trees initially devote considerable energy to root establishment rather than aboveground growth. In the first two growing seasons (establishment cycle), the yield of top clones at the four sites ranged from 1.8 to 8.0 BDT/acre (4.0 to 17.9 tonnes/ha), with MAI from 0.9 to 4.0 BDT/acre/year (2.0 to 9.1 tonnes/ha/year). In the second cycle, when multiple stems have resprouted from an established **rootstock** (i.e., coppice), the yield of the top clones at the four sites was higher, ranging from 10.3 to 14.9 BDT/acre (23.1 to 33.4 tonnes/ha) after two growing seasons and reaching 17.3 to 29.7 BDT/acre (39.2 to 67.4 tonnes/ha) after three growing seasons. The maximum MAI for the top clones ranged from 5.8 to 9.9 BDT/acre/year (13.2 to 22.5 tonnes/ha/year). These results are consistent with other studies of cutting cycles and yields (Pontailler et al. 1999; Verlinden et al. 2015). Biomass yields are expected to reach target values at the second harvest and remain relatively consistent for five to seven two- to four-year harvest cycles (Pontailler et al. 1999; Dillen et al. 2013). After this period, growth will decline, the rootstock should be removed, and new rootstock should be planted.

Table 12.2. Biomass yields (BDT/acre) and MAI (BDT/acre/yr) after each growing season at four AHB demonstration sites across the PNW. Yield is the amount of biomass at the site at a given time. MAI is the average annual growth rate of the aboveground biomass. The trees were harvested at the end of the establishment cycle and resprouted from the cut **stools** (coppice cycle).

		YIELD (BDT/ACRE)				MEAN ANNUAL INCREMENT (BDT/ACRE/YR)			
		Establishment Cycle	1st Coppice Cycle			Establishment Cycle	1st Coppice Cycle		
		2nd Growing Season	1st Growing Season	2nd Growing Season	3rd Growing Season	2nd Growing Season	1st Growing Season	2nd Growing Season	3rd Growing Season
Site		**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
Jefferson, OR	Top Clone	8.0	4.3	10.3	24.3	4.0	4.3	5.2	8.1
	Site Average	5.3	3.3	8.0	17.8	2.6	3.3	4.0	5.9
Hayden, ID	Top Clone	4.3	2.8	11.4	20.9	2.2	2.8	5.7	7.0
	Site Average	3.5	1.3	7.3	15.9	1.7	1.3	3.7	5.3
Clarksburg, CA	Top Clone	6.9	4.5	11.8	17.3	3.4	4.5	5.9	5.8
	Site Average	5.9	2.6	8.5	11.9	3.0	2.6	4.3	4.0
Stanwood, WA [Pilchuck]	Top Clone	1.8	2.0	14.9	29.7	0.9	2.0	7.5	9.9
	Site Average	1.2	0.9	8.0	15.4	0.6	0.9	4.0	5.1

Figure 12.3. Aerial view of hybrid poplars at the Jefferson, OR, demonstration site, which was planted in 2012 and restored to traditional agriculture in 2017. Photo: D. Kilgore.

Estimating Biomass Yield in the PNW

Hart et al. (2015) at the University of California, Davis, developed a **growth model** to predict hybrid poplar growth and yield for the PNW region. The Physiological Principles of Predicting Growth (3PG) forest model (Landsberg and Waring 1997) was modified to include coppiced growth. Inputs such as weather, soil characteristics, and other management factors are used to model the growth of above- and belowground biomass of various hybrid poplar clones and estimate yield for user-specified cutting intervals.

As part of AHB's poplar sustainability assessment, researchers applied the AHB-3PG model to the entire PNW and developed maps that predicted biomass yields on agricultural land across the region (figures 12.4 and 12.5) (Hart et al. 2015). Land under federal ownership, land with slopes over 15%, developed land, or land with unsuitably high salinity or alkalinity were excluded from the maps because they are considered unsuitable for poplar production. Yields are generally higher in irrigated fields (figure 12.4) compared to non-irrigated fields (figure 12.5).

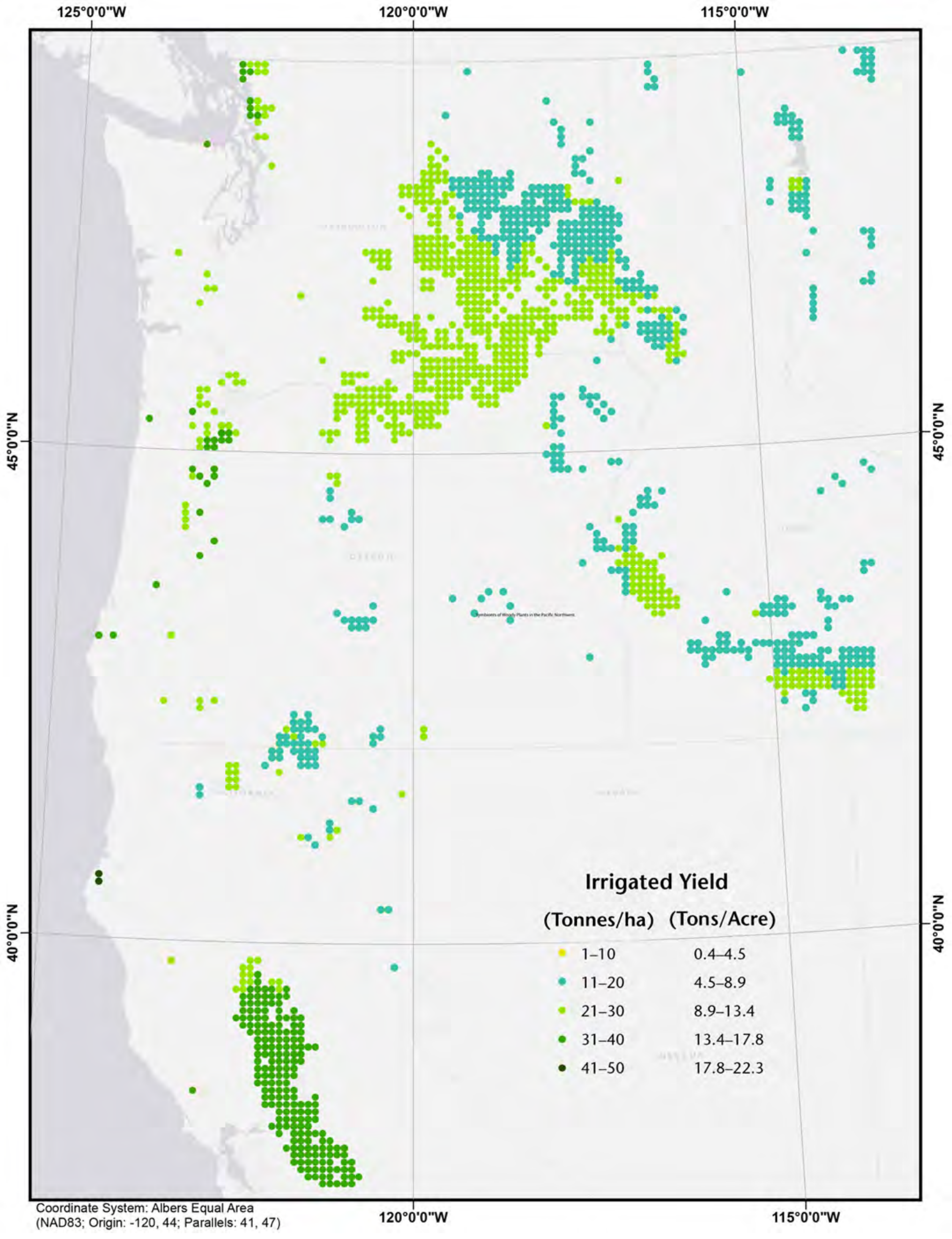

Figure 12.4. Predicted yield (in bone dry tons and tonnes) of irrigated three-year coppice hybrid poplar stands for areas under agricultural practice. The image only includes pixels [64 km^2] with more than 20% of the area identified as cropland. Image: Adapted by B. Nordaker based on Hart et al. (2015).

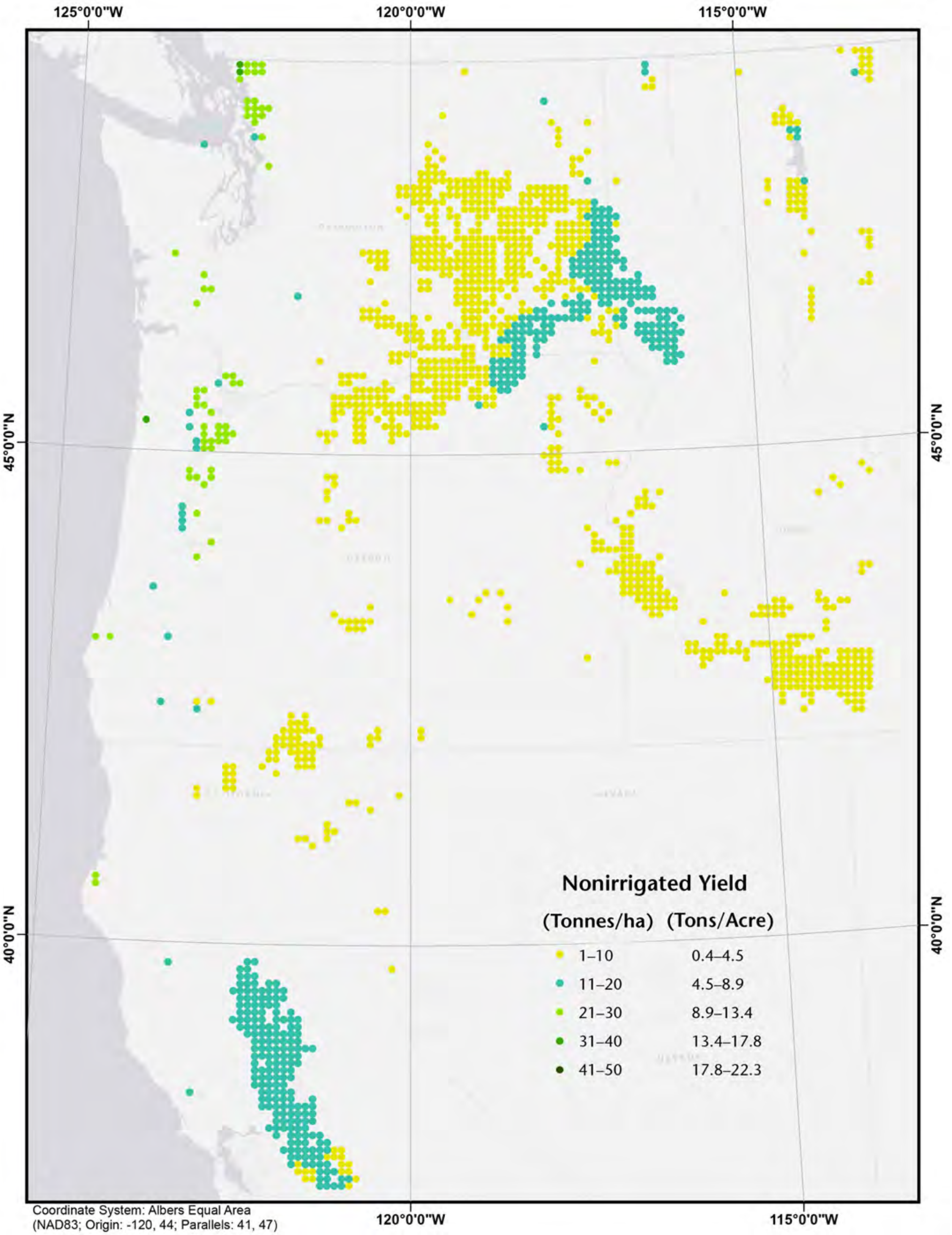

Figure 12.5. Predicted yield (in bone dry tons and tonnes) of a non-irrigated three-year coppice harvest for areas identified as rangeland or marginal land. The image only includes pixels [64 km^2] with areas of more than 20% rangeland or marginal land. Image: Adapted by B. Nordaker based on Hart et al. (2015).

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CHAPTER 13 | RESTORING THE SITE

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When land will no longer be used for a poplar plantation, it will need to be prepared for its next use. **Restoration** in this context is defined as returning the site of a poplar plantation to a state that allows a different type of crop to be planted and grown. The next crop will determine the intensity of the restoration activities. Restoration activities are focused on preventing poplar from resprouting, reducing the size of any remaining woody debris, and creating appropriate soil **tilth** for the next crop. Restoration can be completed in a time frame of one month to two years after the final **coppice** cutting cycle, depending on the number and intensity of restoration activities (Coppice Resources 2006). The method chosen to restore the site depends on a number of factors including:

- Succeeding land use—If a quick turnaround is desired so that another crop can be planted, a shorter and more intensive approach would be warranted, compared to situations where a grower wants to leave the land **fallow**.
- Soil texture—Coarse-textured soils have been found to be easier to restore than soils of a finer texture. Coarse-textured soils will have better drainage, allowing earlier access to the site in the spring. Fine-textured soils may produce excessive dust and the site may be more susceptible to soil compaction.
- Equipment availability—Equipment availability will vary by region, and hiring custom land reclamation equipment operators should be considered (Patterson and Painter 2014).
- Cost of the operation—The cost of site restoration is estimated to range between $400 and $600 an acre.

Restoration Following Three-Year Coppice Rotations vs. Longer Roundwood Rotations

Poplar plantations grown on short two- to three-year **coppice rotations** are easier and less expensive to restore than plantations grown on rotations of eight years or more for **roundwood** production. In a roundwood poplar plantation, the structural root system becomes much larger and needs to be taken out with heavy equipment, then disposed of before the remaining **biomass** can be incorporated into the soil (figure 13.1). For larger trees, total restoration costs can be in excess of $1,000/acre. In contrast, the root systems of coppiced poplars remain small enough that the roots can be incorporated into the soil using the methods described in this chapter.

Figure 13.1. Root and woody debris pile from site restoration activities in Springfield, Oregon, where trees grown for over ten years for roundwood production were removed. Photo: T. Miller.

Overview of Restoration Activities

Site restoration after the final harvest should leave the field with a minimal amount of poplar biomass aboveground. The remaining root systems will be the most prevalent and largest amount of biomass on the surface. There will also be a few cut poplar trees scattered about that were not removed from the field during the final harvest (figure 13.4). Belowground, there will be the **root collar** and **structural roots** in the upper ten inches of the soil and **feeder roots** throughout the soil profile (figure 13.2).

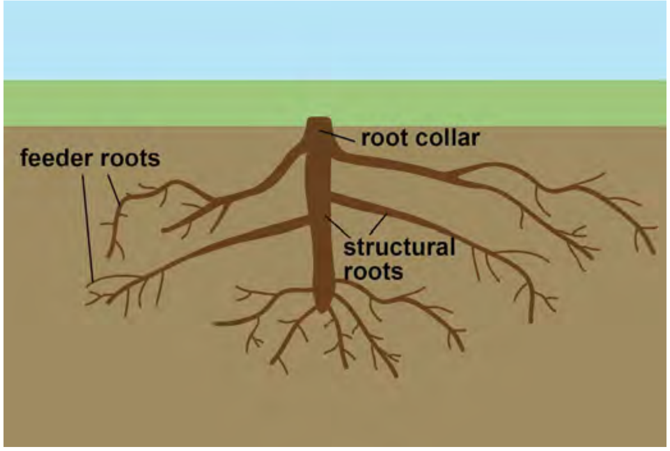

Figure 13.2. The roots of the poplar tree will be the largest source of biomass remaining in the field.

After the final poplar harvest, applying herbicide to resprouting growth after it has reached a height of 8 to 12 inches (20–30 cm) will effectively kill the majority of the live poplar tissue left on the site. A variety of **systemic herbicides**, applied in the appropriate manner and in compliance with all label instructions, can successfully kill the poplar, including their root systems. Systemic herbicide options include glyphosate, metsulfuron methyl, and triclopyr as allowed based on the subsequent use of the land. These types of chemicals are absorbed by the plant's foliage and roots and prevent normal biochemical reaction from occurring, killing the plant. Poplar has a vigorous root system that in some cases will have been established on the site for twenty years or more, so a second herbicide application may be necessary to fully kill it, depending on the timing and type of other restoration activities conducted. When selecting an herbicide product, consider the type and timing of the next crop to be planted as some herbicides will remain active for a year or more after application.

If removal of the dead stumps and structural root material is necessary for future agricultural use, a **power base unit** with a **mulching implement** or a purpose-built mulcher is best suited for restoration. Engine power of this equipment can vary from 100 to 600 horsepower. Intensive mulching of the stump and root material can eliminate the need for first applying herbicide, as it will reduce the material to small fragments that will not resprout. Less-intensive mulching will likely require an initial herbicide application, as described above, or other means to control resprouting.

This chapter describes three restoration scenarios that can be modified to match the unique situation at a variety of sites.

Stump vs. Stool

Stump and ***stool*** are terms used to describe states of a poplar tree grown using coppice management methods. The terms are similar in that they both refer to the lower remains of a tree or stem after it has been cut. The terms are distinct in that a stool is intended for coppice regeneration through regrowth of new stems (figure 13.3). A stump is not necessarily intended for coppice regeneration and could be the remains of a harvested tree that was then treated with herbicide to kill it fully, for example. The term stump may also be used to refer to poplar tree remains in a field that is to be restored for another use. The lower remains of the poplar in figure 13.3 would be considered a stool, as it was left to resprout the next growing season.

Figure 13.3. Because of its ability to regenerate by coppice, poplar growers call this *stump* a *stool*, although the terms are often used interchangeably. Photo: N. Haider.

Restoration Methods

Method 1: Winter Harvest, Spring Restoration

After the final harvest, the poplar field should be clear of debris, except for the remaining poplar stools. The stools will resprout with new coppice growth the following spring (figure 13.4). When the **shoots** are about 8 to 12 inches (20 to 30 cm) tall, apply a systemic herbicide to the regrowth. The sprayed regrowth should be left in place for at least two weeks after the herbicide application to allow full absorption and translocation of the herbicide to the roots (Dimitriou and Rutz 2015). Because of poplar's strong ability to reproduce by **vegetative propagation**, even a small amount of live material has the potential to sprout. After the sprayed regrowth has died back, a mulching implement should be used to reduce the stumps to ground level (figure 13.5). A second pass through the field with a subsurface mulcher will incorporate remaining woody debris into the top 8–12 inches (20–30 cm) of soil (figure 13.6).

The next intended agricultural use of the site will dictate the next steps. Additional mulching passes or conventional soil **tillage** may be required to establish the next crop. A high amount of woody material incorporated into the soil may cause a temporary nitrogen deficiency for plants (figure 13.7) due to the high use of soil nitrogen by soil microbes working to break down the carbon-rich material. In these cases, nitrogen amendments may be required to meet the nutritional needs of future crops. The site can also be left fallow for a year to allow time for the woody debris to break down enough such that sufficient nitrogen is available to plants. Nitrogen deficiency is not always an issue, though, as seen in figure 13.8 where a healthy and uniform wheat crop was produced in the growing season immediately following restoration from a poplar plantation. Land managers should conduct a soil test prior to planting the next crop to ensure adequate nutrients, then watch for any signs of nitrogen deficiency in subsequent crops and respond accordingly.

Figure 13.4. After the final harvest, the debris remaining in the field will be minimal, consisting mostly of resprouting stumps or stools and errant branches and stems. Once the remaining stumps resprout with spring growth, the poplar field is ready for an herbicide application to begin the site restoration process. Photo: A. Himes.

Figure 13.5. A mulching implement is used to level the stumps to the ground. Photo: A. Himes.

Figure 13.6. A subsurface mulcher breaks up and incorporates the woody debris into the soil. Photo: A. Himes.

Figure 13.7. A former poplar plantation produced a crop of wheat the summer after a winter restoration. Growth was slightly depressed in the areas over the former poplar rows as is evident by the faint striping. A nitrogen deficiency due to the breakdown of woody debris is the presumed cause of the striping. Photo: A. Himes.

Figure 13.8. After restoring this former poplar plantation in Jefferson, Oregon, the subsequent wheat crop did not appear to be impacted by the immediately preceding poplar crop. Photo: R. Stonex.

Method 2: Summer Mulching

When restoration activities occur in dry summer months, mechanical activities alone may be adequate to restore the site to a usable state. Lack of moisture combined with the mechanical degradation of woody material into small pieces will prevent resprouting of any living poplar remnants. Figure 13.9 shows midsummer regrowth and stumps being mulched by a 135 HP tractor and a PTO Prinoth M550 mulching attachment. Following this initial pass, a Prinoth Raptor 800 (figure 13.10) was used to incorporate both the scattered surface and belowground biomass into the soil. A finishing pass (or passes) with conventional agricultural implements will further prepare the site for the next crop (figure 13.11).

Figure 13.9. The tractor-powered Prinoth M550 is used to mulch stumps and poplar regrowth in August after a late winter harvest. Photo: P. Townsend.

Figure 13.10. The purpose-built Raptor 800 incorporates the mulched biomass and belowground root material into the soil. Photo: P. Townsend.

Figure 13.11. A finish disc was used to smooth the soil in preparation for a new wheat crop. Photo: R. Stonex.

Method 3: Herbicide Followed by Delayed or Minimal Mechanical Activity

The third method prevents the poplar from resprouting, but the woody material is left intact to be broken down by natural processes. To restore the field, apply a systemic herbicide (for example, glyphosate or triclopyr), as allowed based on the subsequent use of the land, to kill the poplar (as in *Method 1*). Leave the woody material in place, rather than mulching the woody debris into the soil. Forgoing the mulching step is a lower-cost alternative that may be suitable, if the next agricultural use will be pasture such that simply overseeding with the desired forage crop is sufficient. Alternatively, if the next agricultural use is a year or more away, the subsequent mechanical treatments could be delayed, allowing natural processes to start breaking down the woody debris in the meantime. When mechanical treatments are applied, they will require less energy and intensity, thereby reducing that expense.

Conclusion

Using the methods described in this chapter, a poplar plantation can be methodically restored and prepared for another agricultural use after the final poplar harvest. When growing poplar on short (three-year) coppice rotations, the residual stumps remain relatively small compared to poplar stumps left behind after roundwood production. This allows the stumps, roots, and other woody biomass remaining in the field to be ground up and incorporated into the soil rather than needing to use heavy equipment to remove stumps and other residual material. When restoring a poplar plantation, poplar growers should focus on the three goals of restoration: (1) prevent the poplar from resprouting, (2) break up and incorporate any remaining woody debris into the soil, and (3) prepare the soil for the next crop. Specific restoration steps will depend on the restoration budget, restoration timing, and desired subsequent crop.

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CHAPTER 14 | PRODUCTION ECONOMICS

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Poplar Economics

The economic success of growing **hybrid** poplar as biofuel **feedstock** in the Pacific Northwest (PNW) is directly related to the future development of regional biofuel and biochemical industries. If such industries develop, more market opportunities will be available to growers. This chapter provides a framework for assessing expected economic costs and returns for a poplar **biomass** production system.

The economics of poplar biomass production depend on a variety of factors, with biomass pricing and land cost being the two factors with the greatest impact on profitability. Other important costs to consider include harvesting, biomass transportation, crop care, and **planting stock**.

Purpose-grown energy crops could be indispensable due to their ability to reduce the uncertainties of both biomass supply and pricing of nondedicated feedstock, such as forestry and agricultural residues. As biofuel and bio-based chemical production are in their developmental stage, biomass price levels are modeled and not a product of actual market pricing. Future subsidies, incentive programs, or higher fossil fuel prices may help growers produce biomass at a competitive price. As biofuel markets evolve, producers will likely purchase a variety of feedstocks for conversion (e.g., poplar, wheat straw, corn residuals, wood residues), having a range of prices. As a purpose-grown energy crop, poplar biomass offers **biorefineries** a consistent and high-quality source of feedstock that can be easily fractionated to produce fuels and chemicals, which in turn may support higher pricing for poplar biomass (Dao et al. 2017). Future technology improvements that lower conversion costs may also support higher pricing.

Poplar Production Costs

Costs to consider for poplar production include establishment, crop care, land price, and the harvesting and transportation of each rotation's biomass.

Initial Investment Costs

Establishing a new hybrid poplar field involves establishment costs that will support multiple harvests. **Site preparation** and planting stock costs are one-time costs that are incurred at the inception of a plantation that are recovered over 20 years of production comprising a two-year **establishment cycle** followed by six three-year coppice cycles. These costs can vary depending on the site condition, soil quality, and prior management practices. See Chapter 5 for more information on plantation establishment and planting procedures.

Annual Crop Care Costs

Annual crop care includes all activities associated with poplar production after planting. Weed control (mowing, herbicide, hoeing, etc.) will need to continue through each cutting cycle as well as **pest** and **disease** control. Other potential cost factors could include nutrient amendments and irrigation. These costs depend greatly on the quality and location of the site. Average crop care costs will vary year to year and site to site. Spending more on activities like weed control early in the rotation can save money in the long term by reducing costs and increasing profits in later years.

Harvest Costs

Harvesting is the most expensive activity on a short-rotation poplar plantation. One significant difference between **coppiced** poplar and annual crops is that with poplar the cost of harvesting activities is only incurred once every three years. When the field is harvested, three years of biomass growth is collected. Growers should also keep in mind that **yields** at the initial harvest (two years after planting) probably will not be as great as yields from the subsequent coppice harvests beginning in year five, when biomass regrowth is from established root systems (see

Chapter 12). Having only one establishment cycle mitigates the revenue impact of lower first cycle harvest yields when considering the full 20-year life span of the plantation. The harvest costs for **coppice rotations** are higher due to higher yields that increase the operating hours of the harvest equipment. However, the increased yields will make up for the increased harvesting costs, lowering the overall cost per unit of biomass harvested. See Chapter 11 for more information about harvesting equipment and processes. Harvest costs might include smoothing rutting in **alleyways**, **landing areas**, and other truck access points to the field and removing excess debris.

Transportation Costs

When doing a financial analysis of biomass production, if delivered biomass prices are used, the cost of transportation from the field to the refinery will need to be factored into the production budget. Transportation costs will vary depending on the point of product delivery and can represent a large cost factor in the production system. Transportation costs will fluctuate with fuel prices, equipment operating costs, and distance to market.

Land Prices

The cost to acquire land, either through a purchase or lease agreement, should also be included in the total production cost. Land prices vary greatly by location and site quality. Irrigated land is generally more expensive than non-irrigated land, but yields can be higher with irrigation. On high-quality irrigated land it will likely be challenging for poplar growers to compete in land markets with growers of conventional agricultural crops. On sites with access to municipal and industrial effluent, irrigation may be more cost-effective after including the environmental benefits that could be achieved using effluent resources (see Chapter 16). Purchasing or leasing land will be driven by local or regional land markets as well as the individual grower's business model.

Biomass Production Cost Calculator

The Biomass Production Cost Calculator (BPCC) is a spreadsheet-based tool designed to help growers assess the economic feasibility of growing hybrid poplar as an energy crop (Shuren et al. 2020). The BPCC provides default estimates of costs, yields, and revenues based on the Advanced Hardwood Biofuels Northwest (AHB) Feedstock Team's experience establishing, growing, and harvesting four demonstration farms as part of the AHB project. The BPCC and its default values are not, nor are they intended to be, a definitive guide for producing the crop, and the outputs of the model are not a guarantee of results. Rather, the default estimates are provided as a starting point that users can then customize to fit their own specific situation and explore how different variables impact economic outcomes. The BPCC is free to download from https://hardwoodbiofuels.org/audiences/poplar-growers/decision-support-tools-for-growers/#BPCC.

The variables that can be customized in the BPCC include:

1. **Production Schedule**
    - Length of the establishment cycle in years
    - Length of the coppice cycle in years
    - Number of coppice cycles to determine total rotation length
2. **Production Activities**
    - Land cost as either a lease or purchase
    - Site preparation
    - Plant material, planting, and crop establishment
    - Crop care activities and intensity
    - Harvesting
3. **Farming and Harvesting Equipment and Labor**
    - Size and horsepower
    - Equipment operating cost per hour
    - Cost per hour of equipment operator
    - Manual labor costs
    - Transportation cost for biomass delivery to the biorefinery
4. **Chemical Use**
    - Herbicides, insecticides, fertilizers, and rodenticides
    - Application rates and frequency of application
    - Chemical cost
    - Application cost
5. **Administration**
    - Property management fees
    - Administrative and accounting fees
    - Property and income taxes
6. **Biomass Yield Estimates**
    - Establishment yields after one or two growing seasons from planting
    - Coppice yields after one, two, or three growing seasons

Production needs, costs, and yields will vary by geographic location. The BPCC calculations are based on data from the four AHB demonstration farms:

1. Clarksburg, California—representing Sacramento Delta farmland
2. Hayden, Idaho—representing upper Idaho Panhandle farmland
3. Jefferson, Oregon—representing Willamette Valley farmland
4. Pilchuck, Washington—representing North Puget Sound uplands

See Chapter 1 for more information on the AHB demonstration farms. See Chapter 12 for information on yield data from these four sites.

Financial Analysis Metrics

In-depth discussions of financial analysis are available in forestry or agricultural economics textbooks (e.g., Klemperer, 1996). Here we briefly review two common metrics, **net present value** (NPV) and **internal rate of return** (IRR), which are the two key outputs of the BPCC.

Costs and revenues occur in different years in a hybrid poplar production system. In order to compare them, the time value of money, as expressed as a compound interest or **discount rate**, must be considered. This can be done by computing the NPV, which is the sum of all cash flows discounted to the present from their respective years of occurrence.

NPV will vary widely depending on the discount rate that is used. The higher the discount rate, the less value future cash flows have. This gives initial expenses greater weight compared to future returns such that NPV will typically go down as the interest rate goes up or the time horizon lengthens. A positive NPV means that the present value of the revenues exceeds the present value of the costs at that discount rate and so the investment would be considered acceptable. Similarly, a negative NPV means the present value of the costs exceeds the present value of the revenues at that discount rate and the investment is not acceptable. When comparing options, a higher NPV indicates a better return given the desired discount rate. An NPV of zero means that the return on investment was exactly equal to the discount rate. The discount rate that causes NPV to equal zero is known as the IRR.

The challenge of NPV is selecting an appropriate discount rate. Investors often select a discount rate based on what a competing investment would yield. For instance, if making a choice between investing money in growing hybrid poplar or investing in a fund that earns 6% interest, a 6% discount rate would be appropriate for computing the NPV of the hybrid poplar system. The discount rate also reflects the risk of an investment, with investors demanding higher returns on investments that have a higher risk of yielding a loss. Ultimately, the discount rate is an individual business decision based on alternative investments of comparable risk and the investor's risk tolerance.

There are advantages and disadvantages of using NPV versus IRR. An advantage of using IRR is that it is independent of a discount rate and allows for easy comparisons between investment options (e.g., hybrid poplar production with a 7% IRR versus a fund that yields 6% or row crops that yield 6.5%). IRR works particularly well when there is one expense (investment) at the beginning of the project followed by revenues in later years. When there are multiple expenses occurring at different times, such as with forestry or hybrid poplar production, IRR may not be as straightforward and, in some cases, there can be multiple IRRs (i.e., multiple discount rates that would cause NPV to equal zero) (Gansner and Larsen 1969).

NPV at an appropriate discount rate avoids this potential and also allows for some different kinds of assessments. For instance, if a grower wants to earn a 6% rate of return and the NPV for a hybrid poplar system, not including land costs, is $500/acre, this implies that the grower can spend up to $500/acre on the land and earn an overall return on investment of at least 6%. Similarly, an NPV of -$500 indicates that an initial subsidy of $500/acre (plus the cost of land) would need to be given to that grower in order to achieve the desired return.

If an investor knows what rate of return they would like to make given the perceived risk of the venture, an NPV calculation is a good way to compare options. If an investor wants to compare a hybrid poplar venture against financial instruments with known rates of return, then an IRR calculation may be more useful.

Ultimately, both calculations are informative, and both are computed by the BPCC.

Market Price

The market price of poplar biomass will ultimately be the main determinant of financial success for growing hybrid poplar for **bioenergy** feedstock. In 2017, Chudy et al. (2019) reported that the average market price for forest biomass in western Washington and northern Oregon was $41 per **bone dry ton** (BDT) or $46 per **bone dry metric ton**

Table 14.1. Example financial calculations using the BPCC for a range of market prices and discount rates.

Delivered price per BDT	NPV/acre 3%	NPV/acre 6%	NPV/acre 9%	IRR
$41	-$2,442	-$1,961	-$1,646	N/A
$59	-$249	-$411	-$516	0%
$61	$0	-$235	-$388	3%
$63	$333	$0	-$216	6%
$67	$752	$296	$0	9%
$70	$1,153	$579	$205	11.16%

(BDMT), reaching a high of $70/BDT ($77/BDMT) delivered. Table 14.1 is an example of financial calculations using the BPCC, including IRR and NPV/acre at a 3%, 6%, and 9% discount rate. This example uses the default cost and yield assumptions for the Pilchuck location and assumes no land cost and a two-year establishment cycle followed by six three-year coppice cycles for a total rotation length of 20 years. This example uses the two BDT price points above as well as the price points at which IRR would equal 0%, 3%, 6%, or 9%.

The example in table 14.1 demonstrates the impact that even small price changes have on the financial return. Market uncertainty will be one of the biggest challenges for hybrid poplar growers. Since this example assumes no land cost, the positive NPV values in table 14.1 show the present value of what could be paid for land while still obtaining that rate of return. Where the NPV values are negative, a subsidy of that amount plus the cost of land would be needed for that rate of return to be achieved. Growers should research state and federal biomass production incentives when they are considering poplar as a potential crop.

Many other financial outcome comparisons can be done by changing different cost, production method, location, and price values. Rather than present more here, we encourage growers to experiment on their own by downloading the free BPCC tool and the User's Guide.

Conclusion

Numerous variables must be considered when assessing the financial performance of growing hybrid poplar as a bioenergy feedstock. These include production methods; costs of equipment, labor, and materials; the cost of land; biomass yields; market prices; and desired return. One of the biggest drivers of financial success will be the market price for biomass. Growers should research market conditions carefully as well as available subsidies or incentives.

The BPCC is a free tool available to growers to analyze the financial outcomes under various conditions.

Suggested Additional Reading

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CHAPTER 15 | SELLING TO A BIOREFINERY

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Contracts with the Biorefinery

Contracts between **feedstock** producers and **biorefineries** will be necessary as new biofuel industries develop. A poplar grower will want to secure a market for the poplar crop before it is planted, and biorefineries will want to secure a reliable supply of feedstock for biofuel production. Because a biorefinery will require significant capital to build, it will be critical that a feedstock supply is guaranteed for a long period of time, likely ten or more years. In utilizing contracts, biorefineries may entice growers to participate in the biofuel supply chain by offering payments during the **establishment period** of crop production when the crop is not yet ready to harvest. Contracts may alleviate barriers to poplar production, such as uncertainty about the profitability of poplar due to little commercial history and lack of technological and logistical knowledge (Alexander et al. 2012). In utilizing contracts, growers can be assured that their profit from the contract is at least as good as the next best alternative use of their land (Rosch et al. 2012).

Because of the many scenarios that may exist, researchers suggest that a variety of contract options should be offered to growers by the biorefinery. Contract selection will depend on the willingness of each party to engage in high- or low-risk situations. Mutually agreeing on a contract will depend on the risk tolerance for both the grower and the buyer (Yang et al. 2014; Alexander et al. 2012). Growers are advised to consult a legal professional who can provide independent advice on contracts prior to signing.

Grower Cooperatives

Small-scale growers could form grower cooperatives where multiple growers jointly negotiate with **biomass** buyers. Additional benefits might include coordinating harvesting activities to ensure on-time delivery and quality control of the feedstock, creating opportunities for growers to be involved with **bioenergy** policy making, and improving communication between growers for more effective knowledge sharing and technology transfer. Grower cooperatives might also make it more economical for small-scale growers to be certified as sustainable biomass producers (see Certifying the Feedstock section of this chapter). Biorefineries will likely appreciate grower cooperatives as a single point of contact rather than many individual poplar growers. Grower cooperatives would provide a high level of assurance for on-time delivery of poplar chips of a consistent quality with respect to chip size and chemistry (Downing et al. 2004).

Meeting the Renewable Fuel Standard

The **Renewable Fuel Standard** (RFS) was created under the Energy Policy Act of 2005 and was expanded by the Energy Independence and Security Act of 2007 to become the **Renewable Fuel Standard 2** (RFS2), which established renewable fuel volume mandates in the United States. The RFS2 required that 36 billion gallons of renewable fuel be blended into transportation fuels by 2022. The RFS and RFS2 aimed to significantly reduce net greenhouse gas emissions from the transportation sector, reduce imported petroleum, and encourage renewable energy development in rural communities.

Renewable Identification Numbers (RINs) are credits issued by the United States Environmental Protection Agency (EPA) as incentives to meet the targets set forth by the RFS2. A renewable fuel producer benefits by generating RINs for the biofuels that they produce. RINs are generated when a fuel producer makes a gallon of renewable fuel. Petroleum refineries and importers of gasoline and diesel fuel will purchase RINs from biorefineries to meet their RFS2 obligations since they are not producing renewable fuels themselves. The value of RINs provides an economic incentive to use renewable fuels.

The price of a RIN is a percentage of the cost of a gallon of renewable fuel, which fluctuates as a result of market factors such as the price of oil and production costs of the biofuel, including the price the biorefinery pays for its feedstock. For example, high oil prices and low feedstock costs would create a favorable market for biofuels, as there would be higher demand for them. When biofuel supplies in the market increase, the price for RINs would decrease.

As an energy crop, poplars are not yet recognized as an acceptable feedstock under the RFS2. The EPA has proposed rule changes that would allow poplar to qualify. Under the proposed rule, short-rotation poplar would be an allowable feedstock if it is grown on nonfederal land that was cleared or cultivated for agriculture or managed as a tree plantation prior to December 19, 2007, and has been actively managed as such since that date. As of January 2022, no final determination on the rule has been made. Updates on the rule-making process are posted on the EPA's Renewable Fuel Standard Program website at https://www.epa.gov/renewable-fuel-standard-program/proposed-renewables-enhancement-and-growth-support-regs-rule.

If the rule is approved, poplar growers would need to supply the fuel producer with documentation that ensures the definition of renewable biomass is being met and allows feedstocks to be traced from their original producer to the renewable fuel production facility. Fuel producers would be required to list all species and **hybrids** that they intend to use and provide written justification as to why each feedstock meets the definition of short-rotation hybrid poplar, including that the harvest rotation is less than ten years. To verify that the feedstock qualifies as renewable, fuel producers would have to maintain written records from their feedstock suppliers for each feedstock purchase that identifies the type and amount of feedstock and where the feedstock was produced. Written documentation could consist of maps or electronic data identifying the boundaries of the land where the biomass was produced, product transfer documents or bills of lading tracing the feedstock from that land to the renewable fuel production facility, and other written documentation that serves as evidence that the feedstock qualifies as renewable (EPA 2016). This information would be used to generate RINs for the renewable fuel. Growers should seek specific documentation requirements from their biomass buyer.

Certifying the Feedstock

Although biofuels are shown to have several environmental benefits, they have been shown to have negative environmental impacts to land, water, wildlife, and society if they are not produced in a sustainable manner (Cantamessa et al. 2022). To ensure that biofuels are sustainably produced, growers can voluntarily participate in several third-party certification programs (listed below) that aim to verify the sustainability of renewable fuel products. Sustainability certification begins at the field level where feedstock producers undergo third-party inspections. The biomass production system is evaluated based on a range of criteria that include water, soil, biodiversity, greenhouse gas emissions, land use, and waste.

Small-scale growers may find that certification is cost prohibitive for their production quantities. In this case, growers can still adhere to sustainability standards but not undergo the certification and auditing process. In global bioenergy markets, small-scale growers participate without certification through policies that allow a set percentage of feedstock to come from uncertified sources (Beall 2011). In the United States, renewable biofuels are regulated through the RFS, and third-party sustainability certification is not required. However, for marketing purposes, fuel producers may look to further highlight the sustainability of their products to capture a premium price. Sustainability certification labels can be used to accomplish this, and growers could capitalize on any price premium that certification offers (Schubert and Blasch 2010). Since poplar feedstock markets may be dominated by large-scale industrial growers, small-scale growers could make certification more economical through a group certification scheme as a cooperative group of growers with similar production systems.

Sustainability certification can be obtained from:

- The Roundtable on Sustainable Biomaterials: https://rsb.org/.
- The Council on Sustainable Biomass Production: https://merid.org/case-study/council-on-sustainable-biomass-production/.
- Forest Stewardship Council: https://fsc.org/en.

Conclusion

Growers' relationships with feedstock purchasers will be critical to the success of their enterprises. At the base of the supply chain, these relationships will form the foundation of a renewable fuel industry. By understanding the production and marketing needs of biofuel producers, growers can produce higher-value feedstock. By forming cooperatives, growers can reduce risks and increase their economy of scale. Mutually beneficial contracts will ensure that both growers and fuel producers maintain profitability.

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CHAPTER 16 | ENVIRONMENTAL SUSTAINABILITY

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A sustainable biofuel production system is one that is economically viable, manages and conserves natural resources, ensures social well-being, and has a realistic expectation for the system to operate indefinitely. The expectation of sustainability is high for **hybrid** poplar energy crops that have the potential to provide both a profit to growers and environmental benefits to society, including mitigating climate change. The use of renewable **biomass** for biofuel and bio-based chemical production can be part of a solution to both the dependence on and depletion of fossil fuels and global climate change. However, care must be taken to ensure that negative environmental, economic, and social impacts of biofuel production are identified and mitigated as the industry develops.

This chapter reviews how poplar plantations managed using the techniques described in this manual can make the agricultural landscape more environmentally sustainable, looking at both **feedstock** production and feedstock conversion.

Soil and Water Quality

Regarding soil and water quality, short-rotation poplar plantations are generally considered a beneficial alternative land use compared to fields with annual agricultural crops (Stanturf et al. 2001; Updegraff et al. 2004; McKay 2011; Cantamessa et al. 2022). As a perennial crop, establishment impacts such as tilling and extensive weed control are limited to about once every twenty years. This eliminates annual disturbances to the land. Multiyear rotation poplar plantations require fewer nutrient and chemical inputs than annual crops, while maintaining high **yields** of biomass (Stanturf et al. 2001). Given the poplar trees' established root systems (and associated rhizosphere) and their effectiveness at taking up nutrients and contaminants of concern in soil and water, there are opportunities across the Pacific Northwest (PNW) for poplar plantations to mitigate pollution and intercept it before it contaminates water systems (Stanton et al. 2002).

Soil Quality

Like conventional food and fiber crops, poplar can affect soil quality by causing changes in organic matter, nutrient flux, erosion, and compaction (Mann and Tolbert 2000). The following describes the mechanisms through which poplar plantations can promote ecological benefits to soil:

- Continuous plant cover reduces runoff and decreases erosion potential through: (1) interception of precipitation, (2) water uptake through plant **transpiration**, and (3) a well-developed litter layer that protects the soil, slows water movement, and facilitates soil infiltration.
- Increased root development at greater depths stabilizes soil, improves nutrient uptake, reduces nutrient leaching, increases organic matter input, and improves water access during dry cycles.
- Eliminating annual **cultivation** improves soil health by allowing the organic content in soil to increase, enhancing soil structure and supporting microbial, mycorrhizal, and faunal communities (Mann and Tolbert 2000).

On established poplar plantations in Europe, research shows that soil quality improves under short-rotation **coppice** systems compared to intensive agricultural cropping systems. On three-year harvest cycles, soil chemical and biochemical traits improved (Pellegrino et al. 2011). Because poplar trees are grown as a perennial crop, they tend to increase organic carbon within the soil due to no-till management after crop establishment and high annual amounts of leaf litter (Baum et al. 2009). This improves soil health by improving the soil structure, increasing water-holding capacity, making nutrients more available to plants, and supporting microbial, mycorrhizal, and faunal communities.

Soil respiration is an important indicator of healthy soil. Soil respiration refers to the production of carbon dioxide when soil organisms respire and is a measure of biological activity and organic matter decomposition in the soil. Research on soil biology and soil respiration is continuing for poplar grown on three-year **coppice rotations** in the PNW. So far, results indicate that converting conventional agricultural cropland to poplar **bioenergy** farms does not have adverse effects on soil greenhouse gas flux (Sarauer and Coleman 2018).

Water Quality

When short-rotation poplar replaces annual crops, an improvement in groundwater quality is expected (Dimitriou et al. 2009). Management practices of short-rotation poplar require fewer chemical applications than other crops (Dimitriou and Fištrek 2014). In addition, poplar is effective at removing nutrients and contaminants already in the field (e.g., excess boron) (Townsend et al. 2018). Plantings typically do not require mechanical cultivation after trees are established, so there is a significant period during the rotation (up to 20 years) in which there is reduced risk of sediment pollution through soil erosion by wind and water, improved nutrient uptake, and reduced losses to leaching (Updegraff et al. 2004; Dimitriou et al. 2009). For **alleyways** and field perimeters, mowing, rather than tilling, is likely adequate for weed control. Mowing maintains the sod cover, which provides wildlife habitat and can improve access to the field in wet conditions. Converting fields to poplar bioenergy crops can result in reduced amounts of ammonia-N, nitrate-N, phosphorus, pesticides, and herbicides in runoff, with consequent improvements in surface water and groundwater quality (Mann and Tolbert 2000; Updegraff et al. 2004).

Phytoremediation

Poplar can help heal degraded or contaminated landscapes. Poplar can be used in **phytoremediation** projects that involve using plants to clean up or remediate sites by removing contaminants of concern from soil and water (Rockwood et al. 2004). Poplars have been shown to be highly effective for phytoremediation projects (Doty et al. 2017). Their superior growth rates and large leaves maximize rates of transpiration, effectively removing, mineralizing, or immobilizing pollutants. Poplar has been successfully used in the PNW and across the United States to address contaminants in wastewater, farm runoff, stormwater runoff, and landfill leachate (Isebrands et al. 2014; Zalesny et al. 2019). Poplar plantings can take up a wide variety of contaminants, including excess nutrients, inorganic metals, and petrochemical compounds (e.g., fuels, solvents, and pesticides) (Licht and Isebrands 2004) (figure 16.1). Removing contaminants protects water quality and allows contaminated sites to be returned to productive use.

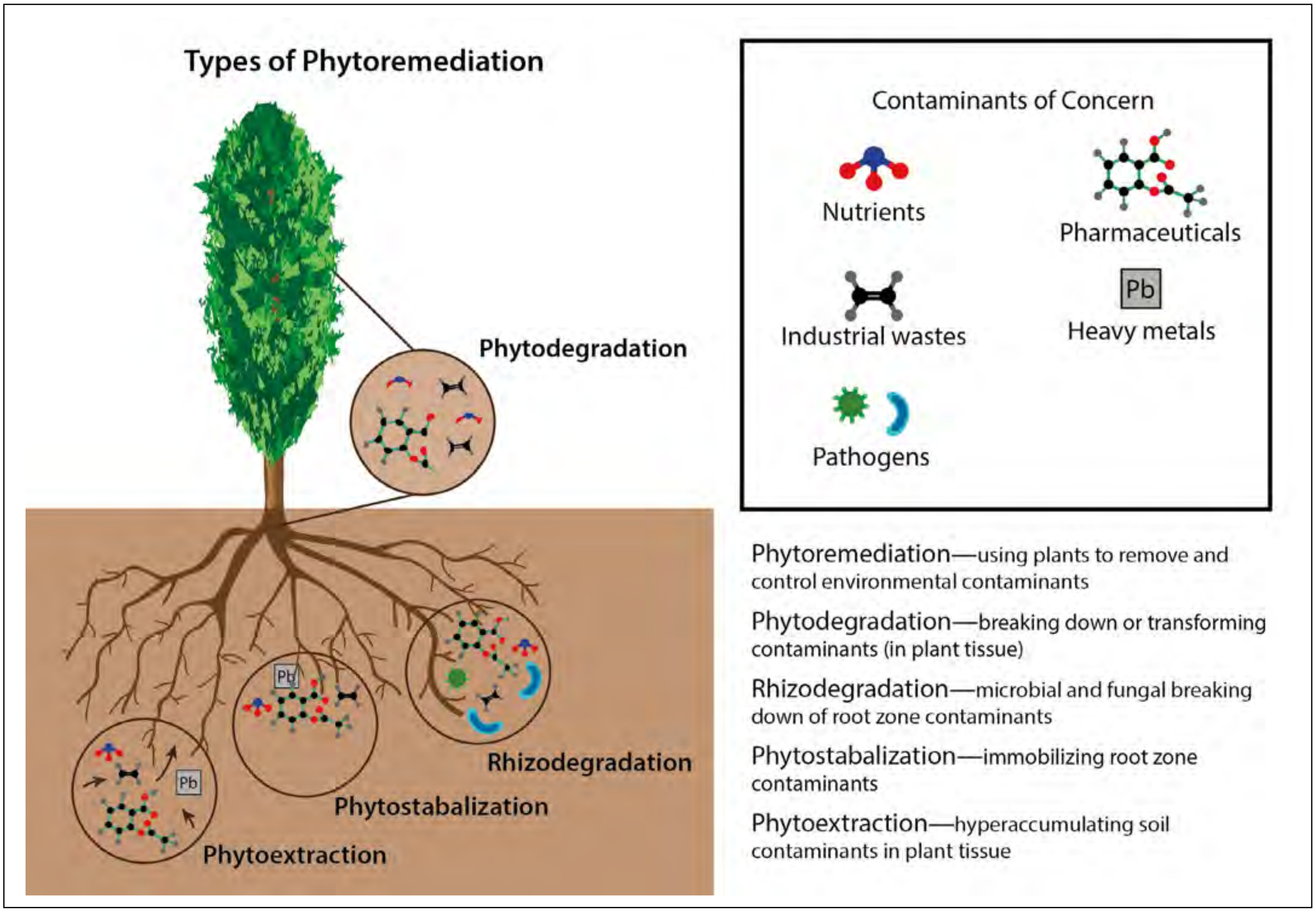

Figure 16.1. Phytoremediation is a management practice that utilizes plants to immobilize or break down contaminants in soil and water.

Phytoremediation projects are typically designed as longer-rotation poplar stands (i.e., not coppiced), but coppiced poplar can also process significant quantities of water (Haider et al. 2018). Coppiced poplars develop a fine root system that serves as an effective filter for the reception of liquid wastes. The large leaves characteristic of poplars exhibit a relatively high transpiration rate and provide an effective "pull" of water from soil. Dissolved nutrients and contaminants in the water are typically broken down and retained by the plant such that they pose a minimized threat to the environment. Often, the contaminants of concern are captured in the organic carbon-rich zone created by microbes that consume root exudates.

Wastewater Treatment

Poplar trees can be very effective at taking up large quantities of effluent from wastewater treatment facilities. Using the production methods described in this grower's manual, poplar can be used to "polish" treated wastewater (i.e., tertiary treatment), removing the pollutants remaining after the previous steps of treatment. In addition, irrigating poplar protects natural water bodies from increased temperatures that result from direct discharge into a river. This helps facilities meet strict discharge restrictions, particularly in summer months when the in-stream flow of their normal discharging water bodies is low (Townsend et al. 2018).

Irrigating a poplar farm with wastewater rather than ground or surface water also avoids withdrawal from local water resources. However, because more **evapotranspiration** occurs in poplar stands than in grass or alfalfa, using wastewater on poplar farms rather than other crops may reduce groundwater recharge or stream flow in systems where wastewater is an important part of water supply.

A number of environmental plantings throughout the PNW utilize poplar to remove excess nutrients from wastewater streams. Examples include: (1) Metropolitan Wastewater Management Commission that manages the Biocycle Farm near Eugene, Oregon (Miller et al. 2018), (2) Hayden Area Regional Sewer Board near Hayden, Idaho (Haider et al. 2018), (3) Woodburn Wastewater Treatment Plant in Woodburn, Oregon (City of Woodburn, Oregon, n.d.), and (4) Chehalis Regional Water Reclamation Facility in Chehalis, Washington (City of Chehalis, Washington, n.d.; Hart et al. 2018). Rather than pumping treated effluent into nearby rivers, these facilities use effluent to irrigate poplar fields in summer months. Some of the facilities also dispose of **biosolids**, a by-product of wastewater treatment, by applying them to the poplar plantations as a fertilizer. Of significance, these example sites are not growing poplar with a coppice system.

Depending on the rigor of treatment, care should be taken to avoid overirrigation of fields so that pollutants do not leach into the groundwater. The appropriate level of application will depend on poplar's water uptake capacity and properties of the contaminants of concern (e.g., dwell time). See Chapter 10 for more information on the water requirements of poplar. Weed control is an important component of irrigated systems because weeds thrive on the available water and nutrients—if allowed to grow unchecked their competition can be detrimental to the trees.

Managing a Multifunctional System

When addressing regulated environmental problems, plantation management will be more intensive if it is achieving a required contaminant control. Careful planning is essential. The operation should be approved by the proper environmental authorities and any necessary permits will need to be obtained. Plantation design should include the installation of monitoring wells to measure the effectiveness of the project. Poplar cultivars should be tested to ensure they will survive at the contaminated site and to determine what soil amendments are needed to enhance plantation productivity. Growers should consult with the **biorefinery** to ensure that contaminants **sequestered** in the biomass through phytoremediation will not interfere with the conversion process or reenter the environment.

Municipal and industrial wastewater treatment facilities, brownfields, landfills, and other contaminated sites are potential early-adoption sites of hybrid poplar bioenergy crops in the PNW, because poplar trees are very effective in taking up large quantities of water and remediating contaminants. Poplar bioenergy crops are thus an attractive approach to achieve environmental and energy feedstock production goals.

Wildlife Benefits

Another environmental benefit of poplar production is the unique and diverse habitat that it can provide in an agricultural landscape. The complex structure of a coppiced poplar tree stand adds considerable physical diversity to farmland, creating wildlife habitat similar to young woodland or scrub habitats (Sage 1998). The structure and cover available to wildlife in a poplar plantation is likely to attract a richness and abundance of species. Additionally, poplar plantations established next to existing forests may help mitigate forest habitat fragmentation in certain situations (Sage 1998).

Determining insect, bird, and small mammal abundance in a poplar plantation helps researchers understand impacts to wildlife communities, as populations of these animals often respond quickly to changing environments. Research finds that bird abundance and species richness are consistently higher in hybrid poplar plantations than in traditional agricultural fields (Moser and Fletcher 2015). When young (two years old) plantations are harvested and regenerated by coppicing, there are no noticeable effects on songbird or small mammal populations, because the coppiced plantations regrow quickly and remain suitable for wildlife species that favor scrubland and young forest habitats (Moser, personal communication, 2015). Research also shows that biodiversity in a poplar plantation will generally increase with plantation age. Though research investigating wildlife use of poplar plantations continues in the PNW, a preliminary conclusion found that plantations contribute positively to wildlife populations as compared to traditional agricultural fields (Moser and Fletcher 2015).

Creating Wildlife-Friendly Poplar Plantations

- Add structure to plantations by leaving existing trees, slash piles, and other debris on afforestation sites.
- Establish alleyways with sod cover to create structure in stands.
- Provide nest boxes, bat boxes, perch poles, and other wildlife-friendly habitat components as appropriate.

Invasive Poplars

Invasiveness is a primary concern raised when non-native tree species are introduced for commercial production. If the crop escapes the planting site, control can be expensive or ineffective. A key indicator of invasiveness is if the species has previously escaped and invaded other areas (Vance et al. 2014). Hybrid poplars bred from non-native species may cross-pollinate with native poplars and thus pose an invasive potential (DiFazio et al. 2012). Some poplars can also root sucker which enables them to spread into natural areas or persist on a site after removal of aboveground biomass (Eckenwalder 2001).

Most of the invasive risk of poplar has arisen from the possibility of hybridization between native (e.g., black cottonwood) and non-native (e.g., Japanese poplar) species. Transgene spread to native poplar populations could dilute or alter the genetic diversity of natural populations and may impact locally adapted traits. Such a scenario could increase or decrease susceptibility of native populations to **diseases**, **pests**, or environmental stresses (Vance et al. 2014; DiFazio et al. 2012).

A common way to limit or prevent transgene spread by tree crops is to harvest the crop before flowering begins. Poplar trees in the PNW usually begin flowering between six and twelve years of age. Poplar managed under coppicing harvest cycles shows a reduced risk of spread since they are coppiced before attaining reproductive maturity; even coppice regrowth originating from older root systems requires several years to reach reproductive maturity. Poplar growers can also use buffer zones as an added measure of protection against pollination and seed establishment occurring from the plantation. However, when used alone, the buffer method is unlikely to provide complete containment (DiFazio et al. 2012).

Some poplars, such as white poplar (*Populus alba)*, that have invasive tendencies through **root suckering** should not be established in plantation settings (Eckenwalder 2001). Black poplar and cottonwood crosses which do not typically sucker have demonstrated good utility in plantations.

Poplar Biofuels in the Carbon Cycle

The carbon cycle for poplar-based biofuels is based on the natural process through which photosynthetically active poplar trees fix atmospheric carbon dioxide and sequester it in tissues (biomass) as the trees grow. When poplar biomass is harvested, converted to fuel, and combusted in a vehicle engine, carbon dioxide that was sequestered in biomass is released back into the atmosphere. As trees on the poplar plantation regenerate, they again sequester atmospheric carbon dioxide to complete the carbon cycle (figure 16.2). As the trees grow, they increase soil organic matter by root tissue and soluble exudates which grow microbial biomass.

Application of this cycle can lower net atmospheric greenhouse gases because carbon dioxide released during the burning of biofuels is sequestered by growing poplar biomass farms in a continual process. In contrast, fossil fuel combustion releases carbon stored within the earth for millions of years, and this cycle raises atmospheric carbon dioxide levels thereby contributing to global climate change (figure 16.3). Poplar plantations can serve as carbon sinks over time, meaning that the natural accumulation of carbon in leaf litter, root exudates, fine roots, and soil will exceed carbon accumulation on the site that occurred during the previous land use (agriculture crops) (Baum et al. 2009).

Using current technology, poplar-based fuels are not carbon neutral, as some carbon emissions do occur while producing biofuels from poplar biomass. These emissions are typically associated with fossil fuels used during the harvesting, transportation, and conversion processes. The net carbon emissions from poplar-based biofuels production are, however, considerably less than petroleum-based fuel production when carbon emissions are measured with a **life-cycle assessment** (LCA).

Life-Cycle Assessment

An LCA is an appraisal tool that provides data on resource consumption and emissions at every stage of a product's production and use. An LCA can be used to compare net emissions generated from the production and use of different types of fuels. As part of the Advanced Hardwood Biofuels Northwest project, researchers used an LCA to compare the **global warming potential** (GWP) of petroleum-based jet fuel to poplar-based **bio-jet fuel** (Gustafson et al. 2013).

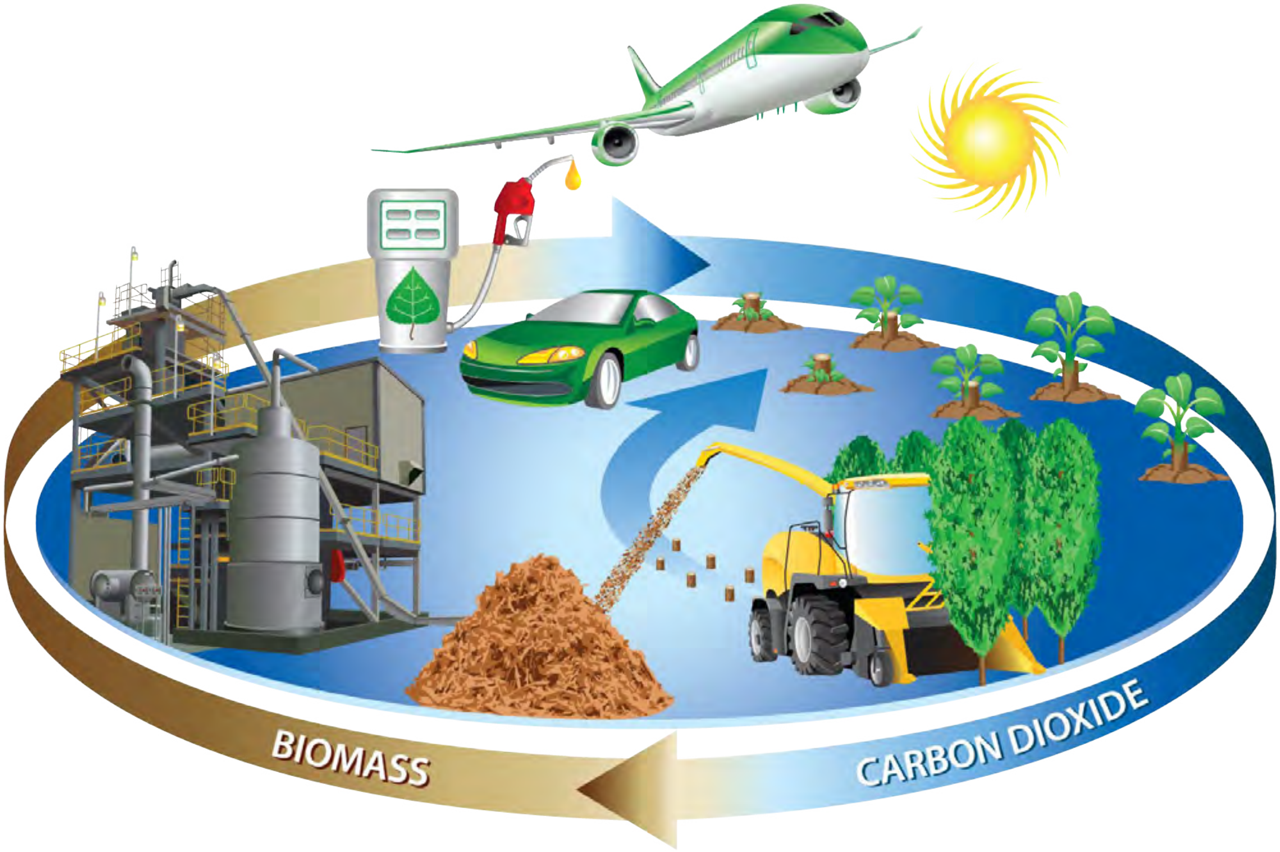

Figure 16.2. The carbon in poplar-based biofuels is part of a natural cycle where trees take up carbon dioxide through photosynthesis. The trees are harvested and converted to a value-added product which can include fuel. When the fuel is burned to power engines, the carbon is released back into the atmosphere as CO2 which is then sequestered again by new plant growth, completing the cycle.

Figure 16.3. Poplar-based biofuels utilize aboveground carbon in a natural carbon cycle. In contrast, fossil fuels consist of carbon removed from Earth's natural carbon cycle millions of years ago.

The poplar bio-jet LCA assessed greenhouse gas emissions during every step of fuel production and use, including growing the poplar crop, harvesting and converting the trees into liquid biofuels, and using the fuels to power aircraft. All greenhouse gases going into and coming out of the atmosphere were accounted for during this process. Measurements of greenhouse gases were converted to a standardized metric known as **carbon dioxide equivalence** (CO_2e) to determine the net GWP (Budsberg et al. 2015).

The LCA indicated that production and use of poplar-based bio-jet fuel could reduce GWP by 30 to 45%, compared to petroleum-based jet fuel production (figure 16.4) (Budsberg et al. 2016). The level of GWP reduction depends on the amount of fossil fuels used during the conversion process. Conversion simulations reveal that the process would be most economical using natural gas (Crawford et al. 2016). Natural gas is currently the most economical fuel for producing the heat and steam required for the conversion process, and it also serves as a source of hydrogen needed to upgrade intermediate products to bio-jet fuel. The GWP of bio-jet fuel can be reduced by using **lignin** instead of natural gas as the fuel for the production of heat and steam for the conversion process, and also as the source for hydrogen to upgrade intermediate products to bio-jet fuel. Conversion simulations with the lowest GWP use lignin gasification for hydrogen production and hog fuel for heat and steam (Budsberg et al. 2016).

Conclusion

Poplar biomass is a promising feedstock for a sustainable bioenergy and bio-based chemical production system. Poplar plantations can provide wildlife habitat and help clean up contaminated soil and water. When combined with wastewater or stormwater management operations, the trees can be irrigated with water that could otherwise have increased temperatures or introduced contaminants of concern in natural waterways. As the industry develops, care needs to be taken to prevent unintended consequences from bioenergy production. This can be accomplished by avoiding species that have a greater potential to become invasive in the agricultural landscape and by continuing to improve conversion efficiencies.

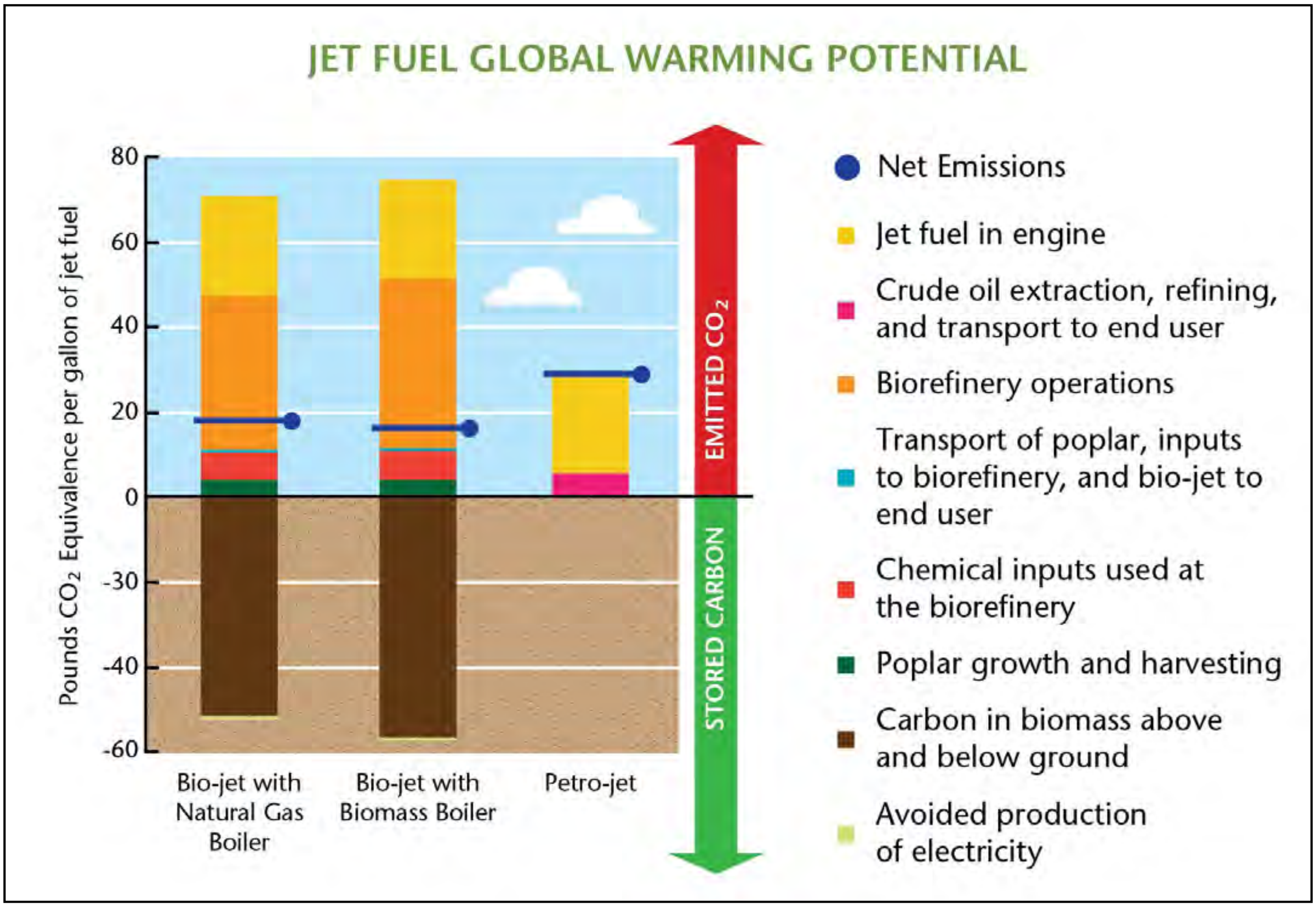

Figure 16.4. The net amount of energy used in the conversion process influences net greenhouse emissions of bio-jet fuel. Net emissions can be reduced by burning biomass instead of natural gas. The LCA model for bio-jet fuels shows that the production and use of poplar-based bio-jet fuels could reduce the GWP of the fuel by 30 to 45% compared to fossil-based jet fuel (Budsberg et al. 2016).

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CHAPTER 17 | CONDUCTING A HYBRID POPLAR BIOMASS INVENTORY

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Introduction

The goal of field **inventory** is an accurate determination of the amount of **biomass** available from a poplar plantation. Data collected from the field are used to estimate the average stand diameter, stand survival (number of living **stools** per acre), and the number of **coppice** stems per stool, each attended by a **confidence interval** estimated at a defined **probability level**. The design of the inventory depends in part upon the degree of accuracy desired by the grower. A well-designed and executed inventory enables growers to correctly project harvestable biomass quantities using **yield tables** developed by Advanced Hardwood Biofuels Northwest (AHB) for specific regions. The biomass inventory procedures detailed in this chapter have been used to assess biomass **yield** at AHB's poplar demonstration sites.

Inventory Design

It is important to plan a biomass inventory that will provide quality information with the least amount of field expenditures (Steel and Torrie 1960). Thus, rather than counting and measuring every tree in a poplar stand, a subset of trees from a group of **sample plots** is measured, saving considerable time both in the field and the office. The fieldwork is laid out and conducted by the **inventory unit:** a group of trees of the same **clonal** variety, age, and condition that is managed uniformly. Doing so will significantly improve the efficiency of the inventory.

Inventory data are derived from a process of **plot sampling** and then extrapolated to the entirety of the stand. **Sampling intensity** is the proportion of the stand that is measured during plot sampling. For example, during the AHB project, approximately one 12-tree inventory plot was established for each acre in an inventory unit. This arrangement gave a 0.83% sampling intensity for inventory units planted at a density of 1,452 trees per acre. **Permanent plots** are used so that the same trees can be remeasured if inventories are conducted yearly to gauge annual growth.

Sizing the Sample Correctly

- Increasing the number of sample plots increases the accuracy and the reliability of the yield projections.
- However, the increase in accuracy plateaus at some point; adding more plots beyond this point leads to diminishing returns and will unnecessarily add costs to the inventory.
- The sampling intensity used in the AHB inventory provided acceptable results in view of the respectable uniformity of clonal stands of **hybrid** poplar.
- The same sampling intensity might even be relaxed with very large inventory units while providing equivalent accuracies at a reasonable cost.

The process of plot installation begins in the office where sample plots are located and mapped on aerial images of the stand. Plot locations are based on acreage and stand dimensions and should be well distributed throughout the inventory unit. They should also be allocated to fairly represent the total variability of the inventory unit. This means that if 20% of the inventory unit has a distinct area of low survival or poor growth, then 20% of the plots should be assigned there to avoid bias that would otherwise favor fully stocked or well-growing sections. To illustrate, a nine-acre **monovarietal block** of clearly uniform stand conditions and rectangular dimensions of 300 feet in width and 1,307 feet in length would have a systematic arrangement of **transects** about every 100 feet running the long axis of the field (figure 17.1). Each of the three transects would contain three plots about 400 feet apart, resulting in a total of nine plots. Note that for the first transect, the first plot is spaced approximately one-half the calculated between-plot distance to move well into the field and avoid **edge effects** (figure 17.1).

Plot measurements should include four variables: tree spacing, tree survival, stem diameter, and the number of coppice sprouts. Estimates of these quantities are all considered adequate when inventory averages are accompanied by confidence intervals of plus or minus 10% of their respective average at the 95% probability level. This means that if the same inventory unit is repeatedly sampled during the present growth period, sample averages would fall within the 10% confidence interval 95% of the time (Steel and Torrie 1960). A process for ensuring the adequacy of the inventory is presented later in the chapter.

Field Procedure

1. ***Navigate to the sample plots***—When sample plots are initially established, locate the first tree, and place a marker before it that will identify the plot when revisited for following inventories in subsequent years. Count off 11 additional trees within the same row for a total of 12. Missing trees owing to **cuttings** that failed to establish should be included in the count of 12. (Mortality is most evident during the first-year inventory.) Drive a second marker into the soil behind the 12th tree (figure 17.2). Wooden markers are preferred, as metal or PVC markers can damage harvesting equipment or contaminate biomass delivered to refineries. Record precise coordinates of the first plot marker using GPS technology; returning to the plots after harvest will be very difficult without these coordinates.
2. ***Measure and record between-row and within-row distances***—Measure and record the distance from tree 1 to the centerline of the adjacent row and the distance from tree 12 to the centerline of the opposite adjacent row (figure 17.2). These row distances will be summed and averaged. Next, measure the distance from tree 1 to tree 12. This distance will be divided by 11 (the number of between-tree spaces among the 12 trees in the plot) to find the average space between trees within the plot row. All between- and within-row distance measurements should be taken in decimal fractions of feet to avoid the complications of converting measurements of feet and inches when performing inventory calculations. It is important to note that these measurements are made just once—the inventory of the first year—and are used to confirm the average square footage of the trees so that the precise number of trees per acre is known when the inventory is extrapolated from the plot data to the entire inventory unit.
3. ***Record dead and missing trees***—Trees that did not survive need to be recorded every time the inventory is conducted, especially after a harvest. This is required in calculating the current **stocking** of the stand.
4. ***Count the stems on each tree***—Count and record the number of stems or sprouts arising from each tree or coppiced stool. Only stems taller than 4.5 feet should be counted.
5. ***Measure stem diameters***—Measure each stem's diameter at 4.5 feet above the ground on each tree, and record as **diameter at breast height** (DBH). Each stem over 4.5 feet in height contributes biomass to the yield and must be measured. If the tree has multiple stems or sprouts arising from a stool, measure every living one that exceeds the 4.5-foot threshold. Diameter can be measured either with calipers or with a diameter tape calibrated to the nearest hundredth of an inch that converts a circumference measurement to a diameter measurement (figure 17.3).

Inventory Equipment:

- Computer with a spreadsheet program, such as Excel.
- A GPS unit for establishing and relocating plots.
- A diameter tape that directly converts circumference measurements to diameter, or calipers for measuring stem thickness.
- A reel tape or spring-retractable logger's tape that preferably reads in tenths of feet rather than inches for measuring between-row and within-row distances.
- A method to record measurements. An electronic data collector such as a tablet computer or a smartphone works well. The data collector is usually preloaded with an inventory worksheet that will automatically calculate average plot diameter, stem count per stool, survival, and tree spacing. Pencil and paper work well in the field, but measurements must then be entered into a computer in the office. This takes extra time and could introduce transcription errors.

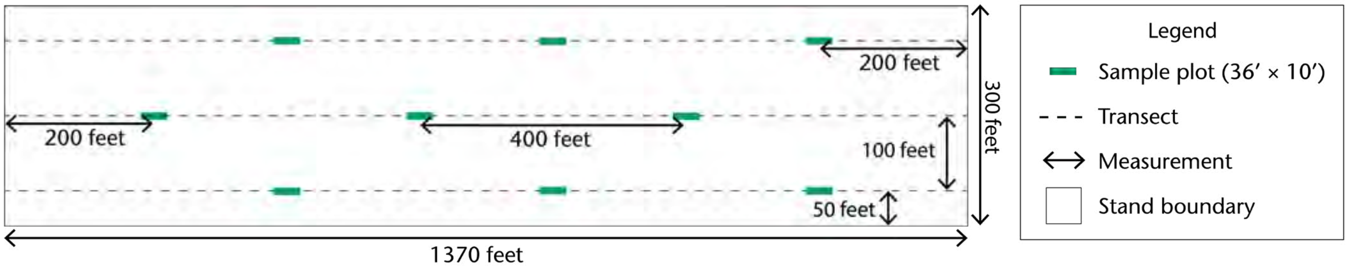

Figure 17.1. Example of nine sample plots systematically located in a rectangular nine-acre monovarietal block of relatively uniform tree growth and survival.

Data Analysis

Summarizing Inventory Data

1. ***Find the average plot DBH***—Calculate the average DBH of the trees in each plot. For trees with a single stem, this is simply the measured DBH of that stem. For trees with multiple stems, sum each stem's DBH, then divide by the number of stems to find the individual tree's average stem DBH.

   (*stem 1 DBH*) + (*stem 2 DBH*) +… (*stem n DBH*) / (*total number of stems*) = *individual tree average DBH*

   Sum the average DBHs and divide by the number of living trees in the plot to calculate the average tree DBH for the entire plot.

   (*tree 1 DBH*) + (*tree 2 DBH*) +… (*tree 12 DBH*) / (*total number of living trees in plot*) = *plot average DBH*

2. ***Find the average number of stems per tree***—Add up the stem counts for each tree and divide by the number of trees in the plot to get the average for the plot.

$$\frac{[number\ of\ stems\ on\ tree\ 1] + [number\ of\ stems\ on\ tree\ 2] +\ \ldots [number\ of\ stems\ on\ tree\ 12]}{[number\ of\ living\ trees]}$$

$$= plot\ average\ number\ of\ stems\ per\ tree$$

3. ***Calculate the plot survival rate***—Divide the number of live trees by the original number of cuttings planted on the plot. This should be 12 in all cases.

$$\frac{[number\ of\ live\ trees]}{number\ of\ planted\ cuttings} = survival\ rate$$

4. ***Calculate average between-row spacing***—Add both measurements of between-row distance and divide the total by two. This will give the average tree spacing between rows (figure 17.2).

$$\frac{[row\ distance\ 1] - [row\ distance\ 2]}{2} = average\ between\text{-}row\ tree\ spacing$$

5. ***Calculate average within-row tree spacing***—Divide the within-row distance (measurement between trees 1 and 12) by 11 (the number of spaces among the 12 trees in the plot) to find the average within-row tree spacing.

$$\frac{[within\text{-}row\ distance]}{11} = average\ within\text{-}row\ tree\ spacing$$

6. ***Calculate the square footage per planted tree***—Multiply the average between-row spacing by the average within-row spacing.

$$([average\ between\text{-}row\ tree\ spacing] \times [average\ within\text{-}row\ spacing])$$
$$= square\ feet\ per\ tree$$

7. ***Calculate the number of trees planted per acre***—Divide the number of square feet in an acre (43,560) by the square feet per planted tree.

$$\frac{43{,}560\ \textit{square feet per acre}}{\textit{square feet per planted tree}} = \textit{trees established per acre}$$

8. ***Repeat***—Repeat these calculations for each plot's inventory data. Average the values across all the plots to get average values for the entire inventory unit.

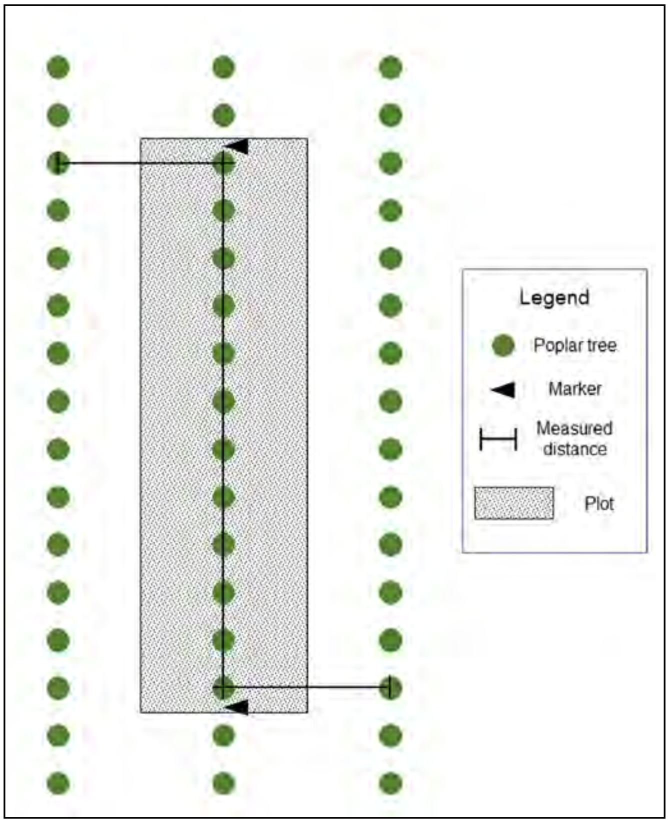

Figure 17.2. Between- and within-row distances are measured for the plot to calculate the precise square footage allocated to each tree at the time of planting.

Figure 17.3. A diameter tape is used to measure DBH based on the tree's circumference. Photo: J. Espinoza.

Determining the Adequacy of the Inventory

The following example details the steps for assessing whether additional plots are needed to ensure that the 95% confidence interval is no larger than 10% of the average stand diameter.

1. ***Find the 95% confidence interval***—The formula for the confidence interval is:

$$95\%\ CI = \overline{x} \pm t_{.05}\left(\frac{s}{\sqrt{n}}\right)$$

Where *CI* is the confidence interval, $\overline{x}$ is the inventory unit diameter averaged over the sample plots, $t_{.05}$ is the *two-tailed* **test statistic** at the 95% probability level, *s* is the **standard deviation** among plots, and *n* is the number of plots. Values of the *t* statistic are found by consulting a *t*-distribution table corresponding to a defined probability level for estimating a confidence interval with n - 1 degrees of freedom.

Determine whether additional plots are needed—This step can be illustrated in the following example. Suppose an initial inventory of a 20-acre stand is conducted using a sample size of 20 12-tree plots per the AHB sampling intensity approximation. The average stem diameter for the inventory unit is 3.25 inches. According to the required standard of accuracy, the confidence interval can be no larger than 10% of this value, or 0.325 inches. The standard deviation among the average plot diameters is 0.404 inches, and t.05 for the 95% confidence interval is 2.093. Using these inputs, the confidence interval is calculated as:

$$95\%\ CI = 3.25 \pm 2.093\left(\frac{0.404}{\sqrt{20}}\right)$$

$$95\%\ CI = 3.25 \pm 0.189 \text{ inches}$$

The width of the confidence interval is the distance between 3.439 inches (3.25 + 0.189) and 3.061 inches (3.25 - 0.189) or 0.378 inches. (Another way to calculate this is to multiply 0.189 by two.) As 0.378 inches exceeds the requirement that the confidence interval be no larger than 10% of the average (0.325 inches), more plots are required.

2. ***Determine the number of additional plots***—An approximation of the number of plots needed to meet the desired level of accuracy can be made using the following equation (Steel and Torrie 1960).

$$n = \left[\frac{2(t_{.05})(s)}{CI}\right]^2$$

Following our example:

$$n = \left[\frac{2(2.093)(0.404)}{0.325}\right]^2 = 27.08$$

The estimate of s and the value of $t_{.05}$ from the original sample of 20 plots are used as reasonable approximations in solving for the expanded sample because the ultimate standard deviation is unknown until the final sample is completed. This fact notwithstanding, with $n = 27.08$, we might expect that expanding our original 20-plot sampling intensity by seven plots will increase the likelihood that the estimate of the inventory unit's average stem diameter is made with a 95% chance that the confidence interval is within 10% of the average. Similar calculations can be performed to find a reasonable sample size for stem count, tree spacing, and survival if desired.

Projecting Yield

AHB yield tables 17.1–17.4 exhibit the tonnage of biomass that can be expected on a per-acre basis at the conclusion of the first three-year coppice cycle. Values in the tables represent only the aboveground biomass.

Three steps are used to project the amount of standing biomass.

1. **Select a yield table based on location**—The yield tables are specific for the four regions where AHB hybrid poplar demonstrations were grown, studied, and inventoried: northern California, Oregon, Washington, and Idaho. More extensive descriptions of features like the climate, soils, physiography, and elevation of the four AHB demonstration regions can be found in Stanton et al. (2020). The numbers in the tables are based on an initial stocking rate of 1,452 trees per acre and complete survival.

2. **Find the appropriate per-acre yield number**—Find the table cell at the intersection of the average DBH of the inventory unit and nearest average stem count to find the predicted **bone dry tons** (BDT) of biomass per acre.

3. **Calculate total yield**—The total biomass yield of the inventory unit is calculated as: (*per-acre tonnage from yield table*) × (*acres in the inventory unit*) = *total yield*

4. **Example using table 17.1**—A nine-acre field near Jefferson, Oregon, was designed to be planted on a 3-foot-by-10-foot spacing (30 square feet per tree, computing to 1,452 trees per acre). Measurements from the inventory unit revealed an average stem diameter of 2.0 inches and an average count of 1.5 stems per stool. The projected yield would be 10.0 BDT per acre based on table 17.1. The yield for the entire inventory unit would be: 10 BDT per acre × 9 acres = 90 BDT.

   This figure can be adjusted further based on the survival rate and the tree spacing. To illustrate, the inventory shows a survival rate of 95%. The actual tree spacing is 29 square feet per tree, resulting in a stocking of 1,502 trees per acre; this is a 3% overage in the planned number of trees per acre (1,502/1,452 trees per acre = 1.03). Total yield can be adjusted for these figures as: 90 BDT × 0.95 survival × 1.03 stocking overage = 88.1 BDT standing biomass.

   Note, however, that adjusting yield for the survival percentage may be disputed, as the distribution of mortality within the inventory unit was not considered. If mortality had occurred in large patches, then the survival adjustment may be proper. On the other hand, if mortality was distributed throughout the unit as individual trees, nearby trees may take advantage of the extra space and compensate for the mortality with increased growth. This could result in less yield loss relative to a stand with the same level of mortality, but one in which the mortality occurs in patches that are too large for the proximate trees to fully exploit. In a similar way, adjusting for the 3% overage in tree count should be done with caution, because the increase in stocking also equates to an overall reduction in growing space that may meaningfully increase tree-to-tree competition such that no additional yield is realized.

AHB Yield Tables

The following AHB yield tables (tables 17.1–17.4) record bone dry tons for a three-year-old coppice stand. For each acre, 1,452 trees are presumed.

Table 17.1. Willamette Valley; Jefferson, Oregon.

	Average Number of Stems per Stool						
Average Stand DBH (in)	1	1.5	2	2.5	3	3.5	4
1.0	1.4	2.1	2.8	3.5	4.2	4.9	5.6
1.5	3.3	5.0	6.6	8.3	9.9	11.6	13.2
2.0	6.7	10.0	13.3	16.6	20.0	23.3	26.6
2.5	11.5	17.2	22.9	28.6	34.4		
3.0	17.7	26.6	35.4				
3.5	25.4						
4.0	34.5						

Table 17.2. Spokane Valley–Rathdrum Prairie; Hayden, Idaho

	Average Number of Stems per Stool						
Average Stand DBH (in)	1	1.5	2	2.5	3	3.5	4
1.0	0.687	1.0	1.4	1.7	2.0	2.4	2.7
1.5	3.1	4.6	6.1	7.7	9.2	10.7	12.3
2.0	6.4	9.7	12.9	16.1	19.3	22.6	25.8
2.5	10.8	16.2	21.6	27.0	32.4		
3.0	16.2	24.2	32.3				
3.5	22.5	33.8					
4.0	29.8						

Table 17.3. Sacramento River Delta; Clarksburg, California.

	Average Number of Stems per Stool						
Average Stand DBH (in)	1	1.5	2	2.5	3	3.5	4
1.0	1.2	1.8	2.4	3.1	3.7	4.3	4.9
1.5	3.4	5.1	6.8	8.5	10.2	11.9	13.7
2.0	6.7	10.1	13.5	16.9	20.2	23.6	27.0
2.5	11.2	16.8	22.4	28.0	33.7		
3.0	16.8	25.3	33.7				
3.5	23.6	35.4					
4.0	31.5						

Table 17.4. North Puget Sound; Stanwood, Washington.

	Average Number of Stems per Stool						
Average Stand DBH (in)	1	1.5	2	2.5	3	3.5	4
1.0	1.0	1.4	1.9	2.4	2.9	3.3	3.8
1.5	3.2	4.9	6.5	8.1	9.7	11.3	13.0
2.0	7.3	10.9	14.6	18.2	21.8	25.5	29.1
2.5	12.0	18.0	24.0	30.0			
3.0	17.4	26.2	34.9				
3.5	23.6	35.3					
4.0	30.4						

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GLOSSARY

abiotic: Non-living chemical and physical parts of the environment that can affect living organisms and the functioning ecosystem.

adventitious rooting: Rooting formation from non-root tissues.

aecia (of rust fungi): Structures producing aeciospores. In the case of poplar leaf rusts, aecia are produced on aecial hosts that are typically Douglas-fir in the PNW. Although produced on Douglas-fir, aeciospores of poplar leaf rust can only infect poplars.

alkaline: Having a pH greater than 7, or above neutrality.

alleyways: The non-planted space between the rows of trees.

alluvial: Derived from eroded, unconsolidated sediment that has been shaped and deposited by fresh water.

Alternaria: A fungal genus comprising approximately 300 species to date; some may be plant pathogens, but many appear to be endophytes.

anaerobic: Without oxygen.

arthropod: Any invertebrate animal in the phylum Arthropoda. Arthropods are characterized by having a segmented body, jointed appendages, and usually a chitinous exoskeleton molted at intervals.

asci: The structures within which ascospores are produced via meiosis. Ascomycetous fungi produce asci.

ascospores: Meiotic haploid spores in ascomycetous fungi.

asexual (fungi): Fungi that are not known to produce spores from meiosis.

basidia: The structures from which haploid spores (basidiospores) from meiosis are produced in basidiomycetous fungi. In the case of poplar leaf rusts, basidiospores are produced in spring on overwintered poplar leaves, and they then infect Douglas-fir needles. It is on the latter that spermogonia and aecia develop.

bedding: The formation of a more or less continuous mound of soil that is used to raise planting material above the water table.

bedding plow: A heavy plow that is pulled behind a tractor. The plow exerts hydraulic pressure on several large discs to create a mound by digging into and overturning the soil.

biocontrol: The use of another organism (e.g., a predator or parasite) to control a pest species.

biodiesel: A vegetable oil- or animal fat-based fuel that is used in diesel engines.

bioenergy: Energy derived from biomass.

biofix: A biological date, specific for each year and each location, when a specific insect species emerges from its overwinter stage.

bio-jet fuel: A biofuel that is made from renewable, organic material that is suitable for use in an unmodified jet engine as a direct replacement for petroleum-based jet fuel.

biomass: Organic material that comes from plants and animals.

biomass head: Specialized farm machinery that attaches to the front of a forage harvester to process high-yielding biomass crops such as poplar and willow.

biorefinery: A facility that converts biomass feedstocks into fuels, power, heat, and value-added chemicals.

biosolids: Sewage sludge that is recycled as fertilizer.

bole: The portion of the tree from the root collar up to the first branch.

bone dry metric ton (BDMT): A metric ton (2,204.6 pounds) of biomass at 0% moisture.

bone dry ton (BDT): 2,000 pounds of biomass at 0% moisture.

broad-spectrum herbicide: A non-selective herbicide formulated to control both broadleaf and grassy weeds.

browse: The leaves, twigs, bark, and buds of woody plants that are eaten by deer.

calcareous: A rock composed of calcium carbonate; chalky; limestone.

canker: A disease characterized by discrete, dead areas of stems of woody plants. Cankers vary in size, shape, and appearance. Canker diseases are caused by a range of pathogens.

canopy closure: When the tree crowns extend to connect between the rows and "closes" together, shading and reducing vegetation at ground level.

carbon dioxide equivalence (CO_2e): Provides a common unit used to describe the global warming potential of any quantity and type of greenhouse gas based on a reference unit of the heat-trapping potential of CO_2.

cation: A positively charged ion, which is the form many key soil nutrients take, including magnesium, calcium, and potassium.

cellulose: The structural component of a green plant's cell walls. It is the most abundant organic polymer on Earth.

cellulosic ethanol: A fuel that is produced from the non-food portion of plants.

chelated: Combined in a reversible chemical bond that usually has high affinity with a metal ion such as iron or copper.

chemical control: The use of natural or synthetic herbicides to eliminate or reduce unwanted vegetation.

chemigation: The practice of applying chemicals (pesticides or fertilizers) to crops by means of irrigation water.

chlorosis: A yellowing of leaf tissue due to a lack of chlorophyll.

clonal block: A segment of field planted with one type of clone.

clone: A genetically identical replicate of a parent tree. In reference to poplar propagation, a clone refers to the asexual replication of a parent poplar variety where a cutting taken from a parent tree is planted and allowed to grow into an individual tree that is an exact genetic replicate of the parent tree from which the cutting was taken.

cold storage: A temperature-controlled refrigerated space used for storing items.

combination plow: Mechanical farming equipment that performs multiple functions concurrently, such as ripping and bedding.

confidence interval: A definition of the degree of certainty that the true average of the inventory unit falls within its upper and lower limits. A 95% confidence interval means that repeated samples taken from the same inventory unit during the *current year* will lead to sample averages that fall within the interval on average nine-and-one-half times out of ten.

conidia: Asexual, fungal spores from mitosis.

coppice: A silvicultural method that regenerates a stand by cutting the trees near the base of the stem, stimulating new sprouts from the cut stool.

coppice rotations: Repeated cycles of production and harvest where trees are planted once, then grown as a perennial crop with multiple harvests occurring over the lifetime of the plantation.

crochets: Curved hooks, spines, or spinules on prolegs of Lepidoptera larvae.

crown: Branches and leaves that extend outward from the main stems or trunk of a tree.

cultivation: The preparation of soil by loosening and breaking it up.

current annual increment (CAI): Amount of biomass accumulated in a stand since the previous year.

cutting: Shoots and branches taken from nursery plants that are cut into lengths for planting.

Cytospora: An old name for fungi now in the genera called *Valsa* or *Leucostoma.*

deciduous: A tree or shrub that sheds its leaves annually.

deer browse: The feeding habit of deer in which deer will feed on the leaves and shoots of plants.

defoliation: Depletion of the leaf surface of a plant.

degree day: A measure of physiological time. The simplest calculation of a degree day is [Maximum + Minimum Temperature] ÷ 2 – Development Threshold for a Species = Degree Days.

diameter at breast height (DBH): Stem diameter at 4.5 feet (1.4 m) above the ground on the uphill side of the tree.

diameter at stool height: Stem diameter at the height the harvesting equipment will cut the stem, which is 4–6 inches (10–15 cm) above the ground for FR Forage Cruiser series with a New Holland 130FB Coppice Header.

dibble bar: A piece of equipment used to plant poplar cuttings. It is made of strong metal, consisting of a horizontal handle at the top of a vertical rod with a footstep attached to the side. It is used to make a hole in the soil where a poplar cutting can be placed.

dioecious: A characteristic of a species where male and female reproductive organs are found on separate individuals, rather than different parts of the same plant.

discount rate: An annual compound interest rate used to discount a future cash flow to its present values. This reflects the extent to which a higher value is placed on present cash flows relative to future cash flow (i.e., the time value of money).

disease (of plants): A condition caused by pathogens that interfere with the normal functions and physiology of plants.

dormant season: The time period when plants are not actively growing, typically the winter months when temperatures are colder and there is less sunlight.

drop-in biofuels: Hydrocarbon fuels converted from biomass that are chemically indistinguishable from petroleum-derived gasoline, diesel, and jet fuel that can be used seamlessly in existing engines and fuel storage and transport infrastructure.

eclose (eclosion): The metamorphosis or escape of the insect from the cuticle of the previous instar; sometimes used of hatching from the egg.

economic injury: A measure of damage to a crop that warrants the expense of a control measure.

edge effect: Differential growth pattern resulting from decreased competition along the periphery of a stand.

endophyte: Bacteria and fungi that live symbiotically within asymptomatic, or healthy-looking, plant tissues.

establishment cycle: The time period between planting and the first harvest (coppice).

establishment period: The time period between when the poplar is planted and when it has captured the site.

ethanol: An alcohol fuel made from plant material.

evapotranspiration: Water loss through the combination of transpiration and surface evaporation.

exit hole: The point of exit for an insect from a substrate.

eyespot: Eye-like markings that can be found on various parts of the animal (wings, tail, etc.).

fallow: A stage of crop rotation when the land is not used to raise a crop. It is also a term used to describe land capable of production but not in production.

feeder roots: Small, fine roots that take up water and nutrients. Feeder roots are typically short-lived, living for one year or less.

feedstock: Organic material that is used to produce fuels or other bio-based products.

fertigation: Delivering fertilizer through an irrigation system.

forage harvester: Traditional farming machinery that is used to harvest grasses, canola, corn, oats, and other crops. With the addition of a specialized biomass head, the machinery is also used to harvest short-rotation woody crops, such as poplar and willow.

frass: The waste product produced by wood-boring insects.

gallery: A passage created by larva, or adult, of an insect within the host.

genetically engineered (GE): The direct manipulation of an organism's genome that changes the genetic makeup of its cells. This includes the transfer of genes within and across species to produce improved or novel organisms.

genotype: The genetic makeup of an organism or a group of organisms.

global warming potential (GWP): A measure used in a life-cycle assessment to describe the effect on the average global surface temperature of greenhouse gases emitted during the production, use, and disposal of a product.

green tons (GT): 2,000 pounds of freshly harvested material, prior to drying (approximately 50% moisture).

growth model: A tool for predicting plant growth based on the plant's growth characteristics and using inputs, such as weather and soil types.

hardpan: A hardened, impervious soil layer, typically found in clay, occurring in or below the soil surface and impairing drainage and plant growth.

headland: The unplanted area at the end of the field that allows space for equipment to move in and out of the field.

hemicellulose: Present along with cellulose in the cell walls of plants. Unlike cellulose, it has a fluid structure with little strength.

heterosis: Hybrid vigor; a phenomenon that describes the performance superiority of a hybrid offspring over the average of both its genetically distinct parents.

hybrid: The offspring of parents from two different species.

hybrid variety: An individual in a species that was created through the pollination of a poplar seed, then replicated. A new hybrid poplar variety is produced when a poplar seed has grown into a plant. Hybrid varieties exhibiting certain traits are selected and replicated through vegetative propagation where a cutting is taken from the parent tree and is allowed to grow into a new individual tree. The new tree is a clone of the parent tree. All clones of a variety will share the same DNA. *Hybrid variety* and *clone* are terms that are used interchangeably in regard to hybrid poplar that is deployed for commercial production.

inoculum: The pathogen used in plant inoculation, which involves deliberately putting a pathogen in contact with a host plant. Inoculum often takes the form of fungal spores suspended in water. That suspension is then brushed or sprayed onto the plant surfaces to be inoculated.

insect: An arthropod animal that has three pairs of legs, a body divided into three parts (head, thorax, and abdomen), and generally one or two pairs of wings.

insecticide: A substance capable of killing insects.

instar: A phase between two periods of molting during the development of an immature insect.

internal rate of return (IRR): The discount rate at which the NPV of an investment is $0. In general, a higher IRR means a better investment. A negative IRR means the investment loses money.

inventory: Systematically generated data on the subject of interest, such as biomass availability, for a particular location at a specific point in time.

inventory unit: A uniform group of trees that are of the same variety, age, and condition and managed as a single unit.

landing area: A place in an agricultural field where the crops, equipment, and other supplies can be temporarily stored.

larva (pl. larvae): An immature insect after emerging from the egg. The term *larva* is often restricted to insects in which there is completed metamorphosis, but it is sometimes used for any immature insect that differs from its adult form.

lesion: Discrete dead or necrotic areas.

life cycle (insect): Sequential development through the egg, larval, pupal, and adult stage, including reproduction.

life-cycle assessment (LCA): A cradle-to-grave analysis of the net climate impacts from all aspects of the production, use, and disposal of a product.

light trap: A physical enclosure that captures insects attracted to a light source.

lignin: The structural material in plants that provides rigidity and is resistant to degradation.

lodging: The condition of a tree shoot or stem that has been damaged such that it cannot stand upright.

lure crops: A crop, such as alfalfa or barley, which is planted to divert wildlife from feeding on the field's primary crop.

male confusion: Type of mating disruption that targets male individuals.

marginal farmland: Farmland characterized by low productivity and reduced economic returns with limited plant resources for use in agriculture.

mating disruption: A form of insect control in which synthetic sex pheromones are maintained artificially at a higher level than the background, interfering with mate location.

mean annual increment (MAI): Average stand growth per year, calculated as the current volume divided by current age.

mechanical control: The use of machines or manual labor to eliminate or reduce unwanted vegetation.

mesophyll: A tissue in plant leaves composed of parenchyma cells packed with chloroplasts that carry out photosynthesis.

microsite conditions: Highly localized characteristics of a specific area, such as soil quality and water availability, which can vary across the larger field site.

mite (Eriophyid): A microscopic arthropod within the Arachnida class that has eight legs in its adult form and can cause a range of symptoms, including leaf bronzing.

monovarietal block: A plantation design in which trees of the same clonal variety are grouped together in the field often in a square or rectangular arrangement.

mulching implement: Mechanical farming equipment that cuts, grinds, and clears vegetation using a rotary drum with steel teeth. It may be manufactured as an application-specific tractor or as an attachment for a tractor, skid steer, or excavator. Mulching implements can cut and grind trees and other vegetation above the ground. Subsurface mulchers are designed to shred roots as well as surface vegetation and incorporate the debris into the soil.

necrosis: Death of most or all of the cells in an organ or tissue.

necrotic: Characterized by dead cells and tissues.

net present value (NPV): The sum of all discounted cash flows over the life of an investment. A higher NPV indicates a better investment given the discount rate.

nymph: An immature form of insects occurring after hatching but prior to adulthood. Nymphs are characterized by hemimetabolous development.

octane: Regarding gasoline, octane refers to the fuel's octane rating. Fuels with higher levels of octane will produce fewer emissions. A higher octane rating means that the fuel can withstand greater amounts of compression before igniting.

parasite: An insect that derives its nourishment from a host without necessarily killing the host.

pathogen: An agent that causes plant diseases.

permanent plot: A stationary inventory plot that is repeatedly visited and measured over time.

pest: An insect or animal whose behavior is detrimental to crops.

petioles: The slender stalk at the base of a leaf that attaches the leaf to the stem of the plant.

pH: A measure of acidity of the system expressed as hydrogen ion concentration in solution.

pheromone: A chemical used in communication between individuals of the same species that causes a specific behavior or development in the receiver.

phytoremediation: A process of decontaminating soil or water using vegetation to absorb or break down pollutants.

planting stock: A supply of materials (e.g., cuttings) for growing a new crop.

plot sampling: A method used for conducting an inventory in which several subsets of the stand consisting of one or more trees are measured to estimate the value of the entire stand.

postemergence herbicide: Herbicides applied to actively growing vegetation.

power base unit: Refers to a variety of mechanical equipment used on a farm, such as tractors, skidders, skid steers, and front-end loaders that have a mechanism to mount and hydraulic pump or PTO shaft to power a mulching implement.

preemergent herbicide: Herbicides applied to prevent seeds from sprouting.

probability level: The percentage of times with repeated sampling that sample values are expected to fall within a defined confidence interval bounding the average of the inventory unit.

proleg: An unsegmented leg of a larva.

pycnidium (pl. pycnidia): A type of fungal fruiting body in which conidia are produced.

Renewable Fuel Standard (RFS): Established by the Energy Policy Act of 2005, the Renewable Fuel Standard is the minimum volume of transportation fuels sold in the United States that must be renewable.

Renewable Fuel Standard 2 (RFS2): An updated Renewable Fuel Standard established by the federal Energy Independence and Security Act of 2007 that increased the minimum volume of transportation fuels sold in the United States that must be renewable compared to the original 2005 standard.

Renewable Identification Number (RIN): A tracking number that is assigned when a gallon of renewable transportation fuel is produced. RINs are used by the U.S. Environmental Protection Agency (EPA) to monitor compliance with the Renewable Fuel Standard.

restoration: Returning a former poplar plantation to a state that allows a different type of crop to be planted and grown.

restricted-use pesticides: Pesticides that are not available to the general public and which can only be applied by licensed applicators.

restrictive layer: An impervious layer of soil that limits water drainage and inhibits root growth, which can affect aboveground biomass yields.

rock-ripping shank: A farming implement that attaches to or is pulled behind mechanical farming equipment such as a tractor. Usually made of steel, a rock-ripping shank is used to break up compacted or restrictive layers of soil. It can also be used to remove rocks and roots from the soil profile.

root collar: The area of the tree where the trunk meets the roots.

root primordia: An organ or tissue in the earliest stage of development, also called latent root primordia.

rootstock: The stem and roots of the tree from which new aboveground growth can be produced.

root suckering: A form of vegetative propagation where a new tree sprouts from the roots of an existing tree.

roundwood: A wood product that is often processed into other products including timber, panel products, veneer, or pulp.

row break: A space within a crop row that allows equipment to maneuver. A row brake is typically used only on exceptionally long crop rows.

rust: Refers to both the diseases caused by rust fungi and to the rust fungi themselves. Rust fungi all belong to the order Uredinales of the Basidiomycetes. Rusts are obligate plant parasites that live off living plant cells and tissues.

sample plot: A subset of trees constituting the sample plot that is used as the basis for evaluating an inventory unit.

sampling intensity: The percentage of trees in a stand that are measured during an inventory.

selective breeding: A process by which humans select and develop plants for specific traits.

sequester: Concerning carbon, *sequester* refers to the long-term storage of carbon in plant tissues (e.g., wood), preventing it from contributing to atmospheric carbon in the form of greenhouse gases.

sexual (fungi): Fungi that do produce sexual spores, such as basidiospores and ascospores, from meiosis.

shoots: New growth of a plant consisting of stems, leaves and leaf buds, flowering stems, and flower buds.

short-rotation woody crop (SRWC): Fast-growing tree species that are harvested after growing periods of up to 15 years, such as poplar, willow, and eucalyptus.

shot hole: Round-shaped damage to the interior of a leaf surface.

signs (of plant diseases): Cells or structures of the causal pathogens.

silvicultural: Relating to the cultivation of trees using intentional management techniques to provide a service or produce a product.

single-pass harvest system: An automated harvesting process where the trees are cut, chipped, and collected in a collection vehicle simultaneously.

site preparation: Preparing an agricultural site for the planting and cultivation of a crop.

special local need: An existing or imminent pest problem within a state for which the state lead agency (Department of Agriculture), based upon satisfactory supporting information, has determined that an appropriate federally registered pesticide product is not sufficiently available. Candidates for SLN registrations may include (but are not limited to) a new method or timing of application, a changed rate, new crop, new site, new pest, a less hazardous formulation, choice of products, or an application to a particular soil type. To be considered for an SLN registration the pest problem must be verified by a university researcher, Extension specialist, or unaffiliated expert.

spermogonia (of rust fungi): Haploid structures producing haploid spermatia that result from infection of needles of Douglas-fir by basidiospores. When spermatia of opposite mating type are inadvertently crossed by insects attracted by the smell, dikaryotic aecia can develop.

standard deviation: A measure of the amount of variation within a data set based on the deviation of individual observations from the sample average. Units are the same as that of the input data.

stocking: The number of trees per acre.

stomata: Tiny openings in leaves through which water vapor, carbon dioxide, and oxygen pass.

stool: The lower remaining portion of a cut tree that has the ability to coppice, unlike a stump that will not regenerate.

stover: The leaves and stocks of field crops (e.g., corn, sorghum, soybean) that are usually left in the field after the grain is harvested.

structural roots: Act as a structural support and anchor the tree, which allows the tree to remain upright.

subsoiling: The use of a subsoiler, a tractor-mounted farm implement that is used for deep tillage to loosen and break up soil at greater depths than could be reached by tilling. It is also called ripping.

symptoms (of plant diseases): The physical manifestation of the physiological or morphological effects on plants of pathogens. Symptoms look irregular or abnormal and they are sometimes, but not always, characteristic or diagnostic of particular diseases.

systematics: The science of taxonomy or classification based on evolutionary relationships of organisms such as plants and fungi.

systemic herbicide: An herbicide that is absorbed, then translocated throughout the plant.

systemic insecticide: A water-soluble chemical (pesticide) that is absorbed and then translocated throughout the plant.

telia (of rust fungi): Structures producing teliospores that do not infect plants. Instead, teliospores form basidia which then produce the spores that infect aecial hosts (e.g., Douglas-fir in the case of poplar leaf rusts).

test statistic: Statistic that displays the probability that a parameter will fall within limits defining the confidence interval.

tillage: An activity that prepares land for the growing of crops. Tilling breaks up and turns the soil, sod, and other vegetation.

tilth: Physical condition of the soil as it affects moisture availability, aeration, infiltration, and drainage.

transect: A series of straight or nearly straight lines across a stand along which sample plots are located.

transgene flow: The transfer of genetic material from one organism to another which introduces new traits into the recipient population.

transpiration: The flow of water through a plant's vascular system from the roots out through the pores in the foliage.

uredinia: Structures of rust fungi that produce spores.

varietal blocks: Grouped arrangements of poplar varieties in the field where a specific variety would be planted together over several rows or acres.

vegetative propagation: A form of asexual reproduction in plants. Occurs when a part of a parent plant, such as a detached stem, root, or shoot, develops into a new individual that is genetically identical to the parent plant.

vertebrate: A chordate animal in the subphylum Vertebrata, generally characterized by a segmented spinal column and a distinct, well-differentiated head (e.g., fish, amphibians, reptiles, birds, mammals).

weed seed bank: Weed seeds that are present in the soil profile and have the potential to germinate.

whip: A slender, unbranched shoot from a plant.

yeast form: Fungi that grow either as hyphal, filamentous mycelium or as budding yeast forms. Some fungi can do both, depending on conditions and phase in the life cycle.

yield: The amount of material that may be removed during harvest.

yield table: A table showing the yield (volume or tonnage) of a stand for a particular region based on survival and stem dimensions developed by plot sampling.

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