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CHAPTER 14

Poplar

S. Y. DILLEN,^a O. EL KASMI OUI,^a N. MARRON,^b
C. CALFAPIETRA^c AND R. CEULEMANS^a

^aUniversity of Antwerp, Department of Biology, Research Group of Plant and Vegetation Ecology, Campus Drie Eiken, Universiteitsplein 1, BE-2610 Wilrijk, Belgium; ^bUnité Mixte de Recherche 1137, INRA-Nancy Université

Écologie et Écophysiologie Forestière, 54280 Champenoux, France;

^cInstitute of Agro-Environmental and Forest Biology (IBAF), National Research Council (CNR), Via Salaria, 00016 Monterotondo Scalo, Italy

14.1 The Poplar Genus

14.1.1 Uses and Interests of the Poplar Genus

Poplars (*Populus* spp.) are versatile trees that naturally occur in a broad range of ecological habitats. Although they typically occupy river flood plains and bottomlands, some species can tolerate desert or arid upland conditions.¹ In temperate regions, they are among the highest yielding trees that are extensively cultivated for forestry purposes as well as in agricultural systems. Hence, poplar trees are used for various applications, including wood products (such as paper, veneer and lumber) and services (such as shelter, shade and protection of soil, water and livestock).² They can be deployed in phytoremediation of slightly polluted or degraded sites, combating desertification and reforestation, and increasingly, poplar biomass is used as a resource of bioenergy, i.e. renewable energy from biological sources.

In addition to the numerous applications, poplar is well recognised as a model tree in physiological and in molecular genetic research.³ The poplar genus has

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Figure 14.1 Summary overview of the principal characteristics of the poplar genus. Poplar has a considerable number of advantages for application as a bioenergy crop. Less favourable or disadvantageous characteristics have been put in italics.

indeed numerous assets justifying the interest of the scientific community: (i) most species are very easy to propagate and to grow under controlled or natural conditions; (ii) the relatively small poplar genome made it the first tree genome recently sequenced;⁴ (iii) it is the first tree genus being transformed with *Agrobacterium*;^{5,6} and (iv) it contains a considerable source of genetic diversity (Figures 14.1 and 14.2).⁷ Nonetheless, the poplar genus also has some important weaknesses including large water requirements associated with its rapid growth, and high susceptibility to disease and insect infestations (Figure 14.1). However, there is a huge amount of variation available within the poplar genus in terms of productivity, resistance to diseases and abiotic hazards, leaf and tree morphology, etc. (Figure 14.2). This genetic diversity enables poplars to grow under a wide range of environmental gradients all over the world, and turns them into excellent candidates for genetic studies as well as for breeding and selection programmes.⁸

14.1.2 Subdivision of the Poplar Genus

The genus *Populus* is part of the Salicaceae family, which also includes the willows (*Salix*) (Figure 14.3). Trees within this family are dioecious, meaning

Poplar

Figure 14.2 mustration of diversity in leaf shape within the *Populus* genus for three genotypes.

Figure 14.3 Subdivisions of the *Populus* genus; section and species within the genus have been identified. The most common species and hybrids used in poplar cultivation, including short-rotation coppice (SRC) systems involve *Populus deltoides*, *P. trichocarpa* and *P. nigra*.¹⁰

that they have either male or female flowers.⁹ The poplar genus is complex and divided into six sections or systematic subdivisions, three of which being most employed in cultivation.¹⁰ These three sections are (i) Aigeiros, including black poplar (*P. nigra* L.) and eastern cottonwood (*P. deltoides* Bartr.); (ii) Tacamahaca, the balsam poplars; and (iii) finally *Populus* (ex *Leuce*), which includes the aspens and white poplar (*P. alba* L.).¹¹ Reportedly, the majority of worldwide poplar cultivation involves species and hybrids in the section Aigeiros.^{10,12} Most of these hybrids are derived from the species *P. deltoides* crossbred with the following species: *P. nigra*, *P. trichocarpa* T. & G., *P. maximowiczii* Henry, *P. ciliata* Royle, *P. szechuanica* Schneider, *P. yunnanensis* Dode, and *P. balsamifera* L. (Figure 14.4), thanks to the ease of intrasectional hybridisation and intersectional crosses with species in the Tacamahaca section. The real advantages of these hybrids over the pure *P. deltoides* parental species are the substantially improved rooting and survival from cuttings, and the higher productivity, also known as heterosis or hybrid vigour, which can be defined as the superiority of the hybrids over their parents.^{13,14} The section Turanga has been gaining importance, in particular since large-scale reforestation and planting programmes have been initiated in China in 1978. The Three-North Shelterbelt Programme is a 35.6 million hectare shelterbelt project across the desert border in

Figure 14.4 Crossability of *Populus* species.^{126,127} * The *P. tomentosa* species presented here does not appear in Figure 14.3 because it has been considered as a hybrid.¹¹

northern China, where poplars make up 60% of the effort, much of it *P. euphratica* and *P. simonii* Carrière $\times$ *P. nigra* hybrids.¹⁵

Note: In this chapter, the word “poplar” refers to the whole *Populus* genus, encompassing poplars s. str., aspens, cottonwoods, and hybrids.

Worldwide, about 80 million hectares of naturally occurring poplars have been reported to the International Poplar Commission (IPC) of the United Nations.¹⁰ Additionally, the IPC recorded globally 5.3 million hectares of poplar plantations. Countries with significant areas of poplar plantations include China (4.3 million ha), France (236 000 ha), Turkey (125 000 ha), Italy (118 500 ha) and Germany (100 000 ha). However, the share of the plantations specifically dedicated to energy purposes is very small: countries reported that only 0.9% of their total wood production (from poplar and willow) was used as fuel wood or as a resource of bioenergy.¹⁰ Existing poplar short-rotation coppice (SRC) systems with the purpose to produce bioenergy are largely experimental. In Italy, the profitability and effects of environment, management regime and clones on biomass production are currently being evaluated for 4000 ha of poplar SRC scattered in the north and the middle of the country.¹⁶ More experimental plantations were reported throughout the world, e.g. in Serbia, Romania and Argentina.¹⁰ Although poplar has been cultivated for many years, the information on planted areas of SRC plantations remains restricted and is less focused on energy use than willow.¹⁷

14.2 Poplar SRC Systems

14.2.1 Synoptic History of Poplar SRC

SRC systems can be defined as high-density plantations of fast-growing perennial species with good coppice and resprout capacity. The above-ground biomass collected at the end of each rotation cycle, generally after two to five years, can be used as a resource of renewable energy, paper pulp or fibres. Management of these SRC plantations is on the interface between agricultural and forestry practices.

In temperate climates, SRC with poplar and willow is being adopted. For many decades, the vigorous growth performance and high biomass yields of the Salicaceae family have been exploited. In the 1930s, after the first artificial poplar hybrids were created, numerous poplar-breeding programmes have been established in Europe, Canada and USA.¹⁸ The concept of SRC was initially launched in the 1960s in the USA, as the “silage” sycamore project.^{19,20} SRC was stimulated in 1973 during the OPEC oil embargo, in the search for alternatives to fossil fuels, and revived in the 1980s as a result of the set-aside policy of the European Union in times of agricultural overproduction. More recently, concerns about climate change and energy security together with spectacular progress in tree genomics and biotechnology have generated renewed interest in SRC with poplar. These scientific and biotechnological advances awaken hopes that in the future more productive and more suitable poplar genotypes can be

deployed in SRC. Thus, far, poplar cultivation and improvement programmes have been primarily concentrated on the production of veneer and plywood.

14.2.2 SRC Principles

To achieve maximal potential yields, poplar SRC is preferably established on loam- or clay-containing soils with adequate water availability. Before planting, site preparation includes ploughing to assure good rooting and harrowing to even out the field. The field should be completely weed free prior to planting either through chemical or mechanical weeding as poplars do not tolerate shade. Given the ability of most poplar species to reproduce easily by means of asexual or vegetative propagation, SRC plantations are usually established from unrooted hardwood cuttings (Figure 14.5). These cuttings are harvested from one-year old or older stems during the dormant season and their size generally ranges from 20 to 30 cm.

A distinctive feature of SRC plantations is their high planting density in order to reach the highest possible yields per unit area. In the Swedish SRC scheme, originally set up for willow, cuttings are planted in a double-row design at an overall planting density of 10 000–15 000 cuttings per hectare.²¹ A second model often used in Italy is characterised by a single-row design with 3 m between rows and 0.5–0.7 m between cuttings within a row, facilitating weed control and accommodating 6000–7000 cuttings per hectare.¹⁶ Initial planting density determines the length of the rotation cycle and vice versa (Figure 14.5).

Careful inspection of the establishment of the cuttings during the first months of cultivation is needed for satisfactory yield levels. Overall, the survival rate of hardwood cuttings at the end of establishment year is rather high, about 90% for commercial poplar clones.^{22–24} Poplars, being light-demanding pioneer species, require mechanical or chemical removal of weeds during the first growing season, or each year after coppice. During the following years, poplar trees attain sufficient height to prevent weed growth. Thus, establishment appears to be the most critical phase throughout the complete life span of SRC. The trees are often coppiced at the end of the first growing season to create an easily harvestable multistem coppice (Figure 14.5) and to benefit from the already existing root systems that are known to enhance growth in the subsequent rotation cycles.^{25,26}

Compared to willow, poplar has a stronger apical dominance and its stools tend to produce fewer but larger shoots when coppiced.²⁷ This difference in coppice and resprout ability between the two genera is probably due to a different breeding strategy in the past. In Europe, poplar-breeding programmes have been focused on single-stem growth and straight stem form, but yield of multistem coppice poplar including coppice ability has been overlooked and requires more attention.²⁸ As a result, several commercial poplar cultivars do not support very short rotation cycles or frequent harvesting. Nevertheless, coppicing is thought to reinvigorate growth, at least in the early rotations of SRC, and obviously avoids replanting costs. In contrast to willow, poplar is

Figure 14.5 Schematic representation of the concept of short-rotation coppice (SRC) culture for the production of bioenergy using poplar. Rotation cycles range typically from 2 to 5 years. (Photo credit for picture on harvest: I. Laureysens; all other pictures: R. Ceulemans.)

availed with wider initial planting densities and longer rotations.^{24,29} In a literature review, it was suggested that the optimum rotation system for poplar is about four years with densities between 2500 and 10 000 trees per hectare.²⁴ In denser plantations a quick succession of harvests reduces stool survival and number of resprouts per stump. However, more research on coppice regrowth traits of different clones is needed for a better insight in and management of poplar SRC.

If possible, harvests take place in winter to take advantage of the frozen soils to enter the field sites with heavy tractors and harvesters, avoiding soil compaction, and to coppice after leaf fall so that nutrients left over in senescing leaves are recycled (Figure 14.5). Out of necessity, harvests are postponed to spring in case soils are too wet in wintertime. Two different harvesting regimes can be applied: (i) the crop can be cut and chipped simultaneously in situ; or (ii) the crop is cut and the stems are chipped as a later operation.³⁰ Poplar biomass can be used as renewable energy resource either for the production of heat and electricity through (co-)combustion and gasification, or for liquid transport fuels through chemical fermentation or thermochemical conversion (Figure 14.5).³¹

The very first projections about potential above-ground dry biomass yields from poplar SRC (exceeding $20 \text{ Mg ha}^{-1} \text{ yr}^{-1}$)^{32,33} were too optimistic. These high yields were obtained in relatively small, experimental and carefully tended plantations and can only be achieved at a larger scale under optimal conditions in terms of climate, water and nutrient availability, i.e. on the best agricultural lands. More realistic and still satisfying yields range from 10 to $15 \text{ Mg ha}^{-1} \text{ yr}^{-1}$.^{26,34,35} The main reasons for yield failure or lower productivity are poor site quality, insufficient weed control and damage due to diseases, insects or wildlife.

14.2.3 Case Study

In 1996 an experimental SRC with 17 poplar clones was established in Boom (Antwerp, Belgium) on a former waste-disposal site, moderately polluted by heavy metals. The field site (0.5 ha) was planted with 5000 hardwood cuttings according to a double-row design. Due to the heavy loam soil, *P. deltoides* and its hybrids experienced difficult root establishment.³⁶ No fertilisation or irrigation was applied after the establishment of the experiment. From 1996 to date, biomass production for a large range of poplar clones has been monitored in relation to other ecophysiological traits during several rotations. This experiment is unique as only a few poplar SRC plantations have been carefully studied for more than a decade.

Coppicing stimulated productivity and biomass production, although this stimulation decreased each rotation.²⁶ Annual above-ground dry biomass production ranged from 1.5 to 10.8 Mg ha^{-1} .^{26,34,37} During the first rotation, clones Hazendans and Hoogvorst (both *P. trichocarpa* × *P. deltoides*) were the most productive clones, confirming the enormous juvenile growth capacity of

interamerican hybrids.³⁸ However, during the subsequent rotations, clones of the pure species *P. nigra* and *P. trichocarpa* displayed the highest yields. This study shows the need for long-term SRC trials to assess the effect of ageing, multiple coppicing and presence of pathogens and weeds on productivity in order to identify the most suitable genotypes depending on the management regime and the lifetime of the plantation.²⁶ Yields during the establishment year(s) are often not representative for future biomass yields as rooting problems or absence of pathogens (such as leaf rust *Melampsora larici-populina*), may give a wrong impression of which are the most suitable clones for a given SRC plantation.

Some clones in the long-term experimental plantation showed considerable potential for phytoextraction of heavy metals.³⁹ Wolterson (*P. nigra*) is a promising clone for phytoextraction of Al and Zn, given its high biomass production and high concentrations of both metals in the wood. Cd uptake from the soil was highest for clone Balsam Spire (*P. trichocarpa* × *P. balsamifera*). To maximize the phytoextraction potential of SRC plantations, harvests have to be advanced to late summer or early fall as metals are primarily concentrated in senescing leaves.³⁹ Nevertheless, poplar SRC holds the potential for the decontamination of sites moderately polluted by heavy metals.

14.3 Breeding

14.3.1 Quantitative Traits: Yield and Yield Components

The breeding of trees (i.e. application of genetic principles to the improvement and management of trees), is with the exception of fruit trees, a relatively recent discipline (see Section 14.2.1). The overarching objective of energy-crop-improvement programmes is the maximisation of yield on the minimum amount of land, with inclusion of environmental, social and economic aspects. Yield is, however, a complex result of numerous structural traits and physiological processes each regulated by different genes, and can be bred for either directly or indirectly through its component traits. Indirect selection for yield has proven its value in food crops, using the “ideotype” (i.e. a hypothetical ideal plant model) approach. Yet, the improvement of food crops usually resulted from reallocation of carbon to reproductive structures or below-ground plant parts, whereas in energy crops, yield includes the above-ground vegetative plant parts.^{40,41} In spite of this apparent contradiction, identification of key yield components is essential for both food and energy crops.⁴²

Many studies were dedicated to unravel the relationships between poplar yield and its component traits. Following these studies, the “SRC poplar ideotype” may consist of (i) rapid stem growth;⁴³ (ii) large individual leaves;^{44,45} (iii) rapid canopy development;⁷ (iv) early bud flush and late bud set;⁴⁶ (v) a high number of branches, particularly sylleptic branches;⁴⁷ (vi) high gas exchange rates;⁴⁸ (vii) good coppice and resprout ability;^{22,49} (viii) high wood quality;⁵⁰ and (ix) low susceptibility to disease and insect pests.^{51,52}

This nonexhaustive list of desirable traits for SRC poplar may vary according to planting density, rotation system, environment and endproduct, and may contain some trade-offs. For example, a high level of branchiness usually reduces the overall wood quality (see Section 14.3.2). For energy purposes, straightness and homogeneity of stems are not aimed for, and breeding programmes should therefore focus on traits more specific to short-rotation systems (2–3 years) such as growth vigour and number of resprouts after coppicing. The large genetic variation found in yield and yield component traits can be exploited in traditional selection programmes producing more suitable poplar genotypes for SRC. Beside the amount of genetic variation, the success of breeding programmes also depends on the selection method and intensity, and the nature of relationships between yield on the one hand and individual component traits on the other.⁵³

14.3.2 Qualitative Traits: Wood Quality

The three main components of wood are cellulose, hemicellulose and lignin (for poplar approximately 45, 25 and 20%, respectively).⁵⁴ Poplar wood is considered a low-quality fuel wood, though largely compensated for by its rapid growth. Compared to many other tree species it is characterised by a relatively low specific gravity (0.3–0.4)^{1,55} and high water content (55–60% just after coppice).⁵⁶ Major energy-related traits of biomass feedstock are: bark and moisture percentages, heating value (calorific value), cellulose/lignin ratio, specific gravity (density), amount of extractives, concentration of inorganic elements including alkali metals and ash/residue content.⁵⁷

Compared to 3-year-old willows, poplar hybrids of the same age appeared to have significantly lower bark percentage, lower specific gravity, lower Ca concentration and higher K concentration.⁵⁷ Percentage of moisture, ash content and N, P, Mg and Na concentrations were comparable between both genera,⁵⁷ and also the calorific values of poplar and willow wood appear to fall within the same range (14–24 MJ kg⁻¹ dry biomass).⁵⁸ Nevertheless, a large variability of wood traits has been observed within the poplar genus, and higher wood quality could be achieved by focusing on energy-related traits in order to create a more energy-efficient poplar biomass feedstock.⁵⁷ Generally, the presence of bark is considered adverse due to its higher moisture content and high accumulation of undesired elements (see Section 14.2.3).³⁹ Therefore, the biomass feedstock from poplar may be considerably improved when tree diameters exceed 4 cm and when the percentage of branches is reduced.⁵⁹ As the tree ages and tree size increases, the percentage of bark decreases together with wood and bark density. A considerable advantage of woody over herbaceous energy crops is the significantly lower amounts of pollutant byproducts of energy conversion.⁵⁹

An important element in wood is lignin (representing 15–30% of the wood).⁶⁰ Lignin provides structural support to cell walls, enables solute conductance in the vascular system, and protects plants against pathogen attacks.

The presence of lignin is somehow conflicting and may be positive or negative depending on the type of energy conversion, i.e. combustion and gasification versus processing of biomass to biofuels.⁶¹ Lignin has a higher calorific value as compared to cellulose (24 and 12 MJ kg⁻¹, respectively).⁶² Hence, when poplars are cultivated for energy production through combustion or gasification, genotypes with higher lignin content are desirable. On the other hand, the presence of lignin hinders the conversion of biomass to biofuel.⁶³ Since the recent boost in biofuel production, lignin engineering has become a major research topic in poplar genetics and genomics, contributing to a better insight in the lignin biosynthetic pathway. In preliminary studies, transgenic poplars with modified lignin biosynthesis proved to be beneficial for conversion to biofuels, i.e. improved saccharification potential.^{63,64} Large genetic variation has been found in the lignin content of poplar wood; so beside genetic engineering lower or higher cellulose/lignin content may also be achieved through traditional clonal selection.⁶⁵

Tension wood, which is often present in poplar in response to stem movements caused by wind or load, is characterised by an additional secondary wall layer of cellulose microfibrils as compared to normal wood. Accordingly, it is enriched in cellulose, and deficient in lignin and hemicellulose.^{66,67} As a result, wood with a high proportion of tension wood might represent a potential feedstock of lignin-poor biomass.

14.3.3 Molecular Genetics and Molecular Biological Tools

Pre-eminently, *Populus* spp. is the “guinea pig” of woody plants because of the exceptionally strong scientific basis and knowledge of the material.^{3,8} Molecular genetic research on poplar has been accelerated since the sequencing of its genome in 2004.⁴ To date, functions of genes or genomic regions in yield,⁶⁸ disease resistance⁵² (see Section 14.3.4), phenology,^{69,70} drought tolerance⁷¹ (see Section 14.4.2) and lignin biosynthesis⁶³ (see Section 14.3.2) have been located on the genetic maps of several poplar species. These biotechnological advances may be of use in creating transgenic trees and in providing new breeding strategies in SRC by reducing the breeding time.^{60,72} Transgenic trees with increased yield and improved quality traits have demonstrated great potential and are currently being evaluated in field trials throughout the world.⁶⁰

14.4 Current and Future Limitations to Large-Scale Poplar SRC

Poplar is a perfect candidate for bioenergy. However, the development of large-scale poplar plantations for this purpose in the European Union and in the member countries of the International Energy Agency (IEA) is rather slow because of a variety of limitations, e.g. (i) the difficult societal acceptance of such plantations due to their presumed impact on the environment; (ii) the

current lack of profitability of SRC plantations in many countries, mostly because of the absence of markets and value chains; and (iii) the sensitivity of poplar to diseases and pathogens that may drastically reduce biomass production during the growing season.⁷³ Despite these drawbacks, further improvement of the cultivation is possible through improvement of the plant material and through concrete incentives of governments (such as carbon credits, CO₂ taxes on fossil fuels and renewable-energy incentives).

14.4.1 Environmental Impacts

The large-scale development of poplar plantations for bioenergy production would require landscape-scale changes; the social and environmental impacts of such changes are not yet adequately understood or accepted. However, these impacts depend mostly on what is replaced by the bioenergy plantation. Indeed, positive effects on soil properties, biodiversity, energy balance, greenhouse-gas (GHG) mitigation, carbon footprint and visual impact are likely, when arable crops are replaced by SRC poplars. Compared to replacement of set-aside and permanent extensive grassland, benefits are less apparent.⁷⁴ Moreover, biodiversity in SRC appears to be strongly correlated with the density of the canopy (determining the abundance of the herbaceous layer), and with the rate of litter breakdown. Compared to exotic species (*Eucalyptus* and *Nothofagus*), a poplar canopy is less dense and litter turnover is fast, favouring a rich arthropod diversity.⁷⁵ In general, less is known about the consequences of large-scale deployment of the C4 grass *Miscanthus*, in comparison with SRC willow and poplar, including the effects on biodiversity and hydrology.⁷⁴

14.4.2 Water and Nutrient Requirements

Poplar is an interesting species for bioenergy purposes because of its unequalled growth under temperate latitudes, when the rooting system is well established. However, poplar is rather demanding in terms of soil quality, notably water retention and drainage, as well as soil fertility. Productivity may be strongly limited by water availability.^{76,77} For instance, in a nursery plantation with 17 000 single-stem plants per hectare, a reduction of one third of the fresh biomass and of 15% of stem height and circumference have been observed in nonirrigated versus irrigated plots, for commercial hybrids as well as for hybrids from controlled crosses.^{78,79} After coppicing, a second growing season without irrigation caused a 45% reduction of fresh biomass accumulation and a 25% reduction of stem growth in height and circumference.

A partial shift from fossil-fuel derived energy toward large-scale application of highly water consuming energy-crop plantations may have strong implications for local fresh-water availability and quality.⁸⁰ In this context, more water-use-efficient genotypes are required. At the whole plant level water-use efficiency (WUE) is defined as the ratio between biomass production and water consumption. The identification of poplars combining satisfactorily high

productivity and high water-use efficiency would represent a considerable advance in more sustainable poplar cultivation.

Removal of biomass after each rotation generally causes a rapid depletion of the soil fertility.⁸¹ Harvests usually occur after leaf loss, but nutrient retranslocation of senescing leaves to the perennial organs (roots and stumps) is small in comparison with retranslocation to the bark. The bark is particularly rich in mineral elements and its proportion in the exported biomass is high for short rotations (e.g. 2–3 years). Still, compared to herbaceous energy species (with the exception of *Miscanthus*), poplar is characterised both by a high nutrient-use efficiency (NUE, defined as biomass produced per unit of nutrient absorbed, notably N, P and K) and by a large variation for NUE.^{82–84} These two properties allow the selection of poplar genotypes maintaining high biomass production with a limited amount of fertiliser inputs.

14.4.3 Pest and Disease Sensitivity

Bioenergy plantations are dense, and the microclimate under the canopy frequently induces the development of pests and diseases. In North America and Europe, poplars are hosts to many pathogens and insect pests, including leaf rusts, stem cankers, galls, boring, sucking and defoliator insects, several of which severely impair plantation productivity.⁸⁵ A few create major limitations to economic production.⁸⁶ Leaf rust diseases are among the most devastating on poplars, notably *Melampsora larici-populina* Kleb., which is considered one of the ten most important sanitary problems threatening forests.⁵² This disease can cause premature defoliation that may reduce biomass accumulation and growth vigour in severely affected plantings (Figure 14.6). Defoliation may provoke infections by secondary organisms and may also subject shoots to increased winter injury. Durable resistance to leaf rust is one of the top priorities of poplar-breeding programmes in Europe.^{10,52} Once more, the wide diversity present within the poplar genus and the ease to produce new clones and hybrids is the key quality of this species, enabling the use and generation of resistant genotypes, able to compete in the poplar/rust “arms race”.

14.4.4 Effects of Global Change on Poplar SRC

Fast-growing species such as poplars are usually more responsive to environmental changes than other forest species. When we mention climatic changes in experiments involving trees we often refer to one or a few factors. However, the phenomenon involves complex interactions among various factors such as atmospheric CO₂ and tropospheric O₃ concentrations, air temperature, UV-B radiation, environmental pollutants, drought events, etc. The impact of climate change on photosynthesis and growth of poplar SRC has been intensively studied. Although most of these experiments were carried out with poplars under elevated CO₂ over the last decades,^{87,88} some studies have also examined the impacts of O₃ and warming on poplars.^{89–91} Elevated CO₂ was reported to

Figure 14.6 Impact of leaf rust on a poplar plantation established in May 2003 under the framework of the European project POPYOMICS (QLK5-CT-2002-00953) near Orléans (central France) at the end of the second growing season. Two blocks were treated with fungicides while one block was not treated against leaf rust. (Photo credit: C. Bastien (aerial view), N. Marron.)

stimulate photosynthesis in many field experiments with trees by about 50%,^{92,93} but fast-growing trees like poplars are usually stimulated even more by elevated CO_2 because of their indeterminate growth and the theoretical unlimited sink capacity.⁹⁴ Interestingly, in poplar, the stimulation of elevated CO_2 on photosynthesis and growth has been much higher in field experiments than in closed chambers, probably because of the limitations in sink strength in closed-chamber experiments.⁸⁷

The stimulation by elevated CO_2 on productivity has been observed in the three largest experimental facilities involving poplar species in SRC, i.e. the POP-EUROFACE (Italy), the AspenFACE (USA) and the Biosphere 2 (USA) experiments with stimulations of both above- and below-ground biomass ranging from 20 to 40%.^{95–97} The AspenFACE experiment evidenced a loss of productivity due to increased O_3 levels, except for the most tolerant clone.⁹⁸ The loss of productivity that O_3 causes applies to most components of growth, but root growth appears to be most severely impacted.⁹⁰ In a recent meta-analysis, the effect of O_3 on leaf gas exchange from different experiments was

reported, and the genus *Populus* was listed as one of the most sensitive among those studied.⁹¹

14.4.5 Life-Cycle Assessment (LCA)

As opposed to agricultural crops, trees are long-lived organisms with a complex structure and considerable carbon sinks in perennial tissues. Regardless of short-rotation cycles, the long lifespan of these perennial crops might significantly influence acclimation processes.⁹⁹ In contrast to traditional forest plantations, the management of SRC is quite dynamic. The length of the rotation and the cultural practices used in management should be reconsidered to maximize the positive aspects and/or minimise the negative effects of climatic changes.¹⁰⁰

There is a great potential for SRC to sequester carbon (C) in soils. Forest and agricultural soils can accrete C at average rates of $0.3 \text{ Mg ha}^{-1} \text{ year}^{-1}$ with a maximum as high as $3 \text{ Mg ha}^{-1} \text{ yr}^{-1}$.¹⁰¹ Although an initial decline in soil organic carbon (SOC) was not found by Coleman et al.,¹⁰² SOC in some cases may initially decline during the establishment of SRC plantations,¹⁰³ followed by a predicted increase after 5 years.¹⁰⁴ Global change and especially the increase in atmospheric CO_2 might influence the C cycle between the plantation and the atmosphere, in particular the C sequestration by soil. The elevated CO_2 concentration will probably increase the fraction of C incorporated into the soil in poplar SRC although this might be counterbalanced by the increase of O_3 levels.^{105,106} It has been estimated that the long-term conversion of 20% of present arable land area of the European Union into bioenergy tree crops and natural woodlands would increase soil C stocks by about 5% over a century and would offset European C emissions by about 4%.¹⁰⁷ This figure is comparable with the Kyoto obligations.

Poplar SRC could be very effective in directly reducing CO_2 emissions to the atmosphere, since considerable amounts of renewable energy are produced by the SRC culture, thereby reducing the use of fossil fuels, i.e. a substitution effect that continues over different years. By comparison, carbon sequestration in natural forests is diminished as the forest reaches maturity. With regard to energy substitution, SRC reduces emissions with 24 to $29 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$, while an oak-beech mixed forest reduces only 6 to $7 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$.¹⁰⁸ The POP-EUROFACE experiment allowed estimating a future CO_2 reduction potential of poplar SRC between 95 and $108 \text{ Mg CO}_2 \text{ equivalent ha}^{-1} \text{ yr}^{-1}$. If expected arable area potentially available in Europe were available for production of woody biomass from SRC, by the end of 2100, 1805 up to 4212 Mton CO_2 equivalents year^{-1} could be mitigated by producing energy from poplar biomass.¹⁰⁹

14.5 Economic and Energetic Analysis of SRC Poplar

At present, a key constraint to the commercialisation of SRC for the production of heat, electricity and/or liquid fuels is the economic feasibility. General

conditions have to be met to make SRC competitive to fossil-fuel sources. First, the feedstock price and the costs of biomass conversion have to be competitive with fossil-fuel-derived energy. Secondly, the price offered by the converting facilities to the farmers has to be high enough so that energy crops are at least as profitable as conventional food crops. Accordingly, a number of measures to increase the competitiveness of energy crops in comparison with fossil fuel-derived energy and traditional agriculture appear vital in order to increase the economic viability of SRC.

14.5.1 Costs of Poplar for Bioenergy

The cultivation costs of poplar in a SRC culture involve (i) establishment costs (initial weed and pest control, soil preparation, (mechanical) planting, planting material and wildlife control); (ii) operating costs (land rent, ongoing weed and wildlife control, soil fertilisation and irrigation, harvesting, storage and transportation of the biomass product); and (iii) costs of processing and converting the poplar wood to heat, electricity and/or liquid fuels.¹¹⁰ However, the latter goes beyond the scope of this chapter and will therefore not be discussed.

The estimated costs of the production of poplar biomass in SRC differ to a great extent depending on the location of the plantation. The land rent as well as the biomass yields, which are both strongly associated with the location of the plantation, account for most of the variation in estimated production costs (Table 14.1).¹¹¹ Different framework and methodological approaches make up much of the remaining variation in cost estimations. The figures presented in

Table 14.1 Overview of yields and delivered costs of hybrid poplar in SRC systems.

Location	Approach	Rotation length (years)	Yield (Mg dry biomass ha ⁻¹ year ⁻¹)	Delivered costs ^c (USD Mg ⁻¹)	References
USA	Full economic	7	6.7–20.2	40.6–94.3 ^a	112
USA	Full economic	7	11.2	52.8–59.3 ^b	112, 121
USA	Discounted cash flow	5–8	16	40	122
USA	Discounted cash flow	5–8	16	38.8	123
Spain	Full economic	5	13.5	27.3–35.1 ^{c, f}	124
Italy	NA	2	10	109.8–131.8 ^{d, f}	125

^aDepending on the yield: the higher the yield, the lower the delivered cost.

^bDepending on the transportation costs ranging from 5.5 to 12.0 USD per Mg dry biomass. Values for transportation costs were taken from a similar study.¹¹²

^cDepending on the transportation costs ranging from 3.5 to 13.4 USD per Mg dry biomass.

^dDepending on the size of the cultivated area: the larger the area, the lower the delivered cost.

^eThe delivered costs were calculated for the full production process from establishment of the plantation to the delivery of the biomass feedstock at the conversion plant.

^fCosts were converted from EUR into USD using the average EUR-USD exchange rate for 2008, namely 1.46. Source: <http://france.usembassy.gov/irs-euro.html>.

Figure 14.7 Total breakdown of total financial costs among poplar SRC activities in two studies in the USA (light grey bars: study from Strauss et al.;¹¹³ and dark grey bars: study from Linville and Betters).¹¹⁴

Table 14.1 consider two financial models, i.e. full economic accounting model and discounted cash-flow model. The full economic accounting approach provides a structural annual review of all costs (variable and fixed cash costs, and opportunity costs of owned resources) involved in the production of biomass feedstock, from the plantation establishment to the delivery of the feedstock at the conversion plant.^{112,113} The discounted cash-flow model, on the other hand, identifies the total investments and the related operating costs or revenues over the entire lifetime of the plantation.

A breakdown of the total financial costs among activities in two studies showed that land rent, harvest and transportation costs largely contributed to the total costs of poplar SRC (Figure 14.7).^{113,114} Poplar biomass has a lower energy density than fossil fuels, which translates into relatively large amounts of biomass required to generate one energy unit. Consequently, large plantation areas distributed over large geographic areas are required, resulting in high land rent, harvest and transportation costs.¹¹⁵ Irrigation was not considered in this breakdown, as several studies reported very high costs for irrigation that were not compensated by a comparable increase in biomass yield.^{113,114}

14.5.2 Energy Balance of Poplar SRC

A basic requirement of any (bio)energy generation system is that the energy produced must be larger than the inputs of nonrenewable energy required for the establishment and operating of the system.¹¹⁶ Thus, an analysis of the energy balance of poplar SRC in addition to the economic assessment is essential. The energy balance entirely depends on the boundaries of the considered system. In the next sections the boundary will be placed at the farm gate, unless otherwise mentioned. The transportation of the feedstock from the farm to the conversion site and conversion steps will not be considered, as this

would result in widely divergent figures depending on the conversion technology used. Furthermore, solar energy and human labour will not be taken into account as energy sources.

The energy requirement (i.e. the ratio of total nonrenewable energy input to total energy content of biomass feedstock) for poplar production is in the order of 0.05 MJ MJ^{-1} that corresponds to an energy ratio (i.e. $1/\text{energy requirement}$) of 20.¹¹⁷ The energy ratio has to be larger than one if the system is to produce more energy than it consumes. A Belgian study assessed the energy balance of poplar SRC, considering three levels of management regimes with regard to the nature and the amount of inputs (fertilisers, pesticides, etc.) as well as to the scale of mechanisation.¹¹⁸ The energy ratios in this study ranged from 21.5 to 25.6. When a local transportation of about 30 km was included in the energy balance, the energy ratio declined to a range of 17.2 to 20. In both cases the scenario with the most intensive management regime yielded the highest positive energy ratio, even though its total energy costs were higher. Better crop management, resulting in higher biomass yields, clearly outweighs the higher energy costs.¹¹⁹ The energy balance of poplar (and willow) turns out to be quite positive in comparison to other energy crops, such as alfalfa, switchgrass and reed canary grass, which all have significantly larger energy requirements than poplar.¹¹⁷

The breakdown of the total energy costs indicated that crop maintenance (fertilisation, pesticide, etc.), harvest and transport are the most energy intensive activities.¹¹⁸ In particular, the production of fertilisers is very energy demanding, given the high energy cost of nitrogen (1 kg of nitrogen $\frac{1}{4}$ 57.5 MJ). In this study, crop maintenance represents between 32 and 39% of the total energy costs, depending on the intensity of the SRC cultivation practices. Obviously, the incidence of (local) transport on the total energy costs is subject to the distance between the farm and the conversion site. The total energy requirement of bulk road carrier transport in the UK was estimated about

$1.1 \pm 0.04 \text{ MJ Mg}^{-1} \text{ km}^{-1}$.¹²⁰ The precise share of the different activities in the total energy costs depends not only on the management practice used but also on the boundaries chosen. The more activities or energy inputs considered (e.g. inclusion of regional transportation), the larger the total energy costs and consequently the smaller the share of the different activities will be.

The lack of comprehensive accounting methods to assess financial as well as energy costs of different activities involved in the production of SRC largely explains the differences among the results of existing studies. To provide accurate and unambiguous results, a full system analysis of poplar SRC from the planting to the energy conversion in combination with standardised calculation and accounting methods is indispensable.

14.6 Conclusions

Characterised by rapid growth rates and good coppice ability, poplars hold several trumps for bioenergy. Large genotypic differences occur in tree

physiology, morphology and responses to biotic and abiotic stresses among and within poplar species and their hybrids. This rich source of genetic variation can be exploited in poplar-breeding programmes aiming at improving poplar material for SRC, mainly in terms of yield and quality traits. Yet, greenhouse gas and net energy balances as well as economic analyses of a poplar SRC life cycle represent a promising area for future research.

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