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Poplar

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11.1 Introduction

*Populus* consists of 25–35 species and among them hybridization is common. The genus itself has a large genetic diversity with some species growing 50 m tall with trunks of up to 2.5 m in diameter. All *Populus* species from family *Saliceae* are common in temperate climate zones but they are limited in tropical zones because the maximum temperature they can tolerate is approximately 30°C. Among the various species, *Populus alba* grows primarily in southern and central Europe, *P. tremula* in Europe and Asia (mainly in India), and *P. tremuloides* in North America with their northern border being Alaska. There are some reports concerning *Populus deltoides* growing in India [1], and although some *Populus* genotypes can be successfully grown on saline-sodic and alkaline soils, some tested clones could not survive those soil and climatic conditions in Uttar Pradesh province. In an age of globalization there is an increasing tendency for farmers, foresters, and owners of recreation areas to introduce different poplar species in non-native environments. Therefore, numerous *Populus* species are often found outside their natural borders. In Europe, for example, the most frequently grown poplar is hybrid *Populus × euroamericana* (*Populus deltoides × P. nigra*).

Berndes et al. [2] identified poplar short-rotation plantations (SRPs) as one of the most important sources of biomass for energy purposes, pointing out their energy and environmental soundness. In the United States, poplar species have been grown commercially for more than 100 years [3] and although, to date, business conditions have restricted their
cultivation to specific geographic locations, those developments have provided proof of concept for growing short-rotation trees using intensive agricultural techniques. Therefore, looking to the future and to the great opportunity to develop a viable biomass energy feedstock supply, the poplar industry in many countries is well positioned to play a significant role in meeting global energy needs. Poplar species and their numerous hybrids are very productive genotypes due to their rapid foliar production, very high leaf area index and high photosynthetic rates. It was stressed [4] that the *Populus* genus, which contains more than 30 species worldwide, has remarkable clonal variation for both biomass production and distribution. Therefore, some species and clones are much more suitable for lignocellulose biomass production than others because they can allocate more biomass to aboveground plant parts than to roots. By understanding genetic variability among poplar species, Wullschleger \textit{et al.} [4] pointed out that there is a starting point for future breeding programs aimed at obtaining clones of high and reliable yield level with a desirable distribution of assimilates in plant biomass.

Poplar is also one of the so-called energy crops that can, theoretically, improve relations between agriculture and environment. For example, studies on 12 poplar genotypes grown on marginal and agricultural soil in Hungary [5] confirmed wide genetic variability with average biomass yields of 27 Mg ha$^{-1}$ ODM (oven-dry matter) and average energy yields of 309 GJ ha$^{-1}$. With regard to carbon, the authors reported that the balance was always positive (i.e. the amount of carbon emitted to the atmosphere as carbon dioxide during combustion was always less than the amount of carbon sequestrated in SRP poplar biomass) because of the high content of carbon in roots, litter and stools. Therefore, under Hungarian conditions, short-rotation poplar can be an effective carbon sink and source of renewable biofuel. Many other environmental benefits associated with growing poplar for energy have been presented from a United States perspective [6], with the prediction that in the United States growing poplar in short-rotation systems will link phytoremediation of contaminated soils with bioenergy production.

### 11.2 Cultural Practices

Soil demands of the genus *Populus* are similar to requirements of *Salix* because of the fact that poplar trees can grow very well on a very wide range of soils – sandy as well as loamy clay, but they cannot grow on sites without proper drainage. The optimal soil pH value for poplar is around 6.5.

The most critical limiting factor for poplar cultivation is water availability, and therefore it is considered to be common knowledge that dry areas should be avoided. The physiological reason for this response is a very high evapotranspiration rate – as high as 5 mm day$^{-1}$ for each mature tree. Fortunately, there is substantial genetic variation for this important physiological trait. For example, water consumption by *P. balsamifera* and *P. nigra* is low and these species are considered to be relatively drought resistant compared to other species. On the other hand, the root system of *Populus* trees cannot be considered as flood resistant. Under conditions of permanent flooding (i.e. lasting longer than one month) several poplar species showed reduced photosynthetic capacity and other plant metabolism disorders, leading to lower growth [7, 8].

Guidi and Labrecque [9] studied growth and performance of the hybrid poplar *Populus maximowiczii* × *P. nigra* in a pot study with very high (five times higher than field capacity) water supplies. Their focus was on assessing the suitability of poplar for
puriﬁcation of wastewaters from aquaculture and the chemical composition effects of drainage water. They found that evapotranspiration rates were higher in plants using wastewater. Overall, however, poplar biomass was severely reduced by high water supply because the conditions, which were similar to permanent ﬂooding, inhibited root growth. Leaf and stem tissue nutrient levels were lower for the high water treatment compared to an optimal water supply. Therefore, although low nutrient content in drainage water conﬁrmed that poplar can be suitable for removing nitrogen (N) and phosphorus (P) from wastewater, nutrient removal was more efﬁcient when the trees were grown at an optimum water content. The overall conclusion of this pot study was that poplar could successfully remove nutrients from polluted water, provided an intensive selection program was used to ﬁnd genotypes capable of growing under conditions with excess water. This conﬁrmed previous ﬁeld studies [10] using poplar as a vegetative ﬁlter that had suggested that irrigating short-rotation poplar plantations with pretreated wastewater could substantially improve wastewater quality before its release into surface waters, if the water contained sufﬁcient nitrogen and phosphorus to meet plant demands.

The economic and energetic viability of growing SRP poplar in Northern Italy were investigated by Manzone et al. [11]. They obtained a SRP biomass yield of 10 Mg ha\(^{-1}\) year\(^{-1}\) ODM for eight years using a high planting density of 6700 cuttings per hectare, a two-year cutting cycle, an intensive program of chemical weed control, nitrogen fertilization and a Class combine harvester. This resulted in a very high energetic efﬁciency coefficient of 13 – reﬂecting the relationship between output and input energy despite the energy required for the intensive agricultural inputs. Despite the very positive energetic balance, economic sustainability of SRP poplar will depend on political choices, including the price of wood chips and subsidies available for other fuels.

The potential of SRP poplar in Sweden was presented by Christersson [12]. Nine poplar plantations established beginning in the 1990s and their performance were reviewed. The author pointed out the necessity for proper selection of clones because, in some locations, Populus trichocarpa \(\times\) P. deltoides hybrids did not survive, whereas P. trichocarpa clones performed very well. The other factor determining high productivity appeared to be spacing. It was stressed that in Sweden poplar plantations can be treated as multifunctional because only part of the trees were harvested for biomass energy while the rest remained for longer periods before cutting them for pulp or timber, thus resulting in best economic indices for combined energy and pulp plantations. The other function of poplar plantations in Sweden is their use in vegetative ﬁlters. There are several economically sound examples where sewage treatment plants use poplar plantations as the last stage of efﬂuent puriﬁcation, and farmers are paid by local sewage treatment plant for this service.

### 11.2.1 Establishment

When establishing commercial poplar genotypes, biomass productivity and pathogen tolerance or resistance are frequently used as primary selection criteria. Water consumption has traditionally been considered less important in breeding programs, since poplar production was traditionally restricted to areas with high plant available water. Furthermore, if potential negative consequences of global warming are considered and drought is projected as a more frequent occurrence, poplar breeders need to increase efforts focused on the genetic base for drought resistance [13]. This need was veriﬁed by modeling projected twenty-ﬁrst century climate changes, with the conclusion that short-rotation forestry could be severely...
affected by water deficits and, therefore, some type of response action needs to be pursued in today’s breeding programs [14].

Larchevêque et al. [15] reported that drought resistance of poplar hybrids can be improved considerably by including *Populus balsamifera* in breeding programs because this species shows stomatal control of photosynthesis that can overcome certain disadvantages of this species, such as higher resin content and dark colored heartwood. The authors concluded that hybrids with *P. balsamifera* can be very suitable for short-rotation plantation for energy purposes because they are able to grow even under a medium water stress, and even is a more severe drought occurs plants are able to resume growth when water is available again.

Some authors have mentioned other mechanisms of drought resistance within the genus *Populus*. Among them, the most effective seem to be decreased leaf area, leaf abscission, enhanced root growth rate and increased water use efficiency [16, 17]. It was stressed that the magnitude of the reduction in leaf area under conditions of water deficit was a good indicator of drought resistance within the studied clones. The main conclusion after screening 29 hybrid poplar genotypes was that there is a large potential for improving water use efficiency while maintaining high productivity [17].

Afas et al. [18] studied root characteristics of five poplar clones grown under conditions of short-rotation coppice and found that the vast majority of roots (in terms of both their biomass and total length) were located very near the surface (0–5 cm). They also identified a close and positive correlation between root biomass and aboveground productivity. Other authors have also reported significant and positive correlations between leaf area index (LAI) and root area index (RAI) – calculated as the sum of all root area per plot. Similar variability was found for root biomass as for aboveground biomass among the clones studied, with some showing high root density and high LAI and others a low density of fine roots and low LAI values.

In the United Kingdom [19], the high density of plant roots in SRP poplar was studied because of the possibility that introducing “deep rooting” trees to agricultural space could potentially disturb buried archaeological evidence that is protected by laws and regulations. To quantify both the rooting patterns and depth of rooting by various poplar clones, trenches were dug to expose the root systems of several stools growing on two different soil types. The trenches enabled researchers to observe the root systems and to make precise length and diameter measurements of individual roots. The study showed that the rooting habit of short-rotation poplar was influenced by several factors, including soil physical, chemical and hydrological properties as well as by silvicultural practices, such as cutting frequency, cultivation and fertilization. It also showed that between 75 and 95% of poplar roots were located in the Ap (30–40 cm deep) horizon. Although some roots were found at a depth of 1.3 m, their diameter was less than 10 mm. Furthermore, more than two-thirds of roots were less than 1 mm in diameter. The authors concluded that these results can help break the myth that “deep rooting” poplar will devastate drainage systems made with ceramic pipes.

Poplars are one of best examples of effective symbiosis between roots of higher plants and mycorrhizal fungi. Mycorrhizas in the case of poplar are very effective for many important physiological processes (e.g., enhanced nutrient absorption, protection against root diseases, drought resistance, and winter hardiness) that can be described as a reduction in genotype by environment interaction problems [20]. Wide variation among *Populus deltiodes, P. nigra* *P. balsamifera, P. trichocarpa, P. suaveolens* and 10 different hybrids was shown in
response to colonization of their roots by mycorrhizal fungi. Of even greater significance was that whenever a lack of mycorrhizal symbiosis was recorded, the trees appeared to have both arbuscular mycorrhizas (AM) and ectomycorrhizas (ECM). Furthermore, only the *P. trichocarpa* × *P. suaveolens* hybrid had a higher number of AM than ECM. For the other 28 genotypes that were studied, ECM colonized the root systems more intensively (sometimes by a factor of five). However, there was no correlation between growth parameters (height and stem diameter) and mycorrhizal colonization, indicating it may have occurred at a very early growth stage. It was concluded that in some cases in Alberta, Canada, inoculating with mycorrhiza may be effective when introducing tree species into agricultural or disturbed lands where native mycorrhizal consortia are rather low. In those cases, co-inoculation of ECM and AM fungi with “helper bacteria” can be very effective for SRP systems [20].

Quoreshi and Khasa [21] evaluated mycorrhiza colonization of balsam poplar by inoculating seeds with different combinations of six fungal isolates plus helper bacteria and different rates of fertilizer. The bacteria alone were not effective. Seedlings with the highest mycorrhiza colonization were the most vigorous and after just 10 weeks those inoculated with ECM were taller and had significantly more dry matter than the controls. The nutrient content in seedling tissues was higher, however, only when the fungal species *Paxillus involutulus* and helper bacteria *Burkholderia cepacia* were included in the inoculum. High fertilizer rates usually inhibit mycorrhiza colonization of plants’ root systems but, under the conditions of this experiment, one ectomycorrhizal species (i.e. *Pisolithus tinctorius*) was present as a symbiotic species regardless of the fertilizer rate. Plant biomass was always superior in seedlings with mycorrhiza than in the controls. The best results were found where less fertilizer (e.g. 67% of the standard rate) was applied in addition to the mycorrhiza. Generally, these results show that incorporation of ECM into poplar plantations is effective and can be treated as a standard management practice. Studies will be continued to compare performance of seedlings with and without mycorrhiza under field conditions. Successful artificial inoculation of poplar by ectomycorrhizal fungi was also observed in SRP under the semi-arid conditions of Spanish Andalusia, where it substantially increased drought survival and biomass production (Antonio Ramoz Fernandez, personal communication).

Natural mycorrhiza colonization in SRP poplar and willow were investigated by Hrynkiewicz *et al.* [22] in relation to cutting frequency of dedicated energy coppice systems. For the *Populus nigra* × *P. maximowiczii* hybrid, they found that mycorrhiza frequency and fungal species composition were significantly different for the three and six-year cutting cycles. They concluded that more frequent biomass harvesting promoted mycorrhiza colonization and assumed the response mechanism was based on chemical signals given off by the root system. The authors also highlighted the relationship between mycorrhiza frequency, fungal species and vitality of biomass production within short-rotation coppice systems.

Gunderson *et al.* [23] also studied effects of artificial mycorrhiza colonization of hybrid poplar (*Populus deltoides* × (*P. lauriflora* × *P. nigra*) cuttings by spores of two ECM fungi (*Pisolithus tinctorius* and *Rhizopogon* spp.) when used for phytoremediation of soils with diesel oil spills. It was reported [24] that among the 42 ECM species checked 33 were able to degrade at least one aromatic hydrocarbon and some species were able to degraded five different polycyclic aromatic hydrocarbons (PAHs). It was also found that ECM colonization was very effective in terms of poplar growth rate and increases in
aboveground biomass production irrespective of soil contamination by diesel oil. Furthermore, plants with higher biomass accumulation also had more fine roots after artificial mycorrhiza inoculation [23].

11.2.2 Environmental Benefits

Poplar trees can also be grown to provide environmental benefits. For example, one option for managing sewage sludge, which is an unwanted by-product of the water purification industry, is its application on agricultural land as a soil amendment. Recently, because of the food chain contamination risk, there has been a tendency for banning agricultural sludge application in many countries. Therefore, it seems that non-food, non-feed energy crops could provide an alternative application site for sewage sludge from municipal water treatment plants. A high fertilizer value of sewage sludge was noted by Moffat et al. [25] in studies designed to evaluate the effect of sewage sludge application and wastewater irrigation on biomass production of two poplar genotypes. The three-year experiment showed that irrigation affected biomass yield more than sewage sludge application and that waste application at the rates used did not pose any risk for nutrient pollution of groundwater.

The special importance of riparian forest or stream buffer zones is understandable and, therefore, establishing buffer zones in forest or agricultural space is treated as a standard environmentally friendly practice in many countries [26]. Growing poplar in these systems is, therefore, a logical option for combining biofuel production with surface and groundwater protection. Furthermore, this would also increase biodiversity near water courses and their banks. Poplars, because of their physiological properties, are very well suited to have an important role in establishing riparian buffer zones. Henri and Johnson [26] suggested that social debate is needed to determine if riparian zones should be left as a “no touch” area or should be managed. They also evaluated options for managing such buffers and found that harvesting 50% of the area and selling biomass could provide both economic and environmental benefits. Fortier et al. [27] studied a multifunctional system of hybrid poplar riparian buffer in southern Quebec, Canada, and also found effective environmental and economic aspects. They stated that biomass produced in riparian buffers can be harvested for different purposes, especially with a multiclonal structure where some clones could be harvested for energy and some for pulp. When biomass productivity in buffers is considered, it is possible to achieve yields comparable to SRP poplar plantations and, since mineral nitrogen is often a limiting factor, the poplars also provide a very effective way to control nutrient flow to groundwater and surface water resources.

Agro-ecological zones have been used for global, national and regional evaluation of agricultural practices [28]. Recently this methodology was enhanced with digital geographic databases. This advanced technology was used to evaluate agricultural areas in Eastern Europe as well as North and Central Asia for their suitability to produce dedicated energy crops. A large variation in the potential for biofuel production was found among these countries, with the highest potential for poplar production being in the Czech Republic and Georgia, due to good soil conditions and a favorable climate. European energy use was estimated at 111 GJ per capita, with Latvia, Lithuania, Hungary and Estonia having the potential to produce more than 140 GJ per capita of bioenergy. The studies also identified
some technical and non-technical barriers for bioenergy utilization, thus emphasizing the necessity for future research programs.

The economic soundness of poplar plantations for energy was also evaluated by Yemshanov and McKenny [29]. They constructed two scenarios: (1) “business-as-usual,” where only the biomass has value; and (2) a “fibre + carbon” scenario, where benefits from sequestering carbon in silvicultural systems are included. Many factors were considered, with transportation costs appearing to play a very important role. When burnt for energy, the cost for 1 GJ from biomass ranged from $4 to $5 for scenario 1 and started at $3 for scenario 2. Obviously, adding the benefits of carbon sequestration helped but, as the analyses show, biomass cost was still higher than the price of low-quality coal currently being used by power plants. Assuming the option of producing bioethanol from poplar biomass becomes feasible, the economics of biomass production will be substantially improved.

Several authors point out that the most important environmental effect of SRP poplar is the perennial nature, which promotes increased diversity and frequency of many soil organisms and the beneficial impact on soil organic matter [30]. The use of SRP poplar as a vegetative filter was also studied by Coyle et al. [31], who concluded that coppicing poplar was suitable for this purpose because of the extensive root system and high evapotranspiration rate. Poplar clones in their study were irrigated with leachate from municipal landfill and compared with control treatments receiving mineral fertilizers. Effects on soil meso and microfauna were also compared. They reported that microfauna (i.e., soil nematodes) as well as mesofauna (mainly insects) were more abundant in control treatments, while with the leachate, biodiversity among soil organisms was much higher. Based on these findings, the authors concluded that introducing phytoremediation technologies did not always lead to higher sustainability within the soil environment.

Studies on growth, biomass distribution and nutrient use by eight poplar (Populus balsamifera L., P. trichocarpa Hook) and hybrid poplar (P. trichocarpa Hook × P. deltoides Bartr.) clones in Sweden were conducted by Karačić and Weih [32]. The clones were chosen from Canada because its latitude is similar to that of Sweden. The objective was to evaluate genotype by environment interactions with a special focus on phytoremediation. All studied clones showed a high and positive response to irrigation. The results helped identify clones that were better suited for phytoremediation, which involves the application of as much water and nutrients as possible with minimum leaching from the system.

In California, U.S.A., irrigation water can have bad quality because of high selenium, boron, and/or sodium chloride concentrations. Research being conducted by Bañuelos et al. [33] is, therefore, focused on identifying plants that are resistant to elevated levels of these contaminants. Trees have an advantage over vegetative plants because they transpire large amounts of water, produce high amounts of biomass, live longer, have deeper roots, and, for many species, can re-grow after being cut. Poplar is one species that has all of these features and, therefore, this genus is widely used for phytoremediation. However, because of the wide genetic variation among species, hybrids and clones of this genus, screening experiments focused on the tolerance of the various genotypes are essential. Among the findings of this research were differences in the chloride and boron concentrations of both lower and upper leaves in poplar genotypes classified as susceptible or resistant to high concentrations of these micronutrients. The mechanism of resistance to high salt concentrations in the irrigation water was also identified as being early abscission of lower leaves containing a high concentration of chloride. Although the physiology of boron tolerance or toxicity
remains to be determined, it appears that boron uptake is inhibited when irrigation waters contain elevated chloride concentrations although other resistance mechanisms may exist within the *Populus* genus.

Poplar grown in SRPs was also able to effectively degraded ethylene glycol, which is present in the environment because of its use as a coolant and deicing agent. Two mechanisms for removal of ethylene glycol (microbial degradation in the rhizosphere and uptake by the trees through evapotranspiration) have been identified [34, 35]. Based on these results, it is very probable that similar mechanisms can be effective for removal of other organic compounds. This was verified by Jordahl *et al.* [36], who reported that hydrocarbon degrading microorganisms were more common in the rhizosphere of poplar trees than in bulk soil.

Growth and survival of poplar clones at sites contaminated with hydrocarbons and at sites polluted by long-lasting industrial activity near Lake Michigan were investigated by Zalesny *et al.* [37]. In some spots, the pollution level exceeded 1% hydrocarbons per kilogram of soil. The average poplar survival rate was 67%, with the variation ranging from 56 to 100% and losses being higher for 60-cm cuttings than for 20-cm cuttings. The growth rate was the highest for commercial clones bred for SRP energy production.

To minimize bioaccumulation of toxic trace elements, Wang and Jia [38] proposed growing poplar or larch on contaminated soils. The reason for selecting these tree species for phytoremediation was the fact that deep roots are able to create microenvironments in the soil where immobilization or uptake of the metals can occur. The growth of two tree species in soil spiked with a mixture of cadmium, copper and zinc was investigated by Wang and Jia [38], who found that poplar could remove 56.2 g ha$^{-1}$ of cadmium, 196 g ha$^{-1}$ of copper and 1170 g ha$^{-1}$ of zinc. Heavy metal transferring capacity from roots to aboveground organs was higher in poplar than larch, leading the authors to propose growing poplar on contaminated soils.

Poplar cannot be considered as a cadmium hyperaccumulator because it is able to take up only 10 mgCd kg$^{-1}$, whereas the known hyperaccumulator *Thlaspi caerulescens* can accumulate 100 mg kg$^{-1}$. However, because of the high biomass production in poplar plantations the total accumulation of cadmium is considerably higher per hectare and can actually reach 1000 gCd ha$^{-1}$ for poplar compared to just 250 gCd ha$^{-1}$ for *T. caerulescens*. Pietrini *et al.* [39] reported the results of studies on cadmium phytoremediation potential of several poplar clones. They found high genetic variation among the 15 Italian clones that were studied. The most promising clones showed three desired strategies that could positively affect phytoremediation. Firstly, a relatively high cadmium accumulation level in wood parts; secondly, high leaf tolerance when measured as photosynthetic activity; and, thirdly, a very fast juvenile phase growth rate. The authors concluded that the best indicators of suitability of given poplar genotype for phytoremediation would be some chlorophyll fluorescence parameter.

Finally, a Life Cycle Assessment (LCA) approach was used to quantify the environmental impact of Italian poplar plantations [40]. Two types of short-rotation plantations (a 1- to 2-year cutting frequency and a medium cutting frequency of >5 years) were distinguished. All energy inputs and outputs were taken into account as well as other environmentally important aspects (acidification potential, eutrophication potential, global warming potential, ozone layer depletion, human toxicity potential, ecotoxicity potential, photochemical oxidation formation potential) in a life span of poplar plantations grown for energy purposes,
from field preparation (in the first year) to field recovery (in 25th year). It was concluded that from the environmental aspect the best solution is to replace industrial fertilizers with cattle manure; this can reduce total energy use by 19.8%. The authors also concluded that future environmental soundness can be improved by breeding of high-yielding clones of different poplar hybrids.

11.2.3 Disease and Pest Control

Leaf rusts are very common in poplar and they are caused by species of *Melanospora*. The genus *Melanospora* comprises several species that are able to infect trees from the genus *Populus*. Sometimes, heavy infections can lead to early leaf drop, delay of the flushing time of poplar in the next season and finally result in decrease of growing rate. Leaf rust is the most important disease of poplar [41]. Also, they are known many form of canker caused by fungi (*Septoria musiva* and *S. populicola* being the most pathogenic species); bacterial cankers have been frequently recorded, too (*Xanthomonas populii*). There is widely expressed opinion that *Melanospora* can cause economically important damages, particularly in the case when infection starts relatively early in the tree life, that is, during first ten years of tree life. When poplar is grown in a SRP system, rust can occur in seasons when weather conditions can favor fungus development but, so far, no fungicides are recommended for control of fungal diseases. There are two obvious reasons: the first is that energy crops in general should be treated as plantations of low-inputs in terms of energy, fuel and pesticides usage where environmentally benefits should be gained; the second reason is that even severe infection can cause substantial economic losses [41,42]. In contrast to agricultural or vegetable crops, where good appearance and lack of all symptoms of fungal or bacterial infection are of key importance as they are used as food or feed, in the case of bioenergy crops, where all aboveground parts of the crops are intended for use as energy biomass, fungal infection has marginal importance. There are reports that even total defoliation of poplar cause by rust in one growing season did not affect biomass yield in the following season [43, 44]. There is well-established opinion that disease control of poplar grown for lignocellulose biomass is based on breeding programs where resistance or tolerance of clones to leaf rust and canker are included in commercial genotypes [41–43]. What makes the process of breeding resistant clones a never ending activity is the fact that pathogens are able to evolve; there are many cases when pathogens successfully infected previously resistant clones, breaking clonal resistance [45].

On the other hand, within the genus *Populus* is almost a never ending genetic variability in each economically important trait, including resistance to diseases; therefore, the perspective for increasing resistance to rust and canker seem to be very good. Coyle et al. [42] warned against taking only one breeding criterion (most frequently biomass yield), which can result in establishing monoclonal plantations, with all the consequences of such a practice.

Leaf-eating insects occur on poplar in great variability, with gregarious poplar sawfly (*Nematus malanapis*), poplar shoot borer (*Gypsonoma aceriana*) and other larvae of Lepidoptera being the most common. As in any other crops, herbivorous insects have to be controlled only when the economic loss threshold is exceeded. It is pointed out that because of the fact that poplar plantations are functioning as nesting habits for many birds – including song birds, which are very scarce in the landscape where only typical agricultural
crops are grown – chemical control of insects in SRP is not desirable. Sage [46] reports that 41 bird species were recorded in SRP and among them 30 song birds not found in another habitat in the vicinity. In many countries, poplar and willow SRP are treated as very good habitats for game animals, including pheasants, which are introduced by hunters’ associations [47, 48].

Poplar grown in a SRP system can be particularly susceptible to infection by insects when re-sprouting starts in early spring after winter harvesting. Therefore, mechanisms of plant resistance should be studied and some conclusions have been drawn concerning the necessity of manipulating the chemical composition of leaf tissues; this can be achieved by proper selection of genotypes [49, 50].

11.2.4 Harvest Management (Cutting Height, Season, Frequency)

Optimum cutting cycle and plantation design were the focus for studies with three fast-growing clones at three locations in the United Kingdom. *Populus trichocarpa* was evaluated at two spacings (1.0 × 1.0 m and 2.0 × 2.0 m) and two- or four-year cutting cycles [51]. Annual yield of biomass was always higher in the longer cutting cycle and the 1 m² spacing generally had a higher biomass yield than the 4 m² option. The authors pointed out that all poplar cones gave higher yield at the site with the highest annual rainfall. They also suggested that the reason for better yields with the longer cutting cycle was a proper balance between root system and aboveground organ development. The authors also noted that a four-year cutting cycle is more economical due to lower harvest cost per unit dry matter.

di Nasso et al. [52] pointed out that plant spacing and cutting cycles are the most crucial factors for successful establishment and biomass production by short-rotation poplar. Their report summarizes results of long-term studies (12 years) designed to identify the most important production indices in relation to different cutting cycles (from annual to triennial). They found that the shortest cutting cycles resulted in increased stool mortality, making the shortest cutting cycle less efficient than the other cycles studied. The highest efficiency in terms of energy output was noted for a triennial cutting cycle. The authors stated that the energy balance was positive for all studied cutting cycles and that for short-rotation plantations good soil fertility plus low rates of fertilizer and pesticide application were important for making short-rotation poplar plantations a perfect example of sustainability in twenty-first century agriculture.

Fang et al. [53] also tested four planting densities and three poplar clones at three cutting frequencies. Each of the experimental factors significantly affected obtained biomass yield, with the highest annual production being obtained with a six-year cutting cycle. They concluded that, for China, a longer cutting cycle should be recommended because regardless of plant density biomass yield increased as cutting cycle length increased (i.e. from 10 to 13 Mg ODM ha⁻¹ yr⁻¹ when going from a four to six-year cutting cycle).

Guidi et al. [54] quantified the relationship between chemical composition of biomass obtained from SRP poplar and cutting frequency of plantations in order to answer the crucial question of “how to manage the plantation to achieve good quality of biomass for biochemical conversion into liquid biofuels.” They concluded that different cutting cycles did influence the biochemical conversion rate of the poplar biomass, with the highest ethanol yield being associated with a four-year cutting cycle. This occurred because, at that age, the relative content of cellulose was much higher than in poplar biomass obtained
from two-year cutting cycles, when the hemicellulose content was higher, or from six-year cycles, when the lignin content was greater because of the additional two years of growth.

11.3 Genetic Improvement

Genetic variation and genotype by environment interactions in SRP poplar were studied using growth and production of biomass as first-year selection criteria by Sixto et al. [55]. Investigations were carried out at several locations in Spain to identify the regions where production of biomass for energy would be most effective. Nine poplar clones that were commonly grown in Europe for timber as well as Italian clones specifically bred for SRPs were evaluated. An additional selection criterion of rapid juvenile growth was applied, since it can be very important if very short rotation periods (i.e. no longer than three years) are introduced. Clone stability was also taken into account using bi-plot analyses. Among tested clones, there was very high variability in juvenile production, ranging from 1.7 to 8.0 Mg DM ha\(^{-1}\). The degree of interaction between genotype and environment was different among sites and led to the conclusion that along the shores of the Henares River in the middle of Spain and near La Tallada in northeast of Spain were the most suitable for poplar breeding programs because of the high variability among clones that was recorded.

Recognizing that there are large numbers of poplar clones growing in SRPs that need to be evaluated for their performance, Guo and Zhang [56] used cluster analysis with several easily measured indicators of survival rate and tree volume index to screen the suitability of poplar clones for their suitability for energy plantations. They assumed that maximum biomass production could be obtained if genotypes have a high survival rate and high productivity per plant. Deckmyn et al. [57] reported that the process-based model known as SECRETS (Stand to Ecosystem and EvapoTranspiration Simulator), which had been developed to simulate the growth of mixed forest species, could also accurately and realistically simulate the growth of poplar clones. They concluded that this model could be used to help in decision making and planning of biomass production of poplar on a regional scale, but the main advantage was the option of using it to identify management options for short-rotation poplar plantations.

11.4 Utilization

Poplar trees have been extensively cultivated in many countries and several different technologies for using their biomass have been implemented. Using wood obtained from SRP poplar as a fuel has energy, economic and environmental advantages when compared to coal and other fossil fuels. When used for direct combustion in heat and power plants, wood biomass has advantages over herbaceous biomass because of the lower quantity and higher quality ash that, in many cases, can be returned and applied as a soil amendment. The quantity of ash is related to chemical composition and bark content. Therefore, Guidi et al. [58] conducted studies to determine allometric relationships to predict fuel quality of poplar biomass before harvesting was undertaken. They found a significant relationship between bark content and main stem diameter at 130 cm (diameter at breast height, DHB) and pointed out that for DHB classes between 1 and 4 cm there was a rapid reduction in bark content compared to stems with a DHB of less than 1 cm. This indicated that it is more
rational to harvest SRP poplar in three or four-year cutting cycles or to use poplar clones that do not produce a high number of low DHB stems.

Poplar wood can also be treated as a feedstock for production of second and third generation biofuels through conversion of lignocellulose into ethanol [59] and other fuels. However, it is important to recognize that lignocellulosic biomass is a complex matrix of hemicellulose, cellulose and lignin and, therefore, pretreatment (sometimes called prehydrolysis) is required before the biomass can be converted into liquid fuels. Authors studying different methods of *Populus nigra* biomass pretreatment (steam explosion and hot water pretreatment) have found that the former process gave better cellulose recovery when measured by enzymatic conversion of the biomass into bioethanol [60, 61]. In an extensive review, Huang *et al.* [62] also reported numerous technologies designed to provide the most effective pretreatment of lignocellulosic biomass and conversion into ethanol. They concluded that the best results have been achieved when complex methods (i.e., chemical, physical, and/or biological pretreatments) were combined. For enzymatic hydrolysis and fermentation, the most important and efficient method utilized cellulase produced by the commercially available fungus *Trichoderma reesei*.

Zhang *et al.* [63] presented an interesting but challenging approach to utilize the lignin and hemicelluloses in addition to the cellulose components. According to their citations, economically sound and environmentally friendly technologies for processing these components, once considered waste, have been developed and are being used to produce marketable products. Among them is the potential to replace phenolic compounds from the oil industry with lignin-originated products, while hemicelluloses, because of their less stable nature, can be converted to a mixture of monosaccharides.

Van Acker *et al.* [64] reported that by using biotechnology, poplar biomass can be converted into liquid biofuels without costly and energy consuming pretreatment. This can be achieved by reducing the amount of lignin in the wood biomass or by changing its composition to obtain forms that are more susceptible to chemical degradation, thus making saccharification more efficient. The key enzyme in the phenylpropanoid pathway for lignin modification is cinnamoylo-CoA reductase (CCR). Trees that have been genetically modified in terms of CCR regulation were originally produced for the pulp industry, but this trait appears to be even more suitable for processing of poplar wood into second generation biofuels, since saccharification was increased by 50%.

Klasnja *et al.* [65] compared the calorific value of willow and poplar biomass, with special attention given to a comparison between old and young stems of both species. Bark was separated from wood. The higher heating values of oven dry poplar wood (calculated for the whole tree with an adjustment based on the proportion of bark) ranged from 15 787 to 24 275 kJ kg\(^{-1}\) for one and two-year old clones of hybrid I-214, respectively. The authors concluded that the calorific value of wood is more favorable than that of bark, and the highest calorific values refer to two-year-old trees. Their other conclusion was that woodchips from young SRPs harvested biannually could be used as biofuel without the bark separation needed when using older stems.

### 11.5 Carbon Sequestration and Soil Response

Another function of fast-growing tree species such as poplar is their potential role as an effective carbon sink. Intensive management of SRP poplar for biomass energy could help
to partially offset carbon dioxide emissions due to short-term turnover of fine roots and long-term accumulation and decomposition associated with larger roots and stumps. Rytter [66] provides calculations that are based not only on above and belowground biomass production data from field experiments, but also on fine root turnover, litter decomposition, and increased production levels from commercial plantations. Carbon accumulation in woody biomass, above and belowground, was estimated at 76.6–80.1 MgC ha\(^{-1}\) and accumulation of carbon in the soil at 9.0–10.3 MgC ha\(^{-1}\) over the first 20–22 seasons of plantation growth. The average rates of carbon sequestration were 3.5–4.0 MgC ha\(^{-1}\) yr\(^{-1}\) in woody biomass and 0.4–0.5 MgC ha\(^{-1}\) yr\(^{-1}\) in the soil. In each of his calculations, SRP poplar showed a higher carbon sink potential than for willow. Similar studies were carried out in China [67] where they also found that SRP poplar had higher carbon sequestration capacity than any annual cropping system in their country. They reported that carbon concentrations in poplar organs ranged from 459 to 526 gC kg\(^{-1}\) DM with the highest levels in stemwood and the lowest concentrations in coarse roots.

Jaoudé et al. [68] expressed doubts regarding the ability of poplar plantations to have a positive effect on carbon storage, arguing that if intensive management practices and commercial fertilizers were used, increasing emissions could reduce carbon storage in the soils. The processes for increasing carbon dioxide emission from short-rotation plantations were connected with soil respiration and included the following components: root respiration, heterotroph respiration (including microbial respiration of plant residues, turnover of soil organic matter, and rhizomicrobial respiration). It was found that coppicing increased carbon dioxide efflux from soil compared to the pre-coppicing period, but when nitrogen fertilizers were applied it caused a rapid and significant reduction of total soil carbon dioxide efflux by changing the metabolic pathways for both for hetero- and autotrophs.

The long-term effects of SRP poplar on soil properties is a matter of discussion in many countries, where some opponents of woody crop plantations have alleged that after 25 years of such management, soil nutrient levels are exhausted and special, long-lasting rehabilitation is needed. Recent studies in Germany [69] helped dispel this myth by providing data for sites where short-rotation poplar was grown for four rotations. The most important soil parameter (i.e. soil organic matter) was improved by 6.2 Mg ha\(^{-1}\) during the 12 years of poplar growth. Higher microbial activity was also recorded. There was some depletion in phosphorus and potassium but no negative yield effects and, furthermore, those nutrients can be easily supplemented with good management. With regard to soil physical properties, soil bulk density decreased and pore volume increased during the 12 years of short-rotation poplar growth.

Luo and Polle [70] evaluated effects of elevated atmospheric carbon dioxide concentrations on three poplar genotypes grown in SRPs to determine if the energy content would change. They found that changes in carbon dioxide concentration modified biomass composition more than nitrogen fertilizers. Long-term elevated carbon dioxide concentrations increased the quantity of lignin in the wood. Since lignin has the highest calorific value of all wood components, this suggests that elevated carbon dioxide could actually result in better poplar biomass if it is burnt directly as a fuel. The other important observation was that higher nitrogen rates were necessary for the poplar to utilize the additional carbon dioxide in the atmosphere.

Environmental benefits associated with converting arable land to short-rotation poplar were presented by Updegraff et al. [71]. With regard to potential greenhouse gas mitigation,
they noted high differences in calculations of carbon content. Other benefits included a reduction in erosion and agricultural runoff that can lead to surface water protection. They also pointed out that short-rotation poplar plantations cannot be treated as conservation system because of the intensive agricultural practices that are used to sustain the plantations, but the management strategies and environmental benefits are attained by the site and growing conditions. Updegraff et al. [71] also considered the environmental benefits of converting arable land into SRP poplar by constructing three scenarios of 10, 20, or 30% conversion in Minnesota, U.S.A. They assumed two scenarios for utilization of the poplar biomass – wood production or energy generation – and included an assumption that an offset for carbon sequestration would be introduced. Modeling of the three scenarios gave results that had a very high level of uncertainty because of difficulty in quantifying the most crucial environmental benefit (i.e. carbon sequestration). They simply could not obtain an accurate estimate of belowground biomass and carbon dynamics. Therefore, they concluded that the benefits, when treated as offsets in monetary terms, could only be estimated with a very wide range of between $44 and $96 ha$^{-1}$.

References


