6 Environmental Applications of Poplars and Willows

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6.1 Introduction

Poplars and willows have been planted for environmental purposes for millennia. There are reports that poplars were planted to improve the human environment 4000 years ago in the third dynasty of Ur, for streamside stabilization 2000 years ago in what is now the south-western USA by native North Americans and for urban amenities by the early Chinese dynasties (see Chapter 1, this volume). Early settlers in Europe and North America planted poplars and willows (and other species) to provide shelter and to protect crops. There were also a significant number of linear plantings of poplars in cities for protection, visual screens and aesthetics (FAO, 1980; Isebrands and Karnosky, 2001).

For most of the 20th century, the primary focus of poplar plantings was for wood and fibre production (FAO, 1958, 1980) (see also Chapter 5, this volume). However, in the late 20th century and the 21st century, the focus of poplar and willow plantings has shifted toward ecosystem and environmental services (Costanza *et al.*, 1997; USDA Forest Service, 2011). Ecosystem services are the goods and services trees provide to society, including watershed services, nutrient cycling, waste management, carbon storage, scenic landscapes, biodiversity and wildlife habitat. In the past, these benefits were valued as public goods and difficult to assess economically. However, as the world population grows, they are now considered vital to human health and livelihoods (USDA Forest Service, 2011; Zalesny, 2011).

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Poplars and willows are making an important contribution to ecosystem services worldwide. In this chapter, we provide a practical worldwide overview of the environmental applications of poplars and willows. Our goal is to synthesize the latest knowledge on these applications with respect to sustainable livelihoods, land use and restoration. The applications covered include land protection, watershed stabilization, waste management and other ecosystem services.

6.2 Windbreaks and Shelterbelts

6.2.1 Introduction

J.G. ISEBRANDS

Windbreaks and shelterbelts have a long history dating back to early agricultural settlement, and poplars and willows have been an important part of these plantings. According to the FAO/IUFRO Forestry Terminology Committee (Ford-Robertson, 1971), windbreaks are a strip of trees and/or shrubs planted to alter windflow and microclimates around farmsteads, homes, orchards and feedlots. Shelterbelts are similar but more extensive, designed to alter windflow and microclimates around agricultural fields (Ford-Robertson, 1971; Helms, 1998). The first systematic planting of shelterbelts was by German immigrants in the Russian Steppes in 1789 to protect fields. The term 'shelterbelt' can be traced back to 1833, and since then there have been thousands of kilometres planted throughout the world (Stoeckler and Williams, 1949). In modern times, poplars and willows have been planted in windbreaks and shelterbelts, especially in the Prairie Provinces of western Canada, the Plains States of the USA and very extensively in northern China (Isebrands, 2007; Richardson *et al.*, 2007).

6.2.2 Worldwide overview

J. KORT AND W.R. SCHROEDER

Poplars and willows are widely used in windbreaks and 'shelterbelts' (i.e. 'field windbreaks' or 'hedgerows') throughout the world's temperate regions (van Eimern *et al.*, 1964). The terms 'windbreak' and 'shelterbelt' are used interchangeably as general terms in some regions and they are hereafter used interchangeably in this chapter for convenience.

Poplars or willows are most suitable for a windbreak if they are adapted to a particular region and provide a good structure on which its effectiveness depends – namely its height, porosity, orientation and the distance between windbreaks. The distance protected by a windbreak is proportional to its height (Tabler, 1980), while the percentage reduction of wind depends on porosity (Heisler and DeWalle, 1988). Dense windbreaks reduce wind speed more but may have greater turbulence and a decreased zone of protection (Heisler and DeWalle, 1988), so a good windbreak design should result in the right porosity for the function it is expected to perform. Porous windbreaks are best for wind erosion control (Hagen, 1976), while dense windbreaks improve the microclimate for crop growth in their sheltered zone (Rosenberg, 1974). Dense windbreaks are also most effective for trapping blowing soil or snow (Scholten, 1988), but may increase diseases like mildew or create frost pockets (Rosenberg, 1974). For livestock protection, dense windbreaks reduce wind chill in winter, improving weight gains and survival of newborn animals, while tall, spreading windbreaks provide more shade in summer.

Willow or poplar species or clones can be used to create a variety of windbreak structures. Shrubby species or coppice practices can be used to create a dense, multi-stemmed windbreak suitable for trapping snow or soil, especially if more than one row is used. On the other hand, tall, widely-spaced poplar or willow trees result in porous windbreaks with a great distance of even wind protection across the field (George *et al.*, 1963). As deciduous trees, poplars have greater porosity in the winter than in the summer, with over 70% wind reduction achieved by a foliated poplar windbreak compared to 25% in the leafless state (Vézina, 1994). Fan *et al.* (2010) modelled the three-dimensional aerodynamic structure of Chinese four-row shelterbelts of hybrids of *Populus ×beijingensis* W.Y. Hsu, showing that the greatest component of windbreak drag was due to the leaves, while most of the volume was in the trunk. Although their rapid growth makes poplar and willow species attractive for quick windbreak protection, their short lifespan, high moisture requirements, spreading root systems and their negative effects on nearby crops sometimes cause land managers to favour longer-lived, less competitive species, especially in areas of limited moisture. Their susceptibility to drought may result in serious dieback (Rood *et al.*, 2000). Crop growth reductions near the trees have been attributed to moisture limitation (Sharma *et al.*, 2001), shade (Thevathasan and Gordon, 2004) and phytotoxic phenols leached from leaves (Singh *et al.*, 1998), although Pandey (2008) stated that *P. deltoides* shelterbelts had less negative impact on crops than *Eucalyptus* shelterbelts in Haryana state in India. Such drawbacks may make poplars or willows undesirable in some shelterbelts, but land managers need to balance this with their more rapid growth and shelter and their potential economic value.

Where soils and climate are suitable for these species, they may be preferred to other species or used in combination, especially if they have economic, aesthetic or other benefits in addition to their windbreak function. When the value of harvested poplars or willows is significant, using them in windbreaks often allows the land manager to maximize value from the land (Puri and Nair, 2004). Aesthetic considerations are important for poplar and willow windbreaks on the Dutch landscape (Londo *et al.*, 2004), while willows in shelterbelts have also been recommended because of their early pollen production (Vézina, 1994).

The use of poplars and willows in windbreaks in different regions and countries depends on climatic, economic and social or cultural conditions or traditions. This has resulted in a great variety of practices, including poplars for farmyards in the North American Great Plains (Fig. 6.1), pollarded willows along Dutch highways, poplar forest belts on the Russian Steppes or intensively cultivated poplar field boundaries in the Punjab and Haryana states of India. Some of these regional practices are described below.

In North America, poplar hybrids and willows are recommended in western Canada and the US Great Plains States, as one of the rows of multiple-row windbreaks for farmyard protection (Fig. 6.2), because of their rapid

Fig. 6.1. Windbreak comprised of multiple species, including poplars, in Saskatchewan, Canada. Photo courtesy of Agriculture and AgriFood Canada, Indian Head, Saskatchewan, Canada.

Fig. 6.2. Multiple-row poplar shelterbelt in Saskatchewan, Canada. Photo courtesy of Agriculture and AgriFood Canada, Indian Head, Saskatchewan, Canada.

height growth (Isebrands and Karnosky, 2001; Agriculture and Agri-Food Canada, 2005), and they are similarly used in eastern regions (Vézina, 1994; Volk *et al.*, 2004). Schroeder and Kort (2007) have reviewed the advantages of poplars and willows in North America. They give details of shelterbelt design and function. Slower-growing, longer-lived species complement the rapid growth of the poplar over time by increasing both windbreak density and the windbreak's lifespan. Kenney (1992) suggested that deciduous hardwoods were not suitable for windbreaks because of their excessive porosity in winter, but George *et al.* (1963) suggested that poplar windbreaks on the US Great Plains would result in even snow coverage across the fields. Willows are used for windbreaks in special circumstances and are especially recommended in wet sites where frequently anoxic soil conditions limit the number of species that can be used. They have tree or shrub forms, some of which produce valuable shoots for the floral trade or for willow chairs or other crafts (Labrecque and Teoderescu, 2004). As shrubs, they can be used to develop roadside barriers that are effective in trapping snow which would otherwise cause traffic hazards. Because selected species or clones are amenable to coppicing, their current use as a bioenergy crop presents possibilities for the long-term management of willow windbreaks which can be coppiced periodically for bioenergy.

In Russia, many thousands of hectares of poplar shelterbelts exist on the steppes, dating from early efforts in 1946–1953 or more recent efforts since 1966 (Schroeder and Kort, 1989). Many of these are in the form of wide, multiple-row shelterbelts that are as much as 500 m apart.

In the UK, Stott and Belcher (1978) considered poplars to be better than conifers for windbreaks because the conifers resulted in turbulence, frost pockets and an increase in the incidence of disease. In France, poplars are considered to be variable in form, so that windbreaks of various porosities can be designed with heights of 20–25 m and rapid growth, while shelterbelt willows are considered to have value as habitat for pollen production and for the floral trade (IDF, 1981). In the Netherlands, Londo *et al.* (2004) concluded that the best configurations of coppice willows for bioenergy production were ecological upland corridors that provided multiple environmental benefits such as the protection of biodiversity. Danish shelterbelts normally include 10–14 species and are multi-row plantings, designed in such a way as to allow for species succession (Als, 1990). They typically include both willows and poplars, which tend to be dominant in the early years of the shelterbelt but, because of their shorter lifespan, eventually yield to longer-lived species.

In South America, poplars and willows are increasingly being used in windbreaks in Chile and in Argentina, where 1500 km of poplar and willow windbreaks provide shelter for important irrigated crops in South Patagonia (Peri and Bloomberg, 2002).

The level of adoption of poplar trees in windbreaks is likely greatest in northern India and in northern China. In India, poplar shelterbelts and plantations have 'spread across the region like a storm' (Singh, 2004) since the 1970s, especially in the northern states of Punjab and Haryana (Dhanda *et al.*, 2004). According to Pandey (2008), poplar species are not among the top ten tree species planted outside forests in India, but are locally important in the Punjab and Hiryana states, comprising 21% of the non-forest trees growing in Punjab. Poplar trees growing in single-row shelterbelts were found to have less negative impact on adjacent crops than eucalyptus trees, being complementary rather than competitive with crops like winter wheat, and have been promoted for this purpose. The high level of adoption has been, in part, due to government promotion and programming, but also because the value of the wood in short rotations, combined with the production of winter crops when the poplar trees are dormant, appears to be a viable practice that reduces the competitive interactions between the crops and the trees (Puri and Nair, 2004). But Puri (2004) cautioned that the advertised benefits of agroforestry systems might be overstated as a development vehicle and for the alleviation of poverty if the right tree and crop species combinations were not used or if the intensiveness of management was insufficient. According to Pandey (2008), large-scale tree planting on private land resulted in lower prices from pulp and paper mills, but poplars were important for fuelwood or for income. Pandey (2008) said that the development of market mechanisms and price stability would increase the use of poplar shelterbelts as standard practice for farmers in northern India.

In the Three North Region of China, many poplar shelterbelts have been planted since 1978 under the Three North Shelterbelt Programme to develop the 'Great Green Wall' (Moore and Russell, 1990; Carle and Ma, 2005). These plantings have included 'forest-net' shelterbelts, in which poplar shelterbelts have been planted in a grid to protect crops or animals from all directions (Fig. 6.3), as well as wood production shelterbelts which are wider, consisting of six or more rows of poplar trees (Moore and Russell, 1990). The entire area addressed by the programme is over 4 million km^2, with over 20 million ha of mostly hybrid poplars as of 1991, most of which are in afforestation plantations (Carle and Ma, 2005). According to Fan *et al.* (2010), there are about 2.2 million ha of hybrid poplar shelterbelts in China (Fig. 6.4). This large-scale use of poplars has been accompanied by research activities to develop superior genetic materials and agronomic practices (Carle and Ma, 2005).

In summary, poplars and willows make good windbreaks if properly designed and managed and if they meet the social and economic needs of the region in which they are grown. The needs may be economic – the production of biomass for bioenergy, pulp or lumber integrated with crop production benefits. They may also be social – the protection of soils, biodiversity or people. Social uses of windbreaks also include the protection of roads, homes and gardens, and they may also be planted for their aesthetic value. Poplar and willow windbreaks are used more in regions where the need is supported by programmes or policies, resulting in several areas in the world where they are adopted in large numbers, most notably in China and India.

6.2.3 Shrub willow living snow fences

T.A. VOLK

In areas where snowfall is prevalent, snow blowing across open fields can create dangerous road conditions for the public, increase the number of accidents and injuries and create expensive, time-consuming and challenging situations for road crews to ameliorate. Snow and ice removal costs in the USA exceed US$2 billion each year,

Fig. 6.3. Shelterbelt of poplars in Three North Region in Inner Mongolia, China. Photo courtesy of J.G. Isebrands.

Fig. 6.4. Shelterbelt in Jiangxi Province, China. Photo courtesy of J.G. Isebrands.

while indirect costs related to corrosion and environmental impacts from snow removal and control activities have been estimated to add another US$5 billion each year. Factoring in costs associated with accidents and injuries would further increase this figure (Tabler, 2003).

The threshold wind speed at which snow will begin to move is around 15 km h^{-1}, and the work ability of wind speed is proportional to the cube of the wind speed (Tabler, 2003), so slight reductions in wind speed can have significant impacts on snow movement and distribution. Structural snow fences have been used for a long time to reduce wind speeds and control blowing and drifting snow along roadways and other key locations. Various types of structural snow fences have been used to reduce blowing snow, including solid wood Wyoming snow fences, slatted wood, porous plastic and, most recently, three-dimensional structures like 'snow snakes' (Tabler, 2006).

Structural snow fences can reduce blowing and drifting snow immediately after they are installed and are an effective choice in some situations, but they have a number of limitations.

One is the high establishment and maintenance costs. One study in Wyoming, USA, showed that 1.6 km of snow fence reduced snow and ice removal costs by US\$14,497 year^{-1} and saved US\$8,256 year^{-1} in vehicle accident costs (Daigneault and Betters, 2000). However, the calculated cost of a double-row, slatted wooden snow fence was US\$10,153 km^{-1} to establish and US\$5,390 km^{-1} to maintain each year. Many structural snow fences like this have to be installed, taken down and stored each year and have a projected effective lifespan of just a few years. Wyoming snow fences are more permanent structures and are also effective, but cost US\$54,112 km^{-1} to establish and US\$1,641 km^{-1} year^{-1} for maintenance (Daigneault and Betters, 2000). Even with these high establishment and maintenance costs, the cost–benefit ratio of these structural snow fences was still greater than two. Another limitation of structural snow fences is that shorter plastic and wooden slatted snow fences can quickly become buried in drifting snow, making them ineffective for the remainder of the winter, and they are they are aesthetically unappealing.

An alternative approach to controlling blowing and drifting snow, as well as providing additional benefits to landowners and the environment, is to design and install living snow fences. These are plantings of trees, shrubs and/or native grasses a short distance upwind of roads, homes, farmsteads, communities or other important facilities (Gullickson *et al.*, 1999). The use of living snow fences to reduce the blowing and drifting snow into roadways and other transportation corridors is not a new concept. In the early 1900s, a number of railway companies planted living snow fences throughout the western USA. By 1915, one company had planted over 500,000 seedlings, though many died during the droughts of 1929–1933 (Perko, 1995). Interest in living snow fences has grown again recently because of the increased costs associated with setting up and maintaining snow fences. Living snow fences can be cheaper to install and maintain than structural snow fences, have a greater height, and therefore can capture more snow. For example, a living snow fence consisting of two rows of conifers and a row of deciduous shrubs was estimated to cost US\$12,700 km^{-1} to install but only US\$207 km^{-1} year^{-1} to maintain (Daigneault and Betters, 2000). A 1.2-m-high snow fence can capture snow up to 1.5 t m^{-1} along its length, while a living snow fence with an effective height of 2.4 m can capture up to 6.8 t m^{-1} (Tabler, 2003). In addition, living snow fences are more aesthetically pleasing, and they have the potential to provide benefits such as wildlife habitat, CO_2 capture and woody biomass for renewable energy and other products.

While living snow fences have many positive attributes, they have some limitations and are often misunderstood. Much of the previous work on living snow fences has been done using slow-growing species that require two or more widely spaced rows for effective control and can take 6–20 years to become effective (Gullickson *et al.*, 1999; Daigneault and Betters, 2000; Tabler, 2003). In addition, living snow fences comprised primarily of trees can outgrow their effectiveness over time, as large openings form near the ground, allowing increased wind speed and reducing snow capture. These traditional designs for living snow fences require large areas, which is a significant limitation in areas where roadside rights-of-way are usually narrow and landowners are less willing to set aside wide strips of land.

There are several options available to overcome these limitations, including the use of a single or closely spaced double row of fast-growing willow or other shrubs. A living snow fence composed of a single row of uncoppiced Streamco willow (*Salix purpurea*) established in central New York State in 1993 began capturing snow after the second growing season and had met its design expectations within 5 years, despite several drier than average growing seasons (Dickerson and Barber, 1999). The landowner, Steve Butts, is also very pleased with the results and has seen a reduction in accidents on his stretch of highway from about seven to ten per year before the willow snow fence was established to zero to one per year after its establishment (S. Butts, 2008, personal communication). Over the past few years at least 12 shrub willow living snow fence demonstrations have been installed across New York State as collaborative projects between state and county Departments of Transportation, Soil and Water Conservation Districts (SWCD), the Thruway Authority, the USDA Natural

Resources Conservation Service and local landowners. Initial results indicate that this approach is effective at controlling blowing and drifting snow 2–3 years after establishment and has relatively low installation and maintenance costs (Fig. 6.5). An important factor in the lower establishment costs is that willow can be established using unrooted dormant cuttings, which are cheaper than bareroot seedlings or plants with root balls.

The most important characteristics for effective living snow fences are the high density of stems and branches during the winter, good height growth, relatively uniform density along the length of the plant and an upright form. Many willows and other shrubs inherently possess several of these characteristics. One-year-old willow on a 2-year-old root system had dormant season densities ranging from 25 to 40%, depending on the variety. Two years after coppicing, the dormant season density was 42–56% (T.A. Volk, 2008, unpublished data) (Fig. 6.6). Many structural snow fences are designed with 50% density. The density of willow snow fences can be varied by selecting varieties that produce different numbers of stems and have different growth habits (Tharakan *et al.*, 2005), changing the spacing between plants, by coppicing to alter the number of stems and degree of side branching and by varying the number of rows planted. Rates of establishment can be modified by changing the size of planting stock, correctly matching plant species to site conditions, which can often be quite harsh near roadways, and altering soil conditions.

An appealing attribute of living snow fences is that they are made up of living plants, and if properly installed, they will be in place and function for decades. However, because they are living plants, they require more planning and care during installation to be successful compared to structural snow fences. Planning should include an assessment of blowing snow conditions at the problem area, determination of the best location and orientation, evaluation of growing conditions for plants, selection of the right plant material and proper site preparation for planting (Gullickson *et al.*, 1999). Some varieties of willow that are vigorous in high-density plantings for biomass production have not been effective in living

Fig. 6.5. A double-row shrub willow living snow fence in central New York State. The shrub willows are 2 years old aboveground on a 3-year-old root system. Photo courtesy of Mark Appleby, SUNY-ESF.

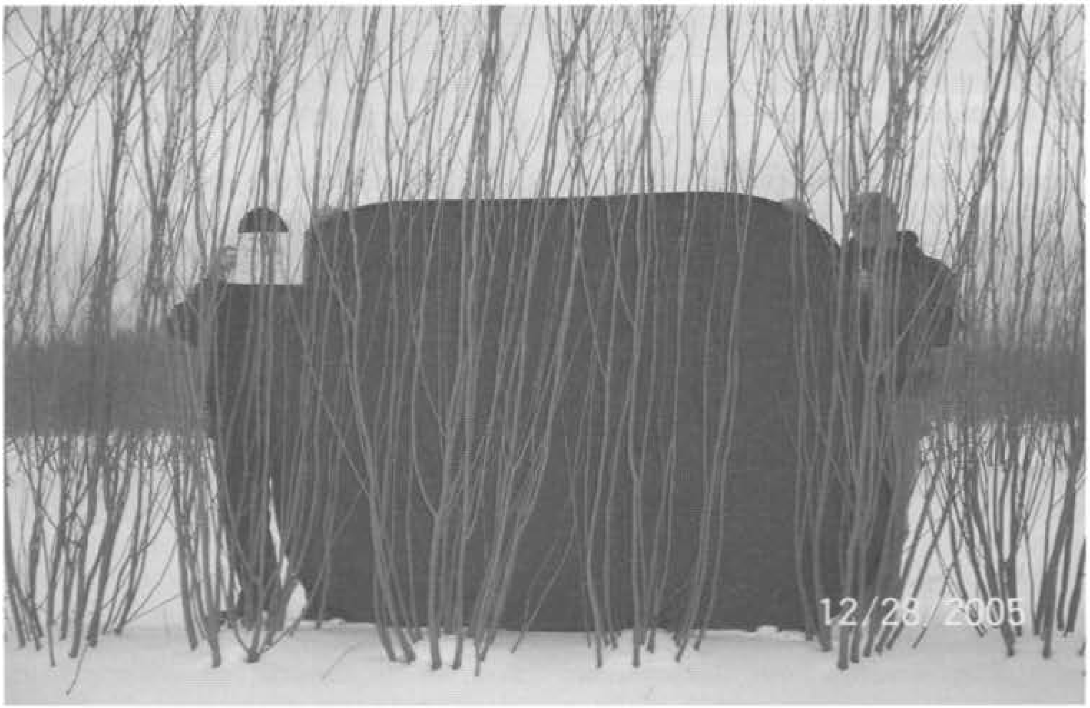

Fig. 6.6. Dormant season density of a shrub willow living snow fence that is 2-year-old aboveground growth on a 3-year-old root system. Photo courtesy of T.A. Volk.

snow fences because the stems tend to spread outward rather than grow upright. In extreme cases, some varieties have grown horizontally rather than vertically when planted in single-row living snow fences. The experience gained from the living willow snow fence demonstration and research projects so far has resulted in several conclusions. Good weed control is paramount in the successful establishment of willow snow fences. The cost of landscape fabric (weed mat) should be considered necessary rather than optional. The use of larger cuttings appears to lead to appreciably earlier snow fence establishment while remaining practical in terms of equipment management. Some varieties of willow should not be used in future snow fence designs because of their tendency to develop a spreading canopy, susceptibility to heavy deer browsing and damage by some generalist insects. Other varieties and species of shrub willow show great promise as material for living willow snow fences due to their relatively unpalatable nature to herbivores, rapid growth and multiple stem growth pattern. Further testing and developing of this application for shrub willows in ongoing.

6.3 Soil Erosion Control and Riparian Buffers

6.3.1 Use of poplar and willow to create forested riparian buffers in the Lower Mississippi Alluvial Valley

E. GARDINER AND J. STANTURF

Background

Flanking the third largest river in the world, the watershed, flood plain and delta of the Mississippi River encompass nearly 41% of North America. The lower flood plain and delta, which comprise the 11 million ha Lower Mississippi Alluvial Valley (LMAV), hold rich alluvial soils that support vast stands of native *Salicaceae* (Fig. 6.7). Several species of poplar (*Populus* spp.) and willow (*Salix* spp.) are native to the LMAV, but eastern cottonwood (*P. deltoides*) and black willow (*S. nigra*) are unquestionably the most dominant *Salicaceae* in the region. Though their range extends beyond the region, these species are most productive on the alluvial soils of the LMAV, where

Fig. 6.7. Black willow (*Salix nigra*) colonizing a sandbar in the Mississippi River, Washington County, Mississippi, USA. Photo courtesy of J. Stanturf.

eastern cottonwood has attained heights over 50 m and black willow has attained heights over 40 m in natural stands (Cooper, 1990; Pitcher and McKnight, 1990).

Historical use of poplar and willow

As commerce developed along the Mississippi River during the 1800s and early 1900s, settlement patterns concentrated deforestation and development along the main river channel and its tributaries and distributaries. These settlement patterns created the need to stabilize banks and construct levees to protect developed property along watercourses. Black willow saplings, because of their pliable stems and their abundance along watercourses, were woven into mattresses to stabilize eroding banks and provided foundations for the construction of jetties and levees (Barry, 1997) (Fig. 6.8). The engineering utility of black willow for bank stabilization is still recognized, but more recent techniques employ the use of willow posts and long cuttings to establish living revetments for stabilization of eroding stream banks (Schaff *et al.*, 2003; Martin *et al.*, 2005).

Poplar and willow riparian buffers

Row crop agriculture is the primary land use in the LMAV, and because of this the principal thrusts behind the establishment of forested riparian buffers in this region is to lessen the impacts of soil erosion and agricultural pollution on water quality. Established riparian buffers function to accomplish these objectives on agricultural landscapes through various mechanisms that include increasing water infiltration into soil, reducing sediment loading to streams and filtering runoff of agricultural nutrients and chemicals such as nitrogen and phosphorus. Eastern cottonwood plantings, in particular, were effective in improving surface water runoff and groundwater quality on a silty loam soil in the LMAV (Thornton *et al.*, 1998). The US government recognizes the benefits of riparian buffers to water quality and maintains a voluntary programme providing private landowners an incentive to establish and manage forested riparian buffers. Through Conservation Practice 22 of the Conservation Reserve Program, the Farm Service Agency of the US Department of Agriculture will cost-share with landowners the establishment of riparian buffers on qualified agricultural areas (www.fsa.usda.gov).

Fig. 6.8. Construction of black willow mats in 1915 for riverbank stabilization in the LMAV. Photo courtesy of J. Stanturf.

Eastern cottonwood has been used more than black willow for creating riparian buffers in the LMAV, primarily because of historical management and markets for the species in the region. An advantage of the past development of the eastern cottonwood industry in the region is that superior clones are available for deployment on specific soils. However, several ecological and silvical characteristics of eastern cottonwood and black willow make both species desirable as dominant tree species on riparian buffers. These species are ideally suited for use in the LMAV because they are native to the region and planting stock is readily available. Both species establish readily from cuttings, are fast growing and will develop forest structure and canopy on alluvial sites relatively quickly. Furthermore, both species can be established on degraded agricultural sites and will tolerate soil flooding and sediment deposition (Broadfoot and Williston, 1973; McKnight *et al.*, 1981; Hook, 1984). As a footnote to the above, in India poplars also are planted along the banks of rivers originating in the Himalayas, to capture soil and debris during periods of flooding (Dhiman, 2012) (Fig. 6.9).

Co-benefits of establishing poplar and willow riparian buffers

The co-benefits of established riparian buffers often provide the additional incentive necessary to encourage landowners to remove land from agricultural production to install forested buffers along drainages (Fig. 6.10). Several co-benefits related to ecology and forest management can be realized through the establishment of well-designed eastern cottonwood or black willow riparian buffers in the LMAV. For example, Gardiner *et al.* (2004) noted that eastern cottonwood plantations provided a favourable understorey microenvironment for the regeneration of other native woody vegetation, thereby providing a viable afforestation practice for facilitating forest restoration (Fig. 6.11). Twedt and Portwood (1997) and Hamel (2003) demonstrated the value of eastern cottonwood plantations as habitat for neotropical and other migratory birds. Additionally, forested riparian

Fig. 6.9. Poplar trees are planted along rivers in India that flood frequently. The trees are often flooded up to 2 m in depth and after flooding there are deep silt deposits. Photo courtesy of R. Dhiman.

Fig. 6.10. Eastern cottonwood (*Populus deltoides*) established as a riparian buffer along the margin of a wetland in the Lower Mississippi Alluvial Valley, Sharkey County, Mississippi, USA. Photo courtesy of J. Stanturf.

buffers can be designed to provide landscape corridors for terrestrial animals and improve invertebrate and fish habitat in adjacent streams.

Linked with ecological benefits, rapidly growing eastern cottonwood and black willow plantations can be used to sequester atmospheric

Fig. 6.11. Eastern cottonwood plantation established as a riparian buffer and interplanted with other native bottomland hardwood species to enhance co-benefits of increased woody plant diversity, etc., Sharkey County, Mississippi, USA. Photo courtesy of J. Stanturf.

carbon quickly (Stanturf *et al.*, 2003). Black willow, a species very tolerant of hydric soil conditions, is especially suited for this role on riparian sites too wet to sustain high productivity of other species. As incentive to landowners, recent changes to the Conservation Reserve Program allow for marketing carbon sequestered in eastern cottonwood plantations used as nurse crops for other bottomland hardwood species. Additionally, well-managed plantations can produce fibre or timber and could potentially produce feedstock for biofuel production (Stanturf and Portwood, 1999; Stanturf *et al.*, 2003).

6.3.2 Streamside restoration and stabilization with riparian buffers in the Pacific Northwest, USA

J.D. JOHNSON

Poplars and willows are well suited for use in riparian buffers and for streamside restoration and stabilization projects in the Pacific Northwest USA. They are native riparian species, having evolved to take advantage of conditions of high water table and periodic flooding. They are often used in combination with the more water-tolerant willows planted along stream edges where the water table is at or near the surface and the poplars are planted upslope from the willows where the water table is lower. The rapid growth of poplars and willows allows them to capture the planting site from competing vegetation, and if whips are used, they will be above the competing vegetation and can shade out the competition as the tree canopy develops (Fig. 6.12). In many instances where slower-growing native species are used, they often are out-competed by aggressive invasive plant species. In the Pacific Northwest, two troublesome invasives are reed canarygrass (*Phalaris arundinacea* L.) and Himalayan blackberry (*Rubus discolor*) that are capable of overgrowing slower-growing native riparian species.

Functions of riparian buffers include sediment reduction, bank stabilization, nutrient removal, pesticide barrier and breakdown, shade and large woody debris recruitment. Of these buffer functions, only the first, sediment reduction, is not an attribute of poplars and

Fig. 6.12. A hybrid poplar buffer established from whips planted in April. The photo was taken in September and the trees are over 5 m tall. Photo courtesy of J. Johnson.

willows, because surface roughness is required to slow surface water flow that facilitates sedimentation. The other five functions, however, are ones that poplars and willows exhibit. Their extensive root systems consist of strong, woody roots needed for bank stabilization and a large mat of fine roots used for nutrient removal and pesticide breakdown. Nitrate uptake from groundwater by a hybrid poplar buffer exhibited a several hundredfold decrease from the adjacent crop into the trees, reducing the level to less than 1 ppm. Poplars' tall stature and dense canopy, as well as rapid stem growth, contribute to their ability to shade streams, which reduces their warming, and as the trees mature and topple, they contribute large woody debris to streams, creating a series of riffs and pools needed for fish habitat.

6.3.3 Erosion control in New Zealand

I. McIVOR

Poplars and willows are used extensively in New Zealand to reduce soil erosion on hill-country farms (Wilkinson, 1999). Out of 11.2 million ha of the North Island in pasture, some 3.7 million ha (32%) require significant soil conservation measures to attain biophysical sustainability. The stabilizing effects of trees in mass soil movement and fluvial processes are well known. The most common tree species used for the stabilization and rehabilitation of the North Island's erodible land are poplars and willows, together with localized timber blocks, usually *Pinus radiata* (Thompson and Luckman, 1993). Poplars and willows are favoured for hillside stabilization because of their rapid development and ease of planting (Fig. 6.13). At planting densities required for hillside stabilization, pasture receives sufficient light to develop underneath the trees. Poplars reduce erosion by drying out the soil and binding soil particles with their extensive root systems. Guevara-Escobar *et al.* (2002) demonstrated that evaporation from widely spaced poplar–pasture systems was significantly greater than from pasture alone. Initially, poplars and willows should be densely planted to ensure rapid ramification of the slope (McIvor *et al.*, 2008). Trees can then be thinned selectively as the root systems develop (McIvor *et al.*, 2009). Individually protected poplar and

Fig. 6.13. Earthflow stabilization using poplar and willow on a hillside near Gisborne, North Island, New Zealand. Photo courtesy of I. McIvor.

willow poles allow land users to plant trees directly into areas susceptible to erosion without having to exclude grazing stock such as sheep and young cattle (Guevara-Escobar *et al.*, 2007). The tree spacing required for slope stabilization ranges from 25 to 156 stems ha^{-1}, depending on the severity and proximity to the actively eroding area. At this spacing, animal production remains the dominant enterprise. Poplars are planted most effectively on the sides of gullies, rather than the gully floor. Here, their deep roots access the subsurface flows that can trigger erosion events. Not all regions and hill slopes are suitable for the establishment of poplar and willow species. Steep gradients, water stress, continuing soil disturbance and desiccating winds inhibit tree establishment and/or subsequent growth on upper hill slopes in many of New Zealand's eastern regions.

Land-use change has been shown to change the soil C stocks, with broadleaf plantations resulting in higher C stocks than pine plantations (Guo and Gifford, 2002). The new Emissions Trading Scheme, introduced in New Zealand in 2008, is providing a large financial incentive for forestation (Maclaren *et al.*, 2008) and has resulted in a marked increase in poplar and willow plantings on erodible pastoral land.

6.3.4 Riverbank stabilization in New Zealand

I. McIVOR AND B. ROBINSON

In New Zealand, planting willows is a valuable tool for use in river engineering. The willows' high root density stabilizes riverbanks and prevents the river from changing course. Periodic 'layering' can promote dense stands of willows that are less likely to succumb to floods. Layering involves cutting larger trees so that the trunk lies on the moist riverbank and subsequently forms shoots and roots along its entire length. Willows improve water quality by intercepting contaminants in runoff or subsurface flow. They also provide a physical barrier to prevent stock from entering the waterways (Fig. 6.14), where they would otherwise cause edge damage by trampling and contamination by urination and defecation. Glova and Sagar (1994) reported a greater abundance and diversity of benthic invertebrates, together with greater numbers of large brown

Fig. 6.14. Riparian planting of *Salix schwerinii, Salix matsudana* × *S.alba* and *Populus deltoides* along the Selwyn River, Coe's Ford, New Zealand. Photo courtesy of I. McIvor.

trout, in willow-protected streams. However, in small streams, willows can reduce biodiversity due to shading out of aquatic flora (Lester *et al.*, 1994). Judicious clone selection is critical for river engineering. It is imperative that the willows do not invade downstream or adjacent areas. Male clones that do not fragment are ideal. *S. fragilis* and other species are noxious weeds in many Australasian waterways, due to vegetative reproduction from fragile shoots (Wilkinson, 1999) that are broken off by the water current.

Poplar and willow from riverbanks as supplementary stock fodder in New Zealand

Poplars and willows used for hillside and riverbank stabilization also provide supplementary stock fodder during times of drought (Wilkinson, 1999). Some poplar and willow clones can maintain production in water stress conditions that result in pasture dieback (McIvor *et al.*, 2005), particularly when managed via pollarding. The foliage and small twigs provide an emergency food source for both cattle (Fig. 6.15) and sheep (Hathaway, 1987; Douglas *et al.*, 1996). Feeding poplars and willows to stock has proven health benefits. Nelson *et al.* (1984) and Barry and Kemp (2001) attributed an improvement in growth and fecundity to high protein, tannin or trace element concentrations in poplar leaves. Moore *et al.* (2003) demonstrated that willow feed reversed weight loss under severe drought conditions and stock progressively ate thicker branches as pasture became scarce. High levels of tannins in willow leaves may effectively de-worm stock. High levels of tannins may also reduce the nitrogen concentration in the urine of ruminants (Carulla *et al.*, 2005). This has environmental benefits due to reduced nitrate leaching from urine patches.

Fig. 6.15. Poplars and willows make palatable stock fodder on New Zealand farms. Carterton, New Zealand. Photo courtesy of I. McIvor.

Feeding poplars and willows to stock may alleviate trace element deficiencies. Many New Zealand pasturelands are deficient in cobalt, zinc and copper (Lee *et al.*, 1999). Poplars and willows can have leaf cobalt and zinc concentrations that are six times higher than pasture growing in the same environment (Robinson *et al.*, 2005). However, poplars and willows may also introduce toxic trace elements into the animal's diet. Most New Zealand pasturelands have elevated cadmium concentrations due to repeated applications of cadmium-rich superphosphate fertilizer (Bramley, 1990). Robinson *et al.* (2000) showed that the commonly used New Zealand varieties of poplar, 'Kawa' (*P. deltoides* × *P. yunnanensis*), and willow, 'Tangoio' (*S. matsudana* × *S. alba*), accumulated cadmium at levels of up to 14 $\mu g\ g^{-1}$ in the dry leaves when grown in a soil containing just 0.6 $\mu g\ g^{-1}$ of this element. This concentration is above levels (1–5 $\mu g\ g^{-1}$) shown to affect livestock adversely (Underwood and Suttle, 1999).

6.4 Land Restoration

J.G. ISEBRANDS

Poplars and willows are pioneering species and some of the first species to revegetate surface mine spoils in the northern hemisphere (Brenner *et al.*, 1984; Chapter 3, this volume). Hybrid poplars, cottonwoods and willows historically have been used to restore surface mine spoils (Hart and Byrnes, 1960; Lumme and Tormala, 1988) and other marginal soils artificially (Misra and Tewari, 1999) for much of the 20th century and beyond (Funk, 1960; Limstrom, 1960). There are many thousands of hectares of former mine spoils worldwide that are in need of restoration (Knabe, 1964; Rockwood *et al.*, 2006).

The early efforts on revegetating mine spoil lands focused on species selection. Many species were tested and successes were dependent on the soil and environmental conditions of the site. Hybrid poplars and willows almost always exhibited the most rapid early growth (Hart and Byrnes, 1960), but performance depended on the clone (Davidson and Davis, 1972; Bungart *et al.*, 2001). Clonal performance was often tied to growth and disease and insect resistance (Davis, 1964; Lumme and Tormala, 1988), as well as regeneration methods. Davidson and Davis (1972) recommended coppice regeneration for the restoration and stand conversion of mine spoils.

The success of regenerating strip-mined land has been attributed to the increased number of microorganisms in the rhizosphere associated with poplar and willow roots (Cundell, 1977). Moreover, some hybrid poplars grown on strip-mined lands have been found to be useful for pulpwood and lumber products (Davidson, 1979).

But despite all these years, more genetic selection and breeding is needed to improve poplar and willow performance and success on these lands (Davidson, 1979; Lumme and Tormala, 1988; Rockwood *et al.*, 2006).

One of the most recent applications of using poplars and willows for reclamation and restoration of strip-mined land is in the coal and oilsands region of western North America (Figs 6.16 and 6.17). Government agencies in Canada and the USA require mining companies to revegetate the mine spoils (and areas disturbed by mining activity) with native species after mining is completed. Therefore, there is a major effort to grow native poplars and willows in greenhouses and nurseries for planting on such land (Fig. 6.18). Focus has been on replanting native species such as aspen (*P. tremuloides*) and balsam poplar (*P. balsamifera*), but these efforts have only just begun (Richardson, 2012) (Fig. 6.19).

6.5 Phytoremediation

6.5.1 Introduction

J.G. ISEBRANDS

Phytoremediation is a general term coined in the early 1990s for an emerging green technology using plants to clean up – or 'remediate' – contaminated soil, sediments, groundwater, surface water and air by removing, degrading and containing toxic chemicals (US EPA, 1998, 2000; Licht and Isebrands, 2005). Phytoremediation technologies primarily use six mechanisms to accomplish clean-up goals:

1. Phytoextraction: the uptake and translocation of contaminants from groundwater into plant tissue.

2. Phytovolatilization: the transfer of contaminants to air via plant transpiration.

Fig. 6.16. Coal strip mine restoration site near Genesee generating station in Alberta, Canada. Photo courtesy of J. Richardson.

3. Rhizosphere degradation: breakdown of contaminants within the rhizosphere, i.e. soil surrounding roots, by microbes.
4. Phytodegradation: the breakdown of contaminants within plant tissue.
5. Phytostabilization: the stabilization of contaminants in the soil and groundwater through absorption and accumulation on to plant roots.
6. Hydraulic control: intercepting and transpiring large quantities of water to contain and control migration of contaminants.

Poplars and willows are some of the most preferred tree species for phytoremediation because they grow rapidly, have many and deep roots and take up large quantities of water and nutrients (Isebrands and Karnosky, 2001; Licht and Isebrands, 2005). They not only take up substantial quantities of water and nutrients but also they provide root surface area for beneficial microbes and mycorrhizae that perform phytoremediation functions.

An International Phytotechnology Society has emerged since 2000 to promote phytotechnologies for cleaning up environmental contamination problems. They have also published a journal since 2002, called the *International Journal of Phytoremediation*, in which the latest applications of phytoremediation are published. In this short time frame, hundreds of articles on the use of poplars and willows for environmental applications have been published. In addition, there has recently been a comprehensive overview published on phytoremediation that features many case studies involving poplars and willows (McCutcheon and Schnoor, 2003).

In this chapter, we give an overview of some examples of the environmental applications of poplars and willows in some of the International Poplar Commission (IPC) member countries. The following contributions are presented in alphabetical order of country.

Fig. 6.17. Oilsand strip mine site near Fort McMurray, Alberta, Canada. Photo courtesy of D. Riddell-Black.

Fig. 6.18. Native balsam poplar grown for strip mine and oilsand land reclamation at Smoky Lake Forest Nursery in Alberta, Canada. Photo courtesy of J.G. Isebrands.

Fig. 6.19. Revegetation of oilfield site with native poplar near Fort McMurray, Alberta, Canada. Photo courtesy of D. Riddell-Black.

6.5.2 Belgium

R. CEULEMANS

Phytoremediation – heavy metals

The phytoremediation potential of a poplar or willow plantation depends on both the biomass productivity rate and the concentration of the element (heavy metals) in the biomass. In the study of Laureysens *et al.* (2004a, 2005), the phytoremediation potential of 13 different poplar clones was examined, together with the analysis of the canopy profiles of heavy metals as well as differences in concentrations among leaves, stems and bark. In terms of productivity, clones 'Wolterson' (*P. nigra* (N)), 'Fritzi Pauley' (*P. trichocarpa* (T)) and 'Balsam Spire' (*P. trichocarpa* × *P. balsamifera* (T × B)) showed the highest aboveground woody biomass production (wood + bark), averaging 18, 15 and 14 Mg ha^{-1}, respectively, after 2 years. In combination with its relatively high Al and Zn concentration in wood, this clone showed potential for the phytoextraction of both metals (Al and Zn) (Table 6.1). Clones 'Fritzi Pauley' (T), 'Columbia River' (T), 'Trichobel' (T × T) and 'Balsam Spire' (T × B) also had a relatively high biomass production, i.e. 15, 12, 13 and 15 Mg ha^{-1} (2-year period), respectively. In combination with a relatively high wood and bark metal concentration, 'Trichobel' (T × T) showed potential for Al phytoextraction, while 'Balsam Spire' (T × B) showed potential for Cd and Zn uptake (Tables 6.1 and 6.2).

Leaf, wood and bark concentrations

Variations in leaf concentrations between clones were high for all metals, ranging between 112 and 174 μg g^{-1} for Al, 3.07 and 8.26 μg g^{-1} for Cd and 411 and 695 μg g^{-1} for Zn in mature leaves (Fig. 6.20). Analyses showed that there was a significant clonal variation for mature and senescing leaves for Fe and Pb; for Cu, clonal variation was significant for all three leaf ages. One single clone containing the highest concentration of all metals at the same time was not found. Generally, clonal rankings in leaf concentration were significantly different among metals and among leaf ages per metal (Fig. 6.20).

Table 6.1. Metal concentrations in wood of 2-year old poplar stems of different clones harvested in August (Aug) and November (Nov).

Clone	Parentage[a]	Al (μg g^{-1})		Cd (μg g^{-1})		Fe (μg g^{-1})		Mn (μg g^{-1})		Zn (μg g^{-1})	
		Aug	Nov	Aug	Nov	Aug	Nov	Aug	Nov	Aug	Nov
'Balsam Spire'	T × B	8.1	11.2	1.11	2.86	6.7	43.6	2.0	1.6	29	39
'Beaupré'	T × D	10.0	16.3	2.36	2.64	10.8	7.1	5.1	1.7	24	32
'Hazendans'		16.5	15.3	1.63	1.01	31.3	77.3	9.6	7.6	31	33
'Hoogvorst'		13.6	15.6	1.94	1.11	8.1	15.8	2.5	3.5	34	37
'Raspalje'		9.5	10.5	1.74	3.18	8.0	13.9	3.8	5.0	38	26
'Unal'		8.3	15.5	2.77	2.63	22.0	6.5	2.1	2.3	26	29
'Columbia River'	T	18.3	12.7	1.43	2.33	18.4	8.7	2.0	1.8	39	37
'Fritzi Pauley'		13.3	11.1	1.11	0.80	58.7	9.2	2.3	2.2	26	28
'Trichobel'		7.9	19.9	1.22	0.70	5.3	20.6	1.4	1.9	26	34
'Gaver'	D × N	8.1	20.4	2.77	2.26	4.9	25.8	2.4	7.5	35	31
'Gibecq'		8.9	14.2	1.63	0.29	4.5	9.6	1.0	2.4	31	51
'Primo'		12.6	12.7	2.88	3.29	5.2	11.7	2.3	2.6	34	54
'Wolterson'	N	13.4	36.8	–	0.91	47.2	59.3	4.6	19.7	42	50

[a] T, *Populus trichocarpa*; B, *Populus balsamifera*; D, *Populus deltoides*; N, *Populus nigra*.

Table 6.2. Mean metal content (SE) per stool and per hectare for six poplar clones in a short-rotation coppice culture. The 2-year old shoots were harvested in November.

Clone	Al (μg stool^{-1})	Cd (μg stool^{-1})	Zn (μg stool^{-1})	Al (g ha^{-1})	Cd (g ha^{-1})	Zn (g ha^{-1})
'Balsam Spire'	976 (116)	64 (7)	2213 (264)	8.7 (1.3)	0.57 (0.09)	19.8 (3.0)
'Fritzi Pauley'	1578 (190)	14 (2)	1570 (191)	13.9 (2.0)	0.13 (0.02)	13.9 (2.0)
'Gaver'	188 (12)	55 (8)	740 (58)	1.5 (0.1)	0.43 (0.10)	6.0 (0.3)
'Hazendans'	370 (64)	17 (9)	1065 (190)	3.2 (0.6)	0.16 (0.09)	9.2 (1.8)
'Trichobel'	596 (144)	13 (3)	1072 (261)	5.5 (1.6)	0.12 (0.03)	9.8 (2.9)
'Wolterson'	648 (35)	51 (2)	2641 (81)	5.9 (0.2)	0.47 (0.02)	24.2 (0.5)

Little or no Co, Cr, Cu, Ni or Pb was accumulated in the wood, and the concentration of Cr in bark was also below the detection limit (0.1 μg l^{-1}). The metal concentrations in bark were significantly higher than the concentrations in wood (Table 6.1), both when samples were collected in August and in November ($P < 0.001$). On average, the Al concentration in bark was ten times the concentration in wood; likewise, the bark concentration of Mn and Zn was six times the wood concentration. The bark concentration of Fe and Cd was, respectively, four and three times higher than the wood concentration, on average.

When sampled in November, clone 'Fritzi Pauley' (T) showed a mean Al concentration in wood of 90 μg g^{-1}, while for clones 'Wolterson' (N) and 'Balsam Spire' (T × B), wood Al concentration averaged 34 and 64 μg g^{-1}, respectively (Table 6.1). For Cd, the concentration averaged 2.2 and 3.3 μg g^{-1} in clones 'Wolterson' (N) and 'Balsam Spire' (T × B), respectively; for Zn, the concentration averaged 147 and 144 μg g^{-1} in clones 'Wolterson' (N) and 'Balsam Spire' (T × B), respectively (Table 6.1). Clone 'Fritzi Pauley' (T) had a mean Cd and Zn concentration of, respectively, 0.7 and 92 μg g^{-1}. Furthermore, metal content per plot was correlated significantly with wood dry mass and total biomass production, but not with bark dry mass. For Cd and Zn, a significant correlation between metal content per plot and number of shoots was found, because clones 'Wolterson' (N) and 'Balsam Spire' (T × B) had the highest Cd and Zn concentration and accumulation (Table 6.1). These results suggest that selection and improvement of poplar clones for phytoextraction should focus on biomass production, stool survival and metal concentration; population dynamics should not be taken into account.

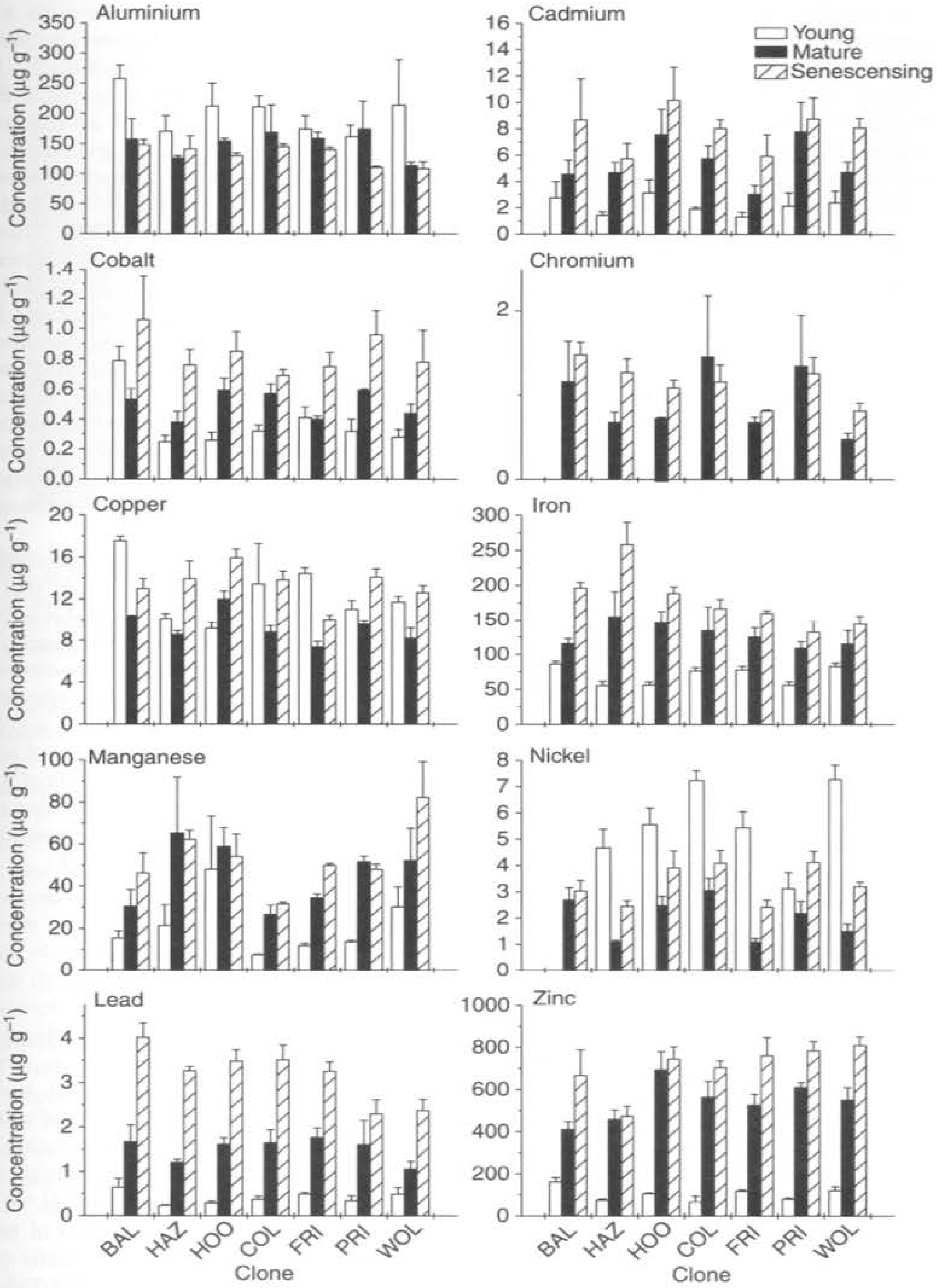

Fig. 6.20. Mean metal concentration in young, mature and senescing poplar leaves for clones 'Balsam Spire' (BAL), 'Hazendans' (HAZ), 'Hoogvorst' (HOO), 'Fritzi Pauley' (FRI), 'Primo' (PRI) and 'Wolterson' (WOL). Mean values of replicates and their standard error bars are presented.

When the transfer coefficients (= plant tissue concentration/total soil concentration) were calculated, Cd, Zn and Cu showed to be taken up most easily by poplar: Cd > Zn > Cu > Mn > Co, Ni > Pb > Cr > Fe > Al. Transfer coefficients differed among leaves, wood and bark, due to the different tissue metal concentrations, but the sequence in the transfer coefficients was similar for these three organs.

Phytoextraction potential

In contrast to the metal content per plant (or stool), the metal content per plot (or per unit of ground area) represents the real phytoextraction potential (Table 6.2), as it includes stool mortality. Clone 'Fritzi Pauley' (T) showed the highest Al accumulation over 2 years, 1.4 kg ha^{-1} (Table 6.2). For Al, metal content per plot was correlated significantly with woody dry mass ($r = 0.513$) and woody biomass production ($r = 0.587$); no significant correlation was found with bark dry mass, number of shoots or mean shoot diameter. Clones 'Wolterson' (N) and 'Balsam Spire' (T × B) showed the highest accumulation of Cd, 47 and 57 g ha^{-1}, respectively, and of Zn, 2.4 and 2.0 kg ha^{-1}, respectively (Table 6.2). For Cd, metal content per plot was correlated significantly with wood dry mass ($r = 0.472$), woody biomass production ($r = 0.503$) and number of shoots per stool ($r = 0.719$) and per plot ($r = 0.706$). For Zn, metal content was correlated significantly with wood dry mass ($r = 0.746$), woody biomass production ($r = 0.806$), stool mortality ($r = -0.543$) and number of shoots per stool ($r = 0.492$) and per plot ($r = 0.526$).

Significant clonal variation in uptake and accumulation was observed for most metals (Tables 6.1 and 6.2) that were analysed, as also shown for willow (e.g. Rachwal *et al.*, 1992; Watson *et al.*, 1999; Aronsson and Perttu, 2001; Pulford *et al.*, 2001). However, clones with the highest concentration of all metals were not found, confirming earlier observations for willow (Riddell-Black, 1994; Pulford *et al.*, 2002).

After 2 years, clone 'Fritzi Pauley' showed the highest accumulation of Al, averaging 1.4 kg ha^{-1}, while clones 'Wolterson' and 'Balsam Spire' showed phytoextraction potential for Cd and Zn, averaging, respectively, 47 and 57 kg ha^{-1} for Cd and 2.4 and 2.0 kg ha^{-1} for Zn (Table 6.2). Several studies have shown that clones with a high uptake of a combination of several metals have not yet been identified (Riddell-Black, 1994; Pulford *et al.*, 2001). This is probably due to the antagonistic properties of several metals. Likewise, hyperaccumulators accumulate only one or a limited number of metals. However, the uptake by these plants is much higher in comparison with poplar or willow. Therefore, Ernst (1996) suggested using these short-rotation coppice (SRC) cultures on slightly contaminated soils. The trees will take up part of the heavy metals and additionally will stabilize the soil, reducing metal leaching and dust blow. The combination of wood for energy production with phytoremediation will make both economically more feasible. Metals in the biomass remain in the ashes or are filtered to avoid translocation of the heavy metal pollutants to the atmosphere (Punshon and Dickinson, 1997).

We did not study root accumulation, although many studies have shown that most metals accumulate in the roots (Kabata-Pendias and Pendias, 1984; Landberg and Greger, 1996). This would imply that for phytoremediation purposes roots need to be ploughed up after the last rotation cycle rather than rototilled and left in the soil. Root metal concentrations and possible clonal differences could be the objects of further research. We have, however, shown that poplar SRC offers possibilities for phytoremediation of slightly contaminated soils (Fig. 6.21).

6.5.3 Canada

M. CARLSON

Canada has had active phytoremediation projects with poplars and willows since before 1990. Emphasis has been on wastewater treatment, hydrocarbon remediation and remediation of solvents and heavy metals on brownfields. Probably the most notable and publicized early phytoremediation project in Canada was the municipal effluent irrigation project in Vernon, British Columbia. In 1988, the joint project between the city of Vernon, the British Columbia Forest Service and the British Columbia Ministry of the Environment began irrigating hybrid cottonwood trees and other tree species on a 10 ha site near Vernon (Carlson, 1992). The wastewater-treated poplars grew very rapidly and

Fig. 6.21. View of the experimental short-rotation coppice culture with 17 poplar clones in Boom (province of Antwerpen, Belgium). The poplars were planted in 1996 and managed on 3-year coppice rotations for more than 10 years. As the plantation was established on slightly polluted wasteland soils (enhanced heavy metals in the soil), the significant phytoextraction potential of the different clones has been quantified. Photo courtesy of R. Ceulemans.

after 5 years the plantation average was 10.6 cm in diameter and 13.6 m in height (Fig. 6.22). Irrigation rates increased from 30 cm in the first year to over 75 cm at year five. Annual concentrations of effluent were 158 kg ha^{-1} nitrogen, 60 kg ha^{-1} phosphorus and 120 kg ha^{-1} potassium. The project has been very successful and has received broad support from the public. The residents enjoy the green landscape, enhanced wildlife viewing, hiking opportunities and cost savings for effluent disposal. Twenty years after the project was initiated, the poplars were harvested and the planting recycled (Fig. 6.23). The site was cleared and a new irrigation system installed. The intention was to plant new hybrid poplar whips at 5 × 5 m spacing to initiate the next generation of Vernon's municipal wastewater programme with poplars.

The Vernon project prompted other municipalities to consider irrigating poplars and willows with treated municipal sewage wastewater. A nationwide Canadian Biomass Innovation Network project, led by Natural Resources Canada, was initiated in Alberta (Krygier, 2011). The project, managed by the Canadian Forest Service, consisted in 2011 of six research and demonstration sites near Edmonton, Alberta. The first site, located at Whitecourt, Alberta, focused on using willow and poplar clones for wastewater disposal and developing an alternative energy source for the region. Clones are monitored for growth, biomass yield, pest incidence, heavy metal accumulation and soil and groundwater quality. After the first rotation, yield was increased with irrigation and no adverse soil chemistry was detected. Enhanced soil nitrogen availability was found after biosolids application. Cost savings were demonstrated as well, thereby prompting expansion at the other sites. Several other private wastewater projects and landfill vegetative caps were initiated using poplars and willows in British Columbia (Passive Remediation Systems, 2012).

Since the late 1990s, there have been phytoremediation projects in Saskatchewan, Canada, using poplars and willows to remediate petroleum-hydrocarbon-contaminated sites and landfill covers (University of Saskatchewan, 2012). University scientists working with Environment Canada, with support from petroleum providers, investigated the potential of using native poplars and willows for petroleum-contaminated site remediation. Emphasis has been on selecting those that exhibit early growth and degrade the

Fig. 6.22. Wastewater-irrigated hybrid poplar plantation, Vernon, British Columbia, Canada. Photo courtesy of M. Carlson.

Fig. 6.23. Regrowth of hybrid poplar plantation irrigated with wastewater, Vernon, British Columbia, Canada. Photo courtesy of M. Carlson.

contaminants of concern. Initially, there was not enough knowledge on which poplar or willow clone would be best in the various regions. Another early problem, not unique to Canada, was that commercial quantities of the better poplar and willow clones were not available for the public. This problem has improved with the availability of more plant materials from commercial nurseries.

Another major centre for phytoremediation research and development in Canada has been at the Plant Biology Research Institute (IRBV) in the Montreal Botanical Garden in Montreal, Quebec. The institute has become a major leader nationally and internationally for research and applications on reclaiming and restoring abandoned contaminated urban sites, known as 'brownfields'. The institute staff uses poplars and willows (and some other plants) to remediate such sites for public use in the Montreal region. Most of these sites have compacted soils, poor drainage and a suite of contaminants in the soil and water. These contaminants often include a mixture of both organic and inorganic compounds. The focus has been on establishing willows and poplars on these difficult sites. The sites that are being restored successfully include those on which wastewater sludge is applied and heavy metal contamination is problematic (Labrecque *et al.*, 1995). The group has employed both willow and poplar coppice as vegetative filters to contain soil and water contamination

(Guidi *et al.*, 2008). They have shown that both heavy metal and nutrient uptake in willows and poplars are enhanced by mycorrhizal fungi (Bissonnette *et al.*, 2010; Fillion *et al.*, 2011). They also work on new ways to establish willows and poplars for different environmental applications on difficult sites (Teodorescu *et al.*, 2011). These establishment techniques have proven successful on petroleum-contaminated sites in Quebec (Guidi *et al.*, 2012). These efforts have used green technology to reclaim and restore brownfields in Quebec.

6.5.4 Estonia

K. HEINSOO

The first seven energy forest plantations were established in Estonia in 1993–1995, within the framework of scientific cooperation of multiple Estonian research institutions and the Swedish University of Agricultural Sciences, in order to promote research and application of fast-growing, short-rotation forestry in Estonia. The total area of these plantations was 3.1 ha comprised of *S. viminalis* and *S. dasyclados* clones originating from the Swedish Energy Forest Programme (Koppel *et al.*, 1996). Since that time, the number of plantations for research purposes has increased twice, based on the planting material originating from Sweden, the UK and local sources. Moreover, in 2008, the area of the plantations was more than ten times larger than in 1998. After 2005, the first *Salix* plantations of private stakeholders were established in Estonia. There was a very high interest among local farmers to start such alternative crop cultivation, and the Estonian Ministry of Agriculture planned to start subsidizing the establishment of short-rotation plantations (SRPs) of 300 ha year^{-1} from 2009. Therefore, a very rapid increase in the SRP area in Estonia is predicted up to 2020.

Because of the local climate, *Salix* has been considered as the most promising tree species for SRP in Estonia, with the average annual biomass growth in fertile soils of 10–12 dry t ha^{-1}. But production can be less due to the lack of soil nutrients, water and weed control, along with frequent late spring frosts and browsing by different mammals (mainly beavers).

At first, the SRPs in Estonia were planted to supply local heating boilers with wood chips, but there were also stakeholders who were interested in producing pellets from this raw material. In both cases, high yield can be achieved only by additional fertilization of the plantations. In order to decrease the costs of fertilization, scientists from the Estonian University of Life Science implemented different applied studies using municipal wastewater or sludge instead of mineral fertilizers. The first results have been promising and are discussed hereafter as three case studies. Larger-scale usage of these methods will depend on sceptical local legislation and the problems of the environmental monitoring procedures required by the Estonian Ministry of Environment.

Aarike case study

The Aarike plantation was first established in spring 1995 with cuttings of *S. viminalis* clone '78183' (clone numbers correspond to the Swedish clone numbering system), but for several reasons was mostly replanted 3 years later with *S. dasyclados* clone '79097'. This plantation was designed specially to purify municipal wastewater originating from a retirement home (approximately 25 persons) in a local village, and the area of the plantation was 180 m^2. The wastewater from the home's different buildings, with a total volume of 20 m^3 day^{-1}, flowed into three septic tanks. After flowing through the septic tanks, the water was fed by gravitational flow on to the SRP. Before planting, the SRP area was isolated from the deeper groundwater by layers of heavy clay and gravel. A serpentine ditch of wastewater divided the system into three blocks, each consisting of four beds constructed with a 20 cm layer of filter material with a 10 cm humus layer on top.

During subsequent years, different components of wastewater (BOD$_7$, NH$_4$-N, NO$_3$-N, Kjeldahl-N, PO$_4$-P, total-P) were analysed periodically from both the inflow and outflow points of this vegetation filter. The results revealed that the purification process was sufficient for biological oxygen demand (BOD), with the value in the outflow exceeding the regulatory limits only rarely during the winter months. The uptake of N compounds was limited due to the poor nitrification process and the purification efficiency of P that was low in all steps (Table 6.3; for details, see Kuusemets *et al.*, 2001). The last result was not unexpected, because the Aarike vegetation filter was, due to limited available land, designed much smaller (at 7 m^2 per population equivalent (p.e.)) than the recommended design criterion (20 m^2 per p.e.) for surface-flow constructed wetlands in cold climate conditions (Brix, 1994).

The willow biomass estimates and chemical analyses of different tissues revealed that only a limited proportion of the above-mentioned elements were restored in the *Salix* plants (Table 6.4). There is strong evidence that most of the pollutants were stored in the filter material or utilized by the soil microbes (Heinsoo and Koppel, 2003).

Nõo case study

The Nõo plantation is situated on a 0.91 ha area of pseudo-podzolic soil that was originally rich in potassium and phosphorus but slightly acidic, with low nitrogen content. This SRP was planted in spring 1995 with several clones of *S. viminalis* ('78195', '78183', '78021', '78012', '82007' and '78101') and one clone of *S. dasyclados* ('81090') growing in different plots. In May 2001, after the winter harvesting of the SRP, half of each plot was supplied with the composted sewage sludge originating from the Tartu wastewater treatment plant. The sludge amount (6.3 t per 0.44 ha) was calculated based on the limiting factor P that should not exceed 200 kg ha^{-1} if the next rotation period was assumed to last for 4 years. During this rotation period, the shoot production was estimated annually from randomly selected and marked plants in both sludge-treated and control sections of each clone plot. In subsequent years, sewage sludge almost doubled the shoot biomass for most of the clones, even though one of them ('78183') was re-harvested in the following winter (Fig. 6.24). Most probably, the exceptional decrease in shoot production in clone '78012' can be explained by the extremely low survival rate of the plants in the sludge-treated section of the plot. Throughout this experiment, we also analysed gravitational water quality from both SRP sections at depths of 10 and 40 cm. The BOD_7, N and P in the water from 40 cm depth did not exceed the limits for wastewater purification systems in Estonia. An increase in BOD_7 at the 10 cm depth was only found during the first year after sludge treatment. By contrast, the amount of P at this depth was higher during the second year of experiment than could be explained by the additional dissolution of some P compounds to the gravitational water over this time.

Table 6.3. Average wastewater purification efficiency (%) in Aarike SRP.

	Period					Period average
	1995	1996	1997	1998	1999	
BOD_7	60	72	60	60	88	75
Total N	23	29	35	41	28	32
Total P	14	19	20	18	9	14

Table 6.4. Estimated N and P removal with the biomass during Aarike SRP harvesting.

	N	P
Purification efficiency (%)	32	14
Annual removal (kg)	35	2.1
Concentration in shoots (%)	0.74	0.07
Stored in shoots (kg $year^{-1}$)	1.14	0.11
Removal in biomass (%)	3	5

Kambja case study

The Kambja SRP was one of the three prototypes that were established in Estonia in 2003 within an EC LIFE Environment project 'Estwaste' (Aasamaa *et al.*, 2010). The main goal of this activity was to find an inexpensive and efficient wastewater purification method for those communities in rural areas whose

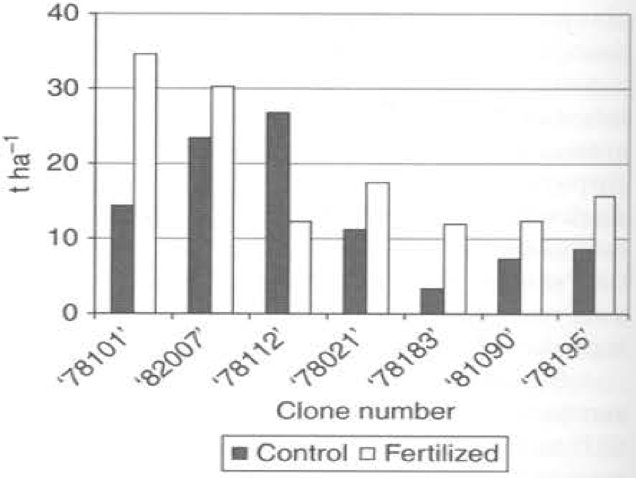

Fig. 6.24. Estimated biomass yields of sewage-sludge-treated and control plots in Nõo SRP in autumn 2003.

previous wastewater purification plants had been amortized since the large economic changes in Estonia in 1995. The first step of wastewater purification at the Kambja site was designed to be carried out in the mechanical filter and wastewater storage ponds only. During the vegetation period, this pre-purified wastewater was to be pumped to the SRP through a specially designed irrigation network. During the winter months, this water was planned to run through the previously existing additional biponds. The wastewater load of the prototype was approximately 1000 p.e. and the SRP was comprised of 16.1 ha of *Salix*, *Populus tremula* f. *gigas* and *Alnus incana* plants, of which 11 ha was supplied with the irrigation pipes network (Truu *et al.*, 2009). The water quality was monitored monthly at different parts of the prototype and the shoot yield estimated annually.

The results of this project affirmed that a vegetation filter could be an efficient wastewater purification option in Estonian weather conditions (Fig. 6.25). The pollutant contents (both organic matter and N) had already started to decrease very rapidly in the storage ponds. However, the outflow from the second biopond had too much N and P to meet the limits for water that may be discharged to natural waterbodies in Estonia (Table 6.5). This problem was solved by discharging the water to the SRP (Heinsoo and Holm, 2008). The gravitational water collected from a depth of 40 cm never exceeded the above-mentioned limits. The additional SRP area of 5.1 ha could be used later for other purposes, e.g. sewage sludge disposal if bioponds need purification. *P. tremula* and *A. incana* had only limited growth during the first years of the SRP as a result of weed problems due to the added water and nutrients. Therefore, we are not able to recommend these species in an SRP with wastewater application in the Estonian climate.

The established prototypes also offered a good overview of problems with wastewater purification systems. One of the main issues is to keep the water distribution as homogeneous as possible without significant increase in pipe network costs (Aronsson *et al.*, 2002). For economic reasons, the maximum wastewater load to the SRP should be estimated. The most critical point is to create a practical method of water collection and monitoring from different parts and depths of the SRP. This is also needed in order to diminish the environmental risks and to permit control of the activities performed by the local environment protection authorities.

Fig. 6.25. As a result of wastewater irrigation, the height of the most promising *Salix* clones at Kambja exceeded 6 m as early as the third summer. Photo courtesy of K. Heinsoo.

Table 6.5. Average concentrations of pollutants in different parts of the Kambja prototype.

	Monitoring point			
Indicator	No. 1	No. 2	No. 3	No. 4
BOD_7 (mg O l^{-1})	63.9	28.0	21.6	–
Total N (mg l^{-1})	25.1	18.9	16.5	7.5
Total P (mg l^{-1})	3.4	3.2	2.7	0.7

6.5.5 Italy

G. SCARASCIA-MUGNOZZA

The enhanced level of pollutants in soil and water due to industrialization is one of the major environmental problems at global scale.

In particular, cadmium is considered one of the most dangerous heavy metals, having toxic effects on plants and animals. Cadmium (Cd) enters the environment from industrial processes, heating systems, urban traffic and phosphate fertilizers; another source of Cd in the soil is the mineralization of rocks (Rauser and Muwly, 1995). Typical symptoms of Cd phytotoxicity are chlorosis, growth inhibition and respiratory and nitrogen metabolism changes, as well as low biomass accumulation. Besides, exposure to Cd causes reductions in water and nutrient uptake and photosynthesis (Sanità di Toppi and Gabbrielli, 1999; Pietrini *et al.*, 2003). To remove Cd and other pollutants from the contaminated areas, unconventional techniques that use biological processes have been applied successfully. In particular, plants can be used for removing heavy metals from soil and accumulating them in the harvestable parts. This technology, called phytoextraction (Kumar *et al.*, 1995; Raskin *et al.*, 1997), is less expensive and environmentally disruptive than conventional remediation systems that consist mainly of the excavation and incineration of soil (Cunningham and Ow, 1996). Other advantages of utilizing plants to clean up contaminated areas are the production of biomass and landscape restoration. The efficiency of phytoextraction depends largely on several plant characteristics such as the capability to hyperaccumulate metals, and also on the non-essential ones, fast growth, a deep and extensive root system and the ability to translocate metals in the aerial parts. Since about 2000, forest trees have been studied to assess their potential to remediate heavy metal contaminated sites (Pulford and Watson, 2003). Some aspects of forest tree biology and cultivation appear promising for a phytoremediation strategy. Among them are the large biomass yield that can be used for energy production, an extended and deep root apparatus, a low impact on trophic chains, the capability of some tree species to grow in marginal soils and other ecological benefits. With respect to hyperaccumulating plants, metal uptake by trees is reported to be less remarkable but, on an area basis, the removal of heavy metals from soil could be more effective due to the biomass production.

Several studies have focused on the potential of willows and poplars to be used for phytoextraction (Riddell-Black, 1994; Pulford *et al.*, 2002; Laureysens *et al.*, 2004b). In fact, these *Salicaceae* are reported to be adapted to grow in severe soil conditions (pioneer species) that characterize contaminated areas, besides their ability to accumulate heavy metals (Pulford and Watson, 2003). Moreover, cultural management of willows and poplars by means of SRC cultures is another promising aspect to be considered for phytoremediation strategies (Ceulemans *et al.*, 1992; Scarascia-Mugnozza *et al.*, 1997; Perttu, 1999). The availability of clones selected for high biomass production and disease resistance is another remarkable aspect in utilizing these *Salicaceae* for phytoextraction. Most of the studies conducted on trees show that tolerance to heavy metals depends on their compartmentalization in the roots and low translocation to the leaves. This is probably the major constraint to overcome for a more efficient utilization of these species to clean up soils from metal contamination. Moreover, a significant clonal variation in heavy metal accumulation was found in poplar and willow (Watson *et al.*, 1999; Laureysens *et al.*, 2004a). In this context, screening of clones characterized by different biomass production for heavy metal accumulation and distribution among the organs could be very effective in selecting plant material with important traits for phytoextraction.

The emphasis of the institute scientific group and co-workers at Consiglio Nationale delle Ricerche (CNR) has been to find plants that extract heavy metals efficiently from contaminated soils and water and to study the association of plants and soil bacteria for degradation of chlorinated hydrocarbons. The results of a hydroponic screening study helped identify promising Italian clones for further testing (Zacchini *et al.*, 2009). Pietrini *et al.* (2010) conducted a screening study of those poplar clones that could be used for Cd phytoremediation.

The results are shown in Table 6.6 and in Plate 21C. These show that clones with high values of net photosynthesis have higher values of total dry mass and Cd content. The efficiency of Photosystem II (PSII) was not particularly affected by Cd treatment and only 'A4A' showed a significant decrease in this parameter. The chlorophyll content observed seemed unrelated to the maintenance of a high photosynthetic capacity. In conclusion, 'SS5'

Table 6.6. Net photosynthesis (A) measured at light intensity of 300 μmol photons m^{-2} s^{-1} (growth conditions), chlorophyll fluorescence ratio of dark adapted leaves (Fv/Fm), total chlorophyll content, total dry mass and cadmium content of poplar and willow clones treated with 50 μM cadmium solution for 3 weeks.

Clones	A (μmol m^{-2} s^{-1})	Fv/Fm (rel. units)	Chlorophylls (a+b) (μg cm^{-2})	Total dry mass (g per plant)	Cadmium content (mg per plant)
'11-5'	6.15 b	0.74 a	25.99 c	11.15 bcd	7.01 bcd
'A4A'	1.03 c	0.47 b	7.96 f	8.24 cd	5.79 cde
'I-214'	4.33 b	0.67 a	14.90 e	16.92 a	8.54 abc
'Luisa Avanzo'	5.29 b	0.73 a	39.94 a	14.50 ab	7.25 bcd
'Lux'	4.97 b	0.68 a	9.32 f	11.99 bc	9.81 ab
'Nigra Poli'	0.55 c	0.72 a	20.36 d	6.69 d	5.27 de
'58-861'	2.28 c	0.74 a	30.03 bc	9.99 cd	2.57 e
'SS5'	8.47 a	0.72 a	31.65 b	18.24 a	11.18 a

Differences among clones were assessed using analysis of variance (ANOVA) and the means were compared using the LSD test. Means ($n = 5$) in the same column followed by the same letters are not significantly different at the $P < 0.05$ level.

showed the best performance for Cd uptake and biomass production. Among poplar clones, 'Luisa Avanzo' and 'I-214' showed favourable data for dry mass and Cd content, while 'A4A' was the clone with the lowest values of all parameters considered.

In a related study, Pietrini *et al.* (2010) showed the spatial distribution of Cd in poplar and willow leaves and how that impacted photosynthesis under different strategies.

An earlier Italian study by Sebastiani *et al.* (2004) investigated the heavy metal accumulation and growth in poplar clones exposed to industrial wastes. The CNR group and co-workers have investigated the linkage between bioenergy production in poplar and willow plantings with soil and wastewater phytoremediation throughout Italy (Paris *et al.*, 2009), an effort that includes selecting Italian clones for use in nitrogen removal, heavy metal removal and for animal waste disposal.

The CNR group has worked closely with scientists at the University of Parma, Italy, on improving the growth, physiological and molecular traits for the phytoremediation of heavy metals and chlorinated organic pollutants using the latest molecular and physiological tools (Marmiroli *et al.*, 2011). The group at Parma has been active in the International Phytotechnology Society and in 2010 hosted the first international conference of the society in Europe.

6.5.6 Korea

Y.B. KOO

Research on phytoremediation began in the early 1990s in Korea. Even though phytoremediation studies were conducted before 1990, it was limited only to removing heavy metals from herbaceous plants as an indoor study and investigating the degree of heavy metal accumulation of plants in the contaminated site of an abandoned mine. From the middle of the 1990s, poplar, a fast-growing species, has been used to remove contaminants and cover hazardous waste sites. Research has been conducted on heavy metal absorption ability, adaptation at a waste landfill site, leachate absorption ability and absorption and adaptation to livestock wastewater of poplars.

Leachate removal and reclamation of a landfill site

An experimental planting of *Populus* ×*euramericana* was established on the Nanjido Waste Landfill site in 1994 and 1995 to evaluate the suitability of the poplar for landfill reclamation. Tree growth was measured and the heavy metal concentrations of soil, landfill leachate and wood were evaluated after harvesting the poplars in 1996. The average height and breast-height diameter were 7.8 m and 9.2 cm, respectively.

This impressive growth performance was much superior to that of trees in the general plantation. The survival rate was also very impressive. The heavy metal concentrations of both the soil and the poplar wood were higher than those reported for other native sites. It is not clear whether the soil brought in to cover the site was from the source of high heavy metal concentration. The high growth rate, high survival percentages and the ability of the poplar to take up and immobilize heavy metals suggest that *P.* ×*euramericana* may be a good species for landfill reclamation (Koo *et al.*, 1997).

To identify poplar species suitable for landfill reclamation, different levels of diluted leachate were used to irrigate poplar trees that were planted into pots with a clay and sand 1:1 ratio. Height and diameter in three species were not significantly different among the different concentrations of leachate treatments. The average evapotranspiration amount of three other species and *P. alba* × *P. tremula* cv. 'glandulosa' were 361 ml day^{-1} and 409 ml day^{-1}, respectively. *P. alba* × *P. tremula* cv. 'glandulosa' was much superior to other species.

Four fast-growing tree species, *P. alba* × *P. tremula* cv. 'glandulosa', *P. nigra* × *P. maximowiczii*, *P.* ×*euramericana* and *Paulownia tomentosa* were used to compare the phytoremediation efficiency on leachate and contaminated soil. The growth performance and contaminant absorption capacity of these species were measured after treating leachate. On the 50% diluted leachate treatment, the hybrid poplar (*P. alba* × *P. tremula* cv. 'glandulosa') showed the best height of 105 cm. *Paulownia tomentosa* showed the highest biomass production, followed by *P. alba* × *P. tremula* cv. 'glandulosa', *P.* ×*euramericana* and *P. nigra* × *P. maximowiczii*. The transpiration rate and stomatal conductance of the hybrid poplar (*P. alba* × *P. tremula* cv. 'glandulosa') were higher than those of other species. The total nitrogen content of *Paulownia tomentosa* was 72,640 mg kg^{-1} in dry weight, and it was higher than that of other species. The heavy metal and salinity content (Na and Cl) of *Paulownia tomentosa* were lower than those of *Populus* spp. (Koo *et al.*, 1998, 1999).

Poplar and willow clones were planted to identify species and/or clones suitable for landfill reclamation at the Kimpo Metropolitan Landfill site in 1997. Growth performance, vitality and visible foliar injury by pollutants, fungi and insects were investigated for 5 years for ten clones from four poplar species and two clones from a willow species. The average survival rate of poplar and willow clones was decreased drastically from 90% in 1997 to 57% in 2001. Among the poplar species, *P. alba* × *P. tremula* cv. 'glandulosa' showed the highest survival rate of 69% and 'Clivus', one of the clones from the hybrid poplar, showed the highest survival rate of 84% (Koo *et al.*, 2002).

Livestock wastewater uptake

Two-month-old rooted cuttings of *P. alba* × *P. tremula* cv. 'glandulosa', *P.* ×*euramericana* and *P. nigra* × *P. maximowiczii* clones were exposed to livestock wastewater, one of the major water pollutants, and to groundwater in order to determine the effects of livestock wastewater on growth response and absorption capacity of the species. For this purpose, five clones of each species were used. In all the species, the height growth of rooted cuttings was better in the livestock wastewater treatment than in groundwater. Of all the poplar species we compared, the height growth was best in *P. alba* × *P. tremula* cv. 'glandulosa'. Aboveground biomass such as leaf and shoot dry weight of all the species increased in the livestock wastewater treatment, while root dry weight decreased. In all the poplar species, the amount of livestock wastewater absorbed was less than that of groundwater. *P. alba* × *P. tremula* cv. 'glandulosa' had the best absorption capacity for livestock wastewater among the three poplar species. The '72-16' clone, one of the *P. alba* × *P. tremula* cv. 'glandulosa' clones, showed the best absorption capacity.

Five 1-year-old clones of each of *P. alba* × *P. tremula* cv. 'glandulosa', *P. nigra* × *P. maximowiczii* and *P.* ×*euramericana* were irrigated with livestock wastewater. Total nitrogen (N), total phosphorus (P) and P_2O_5 content in soil increased with livestock wastewater treatment, but nitrate-N and ammonium-N content in soil did not increase with livestock wastewater treatment as compared with those for groundwater treatment. Total P content in plant tissues decreased with livestock wastewater treatment, while total N content largely increased in comparison with those for groundwater treatment. *P. alba* × *P. tremula* cv. 'glandulosa' was best in dry weight, total amount of nitrogen absorbed per tree and water-use efficiency among the three poplar species (Yeo *et al.*, 2002, 2003).

One-year-old rooted cuttings of *P. alba* × *P. tremula* cv. 'glandulosa', *P. nigra* × *P. maximowiczii* and *P.* ×*euramericana* were also planted in the field close to a milk cow ranch and irrigated with livestock wastewater. The concentration of N and P in the soil treated with livestock wastewater was higher than that in the soil without such treatment. In the livestock wastewater treatment group, *P.* ×*euramericana* showed the best performance in height and breast-height diameter. On the other hand, *P. alba* × *P. tremula* cv. 'glandulosa' showed the best result in shoot dry weight and breast-height diameter, and dry weight of shoots was increased with livestock wastewater treatment. In conclusion, *P. alba* × *P. glandulosa* cv. 'glandulosa' was more tolerant to livestock wastewater than *P.* ×*euramericana* or *P. nigra* × *P. maximowiczii*. Total N and total P concentrations in plant shoots with livestock wastewater were higher than those of shoots without livestock wastewater. Three-year-old *P. alba* × *P. tremula* cv. 'glandulosa' contained 247 g of nitrogen in leaf and stem. The absorption of livestock wastewater increased sharply with age. At age 3, one individual tree absorbed 604 l of livestock wastewater during one growing season.

Other contaminants

Two-month-old rooted cuttings of *P. alba* × *P. tremula* cv. 'glandulosa', *P. nigra* × *P. maximowiczii*, *P.* ×*euramericana*, *P. deltoides* and *P. koreana* × *P. nigra* var. 'Italica' were cultivated at different salt concentrations (0.0, 0.1, 0.5 and 1.0% NaCl) for 60 days. Growth performance, dry biomass and the number of leaves were inhibited drastically with the increase of salinity over all species. The survival rate of the five different poplars reached 70% at 0.1% NaCl treatment, but most of the poplars died with serious visible injury at 0.5 and 1.0% NaCl treatments during the period of the treatment. Consequently, poplars seemed to survive at the lower concentration of 0.1% of NaCl. Height growth and dry biomass productivity of *P. deltoides* at 0.1% NaCl were higher than those of untreated trees. Na^+ contents in leaf, stem and root increased with increase in salinity. Na^+ contents in leaf and stem at 0.1% NaCl treatment were highest in *P. deltoides*. K^+ contents in leaf and root and Ca^{2+} content in root showed a tendency to decrease with increasing NaCl concentration (Yeo *et al.*, 1999).

Rooted cuttings of *P. alba* × *P. tremula* cv. 'glandulosa' and germinated seedlings of *Betula schmidtii* were planted in pots and irrigated with lead (Pb)-containing water for 60 days. In both tree varieties, growth inhibition was observed in 800 and 1500 ppm of $Pb(NO_3)_2$. Most of the Pb was accumulated in plant roots and only a small portion was transported to the shoots. The translocation rates of Pb for *B. schmidtii* and *P. alba* × *P. tremula* cv. 'glandulosa' were 1.6–2.6% and 1.2–1.6%, respectively. The maximum Pb content accumulated in shoots was 468.0 mg kg^{-1} dry weight in *P. alba* × *P. tremula* cv. 'glandulosa' and 602.0 mg kg^{-1} dry weight in *B. schmidtii*. Although tolerance to lead was generally higher in *B. schmidtii* than in *P. alba* × *P. tremula* cv. 'glandulosa', the highest tolerance to lead was observed in the *P. alba* × *P. tremula* cv. 'glandulosa' clone, '72-16'. We think that *P. alba* × *P. tremula* cv. 'glandulosa' and *B. schmidtii* look promising for phytoextraction based on their Pb uptake ability, high biomass production and suitability for large-scale cultivation (Yeo *et al.*, 2001).

6.5.7 New Zealand and Australia

B. ROBINSON

Introduction

Poplars and willows are ubiquitous in the New Zealand rural landscape. In Australia, the use of willows is limited due to the perception that they are weeds. The negative environmental effects attributed to willows are the obstruction and diversion of streams, displacement of native vegetation and an exacerbation of Australia's chronic water shortage due to their high rates of growth and transpiration (Cremer, 2003). In New Zealand, some willow species, especially *S. fragilis* and *S. cinerea*, have become weeds in wetland areas (Lester *et al.*, 1994).

The period 2000–2010 in Australasia has seen an increase in phytoremediation using poplars and willows. The trees are planted on contaminated sites, with the aim of reducing environmental risk. Commercial phytoremediation in Australasia employs poplars and willows as biopumps to reduce contaminant mobility and enhance the *in situ* degradation of some organic contaminants. Phytoremediation using poplars and willows offers a low-cost means of maintaining Australasia's 'clean-green' image abroad. Due to their rapid establishment and high evapotranspiration, poplars and willows are effective in reducing the water flux through contaminated material. This results in less contaminant moving off site and creates an aerobic environment in the root zone that favours the degradation of some pollutants. Poplars are particularly suited to remediation of organochlorines (Ferro *et al.*, 2000), polycyclic aromatic hydrocarbons (PAHs), excess ammonia and nitrates, and the immobilization of heavy-metal contaminants (Robinson *et al.*, 2003).

New Zealand's environmental legislation, the Resource Management Act (RMA) 1992, favours risk-reducing technologies such as phytoremediation. Regulation of contaminated sites is based on their effects on human health and the surrounding ecosystems, rather than on the levels of contaminants contained therein. Thus, phytoremediation using poplars and willows aids compliance with the RMA by reducing contaminant mobility, even if the total levels of contaminant in the soil remain unchanged. Unlike New Zealand, Australia has no overarching environmental legislation. Rather, disparate bills have been passed that address specific environmental issues. These may vary between states. Willows are being used for some wastewater and biosolids applications in Australia, however (Laidlaw *et al.*, 2012).

Most contaminated sites in New Zealand are associated with agricultural and silvicultural production. An estimated 50,000 disused sheep-dipping sites contain elevated levels of persistent pesticides such as dieldrin and sodium arsenate. Numerous sites associated with timber processing contain high levels of wood preservatives. In addition to agricultural and silvicultural contaminated sites, Australia has over 2 million ha of opencast mining and many contaminated sites associated with smelting and processing. Both countries face environmental issues associated with urban development, especially the disposal and treatment of sewage sludge and burgeoning landfills.

New Zealand has a temperate oceanic climate with a high rainfall. Meteorological conditions are ideal for poplar and willow growth, thus making phytoremediation viable for many contaminated sites. However, the high rainfall–evapotranspiration ratio limits the effectiveness of poplars and willows to eliminate contaminant leaching. On the other hand, Australia often suffers from drought and associated soil salinity, which affects plant growth negatively. Such conditions are ideal for poplars and willows to mitigate leaching. Phytoremediation is well suited for the extensive, low-value contaminated sites in Australasia. The low population densities of both New Zealand (14.8 people km^{-1}) and Australia (2.4 people km^{-1}) reduce the pressure for the rapid remediation of such sites. Here, we detail two phytoremediation case studies using both poplars and willows.

Case study 1. Phytoremediation of a contaminated wood-waste pile using poplar

Many New Zealand timber products contain pentachlorophenol (PCP), boron or copper-chromium-arsenic (CCA) to protect the wood against decay. High concentrations of these preservatives occur in wood treatment and wood-waste disposal sites, and pose a risk to receiving waters through leaching. One such site is located at the base of the Coromandel Peninsula, New Zealand (37.2°S, 175.6°E). Sawdust and yard scrapings dumped over 30 years from 1966 produced a 3.6 ha pile, with an average depth of 15 m. Geotechnical engineering ensures no surface or groundwater enters the pile. A holding pond collects leachate that results from high rainfall events. Vegetation had failed to establish naturally. Consequently, evaporation from the pile was negligible, indicated by the presence of saturated material at depths greater than 20 mm.

The annual rainfall of 1135 mm caused regular leaching from the pile into a local stream. Boron-rich leachate raised the stream concentration above the New Zealand Drinking Water Standard (1.4 mg l^{-1}), especially in the summer months when stream flow was low. The site thus violated New Zealand's effects-based

RMA and the local authority demanded that the site be remediated.

The landowners, in collaboration with the local authority, chose phytoremediation to manage the site. They based their decision on model predictions of the cost and effect of the remediation (Robinson *et al.*, 2003). In July 2000, Plant and Food Research Limited implemented a 1 ha trial using ten poplar and willow clones and two species of *Eucalyptus*. Two *P. deltoides* hybrid clones were the best candidates for phytoremediation based on survival, biomass production and boron uptake. There was a large variation in the tolerance of the trees to the wood-waste environment (Fig. 6.26).

In July 2001, the remainder of the pile was planted at a density of 7000 trees ha^{-1}. Fertilizers were added periodically. A pump recirculated leachate that occurred during the winter months and following high rainfall events. This leachate served as irrigation during the summer months. After 3 years of growth, the poplars had formed a closed canopy over 50% of the pile (Plate 21D). This figure increased to 80% the following year, with the tallest trees exceeding 8 m in height.

Before planting, the bare sawdust pile discharged boron-rich leachate during all months of the year. Following phytoremediation, the trees reduced the drainage to the 3 winter months. Summer is the greatest concern for waterway contamination because low stream flows result in less contaminant dilution. During winter, drainage may be released into a nearby stream at times of high flow, when the risk of exceeding the New Zealand Drinking Water Standard is minimal (Robinson *et al.*, 2007).

The poplar leaves at this site had average copper and chromium concentrations of 6.6 and 4.9 mg kg^{-1} dry mass. Arsenic concentrations were below detection limits (1 mg kg^{-1}). These low leaf concentrations will not facilitate the entry of CCA into the food chain. Before abscission, the average leaf boron concentration

Fig. 6.26. A field trial of poplar and willow clones as well as *Eucalyptus* and *Acacia* on a contaminated wood-waste pile, North Island, New Zealand. Note the range in biomass production and chlorosis. The trees in the photograph are 2 years old. Photo courtesy of B. Robinson.

was nearly 700 mg kg^{-1} on a dry matter basis, over 28 times higher than the boron concentration in the sawdust (40 mg kg^{-1} dry matter). While boron is a contaminant at high concentrations, it is also an essential plant and animal micronutrient (Banuelos and Ajwa, 1999) that is deficient for plant growth in many soils. Given the low concentrations of other contaminants, harvested poplar material could be applied to nearby horticultural land that is deficient in this element. Periodic coppicing of the poplars could therefore remove boron from the site. Since the leaves contain most of the boron, coppicing should occur before abscission.

The cost of phytoremediation was NZ$200,000, including a 5-year site maintenance plan. Scientific costs, including the trial planting material and chemical analyses, were higher than the planting and maintenance of the site. The costs of poplar and willow phytoremediation should decrease as an effective clone bank and better site management techniques are developed. Nevertheless, planting trials are essential to optimize the poplar clone and soil amendment regime, especially on non-soil media such as mine tailings. By comparison, the estimated cost of capping the site was NZ$1.2 million.

Case study 2. Phytoremediation of a disused sheep-dip site using willows

New Zealand has an estimated 50,000 disused sheep-dip sites. The surrounding soils contain elevated levels of arsenic, organochlorines and organophosphates. Land-use changes can result in the incorporation of these sites into residential or intensive agricultural zones. Robinson (1995) found a dieldrin plume in groundwater near one such site. Often, sheep dips were installed near wells or streams to facilitate preparation and disposal of the pesticide solution. The measurement of elevated dieldrin concentrations in a well led to the discovery of a disused sheep-dipping site in a nearby asparagus field. Soil analyses revealed dieldrin concentrations from 10 to 70 mg kg^{-1} over 100 m^2. The Dutch Intervention Value for dieldrin in soil is 4 mg kg^{-1} (VROM, 2000). Soil arsenic concentrations were not significantly higher than on adjacent areas, indicating that no arsenic pesticides were used at this site.

In September 2001, this 100 m^2 site was planted in willow clones. By January 2005, the average height of the trees was over 5 m.

Parallel experiments using soil collected from this sheep-dip site showed that willows effected a 20% degradation over a period of 5 months. However, this degradation rate cannot be extrapolated to estimate a clean-up time because the bioavailability of dieldrin bound to different soil fractions is unknown. The biological activity, as measured by dehydrogenase activity, was six times higher in the root zone of willows compared to a pasture species. Previous studies (Eriksson *et al.*, 2000) have shown that biological activity leads to a greater rate of decomposition of some contaminants. Phytoremediation on this sheep-dip site prevents the cultivation and harvesting of asparagus, promotes the degradation of dieldrin and reduces dieldrin leaching by enhanced evapotranspiration. The management of this site will include periodic coppicing of the willows to maintain a high stem density. Periodic soil analyses will reveal the long-term effect of the trees on the soil dieldrin concentration.

Little is known about the role of roots on the *in situ* degradation of organochlorine pesticides or PAHs. Remediation systems therefore have the potential to be enhanced greatly by developing clones that promote degradation or investigating the use of soil amendments that enhance the performance of poplars and willows in this role.

In both New Zealand and Australia, experimental and commercial phytoremediation using poplars has occurred on disused industrial sites with high soil loadings of lead, organochlorine pesticides and PAHs. In all cases, the primary role of the trees is to immobilize and, in some cases, degrade soil contaminants.

The growing populations and economies of Australia and New Zealand create new environmental pressures, especially due to intensive farming and urban development. With additional research combined with successful marketing, poplar and willow phytoremediation will be a valuable tool to combat future environmental degradation.

New developments and challenges

POPLARS AND WILLOWS AS NITROGEN SPONGES. Intensive dairy farming in New Zealand requires the disposal of large volumes of N-rich effluent that is often pumped on to pasture to improve growth. This can contribute to the contamination of receiving waters with nitrates. The ability of poplars and willows to coppice repeatedly makes them promising candidates for use in effluent irrigated systems, either for direct irrigation (Fig. 6.27) or as riparian buffer zone plantings to capture nitrogen from seepage or re-irrigated tile drainage. As with poplars and willows used for hillside stabilization, harvested tree material from effluent-irrigated blocks may provide valuable stock fodder.

A field trial was conducted on a dairy farm in southern Wairarapa in September 2001. Three blocks (225 m^2), each of Argyle (*P. deltoides* × *P. nigra*) poplars and Tangoio (*S. matsudana* × *S. alba*) willows, were planted as 1.2 m stakes. The trees were coppiced annually and the experiment concluded in the autumn of 2004. One block of each species was irrigated with fresh dairy effluent at rates of 2.5 mm and 5 mm a week. One block received no effluent. The biomass production of both species increased two- and threefold on the respective effluent application of 2.5 mm and 5 mm a week. This rapid growth resulted in soft lignified tissue, with a low density. While such material is unsuitable as timber, the soft tissues may improve palatability for stock fodder. At the highest treatment, the trees removed nitrogen at a rate of over 400 kg ha^{-1} $year^{-1}$, over twice the rate of pasture growing under similar conditions (150 kg ha^{-1} $year^{-1}$). Small blocks of poplars and willows may be more effective than pasture at reducing N-leaching because of their deeper root systems and re-evaporation of some incident rainfall (Roygard *et al.*, 1999).

NEED FOR NEW VARIETIES OF POPLARS AND WILLOWS. Poplar and willow breeding has focused on selecting for drought tolerance, disease resistance, lowered wind damage and possum (a marsupial herbivore) resistance (McIvor, 2008). However, future breeding could also focus on developing varieties for biomass production in degraded environments. This not only includes sites earmarked for phytoremediation but also marginal agricultural lands where the trees may be used as stock fodder. Varieties may be developed that take up limited amounts of cadmium while accumulating high concentrations of essential trace elements such as zinc and cobalt. Analyses of various poplar and willow clones have shown that high accumulation rates of essential trace elements are not necessarily correlated with high cadmium uptake (Robinson *et al.*, 2005).

Fig. 6.27. Dairy shed effluent irrigation on to a stand of *Salix matsudana* × *S. alba* near Carterton, North Island, New Zealand. Photo courtesy of B. Robinson.

Conclusions

Poplars and willows have proven environmental and economic benefits in Australasia. There are a growing number of potential roles for these trees. Erosion prevention and riverbank stabilization are still the most important uses of poplars and willows (Section 6.3, this chapter). Emerging roles, with successful case studies, include phytoremediation, wastewater management, supplementary stock fodder, production of industrial chemicals and carbon sequestration. A limiting factor in the use of willows in Australasia is the perception that these trees are weeds and that native species should be replacing them in the landscape. Nevertheless, many of the aforementioned roles cannot be filled by native species within a short time frame, and within an agricultural system, which are often requirements. Research in 2010 focused on developing systems where poplars and willows were combined with native species to enhance the economic and ecological value of farming systems.

6.5.8 Sweden

P. ARONSSON, J. DIMITRIOU AND K. PERTTU

Background

Cultivation of short-rotation willow coppice was introduced in Sweden after the oil crises in the 1970s, with the intention of replacing fossil fuels by renewable energy sources. Comprehensive research, to identify fast-growing species to be grown intensively for energy purposes, suggested that willows in coppice systems were the most suitable for this (Sirén *et al.*, 1987). During the first decade, the land available for short-rotation willow crops was abandoned farmland and appropriate wetlands. In the middle of the 1980s, however, it became obvious that the surplus production of agricultural crops left an opening for the use of more productive farmland. The research then had also shown that willow cultivation on wetlands was extremely difficult for several reasons, e.g. low soil pH and spring frosts. During the first half of the 1990s, investigations had shown that willow crops were suitable also for phytoremediation applications (Aronsson and Perttu, 1994), and that a combination with biomass production for energy purposes was a cost-effective method for wastewater treatment (Rosenqvist *et al.*, 1997; Dimitriou *et al.*, 2009a).

Commercial short-rotation willow coppice crops in Sweden

About 12,000 ha of short-rotation willow coppice crops are grown on Swedish arable land using mainly different clones and hybrids of *S. viminalis*, *S. dasyclados* and *S. schwerinii* (Dimitriou *et al.*, 2011). In 2012, there was one ongoing commercial willow breeding programme in Europe. The breeding was initiated at SLU, Uppsala, Sweden, in the late 1970s and was then commercialized by Svalöf Weibull AB in 1987 (Lindegaard *et al.*, 2001). The breeding programme was later run by the Swedish company, Lantmännen Agroenergi AB, aiming at introducing new varieties (clones) on the European market. During 2005, some 30 clones were registered with breeder's rights by Lantmännen Agroenergi AB, of which seven varieties were being marketed in Sweden in 2012 (see further at http://www.agrobransle.se). In the UK, the IACR-Long Ashton at Bristol managed a willow breeding programme funded by the European Willow Breeding Partnership owned by SW Seed, IACR-Long Ashton and Murray Carter Ltd. This programme lasted from 1996 to 2003 and resulted in six new varieties released on the market with breeder's rights (Stig Larsson, Lantmännen Agroenergi AB, 2010, personal communication).

Willow cultivation is fully mechanized, from soil preparation, planting and management to harvesting and combustion. In the initial phase, approximately 12,000 cuttings ha^{-1} are planted in double rows, to facilitate management (weeding, fertilization, etc.) and harvesting (Dimitriou *et al.*, 2009b). Despite a considerable fertilization effect, Swedish commercial willow plantations are rarely fertilized (Mola-Yudego and Aronsson, 2008). This is most likely due to the high costs for fertilizers (around 1 kg^{-1} N) and the relatively low price for the willow chips (around 33–40 t^{-1} dry matter). However, municipal sewage sludge is applied to most willow plantations, usually 1 year after planting and then repeatedly after the harvests. This reduces the need for additional phosphorus fertilization, but also generates income for the farmers receiving the sludge (Dimitriou and Rosenqvist, 2011). The willows are harvested every 3–5 years, during the non-growing season, preferably when the soil is frozen, using specially designed machines, i.e. converted Claas Jaguar corn harvesters. The aboveground biomass is chipped on site, then stored or transported directly to and burned in combined heat and power plants.

Examples of large-scale phytoremediation systems in Sweden

MUNICIPAL WASTEWATER. Municipal wastewater, i.e. wastewater from flushing toilets, contains nitrogen and phosphorus and is in most cases a well-balanced nutrient solution suitable for fertilizing of plants. For sanitary reasons, however, non-food and non-fodder crops, such as willow cultivations, are preferred (WHO, 2006). During the 1990s, large willow plantations equipped with drip irrigation or sprinkler systems positioned low to the ground were established adjacent to wastewater treatment plants to improve the efficiency of nitrogen treatment while producing biomass irrigated with wastewater. It was assumed that with a growth rate of 10 dry t ha^{-1} $year^{-1}$ and a shoot nitrogen concentration of 0.5% (Aronsson, 2000), 50 kg ha^{-1} $year^{-1}$ of nitrogen would be removed from the field at harvest. Research has shown, however, that nitrogen retention in short-rotation willow coppice can be more than 200 kg ha^{-1} $year^{-1}$ because of denitrification and long-term binding of nitrogen in the soil (Mortensen *et al.*, 1998; Aronsson and Bergström, 2001; Dimitriou and Aronsson, 2004, 2011).

Wastewater irrigation of willows is practised in an elegantly designed system at Enköping (about 20,000 inhabitants) in central Sweden (80 km west of Stockholm) (Plate 21E). The nitrogen-rich wastewater from dewatering of sludge, which formerly was treated in the wastewater plant, is now distributed to an adjacent 75 ha willow plantation during the growing season (Dimitriou and Aronsson, 2005). The applied wastewater corresponds to a load of approximately 150 kg ha^{-1} $year^{-1}$ of nitrogen applied to the plantation by use of a drip irrigation system. The growth has been recorded annually and has been found to be about 10 dry t ha^{-1} $year^{-1}$. Nitrogen leaching to groundwater has also been recorded, and once the willows had established properly, leaching was negligible (unpublished data). Substantial efforts have also been made to quantify the N_2O emissions from the system.

LANDFILL LEACHATE. Landfill leachate (water that has percolated through a landfill) is usually treated together with municipal wastewater in conventional treatment plants. This is generally costly and involves high energy consumption. Therefore, landfill operators are becoming increasingly interested in alternative solutions for on-site treatment. One method is to aerate the leachate and then use it to irrigate short-rotation willow coppice, either on restored parts of the landfills or on adjacent arable fields. The main advantage of this method is the low establishment costs compared with conventional engineered systems (Rosenqvist and Ness, 2004).

A willow plantation established on a restored cover of the landfill decreases leachate formation by means of high evapotranspiration. A near-zero net discharge of landfill leachate *can* be achieved by recycling the leachate into a short-rotation willow coppice plantation, even in the humid climatic conditions of northern Europe. Simultaneously, hazardous compounds in the leachate, for example ammonium and a range of potentially toxic organic substances, are taken up by the willows or transformed and retained in the soil–plant system (Dimitriou and Aronsson, 2007). A high concentration of ammonium in water is an environmental hazard, but nitrification in the soil is usually highly efficient, and thus leaching and discharge of ammonium should be avoidable in such treatment systems. The high concentration of various salts (usually dominated by the seemingly harmless NaCl) often are more problematic. Most salts are not possible to treat in a soil–plant system. Instead, such salts can only be diluted in time and space, but eventually they will reach the recipient water body. Still, the salt concentration needs to be addressed when designing a treatment system, since plants may suffer from either too high ionic strength in the root zone or from direct toxic effect caused by plant uptake of, for example, sodium. In addition, spray irrigation of landfill leachate may cause leaf necrosis and should be avoided. There are clear clonal differences as regards the plants' ability to cope with high salt concentrations (Dimitriou *et al.*, 2006a), and this needs to be considered when selecting varieties for establishing a system for phytoremediation of landfill leachate.

There were about 20 sites in Sweden in 2012 where landfill leachate was used to irrigate short-rotation willow coppice in sprinkler or drip irrigation systems. For example, at Upplands-Bro in central Sweden, a system operated by the company, Ragnsells Avfallsbehandling AB, stores and aerates the landfill leachate in ponds and then pumps it into a 5 ha short-rotation willow coppice field, which is irrigated daily during the growing season with approximately 2–3 mm of wastewater (Dimitriou *et al.*, 2003). Results from irrigating willows with the leachate on both field and controlled conditions indicated that, with careful planning, successful treatment of leachate combined with enhanced biomass could be achieved (Aronsson *et al.*, 2010; Dimitriou and Aronsson, 2010). The landfill operator intended to expand the extent of on-site treatment and planned to treat the entire volume of landfill leachate by irrigation of mainly willows, but also conventional forest.

INDUSTRIAL WASTEWATER. Large quantities of industrial wastewater are produced in Sweden after wet storage (sprinkling) of wood in sawmills and pulp mills (Jonsson, 2004). Sprinkling is carried out in summer to protect stored wood from damage by insects and fungi and from drying cracks. A medium-sized sawmill in Sweden consumes approximately 100,000 m^3 of water annually for watering the stored wood, and large amounts of runoff water from log yards need treatment. This is due to the fact that it contains a range of organic compounds, originating from the tree bark, as well as substantial amounts of phosphorus originating both from the bark and from soil particles attached to the logs or to the tyres of the trucks transporting the logs. Wastewater produced after rainfall or snowmelt can pollute neighbouring catchments or groundwater if it is left untreated. Until recently, in most cases such water has been disposed of in rivers or lakes. Treatment by irrigation of trees or perennial grasses has been tested as an alternative to constructed wetlands. Sandy soils are especially capable of retaining dissolved organic compounds, whereas the retention of phosphorus was higher in a clayey soil (Jonsson *et al.*, 2004). In the long run, the accumulated load of phosphorus needs to be considered since a soil might be phosphorus-saturated and start leaching considerable amounts to ground and drainage water.

SEWAGE SLUDGE AND WOOD ASH. Most Swedish willow plantations are fertilized regularly with municipal sewage sludge. This takes place after harvest, when spreading can be undertaken using ordinary agricultural machinery. Application of sludge to willow plantations is far less problematic compared to application to food crops, due to sanitary and public esteem reasons. In addition, the heavy metal concentration of Swedish sewage sludge used to be high, resulting in a build-up of the soil pool of metals when applied to arable land, and this has affected public opinion about sludge use in agriculture.

Usually, sewage sludge is highly imbalanced in terms of plant nutrients, with much higher phosphorus (P) content in relation to nitrogen (N) and potassium (K). The N is also mainly organically bound and contributes little to the N supply of the plants. Wood ash from the combustion of various wood fuels, on the other hand, contains both K and P but hardly any N. Thus, mixing sewage sludge with wood ash will result in a more balanced PK-fertilizer, which can replace conventional fertilizers (Dimitriou *et al.*, 2006b; Adler *et al.*, 2008). Ultimately, any biofuel-based energy system must include recycling of plant nutrients in the ash in order to be sustainable.

Despite a dramatic improvement of the heavy-metal concentration in Swedish sewage sludge, it still poses a long-term problem. From the point of view of human health, cadmium (Cd) is the most problematic metal. Willows have been shown to take up and accumulate substantial amounts of Cd, and this fact has attracted much attention in the perspective of phytoremediation of contaminated soils (Perttu *et al.*, 2002). However, operators of heating plants using willow chips were concerned because of this, since the result could be wood ash of lower quality. Recent research has shown that growing willows results in a net removal of Cd from the soil which is in the order of 5–10 g ha^{-1} $year^{-1}$ (Hasselgren, 1999; Klang-Westin and Perttu, 2002). The current regulation on the application of sewage sludge to farmland allows an annual Cd load of 0.75 g ha^{-1} $year^{-1}$. Thus, Cd does not pose a long-term problem in sludge-fertilized willow plantations. In fact, theoretically, during the estimated 25-year lifespan of a willow plantation, the net Cd removal can bring soil Cd levels back to pre-industrial levels (Perttu *et al.*, 2002). The situation is not as positive as regards the other heavy metals. These are not nearly as problematic for human health as Cd, but could pose long-term sustainability problems. These metals are not taken up by the willow plants as efficiently as Cd. The uptake of metals has proved to be clone specific (Landberg and Greger, 1996), and thus there might be opportunities for breeding efforts towards maximized metal uptake.

Cadmium and other heavy metals will remain in the different ash fractions (mainly in the fly ash) in the heating plant and will need further attention to be recycled back to arable land. It is technically relatively easy to clean ash from heavy metals, but this environmental service is not being paid for today and therefore heavy-metal-contaminated fly ash (normally about 15% of the total ash produced) is usually disposed of in landfills.

Conclusions

When used for phytoremediation, short-rotation willow coppice crops offer advantages, such as high biomass yields and removal of hazardous compounds through frequent harvests. The high evapotranspiration rate and root tolerance of willows to flooding conditions allow high irrigation rates. In addition, short-rotation willow stands are capable of restoring polluted sites by taking up substantial amounts of heavy metals such as cadmium, as well as retaining large amounts of nutrients in the soil–plant system. Besides removing hazardous compounds successfully, willow coppice phytoremediation systems utilize the nutrients and water applied to increase biomass production. Large-scale systems provide ecologically sound and economically competitive alternative treatment solutions.

6.5.9 UK

Wastewater and Biosolids

A.R. McCRACKEN

INTRODUCTION

Fast-growing energy crops such as SRC willow (*Salix* spp.) and short-rotation forestry (SRF) poplar (*Populus* spp.) are particularly well suited for phytoremediation and offer opportunities for the management of high nutrient wastewater streams and biosolids in Europe (Aronsson and Perttu, 2001). Their rapid growth rate and uptake of large volumes of water potentially enables SRC willow and poplar to absorb nitrogen (N), and to a lesser extent phosphorus (P), from the soil. Furthermore, willow can also effectively take up heavy metals such as zinc and cadmium (Riddell-Black, 1994). This characteristic has been utilized for the extraction of cadmium and zinc from contaminated brownfield sites and has also been achieved using *Salix*, *Populus* and *Alnus* in England, UK (French *et al.*, 2006). In Sweden, SRC willow systems have been developed at several sites for the commercial management of pollutants (Mirck *et al.*, 2005)

EFFLUENTS (WASTEWATER)

Nutrient removal. Energy crops, and especially SRC willow, have high water use, due to their long growing season and relatively deep rooting systems (Jørgensen and Schelde, 2001). This, along with good nutrient-use efficiency (NUE), makes willow an ideal candidate to be irrigated with high nutrient effluents. In an early trial in Poland, Kowalik and Randerson (1994) irrigated four willow species with four levels of municipal wastewater at Osobowice near Wroclaw. For all four species, there was an increase in yield following irrigation, although at the highest level of effluent application (equivalent to >1120 kg N ha^{-1}) the differences were not significant, indicating that the plants may have become nutrient saturated. They suggested that at this particular site, an irrigation load of 1000 mm $year^{-1}$ (525 kg N ha^{-1}), i.e. 50 mm $week^{-1}$, as a maximum, would provide an adequate supply of nutrients for plant growth and also increase the efficiency of N and P removal and improve the quality of effluent leaving the plot. Often, a limiting factor on how much wastewater can be irrigated to a site will be hydraulic loading and plant evapotranspiration rate. In Northern Ireland, due to a relatively high rainfall and high soil water retention, the maximum amount of effluent which can be applied at most sites is around 650 mm $year^{-1}$, although this can vary significantly, depending on specific site characteristics.

In Sweden, when willow stands were irrigated with landfill leachate at an equivalent rate of 1600 kg N ha^{-1} $year^{-1}$, there was a 93% reduction in the N content of the leachate over a 10-year period (Duggan, 2005). Willow stands were responsible for a 96.8–99.9% ammonium removal efficiency and a 43.4–93.3% reduction in total nitrogen in leachates (Hasselgren, 1998), with nitrogen removal being estimated to be 100 kg N ha^{-1} $year^{-1}$ (Borjesson, 1999). Similarly, Brierley *et al.* (2001) reported that SRC willow removed 90% of the mass of N from landfill leachates. In a study in Wales, leachate was added to SRC willow at a rate equivalent to an N concentration of 225 kg N ha^{-1} $year^{-1}$. Based on an N content of 0.5–0.7% N of harvested willow biomass (Scholz and Hellebrand, 2003) and an annual harvest of 10 dry t ha^{-1} $year^{-1}$, this equated to an annual offtake of between 50 and 70 kg N ha^{-1} $year^{-1}$ (Jones *et al.*, 2006). This result would indicate a significant imbalance in N inputs and outputs. However, when a full mass balance of nutrient flows is undertaken for SRC willow, many other routes of N metabolism are identified (Jones *et al.*, 2006).

Polishing. In 1998, an SRC willow plantation was established adjacent to the wastewater treatment works (WWTW) at Culmore, County Londonderry, Northern Ireland, as part of the EU-Fair5 project. Six treatments were imposed: (1–3) three rates of wastewater irrigation from the neighbouring WWTW; (4) clean water; (5) sewage sludge; and (6) zero application control. A full description of the project and the results from 4 years' data are given in Larsson *et al.* (2003). The growth of the willow was increased significantly by the nutrients available in the wastewater. Analysis of both the groundwater and soil water suggested that the impact of treatments, particularly at high levels of nitrogen and phosphorus, was limited even when the application of water and nutrients exceeded the requirements of the plants (Table 6.7). When the wastewater treatment effects were calculated using a mass balance technique on the willow–soil system, it was estimated that 67–74% BOD, 52–75% total nitrogen and 90–98% total phosphorus were removed. The report (Larsson *et al.*, 2003) concluded that the management of a wastewater irrigation system according to water and nutrient requirements of the SRC willow was possible without any negative environmental impacts with regard to oxygen-demanding substances and eutrophying components. However, elevated nitrogen leaching may occur from willow coppice after irrigation with very nitrogen-rich wastewater applied over a short period, e.g. worst-case conditions of 320 kg N ha^{-1} during 8 days (Dimitriou and Aronsson, 2004).

When using untreated primary municipal effluent there are genuine risks in relation to

Table 6.7. Concentration of constituents (means July 1999–April 2000) in superficial groundwater at Culmore, Northern Ireland (mg l^{-1}). Mean values of wastewater (WW) and pure water (PW) are included for comparison (Larsson *et al.*, 2003).

	WW	1 PE[a] WW	2 PE WW	3 PE WW	PW	1 PE PW	Sludge	Control
pH	6.9	6.4	6.3	6.4	7.1	6.3	6.4	6.4
BOD	106	32	35	30	3.6	31	31	31
COD	245	171	149	196	13	126	119	177
N-total	19	6.5	4.5	3.6	2.7	4	4.8	3.3
NH_4-N	18	1.6	1.6	1.6	1.8	1.6	1.7	1.5
NO_3-N	0.53	4.9	2.9	2	0.92	2.4	3.1	1.7
P-total	12	1.3	1.3	0.89	0.02	1	1.3	1.25
PO_4-P	2.0	0.57	0.5	0.65	–	0.48	0.49	0.57
K	11	3.8	4.4	4.3	1.9	3.3	5.2	2.3
Cr	215	91	99	149	24	56	122	58
Cd (μg^{-1})	0.018	0.018	0.017	0.016	0	0.016	0.017	0.014
Pb (μg^{-1})	0.15	0.16	0.28	0.18	0.22	0.18	0.19	0.16
Zn (μg^{-1})	120	70	69	110	25	67	58	70
Cu (μg^{-1})	15	40	39	51	7	40	52	30

[a] PE, Potential evapotranspiration.

transmission of animal or human pathogen via aerosols or contamination of the plantation water systems, including surface water, due to high hydraulic loads. At the Culmore site, there was some contamination of the superficial groundwater by indicator faecal microorganisms, which escalated with increasing application rates of the wastewater. Some of this was related to soil texture that had a high proportion of clay. In soils with high clay, cracks can occur, which allows for the rapid and unhindered transportation of water through the soil profile.

A further trial was established in 2002 close to the WWTW in Culmore as part of a EU Life project called 'Water Renew' (http://www.afbini.gov.uk/ANSWER). Primary effluent was applied to SRC willow, poplar and, for comparison, grass. Nitrogen uptake and removal from the system were monitored carefully. There was no significant movement of nutrients through the soil in the poplar or willow plantations at the rate of application, that is approximately 250 kg N ha^{-1} (Werner and McCracken, 2008). Grass plots are less secure, especially at the end of the growing season. The ability of the woody crops to deal with the high volumes and high nutrient content of the effluent during the period when the soils are virtually saturated and the plants are not actively transpiring is an important part of the investigation.

Economics. An economic assessment of the use of wastewater irrigation of willow in Northern Ireland (Rosenqvist and Dawson, 2005) concluded that the added value of the bioremediation of wastewater using SRC willow had the potential to radically alter the economic sustainability of the crop. Similar results had been reported from Sweden some years previously (Rosenqvist *et al.*, 1997), particularly allowing for the large cost of the conventional removal of nitrogen and phosphorus from effluent.

Despite all of the benefits of using willow for the cost-effective treatment of nutrient-rich wastewaters, uptake of the technology has been limited even in countries such as Sweden. The reasons for this have been due to various barriers such as institutional, structural and technical/geographical (Börjesson and Berndes, 2006). As issues including the implementation of the EU Nitrates Directive (91/676/EC), the EU Water Frameworks Directive (2000/60/EC), increasing concern about climate change and the difficulties of handling waste become more pressing, the use of SRC willow as a means of bioremediation should become more widespread. In many situations, SRC willow is best suited to the tertiary treatment of effluents from small inefficient treatment works or septic tanks.

BIOSOLIDS

Composition. Biosolids (sludge) are the solid residue generated during the treatment of domestic sewage in a water treatment works. Municipal biosolids typically have a dry matter content of just over 30%, a neutral pH and relatively high levels of nitrogen and phosphorus (Table 6.8). Levels of other elements including

Table 6.8. A typical analysis (based on dry weight) of biosolids from Culmore Wastewater Treatment Works taken in September 2006.

Dry matter	31.34%	Calcium	8158 mg kg^{-1}
pH	7.0	Magnesium	1059 mg kg^{-1}
Conductivity	1337 mS cm^{-1}	Potassium	8334 mg kg^{-1}
Ash	29.59%	Phosphorus	9250 mg kg^{-1}
Nitrogen (TON)	0.815%	Sodium	539 mg kg^{-1}
Ammonia (DM)	0.858%	Aluminium	7592 mg kg^{-1}
Nitrogen in DM	2.231%	Boron	9.9 mg kg^{-1}
BD	695 q l^{-1}	Cadmium	0.4 mg kg^{-1}
		Cobalt	4.9 mg kg^{-1}
		Copper	69.8 mg kg^{-1}
		Iron	4330.3 mg kg^{-1}
		Lead	32.2 mg kg^{-1}
		Manganese	121.2 mg kg^{-1}
		Molybdenum	0
		Zinc	35.2 mg kg^{-1}

heavy metals may vary considerably, depending on the intake of the water treatment works, and will change with seasonal factors.

Disposal. Currently, routes for the disposal of biosolids include incineration, landfill, anaerobic digestion, and in some countries, application to land. There is, however, enormous potential in applying biosolids to fast-growing energy crops such as SRC willow, and there are many environmental benefits of applying biosolids to SRC willow, which include:

- diversion of organic waste from landfill, incineration and transportation over large distances;
- diversion of the food safety fears associated with the recycling of biosolids to food and feed crops;
- enhanced energy security through displacement of heating oil and fossil fuels used for the manufacture of artificial fertilizer;
- provision of zero carbon renewable fuel and the associated reduction in CO_2 emissions;
- enhanced soil carbon sequestration through willow root biomass and soil injection of organic waste;
- new agricultural diversification, provision of rural employment and reconnection of urban–rural divide;
- increased biodiversity;
- compliant and sustainable waste management; and
- improved water quality.

Injection into SRC willow. In a commercial trial in Northern Ireland, untreated municipal biosolids have been injected into the soil using a specifically adapted piece of machinery (Fig. 6.28). A track is opened up to a depth of approximately 20 cm and the biosolids extruded into it. A second attachment immediately covers the biosolids so that at no time is it on the surface, reducing odours to zero and significantly reducing health risks from pathogens. A loading of 74 t ha^{-1} can be applied in a single pass, which is best done in the first year, soon after coppicing. Work is currently being undertaken to increase the clearance height of the machine so that biosolids can be applied at any time during the first year of regrowth without significant damage to the plants. In the Northern Ireland trial, biosolids have been applied to SRC willow at the following (equivalent) rates: 37 and 74 t ha^{-1} in a single pass in July 2005, 118 t ha^{-1} in two passes in July and December 2005 and 128 t ha^{-1} in three passes in July and December 2005 and March 2006. The water in boreholes positioned in each plot is sampled at monthly intervals and

Fig. 6.28. Biosolids injection into freshly coppiced SRC willow. Photo courtesy of Rural Generation Ltd.

structured soil samples taken every 6 months. By the end of 2006, no significant increases in water or soil nitrogen or phosphorus were observed. Similarly, there has been no evidence of a build-up of coliform bacteria in the soil or soil water.

In a recent study in Sweden, a mixture of biosolids and wood-ash mixtures were applied to short-rotation willow coppice (Dimitriou *et al.*, 2006b). The application of biosolids/ash mixtures resulted in changes to the soil pH and subsequently to the metal solubility in the soil. A decrease in solubility, particularly of Cd, was not, however, correlated with reduced uptake of the metal by the willow. The effectiveness of SRC willow in accumulating metal contaminants is a combination of the ability to absorb them from the soil and a function of the amount of biomass they produce. Differences in uptake of heavy metals could be related directly to the genetic differences between willow genotypes, and it has been suggested that some of the newer, faster growing and more productive genotypes may be even more effective in the bioremediation of heavy metals (Dimitriou *et al.*, 2006b). Furthermore, as mentioned previously, there could be added benefits in changing to a 2-year harvest cycle, thus increasing the off-take of biomass and contaminants from the site. However, it should also be noted that Cd concentrations will be greatest in the foliage and so the crop may have to be harvested while still green in order to maximize off-take of the contaminants from the site.

The application of biosolids offers a very significant economic benefit for the growing of SRC willow, through a gate fee paid by the water treatment works for disposal of the material. In addition, the willow has shown significant yield increases in response to readily available nitrogen that may offset the yield penalties of moving to a 2- rather than 3-year harvest cycle. Changes in local, national or European legislation, however, may mean that, in the future, biosolids have to be pretreated before application to the soil. Pretreatment could involve heat to kill pathogens or perhaps storage for 3 months, again to effect a pathogen kill. Treatment of biosolids with lime to raise the pH to 12 will result in the destruction of pathogenic bacteria after 24 h (Grabow *et al.*, 1978). There may be serious implications to plant growth from applying biosolids with such a high pH to the soil.

Nitrogen and phosphorus. The information on N requirements of a productive SRC willow plantation is quite varied. However, Labrecque and Teodorescu (2003) calculated that with a yield of 20 dry t ha^{-1} year^{-1} in the third rotation of *S. viminalis*, it would require around 180 kg N annually. If excessive nutrients are applied to a crop, whether in an inorganic form, in semi-solid materials or in liquids, the key risks are:

- leakage of nitrogen (N), which could contaminate the groundwater systems; and
- unacceptable build-up of phosphorus (P) in the soil and/or phosphorus runoff contaminating waterways.

In many of the studies carried out on the fate of nitrogen and/or phosphorus in SRC willow and other SRF crops, the nutrients have been in inorganic form. In these situations, leaching of N has been reported, especially in the establishment year, e.g. Labrecque *et al.* (1997), Hasselgren (1998), Mortensen *et al.* (1998), Alker (1999), Aronsson *et al.* (2000), Aronsson and Bergström (2001), Dimitrou and Aronsson (2004), Godley *et al.* (2004), Goodlass *et al.* (2007), Werner and McCracken (2008) and McCracken *et al.* (2009). In established crops, there are consistently low levels of leaching of N from SRC willow, even when quite high N additions have been made (Mortensen *et al.*, 1998; Aronsson *et al.*, 2000; Heller *et al.*, 2003). The dangers of leakage of N from biosolids are considerably less than from inorganic fertilizers or even effluents.

Nitrogen leaching. It is a legitimate concern that if N application rates are significantly surplus to crop requirements, there will be an accumulation of N in the soil, leading to the excess N leaching from the system and causing contamination of the groundwater. However, numerous studies have demonstrated that the levels of N leakage from established SRC willow are low to zero, in a range of soils, even at excessively high application rates far above normal crop requirements (Dimitriou and Aronsson, 2004). High fertilization rates (up to 153 kg N ha^{-1} year^{-1}) to willow growing on light textured soils resulted in remarkably low concentrations in groundwater at a depth of 2 m (Aronsson *et al.*, 2000). N application rates equivalent to 110–244 kg N ha^{-1} year^{-1} to SRC willow growing in lysimeters in a range of soils from clay to sandy had low to negligible leaching during the second and third year after establishment (Aronsson and Bergström, 2001). In a field study in Northern Ireland using municipal sewage effluent, Werner and McCracken (2008) detected no elevation in N levels in soil or groundwater over a 3-year irrigation period. Nitrogen retention, defined as the difference between nitrogen input through fertilization and nitrogen leaching in vegetation filter plants, is high (Aronsson, 2001).

Nitrogen loading. Not all the nitrogen applied to a crop will be taken up into that crop. In agricultural systems where nutrients are applied according to crop need, typical fertilizer use efficiency for nitrogen is 30%, i.e. 30% of the applied nitrogen is present in aboveground biomass. The other 70% is either present in roots, bound to soil organic matter, used by soil microbial biomass processes or lost through organic nitrogen mineralization and ammonia volatilization, nitrate leaching and denitrification.

The UK *Fertiliser Manual* (Anon., 2010) suggests a yearly off-take of 3 kg N t^{-1} biomass. At 30% availability for a 12 t ha^{-1} $year^{-1}$ yield, this is a nitrogen off-take of 120 kg N ha^{-1} $year^{-1}$. Other work suggests that the typical willow stem N content is 3–4 kg dry t^{-1} wood where no fertilizer has been applied. Stem N concentrations where nutrients are not limited have been measured from 6 to 25 kg N dry t^{-1}. Under these circumstances, annually exported N in harvested stems would be 60–250 kg, assuming a productivity of 10 dry t $year^{-1}$ and ha^{-1}. The lower range of 60 kg ha^{-1} $year^{-1}$ would suggest an application rate of 200 kg N ha^{-1} $year^{-1}$.

CONCLUSIONS

SRC willow and poplar offer realistic and practical approaches for the bioremediation of wastewater, effluents and sewage biosolids. A wide spectrum of *Salix* spp. and *Populus* spp. are efficient at water uptake and the utilization of high levels of nitrogen, which in turn results in increased biomass yields. While less effective in phosphorus uptake, willow and poplar may also have a role in the management of high phosphorus effluents. There is extensive evidence to show that willow is especially good at the extraction of cadmium and zinc from contaminated waste. However, there are issues as to where the heavy metals are accumulated and it may be necessary to harvest plants while leaves are still attached in order to achieve maximum off-take from the site. The application of biosolids to growing willow crops can be carried out during the first year of regrowth. By reducing the harvest cycle from 3 to 2 years, it will be possible to get maximum levels of biosolids to the crop. Short-term studies have indicated that there are minimal problems associated with the build-up of nutrients in the soil or with microbial contamination of groundwater. However, in the application of both biosolids and effluent there are concerns about the long-term impact on the soil, and it is essential that trials are monitored over prolonged periods. This is particularly important where biosolids have been pretreated, resulting in high pH and/or changes in structure or microbiological content.

Phytoremediation and carbon sequestration of degraded lands

N. DICKINSON AND D. RIDDELL-BLACK

Soils of brownfield, urban and industrial areas in the UK provide a large-scale opportunity to use phytoremediation, but the focus here should be on the more realistic possibilities of risk-managed phytostabilization and monitored natural attenuation. The wider practical applications of phytoremediation have a huge scope for cross-cutting other environmental agendas with synergies that involve the recovery and provision of services from degraded landscapes and contaminated soils. Additional focus on biomass energy, improved biodiversity, watershed management, soil protection, carbon sequestration and improved soil health is required for the justification and advancement of phytotechnologies.

Some highly productive non-hyperaccumulator species of plants such as species of *Salix* and *Populus* accumulate concentrations of metals in aboveground parts at significantly higher than the normal ranges found in most plants (Pulford and Watson, 1996, 2003). These plants may provide highly productive crops combined with significantly elevated metal concentration in aboveground tissues. We may be able to identify some genotypes that tend to accumulate high concentrations of more mobile trace elements. Particular examples have been identified already.

Trace elements of concern pertain both to the more phytotoxic elements, for example Zn, Cu, Ni, that may restrict plant productivity and to the more zootoxic elements, for example Pb, Cd, As, that may present a human health risk. Many previously developed brownfield or urban soils affected by waste disposal or aerial deposition from industrial fallout, transport or less obvious diffuse sources of pollution may also meet the just-above-the-contamination-threshold criterion for phytoextraction, but in this case it is generally only the zootoxins that are of concern. These have a very localized and heterogeneous spatial dispersion of pollutants, sometimes with an exaggerated perception of contamination risk (French *et al.*, 2006).

Of the non-hyperaccumulator species most studied in the context of phytoextraction, a combination of high productivity and elevated uptake of Cd and Zn has been identified in various taxa of *Salix* and of B and Se in *Populus* (McLeod and Ciravolo, 1998; Robinson *et al.*, 2000). Both genera are usually planted from stem cuttings, producing clonal plantations that would be expected to show reduced variability between plants compared to plants raised from seed, although this is hardly the case. In one study by French *et al.* (2006), a three-parent hybrid (*S.* ×*calodendron*) of *S. viminalis*, *S. caprea* and *S. cinerea* was identified that generally performed the best in terms of yield and metal uptake, but other studies have found elevated uptake in a range of different species and varieties – in fact, productivity seems to be the most important trait, as several willows in some situations appear to transfer relatively high concentrations of Cd and Zn to aboveground tissues (Dos Santos *et al.*, 2007).

ENHANCED UPTAKE OF METALS USING CHELATES. Many studies have now shown that metal uptake by plants can be accelerated by applying a range of chelating agents including EDTA and EDDS to soil contaminated with Pb and Cu and low molecular weight organic acids such as oxalic acid and citric acid to improve the removal of Cd, Cr and Ni. In one study, the application of EDTA and NH_4Cl to soils as mobilizing agents increased the uptake of metals into *Populus* but induced toxicity symptoms in the crop (Komarek *et al.*, 2007). In another, EDDS enhanced Cu, Cd and Zn uptake in *Salix* (Meers *et al.*, 2007). The same chemicals are well known to increase leaching of metals from soils, which may be unavoidable, thus potentially mobilizing metals towards groundwater. Recent reviews have argued that phytoextraction remain separate from chelate-assisted phytoextraction.

RISK MANAGEMENT AND PHYTOEXTRACTION. Environmental concerns are associated with enhanced mobilization of metals into plants. Food chain risk is the most obvious, and there is some evidence, for example, that cadmium transfer occurs to leaf-feeding invertebrates and to willow-feeding birds. However, higher trophic level accumulation of metals has otherwise seldom been found, except in animals feeding from the soil and the decomposer food web. Nevertheless, leaf fall always occurs to some extent during the growth cycle, prior to harvest, and this may transfer metals from deeper soil layers to the surface in the longer term. Harvest and subsequent disposal of phytoextractive plants potentially also poses onward problems: for example, combustion of biomass may disperse into the atmosphere, unless combustion temperatures are low and particulate emissions are controlled carefully. Incineration, ashing and other methods of contaminated crop disposal have been discussed elsewhere (Sas-Nowosielska *et al.*, 2004).

PHYTOSTABILIZATION OF BROWNFIELD SOILS. There is a much more extensive and well-established knowledge of how to mitigate toxicity in contaminated soil and how to establish a vegetation cover on contaminated land, with many case studies being well documented since at least 1970. A vegetation cover simply may reduce the wind blow of metal-contaminated soil as dust particulates, which can be the largest source of human health risk. Plant evapotranspiration may influence soil hydraulics sufficiently to prevent metals moving towards groundwater (Robinson *et al.*, 2007). In selecting plant species for phytostabilization, it has been shown that some species of *Populus* are unsuitable because of their uptake of high foliar concentrations of Cd (Mertens *et al.*, 2004). On the other hand, *S. caprea* is a stress tolerator and one of the first and only woody plants to colonize metal-contaminated land naturally in northern

Europe. It has been found to translocate high concentrations of Cd (116 mg kg $^{-1}$) and Zn (4680 mg kg $^{-1}$) to its foliage (Unterbrunner *et al.*, 2007).

CARBON SEQUESTRATION ON DEGRADED LANDS. Soil provides the main terrestrial storage of carbon, containing more carbon that the atmosphere and vegetation combined. The decline of stocks of soil carbon in agricultural land is well known and most obviously related to modern agricultural practices and less use of recycled organics. However, in older soils, especially where forests have been converted to agriculture, there appears to be a real risk that a fresh carbon supply stimulates the decomposition of carbon buried in deeper layers (Fontaine *et al.*, 2007). Various forms of organic matter amendments, including composts and sludges, form an important component of many site remediations of contaminated land which often contain younger soils without deep buried layers of organic carbon (Lal, 2007). Clearly, organic amendments have the potential to replenish depleted carbon stocks in degraded landscapes, thereby sequestering significant amounts of atmospheric carbon. Understanding the effects of organic carbon additions and different soil organic fractions on metal mobility has already received considerable attention, but modelling the retention of carbon is only just beginning to receive attention. It is important to understand how it is possible to encourage the long-term accumulation of the recalcitrant humified carbon compounds that become slow-cycling storage carbon.

6.5.10 USA

Overview

S. DOTY

Phytoremediation is the use of plants for the treatment of environmental pollutants. Plants act as solar-powered pump-and-treat systems as they pull up water-soluble contaminants through the roots and translocate them through the plant tissue, where they can be metabolized, sequestered or volatilized (reviewed in McCutcheon and Schnoor, 2003; Pilon-Smits and Freeman, 2006; Vangronsveld *et al.*, 2009; Dhankher *et al.*, 2011). Poplar and willow have been used successfully for the remediation of a variety of environmental pollutants (Rockwood *et al.*, 2004). The rapid growth, high biomass, extensive roots, low maintenance costs and adaptability of these tree species make them ideal plants for phytoremediation projects (Stettler *et al.*, 1996). For example, these trees have far more massive root systems than most herbaceous plants, reaching several metres. A 5-year-old poplar tree can take up 100 l of water day $^{-1}$; at this rate, 1 ha of poplar trees could remove 1.12 kg of a low-level contaminant (1 ppm) in just 1 year (Stomp *et al.*, 1994). Both poplar and willow can re-sprout after the aboveground biomass is removed (coppiced), with little disturbance to the site. This is advantageous because some inorganic contaminants such as metals could be harvested regularly, or flowering could be prevented. Not only does it have an inherent capability of taking up and metabolizing pollutants but also poplar is amenable to genetic transformation methods to enhance that ability drastically. In addition, both tree species harbour a wide variety of microorganisms that improve plant growth and may also assist in the metabolism of pollutants.

INHERENT ABILITY OF POPLAR AND WILLOW TO DEGRADE ORGANIC POLLUTANTS. Low molecular weight (MW) organic compounds such as trichloroethylene (TCE), carbon tetrachloride (CT), chloroform (CF) and benzene are serious environmental pollutants. Most are known or suspected carcinogens, neurotoxins and hepatotoxins. TCE is the most common pollutant at US Environmental Protection Agency Superfund sites, so it has received significant research attention. In field studies, it was demonstrated that hybrid poplar trees (*P. trichocarpa* × *deltoides*) can take up and metabolize TCE (Gordon *et al.*, 1997; Newman *et al.*, 1999) and CT (Wang *et al.*, 2004). When the poplar trees were exposed to TCE at levels typical of those in polluted groundwater, the trees were able to take up over 99% of the TCE. Less than 9% of the TCE taken up was transpired, as detected by leaf bag experiments. In order to determine if poplar cells had an inherent ability to degrade TCE and CT or if microorganisms were responsible for the degradation, studies were conducted with pure poplar cells in cell suspension cultures. When these poplar cell cultures were exposed to TCE, the same metabolites were seen that had been seen in the whole-plant studies (Newman *et al.*, 1997; Shang *et al.*, 2001; Shang and Gordon, 2002). Similarly, when

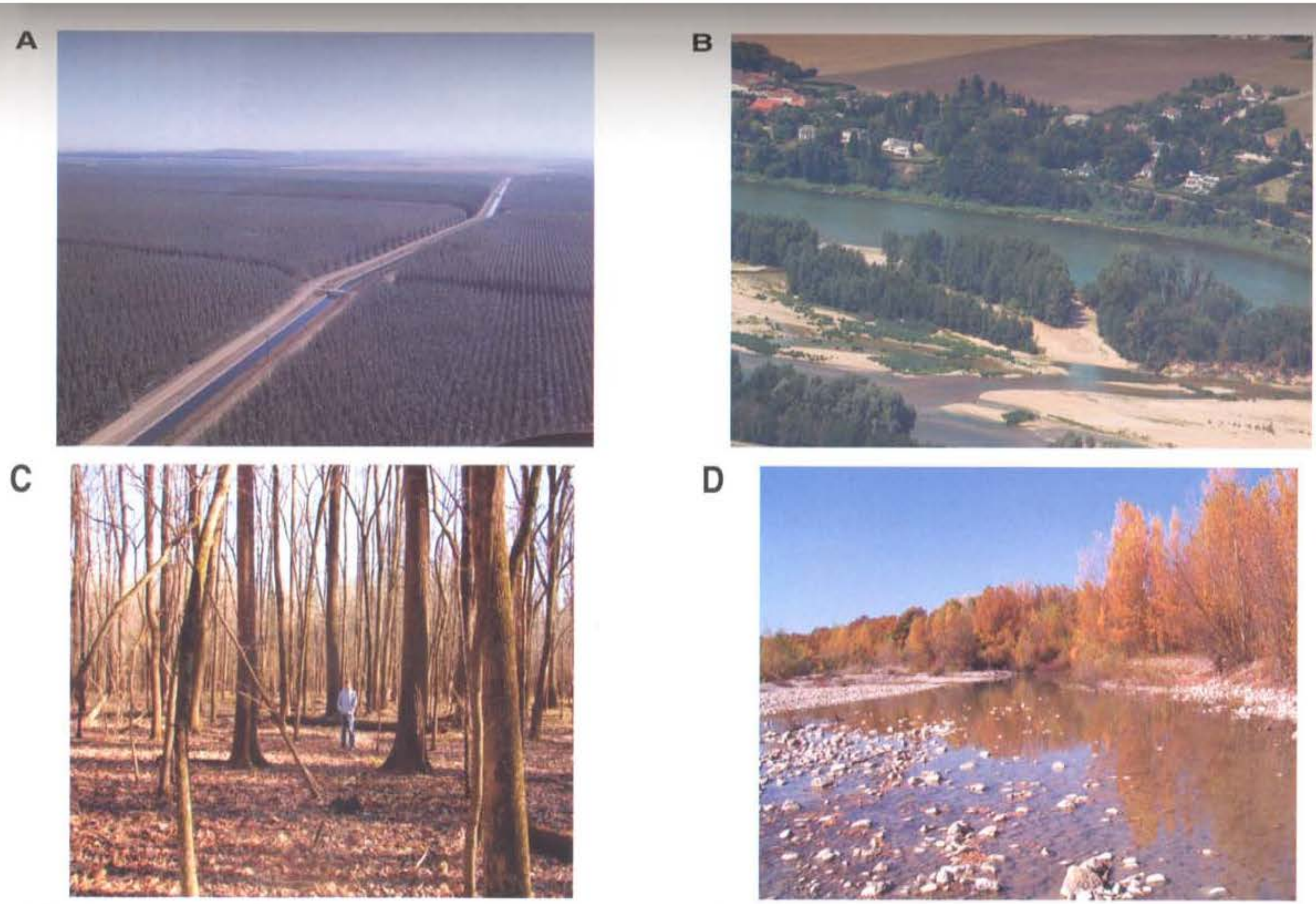

Plate 17. (A) Extensive poplar plantings near Boardman, Oregon, USA. Photo courtesy of Jake Eaton, GreenwoodResources. **(B)** *Populus nigra in situ* conservation unit (Island of Mareau aux Prés, Natural Reserve of St-Mesmin) along the Loire River near Orleans, France. *Populus* genetic resources are often fragmented by agriculture and other human activities. Conservation of this important species has worldwide implications. Photo courtesy of Catherine Bastien, The National Agricultural Research Institute. **(C)** Undomesticated populations are indispensable to the initiation of breeding and varietal development as well as gene conservation programmes. Good examples include *Populus deltoides* from the Mississippi River valley (left) and *Populus nigra* (right) from the Paglia River in central Italy. Photos courtesy of Randy Rousseau, Mississippi State University (left) and Maurizio Sabatti, University of Tuscia (right).

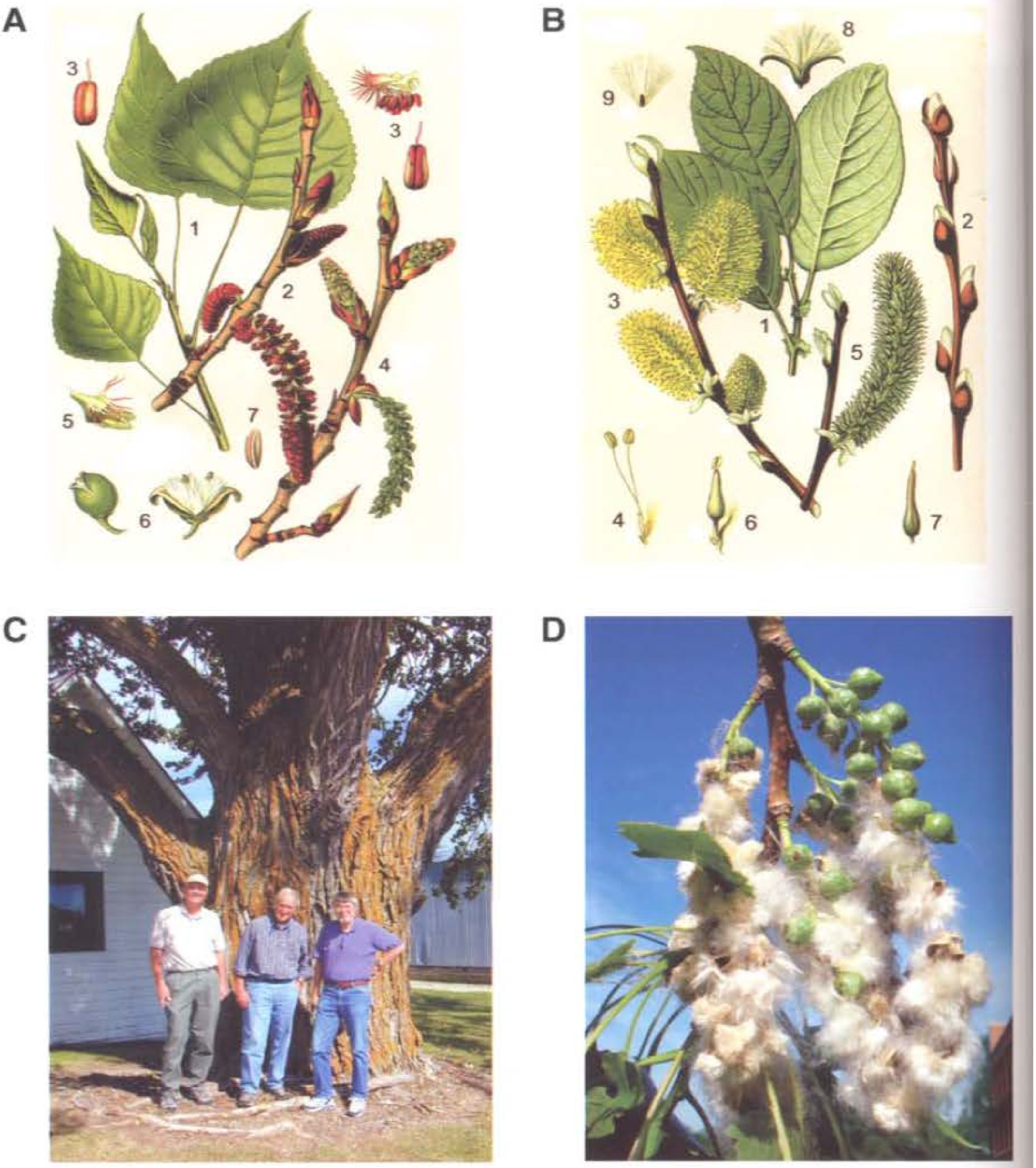

Plate 18. **(A)** Botanical characteristics of a representative poplar, *Populus nigra* (black poplar). 1, Vegetative twig showing rhombic preformed leaf and deltoid neoformed leaf; 2, twig with true terminal bud and male (staminate) catkins in anthesis; 3, male flower and anthers; 4, twig with true terminal bud and female (pistillate) catkins in anthesis; 5, female flower; 6, maturing two-valved capsules: dehiscing capsule (right) shows seeds with cottony coma; 7, seed. Modified from Thomé (1885). **(B)** Botanical characteristics of a representative willow, *Salix caprea* (goat willow). 1, Vegetative twig showing mature leaves and stipules; 2, expanding floral buds (note single bud scale); 3, twig with male (staminate) catkins in anthesis; 4, male flower; 5, twig with female (pistillate) catkin in anthesis; 6, female flower; 7, immature capsule; 8, dehiscing two-valved capsule; 9, seed with cottony coma. Modified from Thomé (1885). **(C)** Specimens of several poplar species, such as this *Populus deltoides*, can grow to large size and may live for several hundred years. Photo courtesy of R. Miller. **(D)** Dehiscing capsules of *Populus deltoides*; the cottony seed soon will take to the air. Photo courtesy of D. Dickmann.

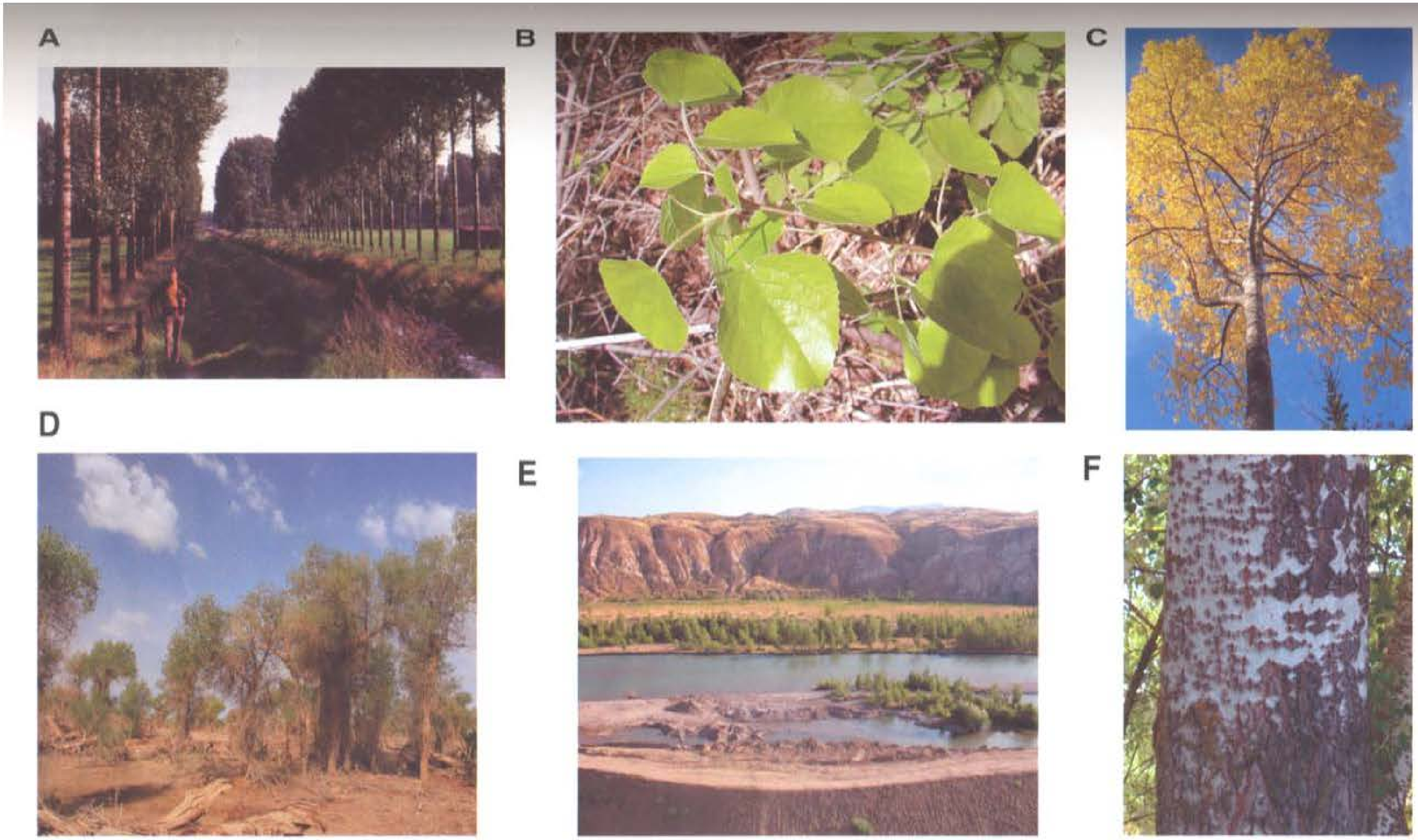

Plate 19. **(A)** The most widely planted hybrid poplar taxon worldwide is *Populus xcanadensis* (*Populus deltoides* x *Populus nigra*), the Euramerican or Canadian poplar, shown here in Belgium. **(B)** The flattened, airfoil-like petioles of poplars in sections *Aigeiros* and *Populus* – shown here by *Populus sieboldii* – cause leaves to characteristically flutter in the wind. **(C)** The usual autumn coloration of poplar leaves is yellow or gold. **(D)** Poplars in section *Turanga* survive in very arid environments, provided their roots can reach the water table. This grove of *Populus euphratica* grows in the Taklamakan Desert in Xinjiang, China. **(E)** Riparian *Populus nigra* impacted by human activity, Turkey. **(F)** Like *Populus alba* shown here, diamond-shaped lenticels and warty outgrowths mark the smooth bark of many poplars. Photos courtesy of D. Dickmann (A, C, F), Maki Laboratory, Tohoku University, Japan (B), Yong-Ling Ow (D) and F. Toplu (E).

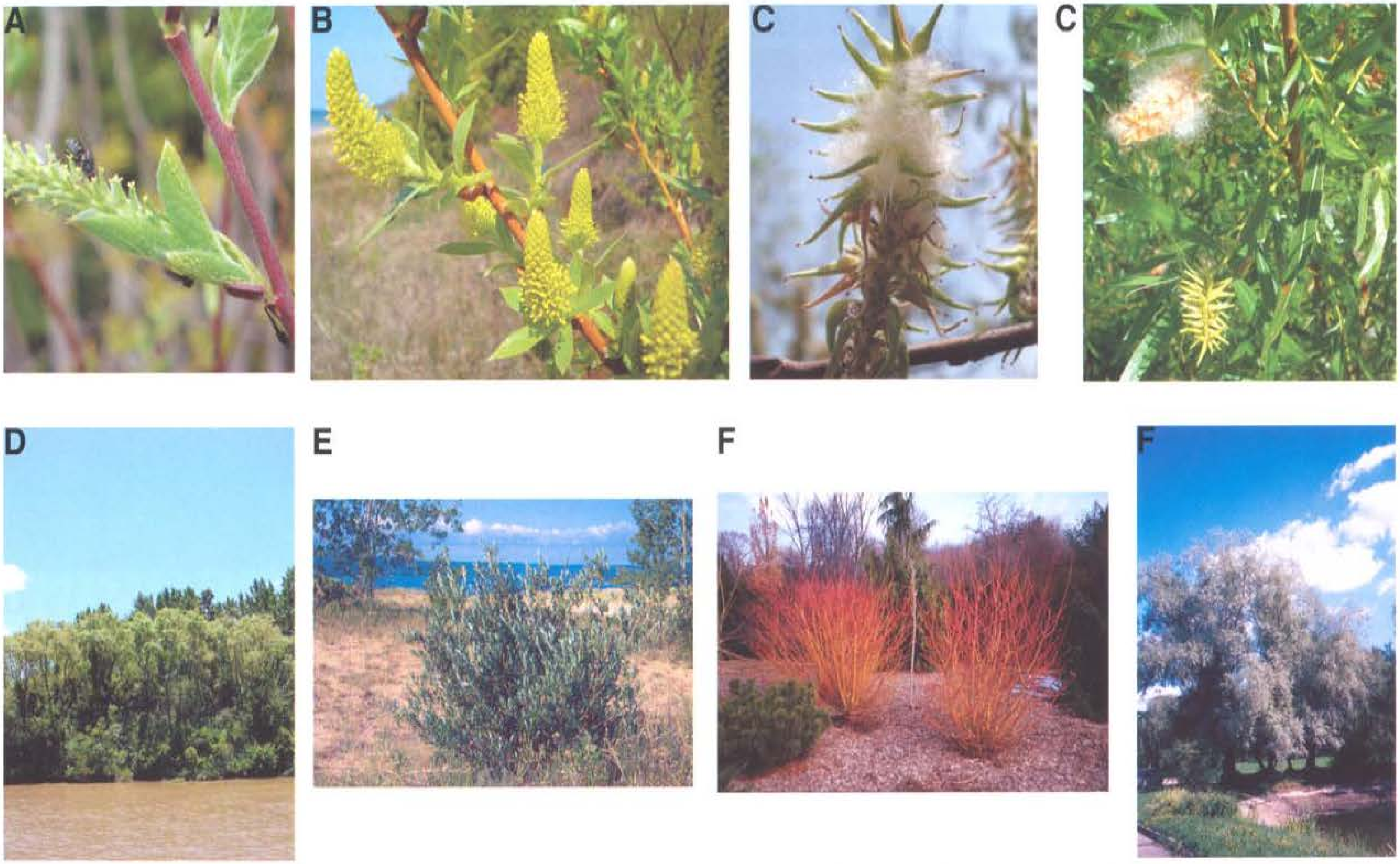

Plate 20. **(A)** A pistillate catkin of *Salix bebbiana* in anthesis. Unlike the wind-pollinated poplars, the flowers of most willows are pollinated by both insects and wind. **(B)** Staminate catkins of *Salix lucida* in anthesis. Note their upright posture and – in this species – the long, foliaceous floral branchlets. **(C)** Reproductive phenology varies among willows, e.g. capsule ripening and dehiscence of *Salix discolor* (left) occur in spring prior to leaf out, whereas in *Salix interior* (right) they occur during early summer after leaves are fully developed. **(D)** *Salix humboldtiana* growing in a seasonally flooded riparian habitat along the Paraná River, Argentina. **(E)** *Salix myricoides* is adapted to drought and heat stress; here it grows on a sand dune on the shore of Lake Michigan, USA. **(F)** Willows are popular ornamentals. Left: Another popular and colourful selection of white willow is *Salix alba* 'Chermesina'. Right: Intense pubescence on both sides of mature foliage produces the striking, silver appearance of *Salix alba* 'Argentea'. Photos courtesy of D. Dickmann (A, B, C) and J. Kuzovkina (D, E, F).

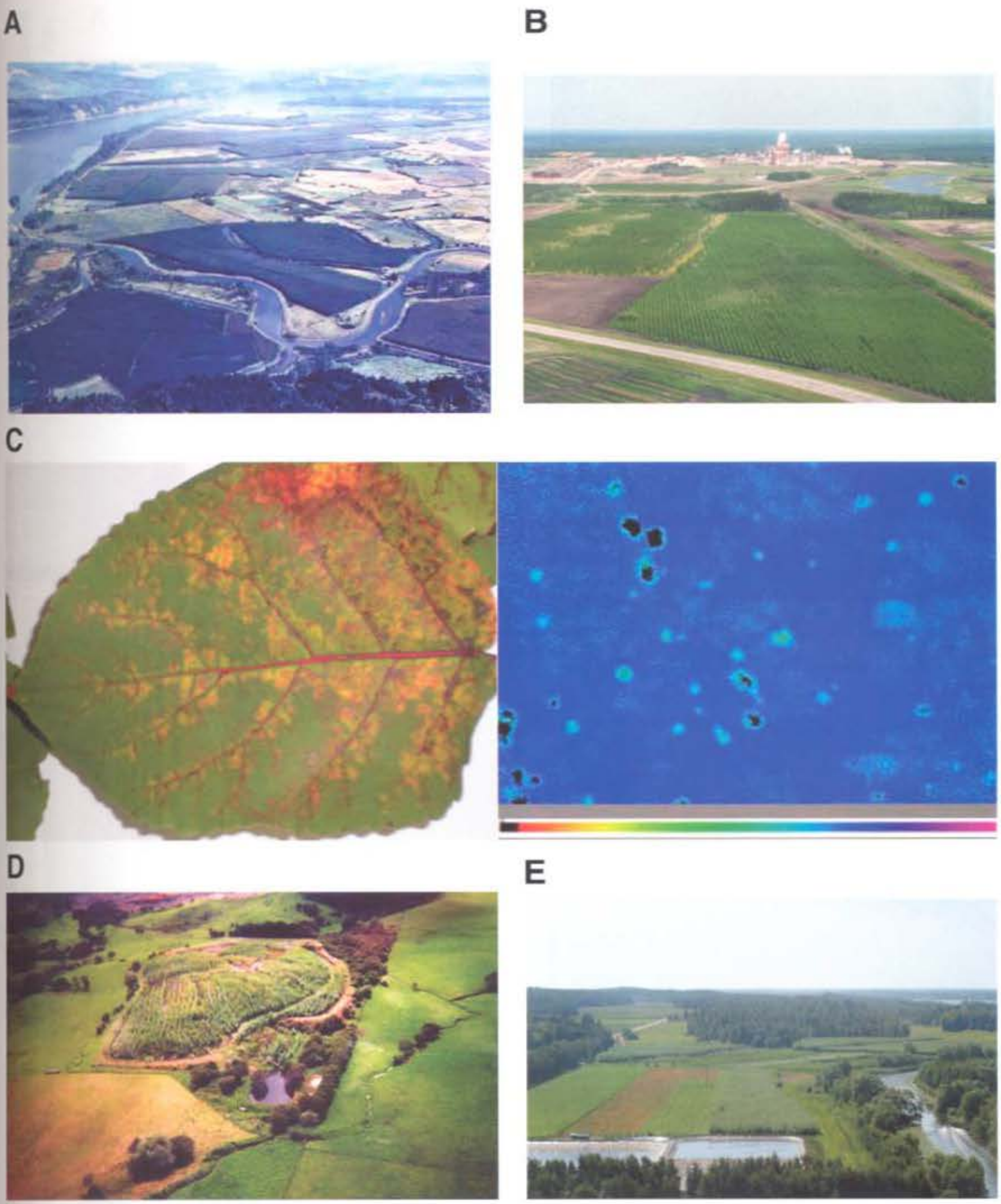

Plate 21. (A) Aerial view of intensively managed *Populus* x*generosa* plantations along the lower Columbia River flood plain west of the Cascade Mountains (Oregon and Washington, USA). **(B)** Large block planting of poplar on private land at Alberta-Pacific Forest Products mill, Canada. **(C)** Effects of cadmium treatment on poplar leaf (left) and chlorophyll fluorescence image (Fv/Fm) after dark adaptation of the same leaf (right). The false colour code depicted at the bottom of the image ranges from Fv/Fm = 0.00 (black) to Fv/Fm = 1.00 (pink). **(D)** Phytoremediation of wood-waste pile, New Zealand. The poplars, mostly *Populus xeuramericana* and *Populus alba* hybrids, are 3 years old. **(E)** Panoramic view of collection ponds for wastewater from wastewater treatment facilities in Enköping, Sweden and short-rotation willow coppice field irrigated with the water. Photos courtesy of GreenWood Resources (A), B. Thomas (B), G. Scarascia-Mugnozza (C), B. Robinson (D) and P. Aronsson (E).

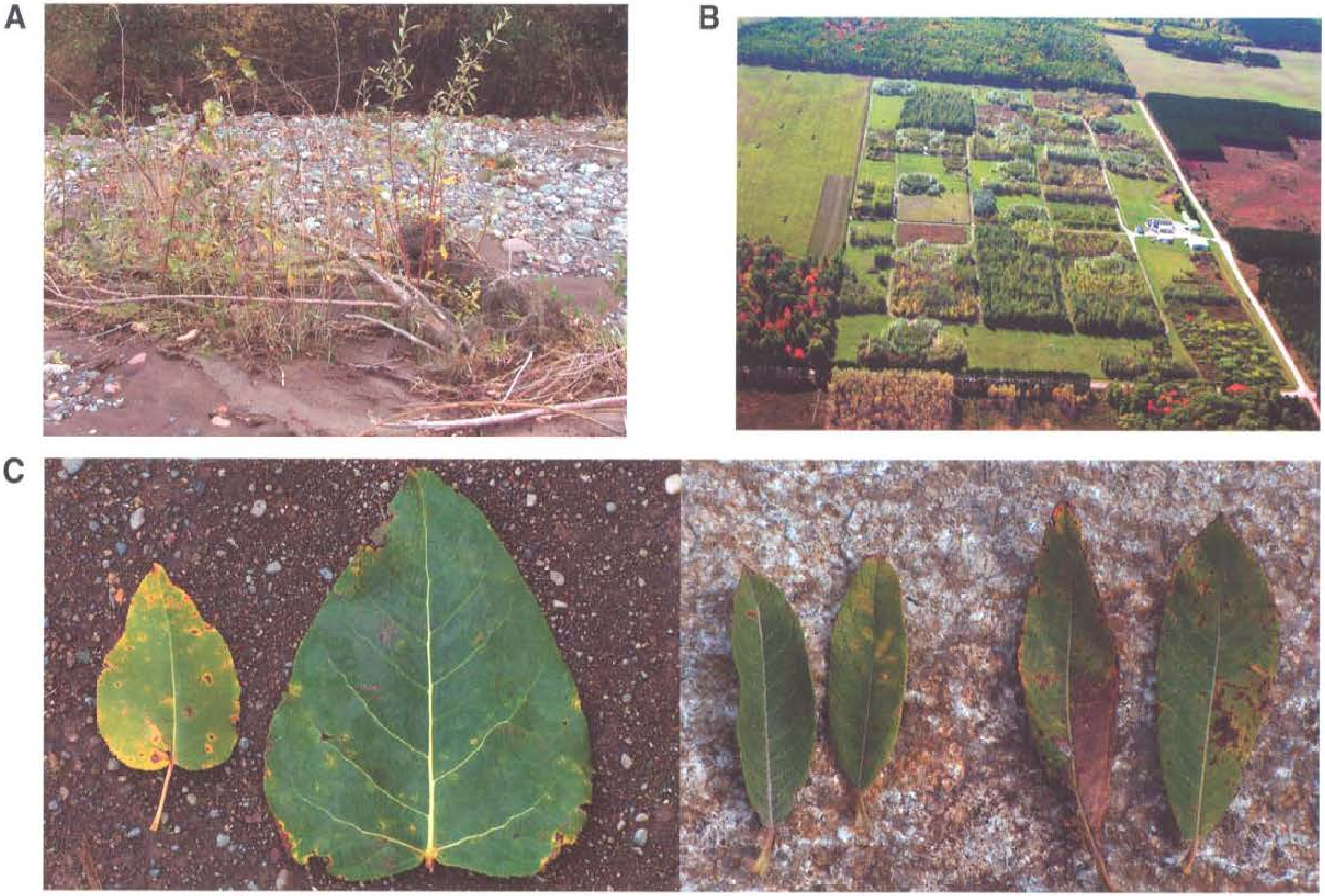

Plate 22. (A) Succession of black cottonwood (*Populus trichocarpa*) and willow (*Salix* spp.) on a gravel bar in the Carbon River, Pierce County, Washington, USA. **(B)** The twelve treatment rings of the aspen FACE experiment are shown here. **(C)** Black cottonwood (*Populus trichocarpa*: left) and willow (*Salix* spp.: right) leaves showing smaller individual leaves on the left in each photograph resulting from poor fertility. Photos courtesy of Jon D. Johnson (A, C) and R. Anderson (B).

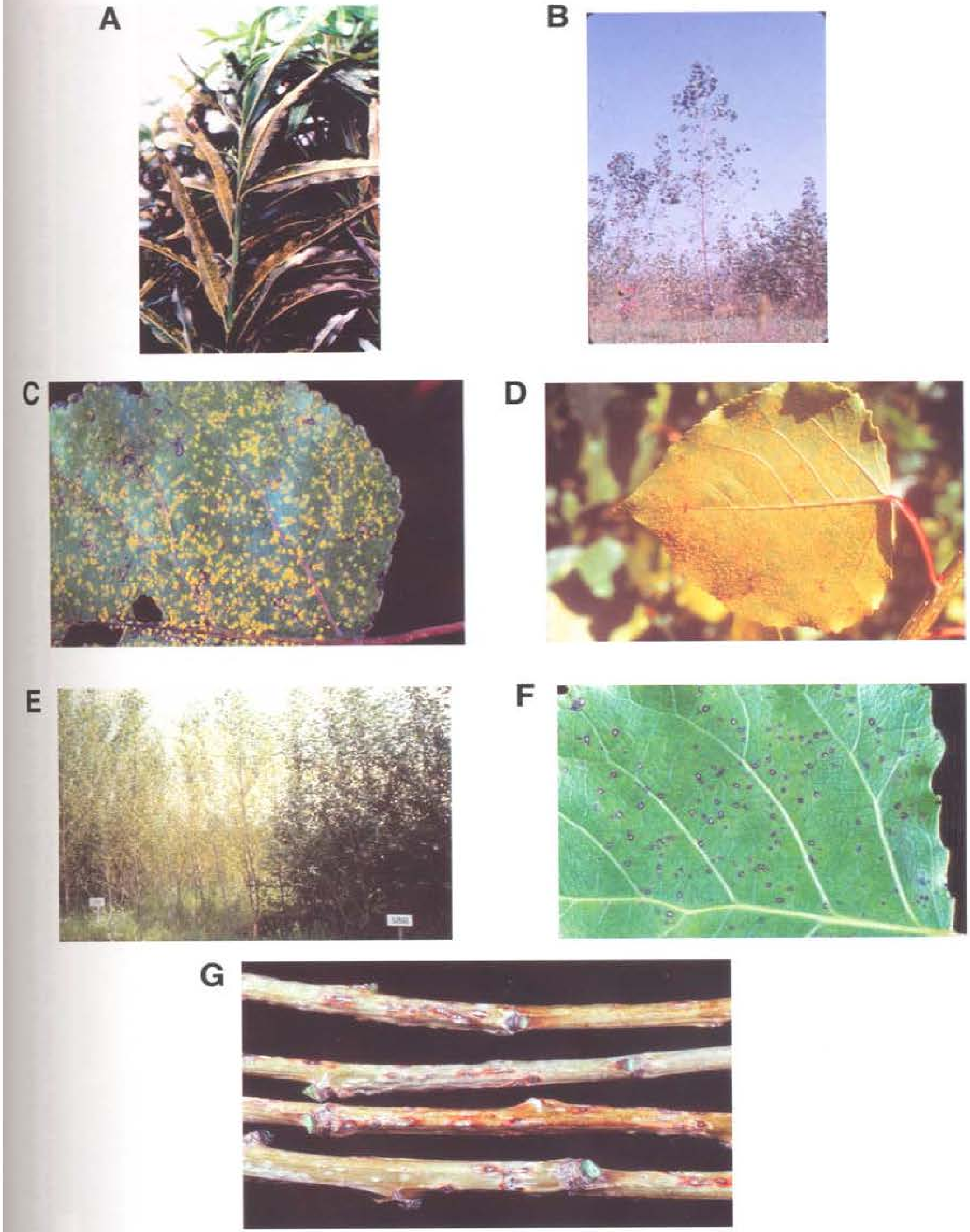

Plate 23. **(A)** *Melampsora* leaf rust on willow. **(B)** Defoliation of highly susceptible poplar by *Melampsora* leaf rust. **(C)** Leaf disease of poplar caused by *Melampsora medusae.* **(D)** *Melampsora medusae* uredinia on poplar. **(E)** Defoliation of poplar clone (left) affected by *Marssonina brunnea.* **(F)** Leaf spots caused by *Marssonina brunnea.* **(G)** Stem lesions caused by *Marssonina brunnea.* Photos courtesy of M. Ramstedt (A) and M. Ostry (B, C, D, E, F, G).

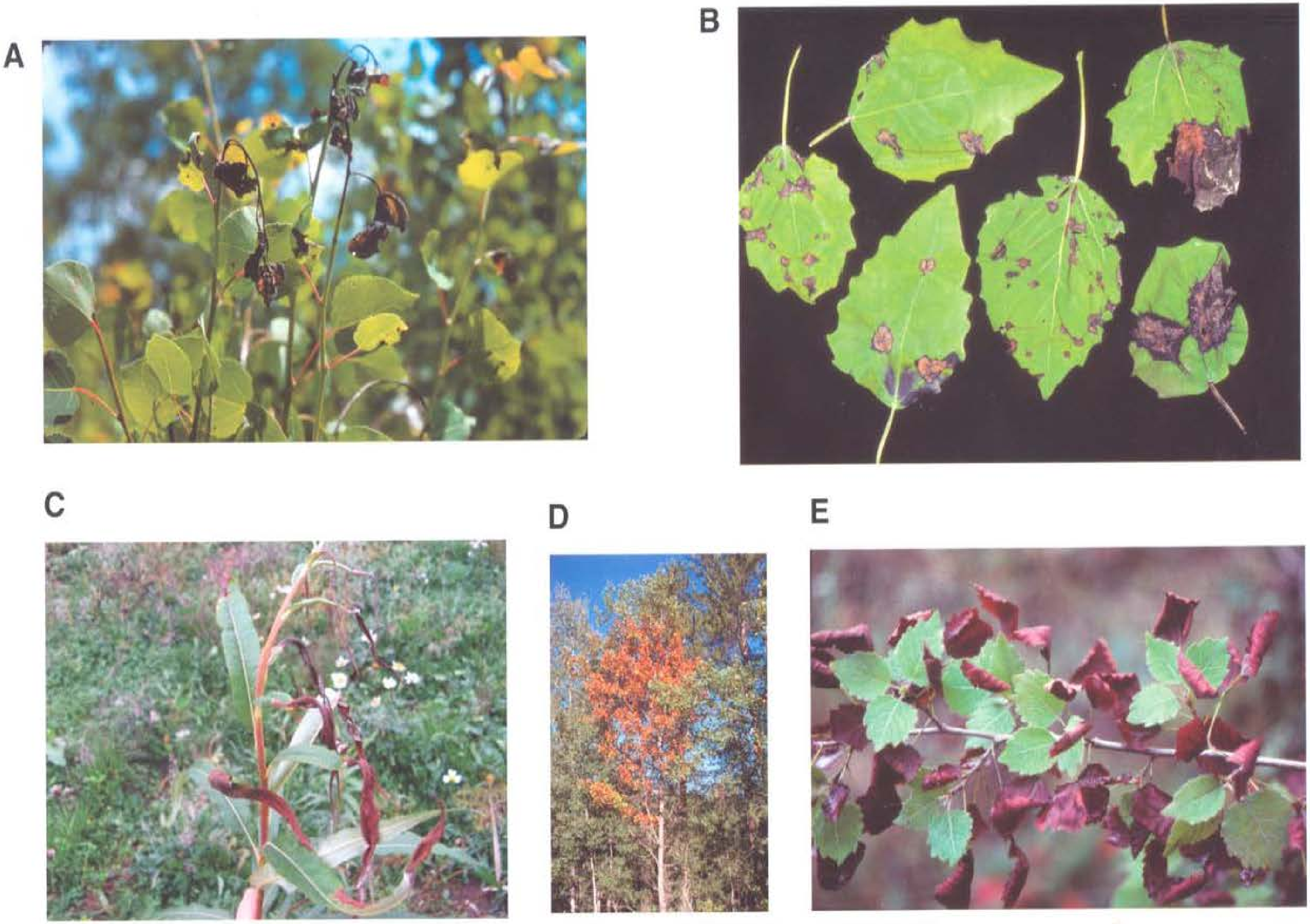

Plate 24. (A) *Venturia* shoot blight of poplar. **(B)** *Venturia* leaf blight. **(C)** *Fusicladium* willow scab. **(D)** Bronze leaf disease of hybrid aspen. **(E)** Leaf symptoms of bronze leaf disease caused by *Apioplagisostoma populi.* Photos courtesy of M. Ostry (A, B, D, E) and M. Ramstedt (C).

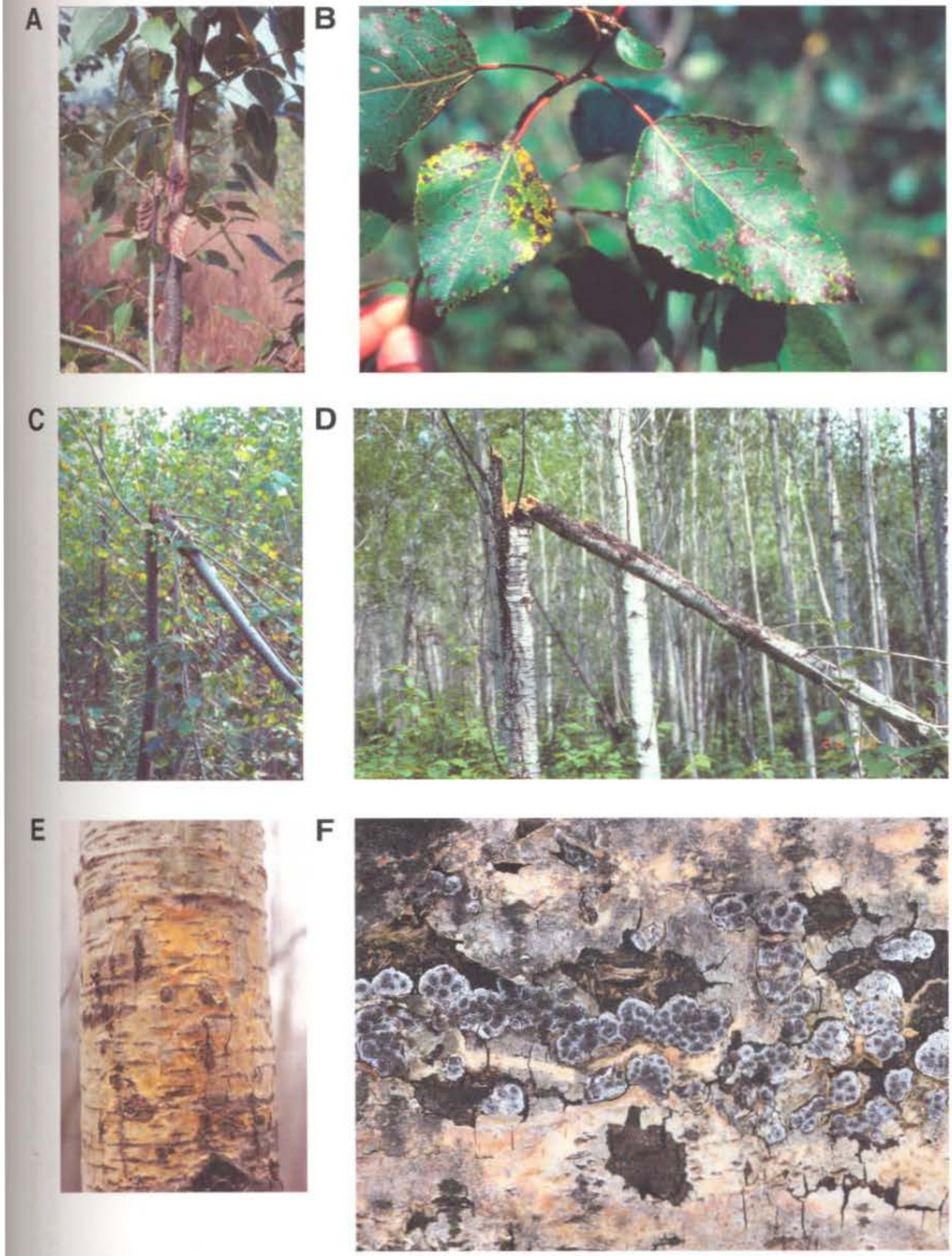

Plate 25. **(A)** *Septoria* canker on poplar. **(B)** *Septoria* leaf spot on poplar. **(C)** Stem breakage of poplar at *Septoria* canker. **(D)** Stem breakage at *Hypoxylon* canker. **(E)** *Hypoxylon* canker on aspen. **(F)** Perithecia of *Entoleuca mammata*. Photos courtesy of M. Ostry.

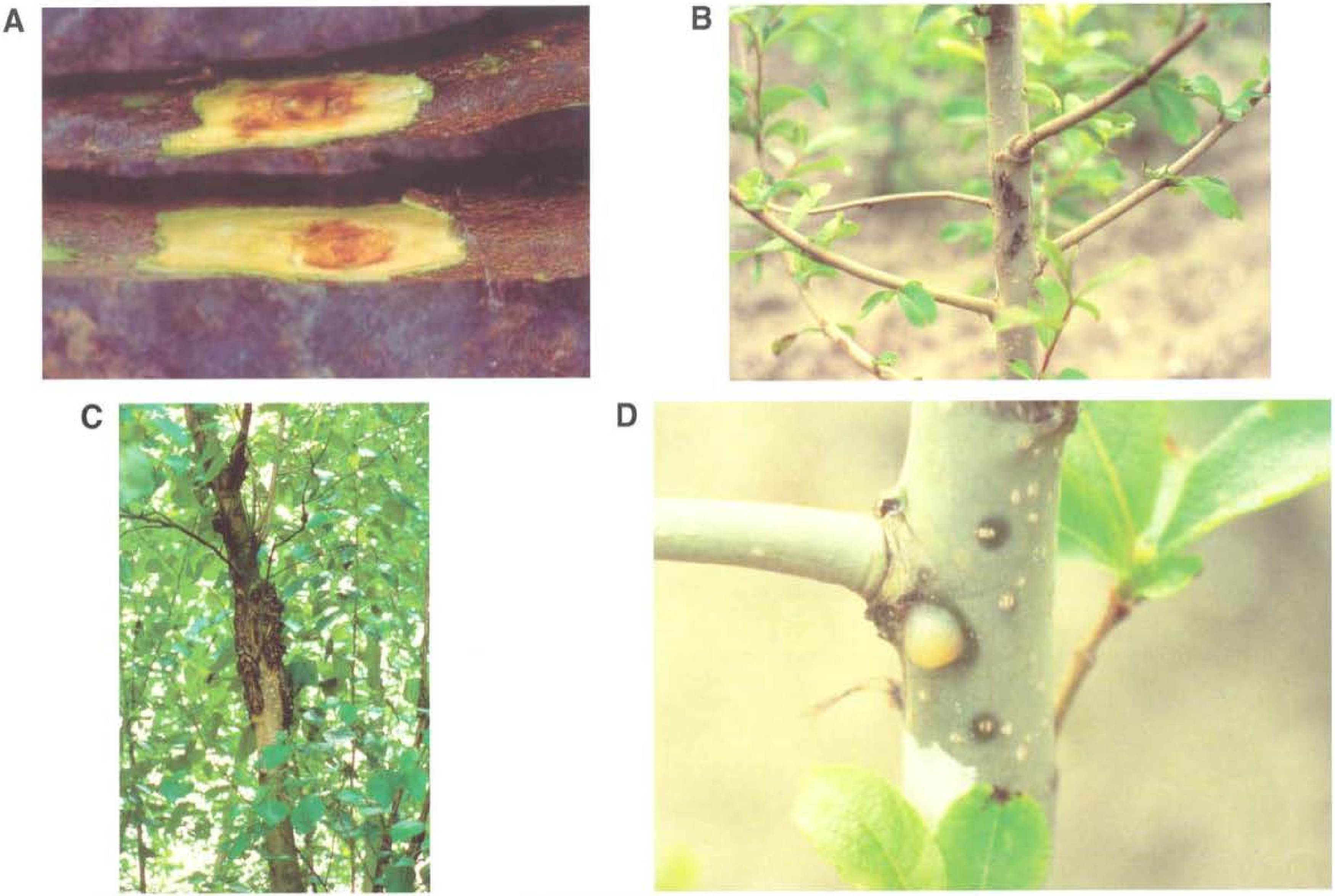

Plate 26. (A) Stem necrosis on willow caused by *Pseudomonas syringae.* **(B)** Young bacterial stem canker. **(C)** Old bacterial canker and rough bark of affected stem. **(D)** Bacterial droplet of a young stem canker. Photos courtesy of M. Ramstedt (A) and M. Ostry (B, C, D).

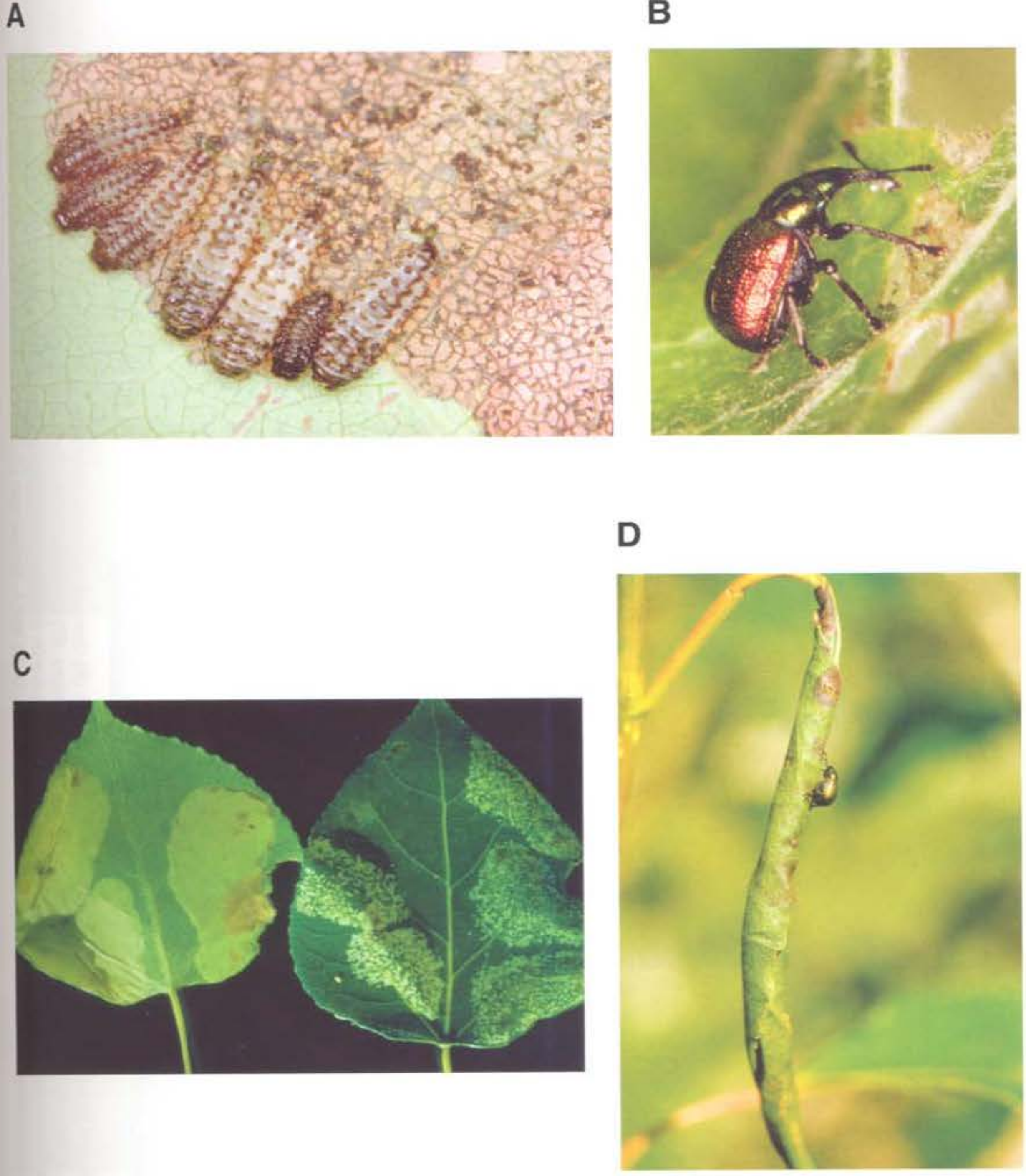

Plate 27. (A) Damage caused by leaf feeders – *Phratora vitellinae* larvae skeletonizing leaf. **(B)** Damage caused by leaf feeders – *Byctiscus populi* adult and feeding damage. **(C)** Damage caused by leaf miners – poplar leaves mined by individual *Phyllonorycter* sp. larvae. **(D)** Damage caused by leaf feeders – *Byctiscus populi* adult on 'rolled' leaf containing eggs. Photos courtesy of A. Delplanque (A, B, D) and L. Nef (C).

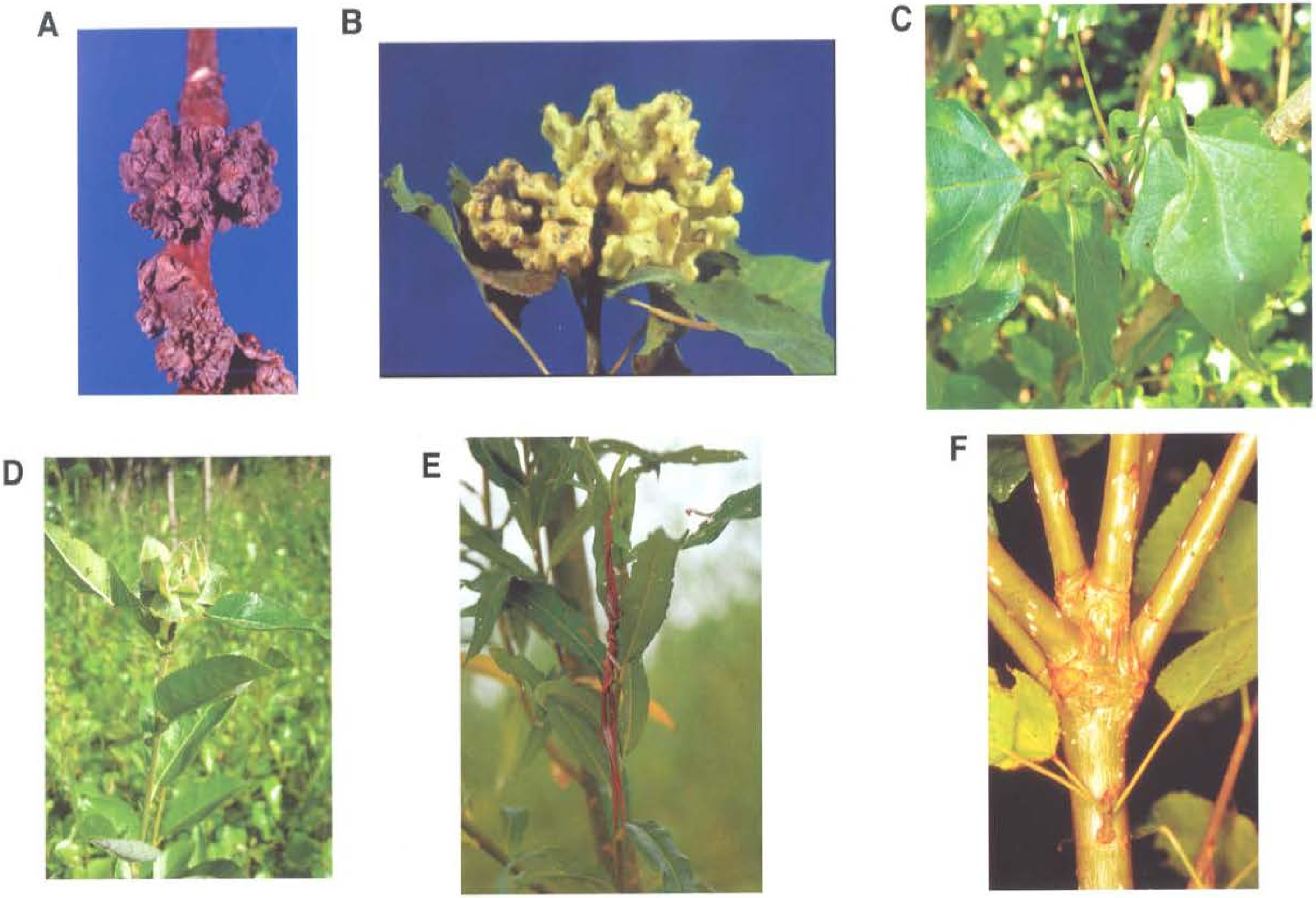

Plate 28. (A) Damage caused by gall formers. Galls caused by *Aceria parapopuli*. **(B)** Damage caused by gall formers. Galls caused by *Mordwilkoja vagabundus*. **(C)** Damage caused by gall formers. Galls caused by *Pemphigus spirothecae* on *Populus nigra*. **(D)** Damage caused by bud and young shoot feeders. *Rabdophaga rosaria* on *Salix myrsinifolia*. **(E)** Damage caused by bud and young shoot feeders. *Byctiscus betulae* on *Salix* sp. **(F)** Damage caused by bud and young shoot feeders. *Gypsonoma aceriana* damage to young poplar shoot. Photos courtesy of L. Nef (A, B), S. Augustin (C, D, E) and A. Delplanque (F).

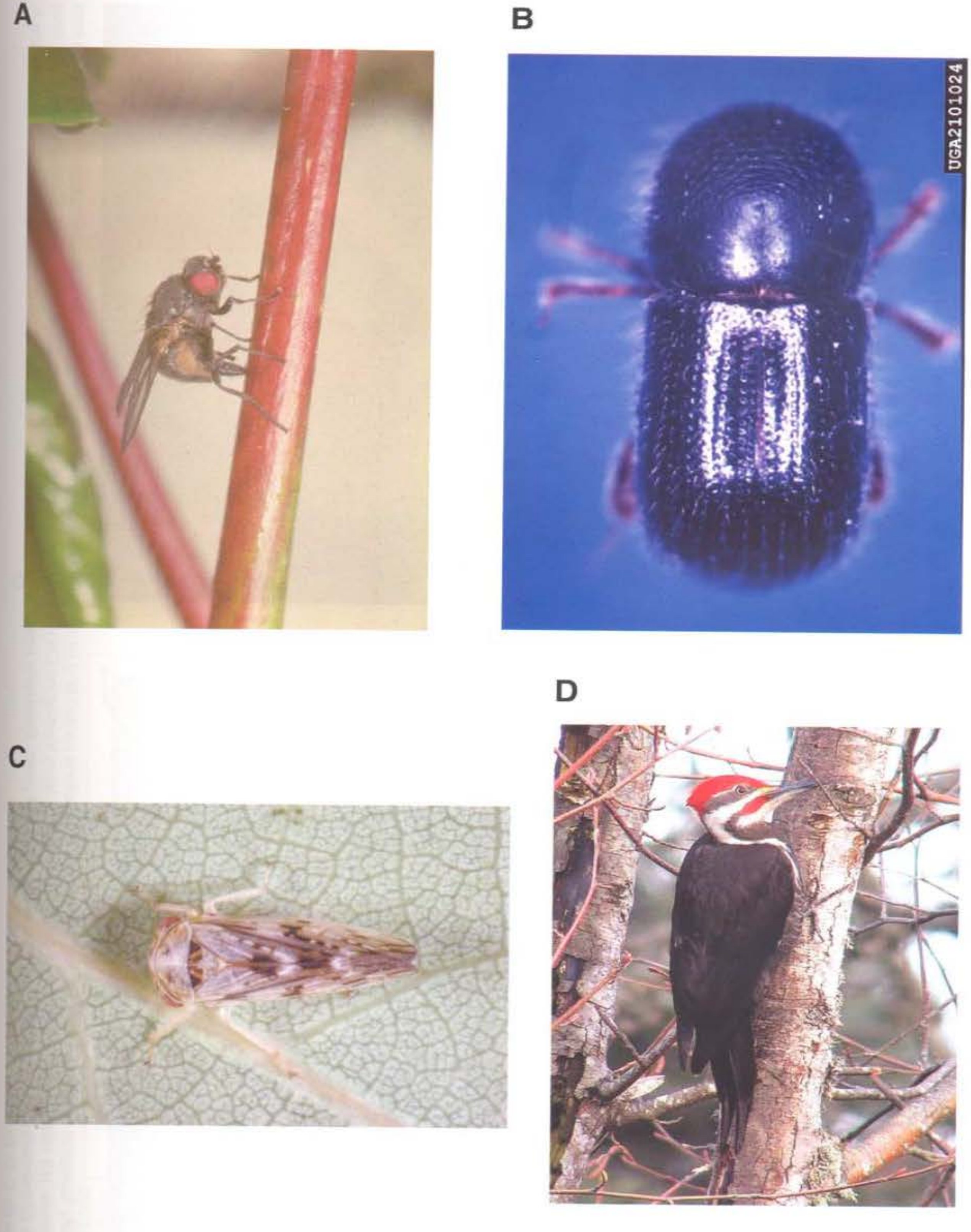

Plate 29. (A) Disease vector, *Phytobia cambii.* **(B)** Disease vector, *Xyleborus dispar.* **(C)** Disease vector, *Rhytidodus decimus.* **(D)** Damage caused by mammals and birds, pileated woodpecker. Photos courtesy of M. Martinez (A), Daniel Adam, Office National des Forêts, Bugwood.org (B), A. Delplanque (C) and J. Charles (D).

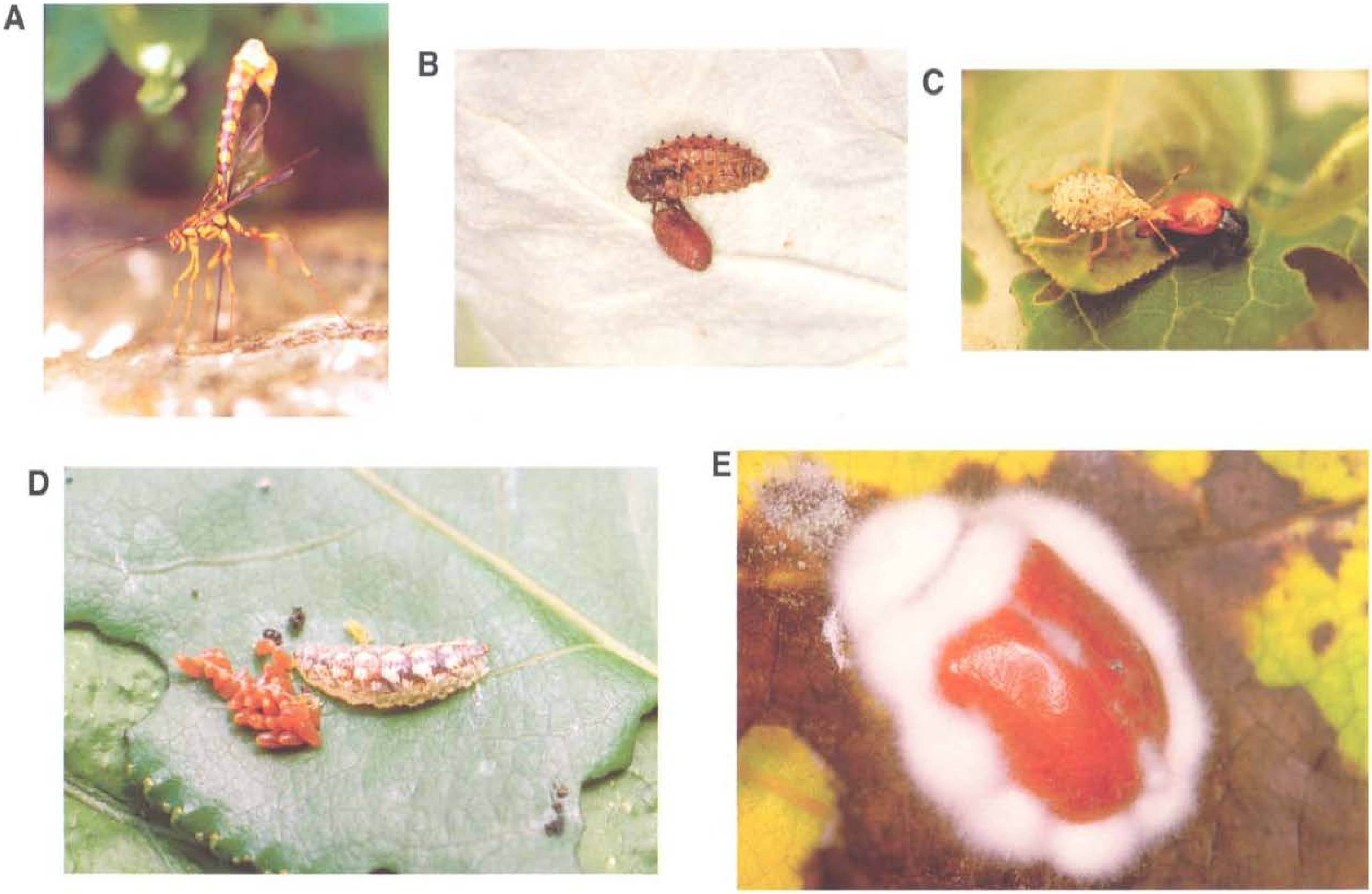

Plate 30. (A) Biological control of insect pests. *Megarhyssa praecellens* parasitizing larva of *Tremex fuscicornis*. **(B)** Biological control of insect pests. Tachinid pupa from *Phratora* larvae. **(C)** Biological control of insect pests. *Arma custos* larva feeding on *Chrysomela tremulae*. **(D)** Biological control of insect pests. *Episyrphus balteatus* larva feeding on *Chrysomela populi* eggs. **(E)** Biological control of insect pests. *Beauveria bassiana* on *Chrysomela tremulae*. Photos courtesy of P. Parra Sanhueza (A) and A. Delplanque (B, C, D, E).

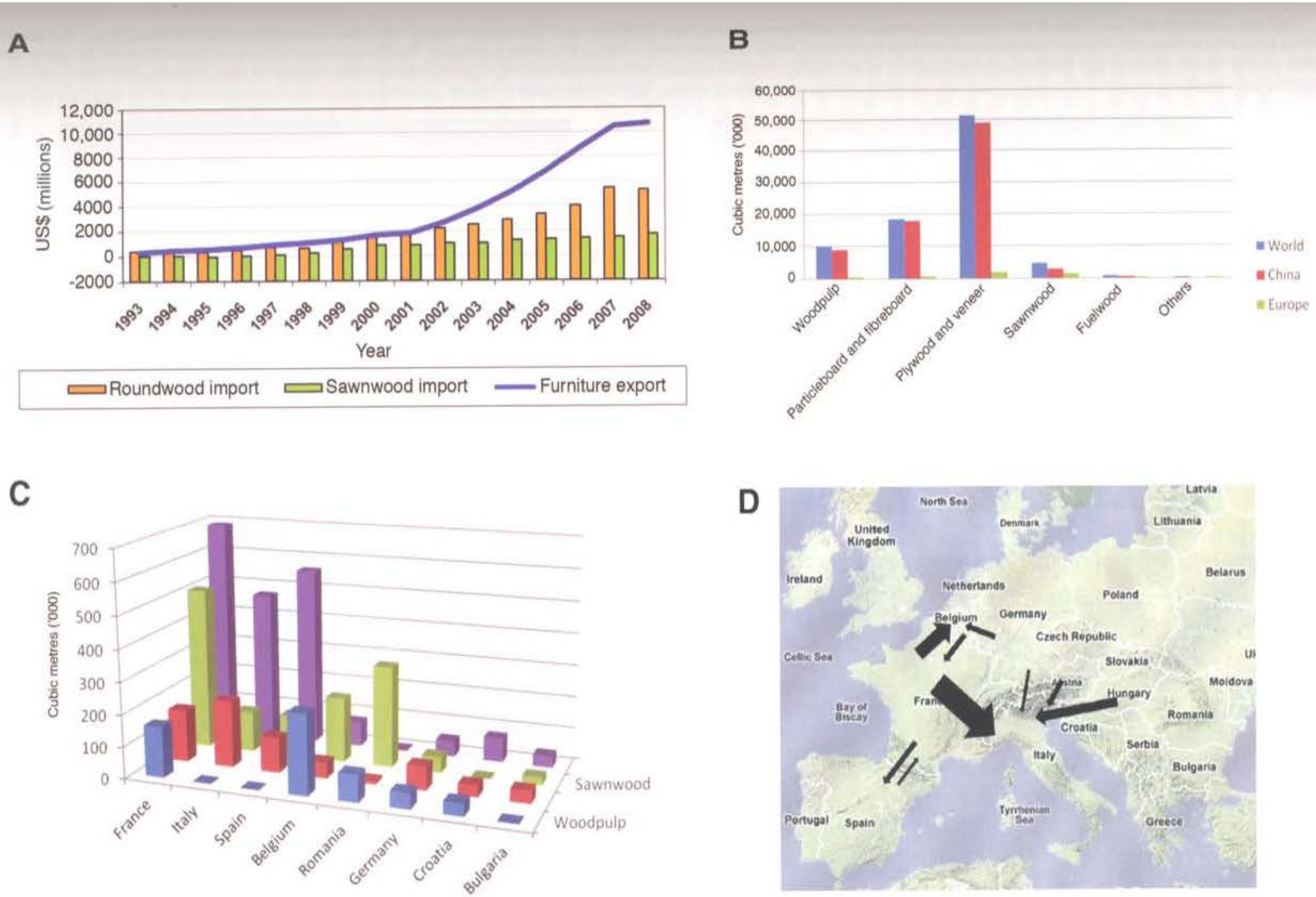

Plate 31. **(A)** Trade trend of roundwood, sawn wood and furniture in China. Data source: SFA (2006, 2009a). **(B)** Importance of China in the production of poplar products in the world. Data source: FAO (2008). **(C)** Production of processed poplar products, 2007. Data source: FAO (2008). **(D)** Major flows of poplar roundwood and sawn wood in Europe, 2010.

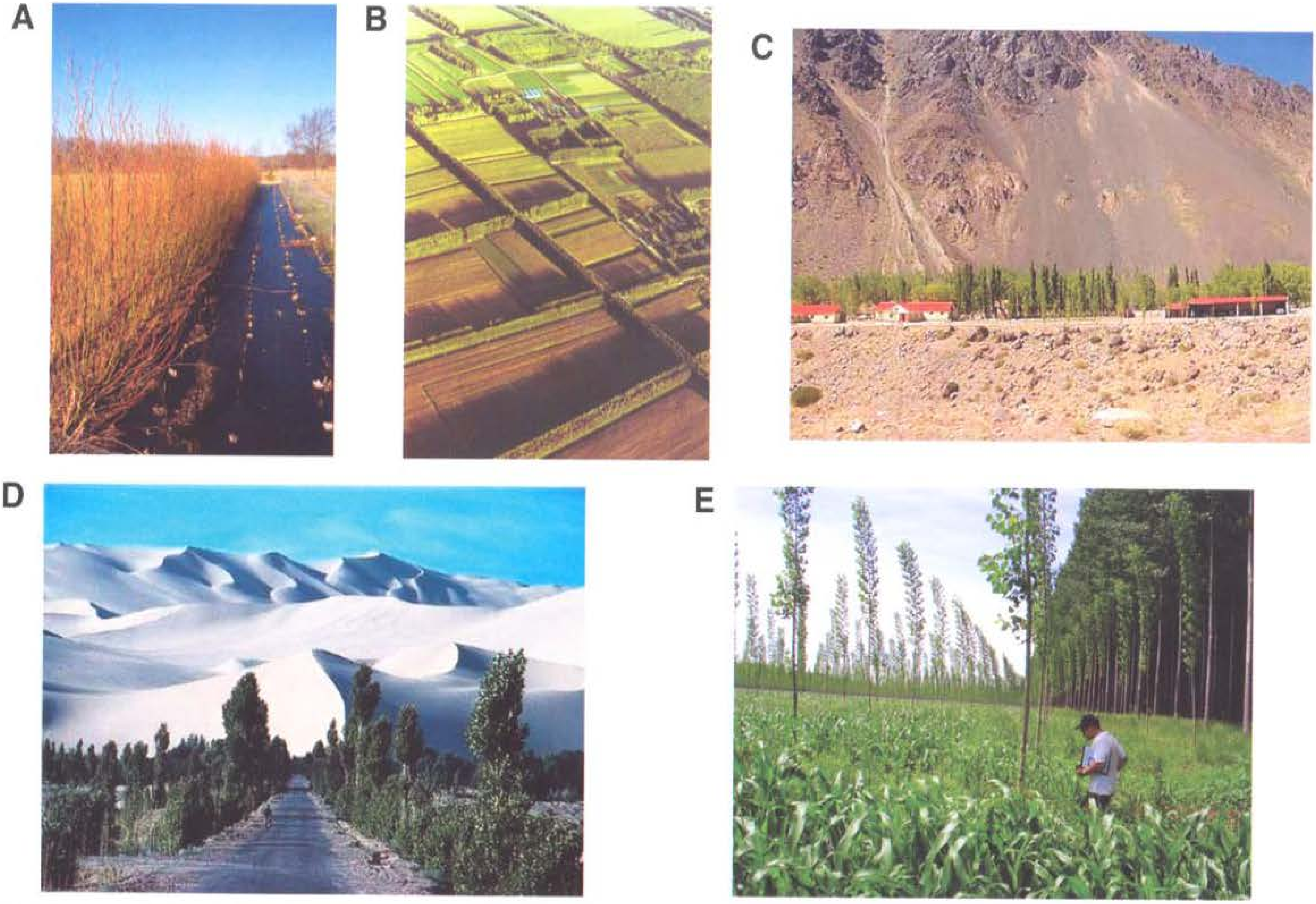

Plate 32. **(A)** The production of willow for various types of furniture and baskets. **(B)** Poplar shelterbelts protect against hot, dry winds and increase humidity, soil moisture and crop yields. **(C)** *Populus alba* and *Salix babylonica* shelter a remote government outpost at around 3000 m in the Andes of Argentina. **(D)** A living, green wall of poplar trees fends off the encroaching desert in Inner Mongolia, northern China. **(E)** Poplars (and willows), trees for society and the environment. Photos courtesy of Fairchild Farms, Canada (A), FAO/Three North Shelterbelt Bureau (B), FAO/J. Carle (C), J.E. Jacquot, http://www.treehugger.com/files/2007/06/living_green_wall.php (D) and FAO (E).

poplar culture cells were dosed with CT, metabolism was clearly evident. The metabolism of TCE and CT by poplar cells is similar to that in mammalian cells. In mammals, the first step in the pathway is initiated by the cytochrome P450 2E1 enzyme, resulting in the TCE metabolites, chloral, trichloroethanol and trichloroacetic acid, and the CT metabolites, chloroform and carbon dioxide (Wang *et al.*, 2002). When the poplar culture cells were exposed to radiolabelled TCE (Newman *et al.*, 1997) or CT (Wang *et al.*, 2002), low levels of radiolabelled carbon dioxide were produced, indicating that poplar cells had the capacity to mineralize these pollutants. Not only do the poplar and mammalian pathways result in the same metabolites but also the CT (Wang *et al.*, 2002) reaction and TCE (S. Doty, 2012, unpublished results) reactions are blocked by the same inhibitors as in mammals. Therefore, the reactions are carried out by similar enzymes.

Most phytoremediation studies that investigated removal of TCE used one or two genotypes of poplar. In a recent study funded by the US National Science Foundation, 9 poplar and 12 willow varieties were chosen for their previous success in phytoremediation efforts or local native significance, and experiments were conducted to compare toxicity, uptake and degradation of TCE (Miller *et al.*, 2011). Although many of the genotypes removed TCE from solution, there was a wide range in the ability of plants to degrade TCE. A wild willow clone showed the highest level of TCE metabolism. There was a sixfold range in the ability of five different clones of *P. deltoides* to degrade TCE. It was speculated that differences in the expression of key enzymes involved in TCE metabolism might explain the different abilities of varieties of the same species.

Another important class of environmental pollutants for which poplar and willow can be used for remediation are the explosives, 2,4,6-trinitrotoluene (TNT), hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX) and octahydro-1,3,5,7-tetranitro-1,3,5,7-tetraazocine (HMX). More than 100 military bases and explosives manufacturing facilities in the USA are contaminated with these chemicals. The groundwater at these sites is contaminated; therefore, the health risk is spread beyond the military bases themselves (Rivera *et al.*, 1998). Research with aquatic plants demonstrated that plants could transform (metabolize) TNT in the absence of microorganisms (Hughes *et al.*, 1997). Both poplar and willow have been used in munitions remediation research. Hybrid poplar (*P. deltoides* × *P. nigra*) was able to take up TNT from hydroponic solution but did not seem to translocate it (Thompson *et al.*, 1998). Using radiolabelled TNT, the authors demonstrated that about 75% of the radiolabel remained in the root tissue even after 42 days, while 10% was translocated to the foliage (Thompson *et al.*, 1998). In soil, the hybrid poplar was less able to remove the TNT, leaving behind 75% of the TNT after a 20-day period. The hybrid poplar metabolized the TNT to 2-ADNT and 4-ADNT and to a number of unidentified compounds. In a study comparing phytoremediation of TNT by hybrid willow (*Salix* clone 'EW-20') and Norway spruce (*Picea abies*), it was shown that nearly half of the aboveground radiolabelled TNT was in bark-free wood of willow compared with about 60% of it in the older needles of spruce (Schoenmuth and Pestemer, 2004). Both tree species readily metabolized TNT.

Polycyclic aromatic hydrocarbons (PAHs) are also prevalent environmental pollutants. PAHs are characterized by low solubility, high soil sorption, hydrophobicity and long half-life for the higher MW PAHs. This class of aromatic hydrocarbons consists of three or more fused benzene rings in linear, angular or cluster arrangements. Some examples of the EPA priority PAHs and their ring structure include naphthalene, anthracene and phenanthrene (3 rings each), fluoranthene, pyrene and benz[a]anthracene (4 rings each), benzo[a]pyrene (5 rings) and benzo[ghi]perylene (6 rings). Since PAHs are lipophilic, adsorption to root surfaces may be another important first step in phytoremediation (Schwab *et al.*, 1998). Ballach *et al.* (2003), Wittig *et al.* (2003) and Kuhn *et al.* (2004) conducted a three-part investigation into the use of poplar cuttings for PAH removal. *P. nigra* cuttings caused a reduction in the amounts of the PAHs, anthracene, phenanthrene, pyrene, fluoranthene, chrysene and benzo[a]pyrene. An extensive field study was conducted using poplar trees to reduce PAH concentration in groundwater (Widdowson *et al.*, 2005). The researchers determined that concentrations began to fall at the time the poplar roots reached the saturated zone, approximately 1 year after planting, and that a variety of factors including rhizospheric microorganisms, plant uptake, phytovolatilization and biodegradation contributed to the decrease in PAH concentration.

Willow has also been used in phytoremediation of this class of pollutants, but with variable success. A stand of willow (*S. viminalis* L. Orm) was used in a field trial for remediation of a site contaminated with PAHs, mineral oil and heavy metals (Vervaeke *et al.*, 2003). After 1.5 years, the plot that was planted with willow removed 23% of the PAHs compared with the unplanted plot that removed 32%. Perhaps the failure of the willow to remove the PAHs at this site was due to the compounding problems of heavy metals and mineral oil. In a study using PAH-contaminated soil from a gas plant, Spriggs *et al.* (2005) determined that black willow (*S. nigra* Marshall) outperformed poplar, ash and the unplanted controls in the degradation of PAHs. In a hydroponic study, willow plants were exposed to a variety of PAHs. Naphthalene killed the plants, while benzo(a)pyrene and phenanthrene had no effect on willow growth. However, in a related study, several willow clones took up naphthalene readily but stalled after 3 days with phenanthrene and pyrene due to severe phytotoxicity (Z. Khan and S. Doty, 2012, unpublished results). Given the wide genetic diversity in willow species, it is not surprising that different varieties would have greatly different abilities in the tolerance and degradation of toxic pollutants.

Poplar and willow have been tested for the ability to take up and degrade a variety of other organic pollutants, including methyl-tert-butyl ether (MTBE), petroleum, ethylene dibromide, dibromochloropropane, pentachlorophenol, trichloroethane, formaldehyde and chlorinated benzenes and toluenes (Newman *et al.*, 1998). In a laboratory-scale phytoremediation study with willow (*S. babylonica*), Corseuil and Moreno (2001) found that willow cuttings could remove more than 99% of the ethanol and benzene in less than 1 week from hydroponics. In a screening study to select clones for petroleum remediation, poplar and willow had high survival rates in soil that was heavily contaminated with petroleum hydrocarbons. For example, the commercial poplar clones, 'NM6' and 'DN34', had 88% and 89% survivability, respectively, as 20 cm cuttings in the contaminated soil. The willow clones, 'Sx61' and 'SV1', had survivability of 63% and 49%, respectively. Overall, poplar and willow have excellent potential to be used successfully for the phytoremediation of a wide range of organic pollutants.

PHYTOREMEDIATION OF INORGANIC ENVIRONMENTAL POLLUTANTS WITH POPLAR AND WILLOW. Remediation of metals presents a different challenge, since the pollutants cannot be metabolized but must instead be translocated to the foliage, where it is harvested more easily or volatilized, such as in the case of mercury. Although most research in this area has focused on natural hyperaccumulating plants, both poplar and willow have been used with some success, as their higher biomass may compensate for the lack of hyperaccumulation ability. In a review by Pulford and Watson (2003), willow is specifically suggested for the phytoremediation of heavy-metal-contaminated lands. Since successful phytoremediation of inorganics relies on the ability of the plant to regrow readily after the upper foliage is harvested to remove the extracted metals, willow is especially well suited for this type of remediation. In a paper by French *et al.* (2006), *Salix*, *Populus* and *Alnus* were compared in a study on the remediation of brownfield land. The five willow clones and *Larix* were able to concentrate copper. Four of the *Salix* clones also concentrated cadmium and zinc up to 13 times higher than the soil concentration levels. Since willow is a fast-growing, high biomass tree, these data are encouraging that cadmium, one of the most serious metal pollutants, could be remediated successfully.

ENHANCING PHYTOREMEDIATION CAPABILITY USING TRANSGENICS. Although trees are capable of reducing the levels of pollutants at contaminated sites, the rates of pollutant removal are not high enough to be of practical value in many circumstances. Other reasons for the genetic engineering of plants for phytoremediation are that some pollutants are too toxic or at too high concentrations for the plants to survive; the plant species that can metabolize the pollutant are not suited for the climate or environment of the contaminated site; or there is no known plant that can remediate a particular chemical. In a modelling study of phytoremediation effectiveness, it was shown that the plantation size that would be required to remediate a plume of

TCE effectively could be quite large and was dependent on a variety of hydrologic factors as well as the length of the dormancy period of the trees (Matthews *et al.*, 2003). A variety of genetic strategies for enhancing phytoremediation have been proposed (Stomp *et al.*, 1994). A simple strategy is to infect the plants with *Agrobacterium rhizogenes*, a soil bacterium that transfers DNA encoding auxin synthesis genes into plant cells. Once the genes are incorporated into the plant genome, the plant expresses the auxins and root development is initiated (Costantino *et al.*, 1994). Poplar is susceptible to *A. rhizogenes*, resulting in a larger root mass (Pythoud *et al.*, 1987). However, these plants are often dwarfed with altered leaf morphology, limiting their practical use.

A more direct method for enhancing the effectiveness of phytoremediation is to overexpress in transgenic trees the genes involved in metabolism or transport of specific pollutants (reviewed in Doty, 2008; Dowling and Doty, 2009; Dhankher *et al.*, 2011). This can be readily achieved by using *Agrobacterium tumefaciens*-mediated plant transformation. Depending on the hybrid and particular clone, reasonable transformation frequencies can be achieved (Han *et al.*, 2000). Increasing the metabolism of the pollutant can cause a strong enough concentration gradient that allows the plant to remove far more of the pollutant than a non-transgenic plant removes. For example, when the cytochrome P450 2E1 gene (*CYP2E1*) was overexpressed in tobacco plants, the transgenics removed 98% of the ethylene dibromide, a substrate of P450 2E1, compared with 63% removal by the null vector control plants (Doty *et al.*, 2000). When the gene was overexpressed in hybrid poplar (*P. tremula* × *alba*), TCE metabolism was strongly enhanced (Doty *et al.*, 2007). Other substrates of P450 2E1 include carbon tetrachloride, benzene and chloroform. The transgenic poplar also removed these chemicals at greater rates than did the control plants (Doty *et al.*, 2007).

Phytoremediation of nitroaromatics is improved significantly with transgenic plants due to the phytotoxicity of these pollutants (Rylott and Bruce, 2008). When bacterial nitroreductase (nfsI) was overexpressed in tobacco plants, the transgenic plants were more tolerant to higher levels of TNT and could metabolize it at far greater rates than the control plants (Hannink *et al.*, 2001). Another bacterial nitroreductase gene (*pnrA*) was introduced into poplar, resulting in increased tolerance to TNT (van Dillewijn *et al.*, 2008). Another common explosive is RDX. A gene (*xplA*) from an RDX-degrading bacterium was introduced into *Arabidopsis* plants and the resulting transgenic plants tolerated and removed high levels of RDX (Rylott *et al.*, 2006). Even stronger improvements in RDX removal were achieved when *xplA* and *xplB*, two genes involved in bacterial degradation of RDX, were introduced into transgenic plants (Jackson *et al.*, 2007). Since military training ranges are often co-contaminated with both TNT and RDX, phytoremediation plants will need tolerance to both pollutants. When both bacterial genes (*nfsI* and *xplA*) involved in TNT and RDX metabolism were co-introduced into hybrid poplar, the plants removed TNT and RDX from solution more rapidly than the control plants (S. Doty, 2012, unpublished data).

Phytoremediation of toxic metals is also improved with transgenics (reviewed in Eapen and D'Souza, 2005; Meagher and Heaton, 2005; Dhankher *et al.*, 2011). Many of the genes involved in metal uptake, translocation and sequestration are being identified using the model plant, *Arabidopsis*, and using hyperaccumulating plants. The phytoremediation potential of these natural hyperaccumulators is limited by their small size, slow growth rates and limited growth habitat (Meagher and Heaton, 2005). Therefore, if the genes were transferred to plant species such as poplar and willow, with their high biomass and extensive root systems, significant removal of the heavy metals should be achieved. Yellow poplar (Rugh *et al.*, 1998) and cottonwood (Che *et al.*, 2003) have been transformed with genes to reduce the toxicity of mercury, resulting in tolerance to higher levels of mercury than the control plants. As with RDX, adding both bacterial genes involved in the metabolism of the pollutant (*merA* and *merB*) in transgenic plants had better results. Transgenic eastern cottonwood trees expressing both genes were highly tolerant to organic mercury, demonstrating the potential for their use in the phytoremediation of this important pollutant (Lyyra *et al.*, 2007).

ENHANCING PHYTOREMEDIATION CAPABILITY USING BACTERIAL ENDOPHYTES. Recently, attention has been focused on the role of endophytic bacteria on phytoremediation (reviewed in Newman and Reynolds, 2005; Doty, 2008; Weyens *et al.*, 2009a; Khan and Doty, 2011)). The term 'endophytic' refers to microbes living within plant tissues rather than rhizospheric bacteria living on or around the plant roots. Some endophytes are diazotrophic and can provide fixed nitrogen to the host plant (Reinhold-Hurek and Hurek, 1998; Doty, 2011). Some of these nitrogen-fixing bacteria have been isolated from wild poplar and willow in their native riparian habitat (Doty *et al.*, 2009). Endophytes can enhance plant growth and increase plant resistance to pathogens, drought and even herbivores (Selosse *et al.*, 2004). Plants can harbour dozens of different symbiotic or neutral bacterial species within the stems and roots, and this microbial community can be altered according to the environmental conditions. For example, at a petroleum-contaminated site, the genes encoding enzymes involved in petroleum degradation were more prevalent in the bacteria from the root interior than from the surrounding soil (Siciliano *et al.*, 2001). Surprisingly, this selection was plant species specific. In other words, some plant species seemed to have the ability to recruit, or selectively expand, the necessary bacteria to remove pollutants. How some plant species are able to recruit the necessary bacteria at a given site is currently an unexplored field of research. In a field test of the phytoremediation of a BTEX plume by poplar, the endophytic and rhizospheric bacteria associated with the trees were credited with the success of the remediation (Barac *et al.*, 2009). The population of BTEX-degrading microorganisms rose and fell with the concentration of the pollutant.

Recently, a novel endophyte of hybrid poplar was isolated that could degrade TCE rapidly (Kang *et al.*, 2012). The molar ratio of TCE removal to chloride generation suggested that this endophyte completely degraded TCE. This was the first report demonstrating that a naturally occurring poplar endophyte could degrade TCE rapidly and aerobically without the addition of toxic-inducing substrates. The strain also produced high levels of plant hormones that promoted root growth (J.W. Kang, 2012, unpublished data).

Not every bacterium with the necessary pollutant-degrading capacity has the ability to grow within the plants where the contamination is present. For this reason, a great deal of work has been done to provide the microbes that can live in a given site with the ability to degrade the pollutant (reviewed in Romantschuk *et al.*, 2000). In a ground-breaking study, the concept of engineering endophytes for phytoremediation was proven to be successful (Barac *et al.*, 2004). The catabolic plasmid from a relative of a yellow lupine endophyte was transferred conjugatively to the natural endophyte, providing the genes for toluene degradation. When yellow lupine plants were inoculated with this altered endophyte, the plants had an enhanced tolerance of toluene. This clear protective effect was only obtained when the natural endophyte was provided with the catabolic plasmid. The original host of the plasmid did not confer this effect since it was apparently unable to establish the necessary relationship with the plant. Conjugation of the required plasmid to native endophytes in plants was demonstrated with poplar trees (Taghavi *et al.*, 2005). Although the trees were inoculated with a toluene-degrading endophyte, the original inoculum was not found in the trees, but rather the genes responsible for the pollutant degradation had transferred to the endophytes already in the poplar. This natural conjugative transfer resulted in increased tolerance to toluene and reduced phytotranspiration of the pollutant.

A field test of poplar inoculated with an engineered TCE-degrading endophyte resulted in reduced evapotranspiration of TCE (Weyens *et al.*, 2009b). Trees in a TCE-contaminated field site were inoculated with cultures of the bacterium. At the end of the growing season, the levels of unaltered TCE transpired from inoculated poplar trees was less than that from uninoculated trees, suggesting that the TCE was metabolized more fully when the trees were colonized by the bacterium.

Endophytes can be engineered to harbour genes for both organic and metal detoxification. A *Burkholderia cepacia* strain containing the genes for TCE metabolism as well as for nickel resistance, and sequestration was used on yellow lupine as a model plant (Weyens *et al.*, 2010). The colonized plants had increased root mass compared to controls when both groups were exposed to TCE and nickel. There was a trend towards decreased phytovolatilization of TCE, although it was not statistically significant. Since many polluted sites are contaminated with both organics and metals, this research is an important step forward in improving phytoremediation.

A poplar-associated bacterium, *Methylobacterium* sp. strain BJ001, degraded TNT, RDX and HMX (van Aken *et al.*, 2004). This pink-pigmented symbiotic bacterium mineralized approximately 60% of the RDX and HMX to carbon dioxide in about 2 months. It is possible that this endophyte of hybrid poplar (*P. deltoides* × *P. nigra* 'DN34') assists in the phytoremediation of nitroaromatic pollutants within the tree.

Endophytes may assist in the phytoremediation of recalcitrant PAHs. A strain of *Pseudomonas putida* containing genes for the degradation of naphthalene protected pea plants from the phytoxic effects of this PAH (Germaine *et al.*, 2009). The inoculated seeds had higher germination rates in soil contaminated with naphthalene, and the colonized plants removed more of the pollutant from the soil and were healthier than the uninoculated controls. Natural endophytes of poplar and willow were isolated that could grow on PAHs (Z. Khan, 2012, unpublished data). One of these endophytes provided strong protection for willow exposed to toxic levels of phenanthrene (Z. Khan *et al.*, 2012, unpublished results). Therefore, there is great potential for endophyte-assisted phytoremediation of this class of pollutants.

SUMMARY. Poplar and willow are being used successfully in phytoremediation applications for some important classes of pollutants. With their high transpiration rates, deep roots, inherent biochemical abilities and amenability to coppicing, the *Salicaceae* family is especially well suited for remediation. As our understanding of the genes involved in the degradation of specific pollutants grows, the ability to increase greatly the success and speed of phytoremediation will continue. Especially in cases where the pollutant is extremely phytotoxic, such engineering strategies may be necessary. An alternative method for improving phytoremediation, the use of microbial plant partners, may also help us reach the same goals. As microbes with the necessary genes for engineering endophytes are identified, and as natural endophytes with pollutant-degrading abilities are isolated, further advances in the phytoremediation of both organics and heavy metals may be achievable.

Metal resistance and accumulation in North American willow species

J. KUZOVKINA

While the resistance to some metals has been documented for a few European *Salix* species, there is very limited knowledge about the potential of North American species of *Salix* for phytoremediation. The use of native species for environmental projects is a high-profile issue in North America, as it decreases the ecological risks associated with the introduction and possible invasion of alien species into new environments (Kuzovkina *et al.*, 2008). With the total number of willow species growing throughout North America at about 103 (Argus, 1999; Chapter 2, this volume), there is a possibility for a broad screening of candidates for environmental applications that are indigenous to North America (Kuzovkina and Quigley, 2005).

The research at the Ohio State University extended the study of willows' response to heavy metals to New World species (Kuzovkina and Quigley, 2004a; Kuzovkina *et al.*, 2004a). The efficacy for the phytoremediation of five willow species was tested by studying copper and cadmium uptake in a greenhouse hydroponic system (Fig. 6.29). The willow species used in the study were *S. discolor* Muhl., *S. eriocephala* Michx., *S. exigua* Nutt., *S. nigra* Marsh. and *S. lucida* Muhl. Hardwood cuttings of uniform 20 cm length were hydroponically rooted in half-strength Hoagland's nutrient solution for 5 weeks prior to the beginning of the experiment. Each cutting was mounted into a plastic pot cover to prevent algal growth and set into a pot containing 900 ml of constantly aerated solution. After 5 weeks, when the root systems were well developed, the hydroponic solution was replaced with half-strength Hoagland's nutrient solution containing either 5 or 25 μM additional Cu or Cd (added as $CuSO_4$ or $CdSO_4$). The experiment continued for 28 days after the addition of metals.

Different species of willow, as well as some clones, varied considerably in their metal translocation patterns and their ultimate resistance

Fig. 6.29. The greenhouse hydroponic system used for screening five North American willow species for their resistance to copper and cadmium. Photo courtesy of J. Kuzovkina.

to heavy metals. The differences between species in sensitivity to high metal content ranged from the stimulation of root and shoot growth to severe inhibition of growth. *Salix* species were less sensitive to Cd than to Cu, and plant growth for most species was not inhibited, even at high concentrations. Growth and transpiration for most species were not decreased by either 5 μM copper or 25 μM of cadmium in the solutions. In *S. exigua* and *S. eriocephala*, 25 μM copper caused foliar injury and reduced dry weight for all species after 21 days. Inhibition of growth in Cd treatments was evident only for *S. lucida*. In contrast, growth of *S. nigra* and *S. exigua* was stimulated even at high Cd concentrations. The copper content of aerial tissues was relatively lower than that of cadmium, while cadmium appeared to be more mobile within the plant. For most species, the highest Cd content was found in wood, while intermediate in roots and lowest in shoots. For Cu treatments, the trend was different and the highest amount of metal was found in roots, while intermediate in wood and least in shoots. The amount of copper found in new growth in 25 μM treatments was lower than that in 5 μM solution.

The results indicate that *S. nigra* is a promising North American species for phytoremediation research because of its high total metal content in plant tissues and its capacity to maintain high biomass during the experiment, especially in Cd treatments (see Fig. 2.22, this volume). *S. exigua* (see Fig. 2.16, this volume) exhibited resistance to Cd but not to Cu. Future field study needs to be conducted to confirm the findings and feasibility of phytoremediation technology using these species.

Stress tolerance in North American willow species

J. KUZOVKINA

Various environmental applications of willows are currently under way in an array of ecotechnological projects aiming to alleviate environmental degradation, to control the cycling of nutrients and contaminants and to provide value-added products (Volk *et al.*, 2006). The sustainability of any constructed ecosystem is dependent on optimum plant performance that is influenced by species autoecology. Plant genotypes should closely match the local climatic and microclimatic conditions (Isebrands and Karnosky, 2001), and plants should be tolerant of the adverse conditions that frequently occur in many degraded landscapes.

Another direction of the research is the selection of *Salix* species that are tolerant of various environmental stresses, with priority given to indigenous North American species. A few studies have identified significant differences among North American *Salix* species in reaction to soil compaction, flooding and ozone (Kuzovkina and Quigley, 2004b; Kuzovkina *et al.*, 2004b). The current research extends the study to the response to water stress of native willow species. Drought poses a serious challenge to plant development, limiting successful establishment and growth, especially in unfavourable soils. Many degraded landscapes that include brownfields, mines, industrial spoils, overburdens, quarries and waste sites are often characterized by shallow and compacted soils with very limited water availability (Chapter 7, this volume).

Though the majority of willows belong to the mesic-hydric type of vegetation, some North American species, such as *S. humilis* and *S. myricoides*, exhibit xeric traits and are better adapted to drought and heat stress (Cowles, 1991). Field observations suggest that other willow species are found on a variety of sites ranging from wetlands and flood plains to mesic or even xeric upland areas. This variation in suitable habitats for different species is under investigation to document a range of drought tolerances in native *Salix* species and to identify the drought resistance mechanism that is present in some species. Greenhouse experiments are being conducted to carry out a screening test to identify the length of drought periods that separate different genotypes, to monitor important plant physiological parameters and to identify drought-sensitive and drought-resistant genotypes. The information on species drought tolerance is very important in the context of various applications including phytoextraction, biofiltration, revegetation of degraded land and bioenergy, to ensure the compatibility between candidate species to site conditions and project objectives, as well as in the context of hybridization work.

Shrub willows for phytoremediation

T.A. VOLK

Shrub willows have numerous inherent characteristics that make them a good choice for phytoremediation, including rapid juvenile growth rates, vigorous coppicing ability that is maintained even after multiple harvests, ease of establishment from unrooted cuttings, tolerance of high planting densities, high degree of genetic diversity and potential for rapid genetic improvement. In addition, willows' perennial nature, extensive and diffuse root systems, high transpiration rates and tolerance of waterlogged conditions make them potentially beneficial for a wide range of other applications. Years of research and development of shrub willow-based biomass production systems in North America (Kenney *et al.*, 1990; Volk *et al.*, 2006) and Europe (Armstrong, 1999; Verwijst, 2001) have expanded the knowledge base about the biology, ecology and management of shrub willows. This information has been used to develop new applications for shrub willows in the north-eastern USA, including phytoremediation (Licht and Isebrands, 2005).

Shrub willows are being used in the USA to remediate and contain sites contaminated with various industrial wastes (Licht and Isebrands, 2005; Mirck *et al.*, 2005). Willows have been shown to uptake heavy metals and organics from soils (i.e. phytoextraction) (Riddell-Black *et al.*, 1997), facilitate the breakdown of organics to non-toxic compounds (i.e. rhizodegradation) (Ebbs *et al.*, 2003) and control water dynamics, including contaminated groundwater flow and water penetration into soils via evapotranspiration (i.e. phytovolatilization and hydraulic control) (Corseuil and Moreno, 2001). Many of the characteristics that make shrub willows effective in biomass production systems are also beneficial for phytoremediation systems. Since willows have developed as pioneer species, they have the ability to survive in relatively hostile, disturbed and wet sites. In addition, they have a high capacity to transpire water (Chapter 3, this volume), which is a beneficial attribute in phytoremediation systems. A broad gene pool (there are over 330 species of willow across the world (Argus, 1999), with many more natural and human-developed species hybrids) provides opportunities to screen and develop willow to grow on a wide range of sites and produce specific phytoremediation effects.

Several phytoremediation projects using willow and hybrid poplar (*Populus* spp.) are currently under way in the north-eastern USA (Table 6.9). Most trials in New York, USA, are related to using willow to control site water problems, either through the management of

Table 6.9. Willow phytoremediation trials in the north-eastern USA (after Volk *et al.*, 2006).

Trial location	Year established	Phytoremediation method	Site contaminants	Number of clones	Planting density (plants ha^{-1})
Utica, New York (Jackson, 2000)	1999	Rhizodegradation	PAHs[a]	8	108,000
Rochester, New Hampshire	2000	Hydraulic control	PAHs	8	36,000
Fort Drum, New York (Kornacki, 2005; Salladin, 2005)	2001	Hydraulic control, rhizodegradation, phytovolatilization	PAHs, herbicides	20	161,000
Solvay, New York (Johnson, 2005; Farber, 2006)	2003	Hydraulic control	Chloride and other salts	40	15,400
Yorktown, Virginia	2004	Hydraulic control	PAHs	8	36,000
Syracuse, New York (Purdy, 2006)	2006	Phytoextraction	Arsenic	4	Greenhouse trial

[a] PAHs, Polycyclic aromatic hydrocarbons.

water entering into the contaminated site (Solvay trial) or by controlling contaminated groundwater chemistry and flow (Rochester, Fort Drum and Yorktown trials). Recently, greenhouse studies examining the potential of willow to remediate arsenic-contaminated soil have been initiated (Purdy, 2006). Arsenic contamination is a widespread problem because more than 40 t of arsenical pesticides were applied annually to farmland, especially apple and other orchards, in the USA in the 1930s and 1940s, and there has been limited redistribution of this material since that time (Renshaw *et al.*, 2006).

Three of the ongoing trials are operational-scale case studies where the willow plantings are expected to contribute to site clean-up through various phytoremediation processes. Since a phased approach was not possible with these trials, a fail-safe design was used to establish the trials. Site preparation was intensive, and unique problems were solved in specific ways at each site. Planting densities were high and a set of known, plastic (wide ecological amplitude) varieties were used, so that if one or more variety failed (up to 50%), the system would likely still function in relation to phytoremediation processes. After 1–3 years of experience, there have not been any large-scale failures in terms of plant mortality. All of the operational trials have monitoring schemes to collect data on willow survival, growth and their impact on a site's contamination levels and/or hydrology. Monitoring results have been turned into action, including the replacement of poor varieties with new ones or the expansion of proven varieties and the adoption of new cultural techniques associated with planting, site preparation and tending.

The two other trials – Fort Drum and the Solvay Wastebeds – have used a phased approach to test, refine and develop a system that can be applied at an operational scale at each site. In the trial at Fort Drum, the goal is to reduce the flow of contaminated water moving through seeps from a landfill using a shrub willow-based phytoremediation system. The system was developed over several years, testing a number of willow varieties and different planting designs. The willows were established in or near seeps in soils that were poorly or very poorly drained, so the challenge was to get the material to thrive in these wet, contaminated conditions. The existing willow biomass establishment system was transformed over several years to create a system tailored specifically to the site's conditions and specific phytoremediation clean-up goals on the site. Different planting designs that were developed and tested included the use of cardboard rings filled with soil, planting boxes constructed from lumber or earthen berms. The first growing season after installing these three designs, survival was high (<93%) for all of them (Salladin, 2005). The aboveground biomass production in the planting boxes and tubes was similar and greater than that of the biomass of the willows planted in earthen berms, (Salladin, 2005).

During 2004 and 2005, piezometer measurements showed that the water table in the area where the willows had been established had been lowered slightly during the growing season, probably due to the increased evapotranspiration from the willows (Thompson, 2006). Water table depths and plant growth were to be monitored as the shrub willows grew over the successive few years. The success of the planting systems over the first few years and the indication that the willows had already had an impact on the water table resulted in plans to deploy this system over a greater area at the site.

The project on the Solvay wastebeds focused on using shrub willows as an alternative cover to a standard geomembrane cap. The project's goal was to minimize the amount of water that percolated into the wastebeds and ultimately decrease the amount of leachate, which had high concentrations of chlorine (Cl) generated from the wastebeds, to reduce the impact on groundwater and surface water in the region. Secondary goals for this project were to produce woody biomass for the renewable energy market developing in the region and to transform the wastebeds into a productive community asset.

The Solvay wastebeds are a by-product of over 100 years of production of chlorine and alkali, which is fundamental to the chemical industry. The process was developed by Ernest Solvay in the 1860s and produced chlorine (Cl_2), soda ash (Na_2CO_3) and caustic soda (NaOH) (Michalenko, 1991). For the production of soda ash (Na_2CO_3), abundant and inexpensive supplies of limestone, salt, water, a reliable and robust process and space to deposit the waste were needed. Many of these features were present on the western shore of Onondaga Lake near Syracuse, New York, so the Solvay Process Company established a soda ash plant there in 1884 and ran it until 1986.

The volume of waste generated by the production of Na_2CO_3 using the Solvay process is enormous: for the production of 0.91 Mt of soda ash, about 10 m^3 of liquid waste is created, containing approximately 0.91 Mt of $CaCl_2$ and 0.45 Mt of NaCl (Michalenko, 1991) and other by-products. This material was deposited into sedimentation basins that were surrounded by berms. By the time the production process ended, the wastebeds covered approximately 600 ha of land 16–21 m deep. Some of this area was converted to alternative uses such as parking areas for the New York State Fairgrounds, construction and debris landfill and the development of malls and other facilities, but six wastebeds remained, covering about 222 ha.

The material in the wastebeds is a harsh environment for plants to become established and to thrive in. Greater than 70% of the Solvay waste consists of silt-size particles made up of calcium and magnesium salts, with Ca making up greater than 86% of the cation exchange capacity (CEC) (Michalenko, 1991). The pH of the material ranges from mid-8 in the top 20 cm to greater than 11 at depths of 40 cm or more.

The first step in developing this system was to screen 38 shrub willow and two hybrid poplar varieties from the SUNY-ESF collection to determine which ones would be the most successful on the wastebeds. Previous studies showed that *Salix* (*S. alba*, *S. bebbiana*, *S. discolor*, *S. purpurea* and *S. rigida*) and *Populus* (*P. deltoides*, *P. tremuloides* and *P.* ×*canescens*) species successfully colonized the wastebeds as the age since deposition increased (Hewlett, 1956). Solvay waste was collected from an area on the wastebeds that had been amended with biosolids in the early 1990s and from another area that was unamended Solvay waste. A 1:1 ratio of ProMix and fine sand served as a control. The willows and hybrid poplar were planted as 12-cm-long cuttings in tubes and grown in a greenhouse for 11 weeks. For 27 of these varieties, biomass was greatest in the amended Solvay waste treatment, indicating that this was a good growth medium. Biomass was greatest in the Promix and sand treatment for 11 other varieties, while two had the highest production on the unamended Solvay waste. In the amended Solvay waste, ten varieties had better biomass production than clone 'SV1', which is a high biomass-producing standard used in various screening trials and the SUNY-ESF breeding programme (Smart *et al.*, 2005). There was a fourfold difference in the root:shoot ratios among these higher producing varieties, ranging from 0.05 to 0.22. While aboveground biomass production was good, the varieties with low root:shoot ratios may be susceptible to the dry conditions found on the wastebeds during certain parts of the growing season.

The positive growth results from the greenhouse screening trial then prompted the design and installation of two subsequent trials, a greenhouse trial to examine the effect of different organic amendments and a field trial on the wastebeds with a limited number of varieties. For the organic amendment greenhouse trial, 'SV1' was used as a standard and two varieties that had higher aboveground biomass than 'SV1' in the screening trial but very different root:shoot ratios were selected. Clone '9882-34' had a low root:shoot ratio (0.06), '9871-31' had a high root:shoot ratio (0.22), while 'SV1' was intermediate (0.17).

This trial used three different organic amendments, Anhueser Busch biosolids (ABB), Bristol Meyer Squibb biosolids (BMS) and lime-stabilized Syracuse metrosludge biosolids (MBS). These were mixed at a 1:1 dry weight ratio to two different depths of mixing, either half the depth of the 34-cm-deep pot or for the total depth of the pot. After 15 weeks in the greenhouse (Fig. 6.30), the total aboveground biomass of the three varieties grown in the ABB and BMS amendments was significantly greater than willow grown in MBS or unamended Solvay waste for both mixing depths (Farber, 2006). The pH of MBS was 12.3 compared to 5.6 for ABB and 6.1 for BMS, which was an important factor influencing growth, since the unamended Solvay waste had a pH of 8.3. Depth of incorporation of ABB or BMS did not affect above- or belowground biomass for '9871-31' or '9882-34'. Based on the results from this trial, a field experiment was established with two willow varieties and three organic amendments in the spring of 2006 (ABB, unstabilized MBS and composted yard waste from an adjacent village). Due to changes in manufacturing processes, the BMS amendment was no longer available. First-year growth data were very encouraging, with height growth exceeding 2 m on many of the treatments.

The first field trial on the wastebeds involved planting a subset of successful willow varieties from the screening trial in areas where the amended and unamended Solvay waste was collected. For the area with amended Solvay waste, ten different willow varieties and two cutting lengths (25 cm and 50 cm) were used in a replicated trial. After the first growing season, survival was greater than 80% for all varieties and treatments, except for two varieties planted with 25-cm cuttings, and aboveground growth

Fig. 6.30. Shrub willows after 15 weeks of growth in a greenhouse trial to test the effect of three different organic amendments and two mixing rates. Photo courtesy of T. Volk.

was good. During the second growing season, survival declined significantly for two of the varieties. This pattern emphasizes the need for long-term and consistent monitoring of phytoremediation field trials to avoid system failures after initial successes. For the varieties that survived, aboveground biomass production was good on the amended Solvay waste. After two growing seasons, aboveground biomass exceeded 20 t ha^{-1} oven-dry for four of the varieties planted with 50-cm-long cuttings. These growth rates are comparable to trials in central New York on agricultural soils (Volk *et al.*, 2006). Production with the shorter cuttings exceeded 15 t ha^{-1} oven-dry for three of the varieties.

The focus of this project was to develop an alternative cap using shrub willows. In order to assess the potential for such a system, it is important to monitor components of the water budget and then model the long-term effect of the willows on the site's water budget, as described in Mirck and Volk (2010). Monitoring of weather data, soil moisture content, throughfall and sapflow (Fig. 6.31) occurred at the site. Data collected were used as input to the SHAW (simultaneous heat and water) model. Initial modelling efforts indicated that an alternative cap could reduce percolation significantly over a 28-year period (Johnson, 2005). These model runs illustrate that it will take several years for a willow cap to become established and fully functional but that, once they are established, they are robust and functional. Work was ongoing to calibrate this model using data collected from the site in order to reflect the water budget dynamics on the site as accurately as possible.

Wastewater treatment

J.D. JOHNSON

As environmental regulations in the USA become more stringent, municipal wastewater treatment facilities are turning to poplar plantations to deal with wastewater reuse in lieu of disposing into adjacent rivers and streams (Fig. 6.32). Typical facilities must dispose of millions of litres of wastewater annually that contain high

Fig. 6.31. Three-year-old willow trial on the Solvay wastebeds where sapflow, throughfall, soil moisture and various plant characteristics are being measured as part of the effort to develop an alternative vegetative cover for the wastebeds. Photo courtesy of T. Volk.

Fig. 6.32. Aerial view of the City of Woodburn, Oregon, USA, hybrid poplar stands used for treating municipal wastewater. Photo courtesy of J. Johnson.

quantities of both nitrogen and phosphorus. One of the early examples of using poplars for wastewater treatment by a municipality was at Woodburn, Oregon, USA (Zodrow, 1999; Isebrands and Karnosky, 2001; City of Woodburn, 2012).

Hybrid poplars are especially well suited for treating this wastewater because their extensive fine root systems readily take up the nitrogen and phosphorus, which is used in growth, and their canopy's large leaf area transpires large volumes of water into the atmosphere (Smesrud *et al.*, 2000). Treatment facilities in the Pacific Northwest of the USA estimate annual transpiration of a closed canopy hybrid poplar stand to be a little over 10 million l ha^{-1} $year^{-1}$. This amount is probably even higher when the wastewater is applied through sprinklers that increase evaporation before the water hits the ground. In drier and warmer climates, application rates can be higher. One issue that often develops over several years of applying wastewater to poplar stands is nutrient deficiencies. Under typical waste treatment processes, many of the nutrients are removed and so the application of high volumes of low nutrient-containing water can lead to nutrient deficiencies through leaching and growth dilution. An inexpensive remedy adopted by many wastewater treatment facilities is to apply nutrient-rich biosolids, a by-product of the treatment process, annually to the poplar stand. In many states, application of biosolids to food crops is not allowed, making its disposal problematic and potentially costly. Wastewater treatment with poplars is now popular is other regions of the USA.

Evapotranspiration covers

L. LICHT

Evapotranspiration (ET) covers, or vegetative caps, are being used increasingly at municipal solid waste landfills, hazardous waste sites and mine sites (Rock, 2012). The primary objectives of these vegetative caps are to minimize water percolation into the buried landfill waste via a 'sponge and pump' mechanism and to prevent surface soil erosion on the cap (Licht *et al.*, 2001). The plants, which are traditionally grasses, shrubs or trees, take up precipitation for growth and release it back to the atmosphere by transpiration (Fig. 6.33). The design of the ET cover provides water storage capacity and evapotranspiration to control moisture and percolation into the underlying waste. The primary tree species used for ET covers are poplars and willows (US EPA, 2003; Rock, 2012). The first ET cover using trees was in 1990 in Beaverton, Oregon, USA, using 1.5-m-long hybrid poplar whips (Licht *et al.*, 2001). There have been a number of successful ET covers since 1990 (Rock, 2012). Nixon *et al.* (2001) have shown that success depends on the proper choice of plant material for the site, as well as good site management. Licht and Isebrands (2005) showed that an ET cap in the state of Washington using hybrid poplar trees was highly successful when properly installed, and additional wildlife benefits were seen as an advantage with the system. Likewise, Abichou *et al.* (2012) found that an ET cover vegetated with native cottonwood was a feasible alternative for use in Florida, USA. Biosolids are often used as soil amendments to enhance ET cover establishment (Felix *et al.*, 2008). Of the 217 ET projects reviewed by Rock (2012), many are using poplars and willows. It is too soon to determine what the long-term performance of these alternative systems will be, but use of native poplars and willows is likely to cause less disturbance to the surrounding ecosystem (US EPA, 2003).

Other research and information

J.G. ISEBRANDS

There are many other research institutions and government agencies in the USA doing fundamental and applied research on phytotechnologies (Rockwood *et al.*, 2004; Strycharz and Newman, 2009). Most of them are working with poplars and willows, and the number of institutions and scientists are too numerous to include here. However, there are several institutions that should be mentioned. Firstly, the US Environmental Protection Agency Service Center in Cincinnati, Ohio, serves as a database manager and clearinghouse for all phytotechnology research and applications in the USA. Their website has hundreds of references to the use of poplar and willow for all aspects of phytoremediation

Fig. 6.33. Buffer planting on Chanute US Air Force Base, Illinois – 3-year hybrid poplar planted to intercept water. Photo courtesy of L. Licht.

(for further information see http://clu-in.org). Secondly, one of the leaders in the phytoremediation of explosives and organic solvents is at the University of Iowa, Iowa City, Iowa. The programme leader for that group is J.L. Schnoor, who is co-author of a state-of-the-art book on phytoremediation (McCutcheon and Schnoor, 2003) and a world expert on the use of poplars and willow for remediation of these compounds in soil and water. Their website refers to hundreds of fundamental and applied articles from their group through the history of phytoremediation in the USA (for further information see http://www.instantref.com/ECSEI/Schnoor-CV.pdf), many of which are on poplars (and willows), e.g. Burken and Schnoor (1998). Lastly, one of the other leaders in the phytoremediation of poplars and willows is in the USDA Forest Service, Northern Research Station in Rhinelander, Wisconsin. The group has a long history of fundamental and applied research projects and is currently led by R.S. Zalesny and co-workers. Their group has carried out extensive research on the interaction of genetics and the environment on phytotechnology applications. This includes work on the irrigation of poplars and willows with landfill leachate (Zalesny and Bauer, 2007a; Zalesny *et al.*, 2007a), choosing genotypes for landfill covers (Zalesny and Bauer, 2007b; Zalesny *et al.*, 2007b), opportunities for utilizing treated wastewater (Zalesny *et al.*, 2011) and clonal variation in rootability with irrigated landfill leachate (Zalesny and Zalesny, 2011). For further information see http://nrs.fs.fed.us/people/Zalesny.

6.6 Ecosystem Services

6.6.1 Biodiversity, environment and landscape

M. WEIH

Tree plantations can have positive or negative effects on biodiversity, depending on location, management and previous land use (Cossalter and Pye-Smith, 2003), and studies on biodiversity in plantations of fast-growing trees often arrive at contradictory conclusions, especially when different kinds of organisms are considered (Hartley, 2002). Plantations of *Salix* and other fast-growing trees grown on agricultural land can improve biodiversity at the landscape level, in particular if the plantations are established instead of cultures of cereals and spruce or fallow ground in a homogeneous agricultural landscape. For example, compared to managed coniferous forests and farmland in boreal Sweden, young poplar and willow plantations, especially if not too large in size, have been concluded to increase vascular-plant diversity (Gustafsson, 1987; Weih *et al.*, 2003). Similar to the observations on floras, fauna diversity (birds and mammals) is frequently found to be higher in willow and hybrid poplar stands compared to agricultural croplands (Weih and Nordh, 2007; Weih, 2008, 2009). Thus, the more extensive management of tree plantations compared to intensively managed cereal crops can improve habitat quality for many organisms, including plants and birds (Christian *et al.*, 1998; Berg, 2002; Weih *et al.*, 2003; Dhondt *et al.*, 2004). In addition, plantations of fast-growing trees appear to have a potential as important habitats for gamebirds (Sage and Robertson, 1994). Plantations of poplars or willows can also affect soil properties positively compared to conventional agriculture. For example, carbon sequestration and water-holding capacity were found to increase in formerly arable soils that were planted with fast-growing willow and poplar for 6–10 years (Kahle *et al.*, 2005). Many concerns are raised regarding the impact of plantations of fast-growing trees on the landscape (Skärbäck and Becht, 2005). However, if used creatively as part of active landscape analysis and design, plantations of fast-growing trees can improve greatly the visual and recreational values of a landscape and, particularly, plantations of relatively small size can improve the aesthetic perception of homogeneous agricultural landscapes by adding variation and structure (Rode, 2005).

6.6.2 Carbon sequestration

M. COLEMAN AND J.D. JOHNSON

A relatively new use for hybrid poplars is to reduce atmospheric carbon dioxide by sequestering it into tree biomass. Due to their rapid growth, hybrid poplars are ideally suited for this use and a number of poplar companies have been exploring the possibility of selling their carbon stores to various industries. Where greatest gains can be made are on marginal agricultural or pasture lands that do not require supplemental irrigation (irrigation requires expenditure of energy from fossil fuels). In 2000, nearly 5.3 million ha were identified in the Pacific Northwest of the USA (Idaho, Oregon and Washington) that potentially could support hybrid poplar plantations for carbon sequestration (J. Johnson, 2000, unpublished data). Estimation of total carbon sequestration rates range from 11 to 20 Mg ha^{-1} $year^{-1}$, depending on clone and climate, resulting in total carbon sequestration after 8 years of between 90 and 160 Mg ha^{-1}. In addition to tree carbon, soil carbon under hybrid poplar stands was found to increase from between 9% in heavier soils to 62% in sandy soils, compared to adjacent soils with annual cropping. Values for soil carbon ranged from 4 to 15 Mg ha^{-1}, with the lower value being found in sandy soil. Hybrid poplar plantations grown for long-term carbon storage could play a very important role in slowing the increase in atmospheric carbon dioxide (Tuskan and Walsh, 2001). For example, the potential of planting poplars on farmland in India for carbon sequestration is being investigated (Gera, 2012).

Coleman *et al.* (2004) compared soil carbon of short-rotation poplar plantings with adjacent agricultural crops and woodlots in Minnesota, USA. They found greater soil carbon in poplars than in paired agricultural crops and concluded that short-rotation poplars offered opportunities for carbon sequestration, as well as erosion control and wildlife habitat improvement in the central USA. Moreover, Sanchez *et al.* (2007) working in the southeastern USA found that native cottonwood when irrigated and fertilized had higher soil carbon than other tree species. These results from a different region also suggest that poplars grown under short rotation offer carbon sequestration opportunities. But, the key advantage with these plantings would still come from the displacement of fossil fuels over long periods (Tuskan and Walsh, 2001).

6.6.3 Poplar growing in the environment of the Walloon region, Belgium

P. MERTENS

Poplar growing in the Walloon region of Belgium is ubiquitous and is often as single trees or small groups (Mertens, 2002). They are usually present in non-forested townships and villages. Poplar culture in these areas is in semi-open environments characterized by ecosystems that provide shelter for herbaceous and shrub undergrowth (Mertens, 1999). These stands provide for a multitude of environmental benefits and ecosystem services as well as traditional social-economic value for landowners, such as wood products. They provide soil erosion control, heterogeneous corridors and edges and landscape aesthetics (Fig. 6.34), biodiversity, fixation of nutrients such as nitrogen and phosphorus and habitat for animals and avifauna

Fig. 6.34. Poplars grown in semi-open environments improve landscape aesthetics. Photo courtesy of P. Mertens.

(Mertens, 1999). These unique semi-open systems provide long-term benefits where human intervention is only needed for occasional commercial operations, leaving the open space to spontaneous native vegetation growth in the rural landscape.

6.6.4 Other emerging ecosystem services opportunities

J.G. ISEBRANDS

There are other intangible benefits from poplar and willow culture that often go unrecognized. They include wildlife benefits such as a greater diversity of non-game animals, invertebrates and fish species when compared to agricultural crops. Poplars and willows also provide winter habitat for upland birds and game animals. Numerous studies have shown the positive effects of maintaining heterogeneous planting edges and multiple age-class vegetation on small mammal populations, breeding bird diversity and breeding bird habitat (Isebrands, 2007).

Another important environmental benefit of poplar and willow plantings in agricultural regions can be with livestock operations. The number of large livestock operations (i.e. cattle, pigs and poultry) is increasing worldwide with human population growth. Some of the most challenging problems with livestock operations are in odour control and animal waste management. Multi-species shelterbelts that include poplars and willows can help mitigate livestock operation problems (Tyndall and Colletti, 2001, 2006; Malone, 2002). The tree plantings dilute manure-generated odour compounds in the atmosphere, deposit odorous dust by decreasing wind speeds, physically intercept dust and absorb volatile odour compounds. At the same time, they provide both visual and sound barriers from the livestock operations, which are appreciated by neighbours (Fig. 6.35).

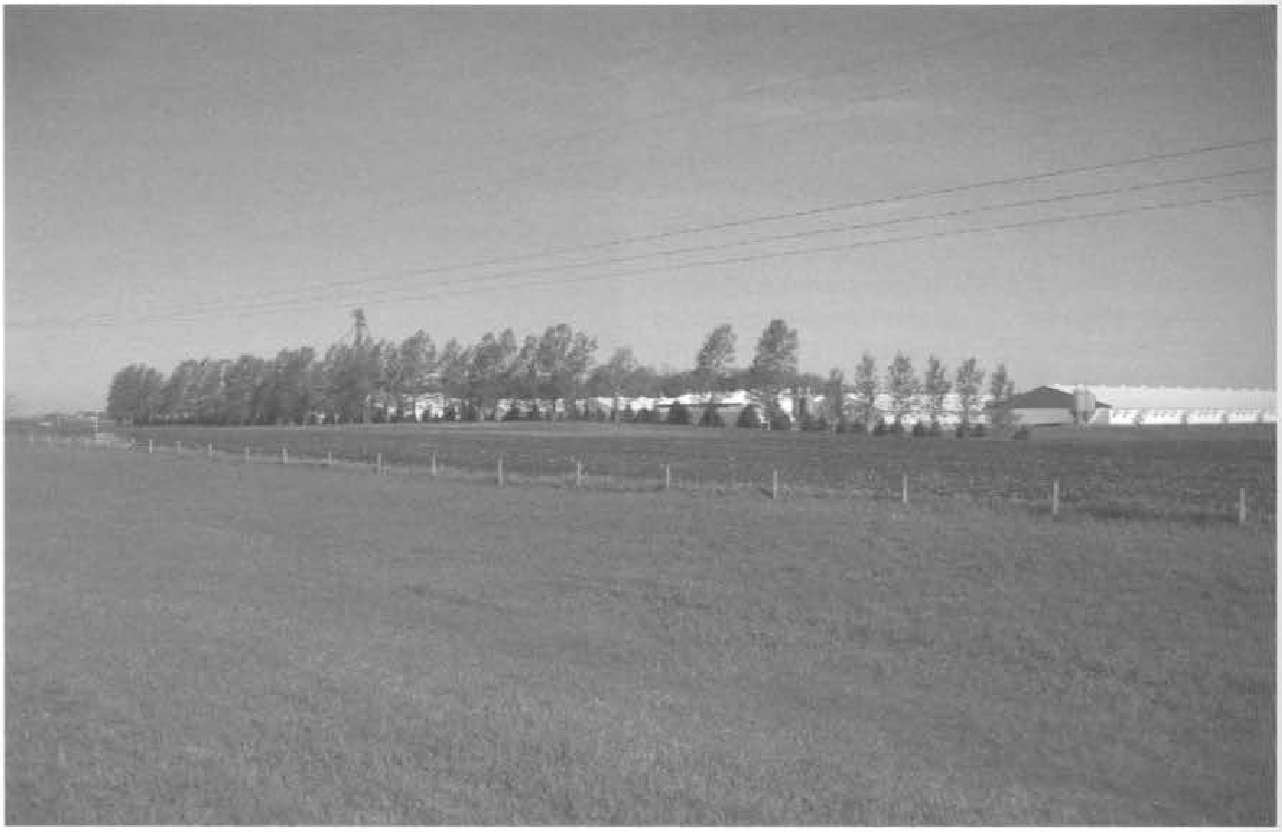

Fig. 6.35. View from motorway of multi-species shelterwood including poplar surrounding a turkey-rearing facility in western Minnesota, USA. Photo courtesy of J. Isebrands.

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