Introduced willows can become invasive pests in Australia

Kurt W. Cremer

PO Box 275
Cooma, NSW
Australia 2630

kcremer@snowy.net.au

Abstract. *Although willows (*Salix spp.*) are much appreciated for their various benefits, concern has grown over the past decade about their invasive natural spread in the water courses of southeastern Australia. The main environmental effects include obstruction and diversion of streams and hence erosion, extensive displacement of native vegetation with loss of biodiversity, and reductions in the quantity and quality of water. So far, only a few thousand kilometres of streams have been infested badly; that is less than 10% of potential willow habitat. Except for some of the* S. cinerea *infestations, it is still possible and worthwhile to control the willows in Australia.*

The following biological features help to explain the spread and provide a basis for control. 1. The original cause of spread has been importation and planting, usually as cuttings of just one or two clones at a time. 2. The bases of the small branches of most of the tree willows in Australia are easily broken. These willows thus tend to spread by broken branches taking root in wet areas downstream. The shrub willow species are far less fragile and thus unlikely to spread by broken branches. 3. Male and female flowers are usually on separate trees. Female trees will usually produce viable seed with pollen from a male of the same species or of any other species of its botanical group (i.e. either tree willows or shrub willows), provided that the trees occur within pollinating distance of each other (up to at least 1000 m) and flower at the same time (most do). 4. In Australia, most of the resulting seedlings are hybrids and are able to grow vigorously and to breed with each other and with both their parents. 5. Except for S. cinerea *and* S. purpurea, *regeneration from seed is virtually restricted to more or less bare sediment that is kept wet for weeks or months from the time of seed shed (about October/November) because the seed lives for only 1-7 weeks when dry, and germinates in about one day when wet, and because the tiny seedling needs much light and has slow root growth. 6. Seed is easily carried by wind for more than 1 km, and some travels up to 50 or even 100 km. Transport of seed or live branches by streams also serves to spread willows, but is less effective, and only downstream. 7. Probably the main barriers to the survival of seedlings are lack of suitable seed bed, rising or rapidly falling water levels, and floods that uproot or bury the seedlings. 8. Conditions suitable for the establishment of large numbers of seedlings probably occur in most south-eastern streams at perhaps 5 to 20 year intervals. Major disturbances, such as wildfire or the collapse of a swamp may also promote massive regeneration from seed.*

National and regional strategies for willow management are being developed and implemented. They range from prohibitions on the importation, sale, and planting of nearly all willows to the total eradication of the most aggressive species; S. nigra *and* S. cinerea. *Regional strategies aim to eliminate naturally regenerated willows and to reduce their sources to manageable levels. That means, 1. Control fragile willows where their broken branches are very likely to take root, and 2. Keep seeding females to minimal numbers and at least 3000 m away from suitable seedbed, and (preferably) keep males at least 2,000 m from compatible females.*

In the coming centuries, alien willows are in a position to change much of the natural environment in Australia and elsewhere.

About the Author
Kurt W. Cremer graduated with forestry degrees from the universities of Sydney and Tasmania. He retired as a Principal Research Scientist from Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Canberra in1987. His main interests of study were: fire ecology and natural regeneration in wet eucalypt forests, wind, hail, snow, and frost damage in plantations, and other silvicultural problems. Since 1993 he has been studying the natural spread of willows and is involved in extensive promotion to control problem willows. To see more information on this research please visit:

http://www.ffp.csiro-.au/publicat/articles/willows/

http://www.hoadley-.net/cremer/willows

INTRODUCTION

Willows (Genus: *Salix*), all introduced from overseas, have been planted widely in the southern half of Australia for protection of river banks and for beauty, shade and shelter. They are particularly valuable where native species are difficult or impossible to grow satisfactorily, i.e. in most of the areas cleared for farming, where willows are often the main or only woody plants and thus of benefit to the landscape and the environment. However, there is now a growing concern about willows spreading into Australia's rivers, from broken branches taking root and from the sometimes explosive spread by seed. A main concern is that multitudes of willow stems within the flood channel will obstruct and divert floods, resulting in the erosion of river banks. Displacement of native vegetation and the resulting ecological changes are also of major concern (Ladson et al.1997), together with the additional water that willows might use in some situations.

ECOLOGY AND BREEDING: TIME OF FLOWERING

Most of the willows in Australia (see Appendix 1) flower for about 3 weeks in spring, around September-October. With the exception of *S. aegyptiaca*, all the shrub willows flowered at approximately the same time and were thus all able to pollinate each other. In the tree willows, the flowering times differed enough to make cross-pollinations between a few of the species unlikely or impossible during the main flowering season. In most regions, the flowerings of the two most widespread tree willows, the female *S. babylonica* and the male *S. fragilis,* have not overlapped and have not resulted in seed production. However, there is also some erratic flowering at other times, especially in the warmer climates. This could occasionally allow cross-pollination between species whose flowering times normally do not overlap.

POLLINATION

Willows are predominantly pollinated by insects, and perhaps partly by wind (Argus 1986). In Australia, both male and female willow flowers are highly attractive to European bees (*Apis*) as well as native bees. Although bees may fly up to 3 or 5 km to collect pollen and nectar (nectar is produced by both male and female willows), crosspollination is usually considered to be restricted to much smaller distances, such as 50 m (Free 1970). However, two sets of female willows were found to produce many viable seeds in each of two years (but not in two other years), even though the nearest compatible male was 1 km away in both cases. To be reasonably sure to prevent pollination, willow males should thus be separated from females by at least 2 km.

SEED PRODUCTION

Flowering and the production of viable seed may begin as soon as 2 or 3 years after germination, provided that the plant is at least 1 m tall if it is a shrub willow, or 2 m tall if it is a tree willow. If growth is slower, flowering begins later and, in some taxa, flowering tends to begin at larger sizes anyway, e.g. in *S. alba*. Once begun, flowering tends to be ample and to occur every year. With, say, 30 flowers per catkin and 50 000 catkins on a large crown, and a potential of several seeds per flower, there could be several million seeds per tree. The actual observed seed production has, however, been less than that potential. It typically ranged from zero, where the catkins produced only fluff that did not shed, to 'ample' where the fluff extruded readily (leaving the fruits empty), and contained more than 10 seeds per catkin. Willow seed production in Australia is mainly from hybridisation. It does not depend on having both sexes of the same species.

SEED RELEASE AND SEED COLLECTION

When the fruit has ripened (in October/November), it dries and opens. In warm, dry weather the seed is then levered out by the movement of the cottony hairs attached to its base. Wind, although not necessary, accelerates that release. The extent to which the cotton is levered out of the fruit is an indication of the abundance of seed. When there is no seed, the fruit may open and show its cotton, but the hairs remain straight and in the fruit. The seed with attached cotton may be pressed into close contact with a wet surface such as tissue paper on a dish kept in a plastic bag to admit light but reduce evaporation.

SEED QUALITY

In more than 100 tests it was found that, if seed production was 'ample' (>10 seeds/catkin), and if the seed was freshly collected, it was usual for 90 to 100% of seeds to germinate and for nearly all of the tiny seedlings to appear healthy. However, when only few seeds were produced, varying proportions of the tiny seedlings of some seed lots were found to be stunted, reflecting, perhaps, poor survival prospects due to unfavourable parentage. Germination tests should be done only on seed freshly emerged from the catkin and they should continue for at least a week to see if the tiny seedlings are healthy.

SEXUALITY

It is usually said that willow trees are either wholly male or wholly female, with only rare exceptions. This would mean that by planting cuttings only from purely male trees, or only from purely female trees, willows could be prevented from spreading by seed, unless viable seed is produced without pollination, and there is no evidence of that.

Unfortunately for willow management, bisexuality (although not usual) has proven to be quite widespread in Australia, especially in hybrids. The observed bisexuals were mainly male, with the proportion of female flowers typically under 10%, but ranging from perhaps 1% to 40%, depending on variations between clones and years. In bisexual trees, male and female flowers usually occurred in the same catkin. Bisexuality occurred regularly and at all ages in *S. x chrysocoma* and two other hybrids of *S. babylonica*, in at least one clone of *S. matsudana x alba*, in *S. aegyptiaca*, and in some forms of *S.* '*alba*'. Neumann (1981) also noted that bisexuals occur mainly in hybrids. Mosseler and Zsuffa (1989) found bisexuals in hybrids as well as in pure species, but these bisexuals tended to become purely male in the second or third year of flowering. Viable seed (not necessarily the result of self-pollination) has been collected from most of the Australian bisexuals (especially *S. matsudana x alba*), although seed has been hard to find in *S. x chrysocoma*.

A serial form of bisexuality was observed once in *S. nigra* when an initially wholly female tree produced wholly male catkins emerging from the tops of female catkins while these were still flowering. In one other instance, *S. nigra* was seen to produce abundant, viable seeds in February, i.e. out of season, and without a noticeable source of pollen, i.e. possibly also a case of 'serial bisexuality'.

In several seedling populations of *S. purpurea* grown from seed, females were so common that males were hard to find. Such female-biased sex ratios are not rare (e.g. Mosseler and Zsuffa 1989).

HYBRIDISATION

It has long been known world-wide that many willows hybridise, but recently it was suggested that breeding between different species is not as common as previously thought. Neumann (1981) considers that hybrids in Europe constitute less than 5% of the total willow population. In their native habitats, the separate identities of species tend to be preserved by the existence of natural barriers to interbreeding (non-overlapping flowering times, non-overlapping geographical and ecological distributions) as well as genetic barriers, especially those between tree willows (subgenus *Salix*) and shrub willows (subgenus *Vetrix*) (Mosseler and Papadopol 1989). Some of the barriers to hybridisation tend to break down when willows are introduced to new environments, where flowering times may be altered or gaps in flowering bridged by other species flowering at intermediate times. Where species that were previously separated geographically are planted side by side hybridisation appears to be facilitated. In the UK, there are many hybrids (some even between shrub willows and tree willows) and thus there is concern that some of the native willows may loose their identity by breeding with the introduced willows (White 1994).

After their introduction to Australia, willows have proven to be especially promiscuous. Although only 4 of the taxa in Appendix 1 are present in Australia as both males and females (No 6, 7, 12, 13), all but two (1 & 13c) are now known to have bred locally. The indications are that, within each sub-genus, probably all fertile willows in Australia will hybridise, provided their flowering times overlap. Although some of the resulting hybrids might not be fit, some are clearly superior to their parents. The unfit ones are not noticed (except in germination tests), but the fit ones may well develop strains that are even better adapted to local conditions. A number of streams are now dominated by varied hybrids of uncertain parentage.

S. babylonica, an example of hybridisation

Most of the *S. babylonica* introduced to Australia belongs to a single clone, i.e. are genetically identical. They are all female and flower early. This earliest-flowering species of female tree willows has co-existed with the later-flowering male clone of *S. fragilis* in much of Australia for more than a century without producing seedlings. However, their flowering only just failed to overlap at Canberra during 1994-98. It might well occasionally overlap elsewhere, especially in coastal New South Wales (NSW). Probably because of such overlap and certainly because of the recent plantings of the early-flowering males of *S. matsudana x alba (*introduced in the 1980s), *S. babylonica* now produces ample seed and seedlings in some rivers. Some of the resulting hybrids are clearly more vigorous than their mother (probably due in part to their stronger resistance to the leaf-rust disease), and these hybrid offspring include females, males and bisexuals with varying degrees of weep, some variety in times of flowering, and often vigorous seed and seedling production. Interestingly, Argus (1986) reported that both male and female trees of *S. babylonica* are widely naturalised in the south-eastern USA.

TIME AND SPEED OF GERMINATION

Some subarctic dwarf willows are unusual amongst willows in not shedding their seed till autumn and then not germinating till spring (Densmore and Zasada 1983). This paper deals only with the more usual pattern, as observed in the species of Appendix 1. The seed is shed when the fruit ripens during October-November, usually over a period of one or two weeks in any one tree. At room temperature the moistened seed germinates within 1 or 2 days, but subsequent growth is slow. The roots elongate only 0.5 mm/day.

GERMINATION AND SURVIVAL UNDER WATER

Willow seed will float on water only while it remains attached to its cotton parachute, but that soon falls off, unless the water is very still. Three tests have shown that willow seed can easily germinate on and under water**,** and that the tiny seedlings can survive under water for up to a month, but they cannot grow till exposed to air. Such tolerance to submersion permits tiny seedlings and larger uprooted seedlings to remain viable while being transported by floods. But it should also be noted that willows probably cannot *emerge* from under water, even though it is common to see their lower stems under water.

LONGEVITY OF THE SEED

In most willows, the seed lives for only 1 to 9 weeks when kept dry and at room temperature, unless it is stored at subzero temperatures (McLeod and McPherson 1973). The longevity in Australia of seed of *S. x rubens, S. nigra* and *S. cinerea* was found to be about 2, 3 and 6 weeks, respectively.

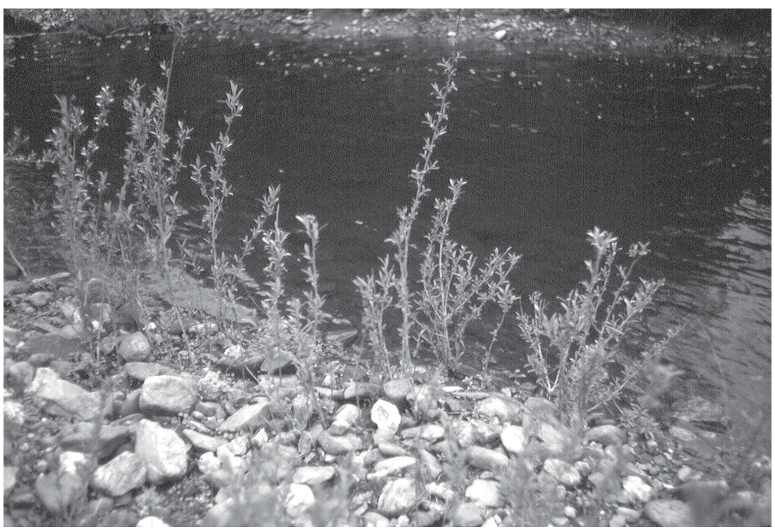
DISPERSAL OF SEED

Willow seeds are highly mobile. There is no evidence for dissemination by insects or animals. Although establishment from seed transported by water is certainly possible (see above), transport by wind is far more important. The tiny seed with its fluffy parachute is superbly adapted to float even in the slightest breeze, and much of it travels for kilometres. Cremer (1999) showed that the seed of *S. nigra* has spread this species to 50 or 100 km in all directions since it was planted at Tumut some three decades earlier. The indications are that the other species in Appendix 1 are not quite as mobile. It is, however, this great mobility which make willows hard to control and requires that control be coordinated regionally and nationally.

Figures 1-2.
1 *(top)*,
Typical willow seed bed. These one-year old seedlings arose from seed shed by the occasionally planted female clone of *S. alba* var. *vitellina* pollinated by the very widely planted male clone of *S. fragilis*.
2 *(bottom)*,
A willow gallery : When willows, that have established from seed at low river margins (Fig.1), grow up their multitudes of stems slow any adjacent flood waters, and this causes sediments suspended in the flood waters to drop out and bury the bases of these willows, making the willows appear as though they had established on mounds. The mounds change stream shapes and hydrology.

ESTABLISHMENT FROM SEED

Live willow seeds will germinate whenever and wherever they are moistened for a day, even if moistened by rain, while still in the opening fruit. Establishment however, depends on a range of factors. Except for *S. cinerea,* the establishment of willows from seed in Australia has been virtually restricted to riparian sites where bare sediments are exposed and kept wet for weeks or months from the time of seed shed in October/November. Seed attached to its parachute is likely to be blown off exposed, dry surfaces, but to adhere to wet surfaces. If the ground is not largely bare, the willows cannot grow because of their high requirement for light. If the surface is not wet within about two weeks of seed shed, the seed dies before it can germinate. If the surface is not moist it is likely to become very hot in the summer sun. Cloudy weather would also help to prevent tiny seedlings from being overheated or dried out on bare gravels. If the ground does not remain moist for weeks or months, the tiny seedling dries out because root growth is initially very slow, less than 1 mm/day. If the seedling is submerged by rising water, its growth is stopped while submerged, but growth can resume if the seedling is exposed to air within a month or so. The importance of water levels is demonstrated when the seed of different species falls at different times while the water level is falling slowly. This may result in the later seedling populations establishing in swathes on the lower lying seedbeds. Such swathes were also observed by van Splunder et al. (1995) and others. Although the barriers to establishment may vary somewhat with species and environment, probably the main limitations are lack of suitable seedbed, rising or rapidly falling water levels after germination, or occurrence of severe floods that wash the seedlings away before they are sufficiently anchored.



As a result of the above influences, willow seedlings typically establish in swathes or ‘galleries’ along the wet edges of gravel bars or at the foot of river banks. But once sediments have accumulated to bury the bases of their stems, these willows look as though they are growing from higher, dry ground.

Most of the perennial streams in the southern half of Australia are occasionally suitable for the establishment of willows from seed. Some are less suitable because they provide little or no bare, wet sediments at the time of seed shed, e.g. the highly regulated Tumut River below Blowering Dam, and most alpine streams, because such streams are full at the time of seed shed and their banks are well vegetated. Some other streams are less suitable because they provide only negligible chances for survival due to the power and regularity of their floods, e.g. the Hunter River. Where floods are most limiting, only a few seedlings can avoid being washed away, and these will be mainly at the very edges where flow is weakest and sediment is least mobile. The indications are that many willows can establish from seed in most streams at intervals of about 5 to 20 years, if seed is available. *S. nigra* may regenerate almost every year in some streams. Where its seed falls during the wet season, *S. nigra* may regenerate in ditches and water courses that are dry most of the year, e.g. near Tumut. Where the seed falls during the dry season, its germination is restricted to the wettest places and its establishment there is threatened by submersion and floods in the following wet season, e.g. near Coffs Harbour. Flow regimes are more important than local climate. Riparian willow recruitment from seed can occur in both moist and semi-arid climates.

Why S. *cinerea* can invade so extensively beyond the streams is not known. Such invasion is aided by clearing, burning and soil disturbance, if the ground is moist at and after the time of seed shed. This invasiveness makes S. *cinerea* a particularly serious environmental threat. In the moist climates of central Europe, *S. purpurea* (and other shrub willows) typically grow on hillsides, but in Australia this is rare and restricted to the moist climates.

VEGETATIVE SPREAD:

Suckering. Unlike the closely related poplars, most willows do not sprout shoots from roots. From Appendix 1, probably only *S. nigra* does so. However, *S. exigua*, imported in 1995/6, suckers vigorously. Because willows tend to have many stems or low branches that sprout roots when they become buried by accumulating sediments, they often look as though they had grown from suckers.

Rooting of detached branches. Except for *S. caprea* (Fjell 1987), willows are usually easily grown from cuttings and this assists their spread, not only by people but also by nature. Such natural spread is only slight in species whose branches are not easily broken off (e.g. most of the shrub willows), but it is important in most of the tree willows (4-10 in App. 1), especially in *S. fragilis* and its hybrids. Although the branchlets of these trees may be tough enough to make baskets, their bases tend to be so fragile that live branches can be broken off by storms or floods. *S. fragilis* has thus come to dominate many kilometres of Australia's streams, especially where branches are caught on rocks.

Layering and toppling. In some species, especially *S. purpurea*, a single plant may develop many hundreds of stems producing a thicket more than 10 m in diameter and thus difficult to control. Layering may also assist modest advances into dryer ground, e.g. when a willow grown at the bottom of a stream bank has a branch take root at the top of the bank. Layering can also result in major advances into still, shallow waters. Willow branches and stems tend to lean towards the water so much that they touch the ground and take root. Such rooting is usually only temporary where strong floods occur, but it can eventually result in extensive thickets in relatively still waters, such as in the lower Murray River and at lake edges. Layering is also promoted when a tree, growing in boggy ground at the edge of a stand, develops its crown mainly towards the open water and eventually falls into the water. When the willows become over mature, they typically do not die, but topple to take root again. Mature infestations thus become self perpetuating, extensive tangles.

Recovery after fire. Willows cope with fire surprisingly well. Where fire is able to reach the stems, the willows are easily girdled (ringbarked) by fire, because their bark is thin, unless the trunks are thick (> 40 cm). However, unless they are old, girdled willows usually produce shoots. In burnt trees, these shoots come from buried portions of the stems.

Where willows grow densely, their shade tends to eliminate nearly all undergrowth and hence the fuels produced by such undergrowth. As the foliage and twigs shed by willows decay rapidly in moist sites, there is usually not enough fuel to carry fires into willow thickets. Such thickets thus tend to exclude any wild fires that burn the adjacent native bush or pastures.

WILLOWS AND POPLARS INTRODUCED TO OTHER COUNTRIES

Willows are spreading also in other countries, but without so far causing major concern, e.g. in South Africa (Henderson 1991) where *S. babylonica* and *S. fragilis* (both are female there!) are spreading only vegetatively. They are also spreading in Canada (A. Mosseler, pers. comm.). New Zealanders heavily promote willows for planting (van Kraayenoord et al. 1995), but also spend much effort in controlling them, e.g. by clearing 1200 ha per year (half of that by aerial spraying) in just the Canterbury region alone (Scholes 1996). Most of the wetlands on NZ's North Island are largely dominated by *S. cinerea* (West 1994). In Colorado, USA, *S. x rubens* and *S. alba var. vitellina*, both introduced, are spreading from rooted branches but not from seed, even though they interbreed to produce many seeds able to grow seedlings in the nursery. Inability to establish in these rivers is probably due to the annual rise in water levels after the seed falls (Shafroth et al. 1994).

One reason why willows may thrive in foreign lands is relative freedom there from pests and diseases. Even so, willows in Australia and New Zealand have acquired quite a few maladies (Spiers 1989), especially the leaf rust that debilitates *S. babylonica* in coastal NSW. In 1998 a voracious sawfly began defoliating various tree willows in New Zealand (van Kraayenoord, pers. comm.).

WILLOWS AND POPLARS IN THEIR NATIVE LANDS

The spread of willows and poplars does not seem to have caused real concern in their native countries. In Europe, at least, this is largely because there is little or no seedbed (usually the streams are full and their banks densely vegetated) and the land is densely settled and carefully maintained. The ecology of colonisation by riparian willows in their native lands is, however, similar to that in Australia. In North America, Europe and Japan, the riparian willows and poplars regenerate from seed germinating on bare, wet sediments at the edges of rivers, especially where these form sand sheets or meander over flood plains.

In at least some of their native lands, willows are succeeded by other hardwoods and by conifers that are able to regenerate in the shade of willows (e.g. Niiyama 1990, van Splunder et al. 1995). The shrub willows generally are not restricted to riparian ecologies. Their regeneration in Europe and America extends also to wetlands and to open spots on mountains (Neumann 1981). In Alaska, establishment of shrub willows on uplands is favoured by hot burns (Zasada et al. 1983) !

In Australia, the natural replacement of willows by other species seems to be restricted to the warmer climates.

Figures 3-4.
3, Invasion by seed : colonisation of exposed stream sediments by multitudes of willows (in this case the aggressive *S. nigra*) can dominate the riparian environment to the exclusion of native species, block flood channels, divert floods and cause erosion of land and structures;
4 *(below right),* Invasion by vegetative spread : a small stream dominated by *S. fragilis* spread vegetatively by detached live branches taking root and by senescent stems falling over and rooting again. Because *S. fragilis* has been so widely planted and since so long ago (>150 years), this is so far the most extensive type of willow invasion in Australia; All photos this article by Kurt Cremer.

Here, certain shade tolerant species may invade the willows: native rainforest species, or, more commonly, shade tolerant weeds, such as *Ligustrum lucidum*, *Lantana camara*, *Rubus fruticosus* and *Acer negundo*. Replacement of willows by more desirable species needs to be assisted in most situations.

EXTENT OF SPREAD IN AUSTRALIA

In the four SE states, willows have seriously infested thousands of kilometers of stream. However the habitat still available for further invasion is at least ten times as extensive. Cremer (1996, 1999) has detailed the buildup of willows in four rivers. The most intractable invasion is that by *S. cinerea*.

S. cinerea **–** This is the most invasive willow in Australia. The spread by seed of male and female *S. cinerea*, in the eastern half of Victoria, is largely beyond control. It is not confined to riparian habitats but ranges extensively also to brackish wetlands at the coast, through wet forests, to alpine bogs, in disturbed as well as undisturbed sites in National Parks and many other places (Carr 1996 and pers. comm.). In NSW it is at present known only at five places and probably is still controllable. In Tasmania there is a still manageable spread south of Hobart. In New Zealand, *S. cinerea* 'has invaded most swamp areas throughout the country' (van Kraayenoord et al. 1995) where it now dominates large areas. It grows on a wide range of soils and can tolerate permanent water logging, poor aeration and a pH down to 3.5 (West 1994). As a serious environmental weed in the cooler, wetter parts of Australia, *S. cinerea* should be totally eradicated wherever that is still possible.

ENVIRONMENTAL IMPACTS

Willows can seriously obstruct streams because their seedlings can establish thickets on exposed wet sediments and they can invade shallow water by the layering of branches and toppling of over mature, live stems. This will obstruct and divert floods with possible erosion of floodplains, roads and bridges.

Information on environmental impacts is sketchy but extensive (Bobbi 1999, Ladson et al. 1997). The largely negative impacts are due to the fact that willows, unlike nearly all native plants:

- produce dense shade during the growing season. This eliminates most native terrestrial plants growing beneath and inhibits aquatic plants. It also decreases the temperature and the oxygen content of the water (with good and bad consequences).
- are deciduous. Leaf inputs to streams are largely restricted to autumn and are massive at this time. This may cause scarcity of food for some organisms at most times, and superabundance in autumn (with consequent anaerobic decay in stagnant waters).
- have underwater roots. These modify the banks, and in shallow streams, cover the ground, eliminating niches for organisms needing shelter in hollows.
- are exotic. Thus willows are a poor link in the food chain for native organisms.

A draft analysis indicates that willows can critically reduce water supplies in certain situations, for instance, when both the banks and the surface of the river bed are dry but the stream is still flowing underground. Removal of the riparian willows could save some 12 million L/summer per km of stream in such a situation in the Canberra climate, provided that this amount of water would have been readily available to the willows' roots. Such a saving could be locally significant where people depend on extracting water from below the surface of the river bed. The above estimate is based on the assumption (justified by the results of Myers et al. 1996) that a dense crop of plants tends to use about as much water as would evaporate from a similarly exposed area of water, provided that ample water is readily available to the plants, and the plants do not readily shut their stomata in response to the air's dryness. The roots of willows such as *S. babylonica* and *S. fragilis*, unlike those of most other plants, do indeed grow under water and effectively follow receding water tables. In a climate like Canberra's, where pan evaporation during December to February averages 7 mm/day, it is calculated that two rows of large willows each with 10 m wide crowns lining a 1 km stretch of river would use 10m x 2 x 1000m x 7mm x 90 days = 12.6 million L/ summer.

MANAGEMENT STRATEGIES AND METHODS OF CONTROL:

Importation, Selling and Planting of Willows. The Australian Quarantine and Inspection Service was made aware of the weed potential of willows in Australia by 1995 and is now restricting additional importations.

Since 1998, the selling and planting of willows in NSW has been restricted to just 3 species: *S. babylonica, S. x reichardtii* and *S. x calodendron* (a hybrid shrub willow with two sterile female clones). This is far safer than the unrestricted use of several hundred species and countless, commonly unidentifiable hybrids. It is, however, a compromise to be used with caution.. The other states have been moving towards similar restrictions. Since 2001, all willows, except the above three permitted species, have been declared as 'Weeds of National Significance' and a strategic national plan for their management has been developed. Currently some millions of dollars per year are spent on willow control.

Regional Strategies. There is no intention to remove all willows. The main aim is to identify the 'problem willows' in each (sub)catchment and to eliminate these selectively. 'Problem willows' are of three overlapping categories, —(a) trees that are not wanted (preferably for a good reason), e.g. where they block the river,—(b) extremely invasive species (e.g. *S. nigra*, *S. cinerea*) that should be totally eradicated wherever that is still possible, and—(c) trees growing in 'problem situations', i.e. trees growing where they threaten to spread excessively from seed or rooted branches (this includes nearly all species, except sterile clones with non-fragile branches).

Dealing with 'problem situations' means: 1. Eliminate self regenerated willows 2. Reduce their sources to acceptable levels. 3. Eliminate fragile willows where their broken branches are apt to take root. 4. Separate males from compatible females by at least 300 m to reduce pollination by bees or by at least 2000 m in order to stop such pollination. Sometimes, a modest amount of seed production from a less aggressive species can be tolerated, if there is little seedbed within 1-3 km and new seedlings are weeded out regularly. In practice, major attacks have been made on *S. cinerea* and *S. nigra,* but none of their populations have yet been eliminated. Most other control projects have been less focused, dealing only with local problems. So far, control efforts have not been sufficiently targeted and extensive to promise comprehensive control.

Methods of Control. The main method is injection of stems with the weedicide Glyphosate. Details of this and other methods are given in Cremer (1999) and in Trounce and Cremer (1997). Painting of freshly cut stems with Glyphosate is particularly effective and the spraying of foliage of shorter plants (< 2 m tall) is often effective as well.

Biocontrol is being considered. It would be good to stop the supply of seed of all species and to eradicate the most invasive species altogether (e.g. *S. cinerea, S. nigra*). However, devastating all species would probably do more harm than good, at present. Willows in Australia have acquired some diseases and pests already (by accident), but the seriously defoliating larva of the sawfly *Nematus oligospilus*, which was recently (1997) discovered in New Zealand, has not yet attacked willows in Australia.

CONCLUSIONS

Although valuable in many situations, willows have become pests in much of SE Australia because of their tendency to invade and extensively dominate riparian habitats to the detriment of stream hydrology and ecology and of riparian habitats. Major efforts are now being made to selectively remove the problem willows. Willow invasions are similar in New Zealand. This could be a lesson to other countries where willows have been introduced. The willows and many other serious environmental weeds will greatly change the native communities of Australia in the coming centuries.

REFERENCES

Argus, G. W. 1986. The genus *Salix* in the south eastern United States. Syst. Bot. Monograph. 9, 1-170.

Bobbi, C. 1999. River management arising from willow removal. Second Australian Stream Management Conference, Feb. 1999, Adelaide, pp 69-73.

Carr, G. W. 1996. '*Salix*', pages 387-398 of *Flora of Victoria,* Vol. 3, ed. by N. G. Walsh and T. J. Entwistle.

Cremer, K. W. 1996. Willow identification for river management in Australia. CSIRO Forestry, Technical Paper 3. 22 pp.

Cremer, Kurt 1999. Willow management for Australian rivers. Natural Resource Management, Special Issue, Dec. 1999, pp 1-22.

Densmore, R. and J. Zasada 1983. Seed dispersal and dormancy patterns in northern willow: ecological and evolutionary significance. *Can. J. Bot.* 61, 3207-3216.

Fjell, I. 1987. Structure and development of adventitious roots in *Salix caprea* and *S. caprea x S. viminalis*. *Nord. J. Bot.* 7, 311-323.

Free, J. B. 1970. *Insect Pollination of Crops*. Academic Press. London. 544 pp.

Henderson, L. 1991. Alien invasive willow species in the grassland biome of South Africa. *Suid-Afrikaanse Bosboutydskrif*, 157, 91-95.

Ladson, A., G. Gerrish, G. Carr and E. Thexton 1997. *Willows along Victorian Waterways*. Dept. of Natural Resources and Environment, Victoria. 123pp.

McLeod, K. W. and J. K. McPherson 1973. Factors limiting the distribution of *Salix nigra*. *Bull. Torrey Bot. Club* 100,102-110.

Mosseler, A. and C. S. Papadopol 1989. Seasonal isolation as a reproductive barrier amongst sympatric *Salix* species. *Can. J. Bot*. 67, 2563-2570.

Mosseler, A. and L. Zsuffa 1989. Sex expression and sex ratios in intra- and interspecific hybrid families of *Salix* L. *Silvae Genetica* 38, 12-17.

Myers, B. J., T. Theiveyanathan, N.D. O'Brian and W.J. Bond 1996. Growth and water use of *Eucalyptus grandis* and *Pinus radiata* plantations irrigated with effluent. *Tree Phys*. **16**, 211-219.

Neumann, A. 1981. Die mitteleuropaeischen *Salix*-Arten. Mitt. Forstl. Bundes-Versuchsanstalt Wien. 134. Heft. 153 pp.

Niiyama, K. 1990. The role of seed dispersal and seedling traits in colonization and coexistence of *Salix* species in seasonally flooded habitat. *Ecol. Res*. 5, 317-331.

Scholes, G. 1996. Willows in Canterbury, New Zealand. Presentation to workshop at Bega, Nov. 1996. 10 pp.

Shafroth, P. B., M. L. Scott, J. M. Friedman and R. D. Laven 1994. Establishment, sex structure and breeding system of an exotic riparian willow, *Salix x rubens*. *Am. Midl. Nat.* 132, 159-172.

Spiers, A. G. 1989. Introduction of poplar and willow pathogens into New Zealand and their effect. *N. Z. J. For. Sci*. 19, 347-352.

Trounce, B. and K. Cremer 1997. *Willow Control*. pub. by NSW Agriculture. 5pp.

van Kraayenoord, C. W. S., B. Slui and F. B. Knowles 1995. Introduced forest trees in New Zealand. 15. The Willows. N Z Forest Research Institute. Bull. 124. 32pp.

van Splunder, I., H. Coops, L. A. C. J. Voesenek and C. W. P. M. Blom 1995. Establishment of alluvial forest species in floodplains: the role of dispersal timing, germination characteristics and water level fluctuations. *Acta Bot. Neerl*. 44(3), 269-278.

West, C. J. 1994. (*ed*). Wild willows in New Zealand. Proceedings of a willow control workshop at Hamilton in Nov.1993. Pub. Dept. Conservation, Wellington. 103 pp.

White, J. E. J. 1994. The possible effects of cultivated introductions on native willows in Britain. p. 113-118 of 'The common ground of wild and cultivated plants'. Proc of conference at Cardiff, U K, July 1992.

Zasada, J. C., R. A. Norum, R. M. van Veldhuizen and C. E. Teutsch 1983. Artificial regeneration of trees and tall shrubs in experimentally burned upland black spruce/feather moss stands in Alaska. *Can. J. For. Res*. 13, 903-913.

Received: August 25, 2003 - Accepted: December 6, 2003

APPENDIX 1. BOTANICAL AND COMMON NAMES

Willows in rural Australia (after Cremer 1996)

Tree species (subgenus *Salix*)

1 S. humboldtiana 'Pyramidalis'	Pencil Willow
2 S. matsudana 'Tortuosa'	Tortured Willow
3 S. x chrysocoma	Golden Weeping Willow
4 S. babylonica	Weeping Willow
4c hybrids of *S. babylonica*	'Weeping Willow'
5 S. alba var. *vitellina*	Golden Upright Willow
6 S. nigra	Black Willow
7 S. matsudana x alba	Matsudana Hybrid Willow, N.Z. Hybrid Willow
8 S. fragilis	Crack Willow*
9 S. alba	White Willow*
10 S. x rubens = S. alba x fragilis	White-Crack Willow*

*these are often incorrectly called Basket Willow in Australia

Shrub species (subgenus *Vetrix*)

11 S. viminalis	Common Osier
12 S. purpurea	Purple Osier
13 S. cinerea	Grey Sallow, 'Pussy Willow'
13a cinerea ssp *cinerea*	Grey Sallow
13b cinerea ssp oleifolia	Rusty Willow
13c S. x reichardtii = S. cinerea x caprea	Pussy Willow
13d S. x calodendron = cinerea x caprea x viminalis	'Pussy Willow'
14. S. glaucophylloides	Broadleaf Willow
15 S. aegyptiaca (syn. *medemii)*	