REPORT NO. 2315

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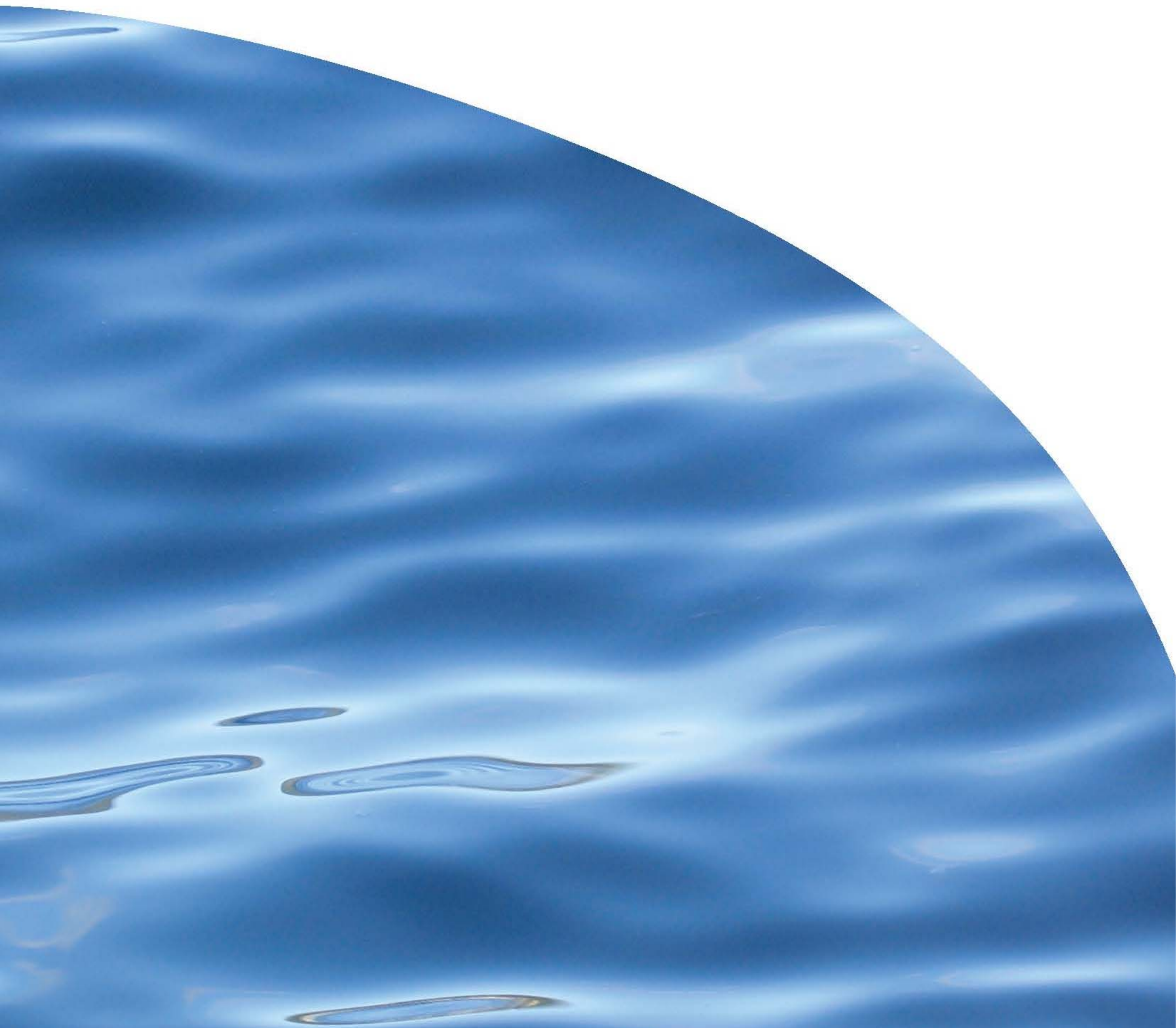

EFFECTS OF WILLOW REMOVAL ON AUSTRALIAN AND NEW ZEALAND STREAM ECOSYSTEMS — A LITERATURE REVIEW OF THE POTENTIAL RISKS AND BENEFITS

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Prepared for MBIE Project C01X1002:Maintenance and Rehabilitation of Aquatic Ecosystems

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ISSUE DATE: 30 April 2013

RECOMMENDED CITATION: Wagenhoff A, Young RA 2013. Effects of Willow Removal on Australian and New Zealand Stream Ecosystems — A Literature Review of the Potential Risks and Benefits. Prepared for Ministry of Business, Innovation and Employment Project C01X1002: Maintenance and Rehabilitation of Aquatic Ecosystems. Cawthron Report No. 2315. 37 p.

EXECUTIVE SUMMARY

Willows (*Salix* spp.) are exotic to New Zealand and Australia, but dominate many riparian habitats because they have been widely planted to control streambank erosion in degraded agricultural catchments, and because some species have become invasive.

Negative effects of willows on stream ecosystems include: 1) increased flooding and reduced land drainage due to the willow roots and branches reducing channel volume and increasing hydraulic roughness, 2) consequential erosion and channel migration, and 3) further spread and loss of biodiversity through replacement of the native vegetation. These issues have raised concern amongst resource managers and the community and in response, some resource management authorities throughout New Zealand and in south eastern Australia have started to implement reach-scale willow control and removal operations.

The destructive removal process and the associated potential risks to stream ecosystems have sometimes caused a public outcry; prompting the need for managers to consider whether the benefits outweigh the risks. This literature review presents the potential risks and benefits to inform resource managers whether reach-scale willow removal and subsequent re-establishment of native riparian vegetation may be an effective rehabilitation measure to increase stream health and the biodiversity of instream and riparian communities.

Very few scientific studies on willow removal effects have been conducted and documentation of such rehabilitation projects is equally scarce. Hence potential benefits are inferred from studies on the mitigation of adverse effects of willows on stream and riparian ecosystems reported in the literature. Potential risks of willow removal are based on knowledge of the ability of willows to retain large amounts of fine sediment and organic matter, and to influence geomorphology and flow patterns. Further potential risks are associated with the loss of the functions that riparian vegetation fulfils.

A key finding of this review is that willow management is complex and context-dependent. The expected ecological benefits as well as potential risks are likely highly dependent on stream size, geomorphology, hydrology, catchment land use and associated stressors, and the extent of willow growth and the taxa involved. Setting management goals tempered by the spatial and temporal limitations to recovery will guide the cost-benefit analysis of intended operations and will be crucial to successful rehabilitation projects. Given the potential ecological risks and negative consequences that are involved with willow removal, this report provides management recommendations for when not to remove willows and for selecting streams where rehabilitation efforts are likely to be most efficient.

TABLE OF CONTENTS

1. INTRODUCTION

1.1. Background

1.1.1. Introduction of willows to New Zealand and Australia

Willows (*Salix* spp.) comprise ca. 450 species and their native distribution is mainly in the arctic, boreal and temperate regions of the Northern Hemisphere (Argus 1997). Willows were introduced to New Zealand and Australia in the 1800s for the purposes of streambank stabilisation in degraded pastoral systems and as shelter and supplementary fodder for livestock amongst others (Wilkinson 1999; Doody & Benyon 2011). Extensive willow plantings for erosion control, however, took place in the 1950s to 1970s in Australia (Holland-Clift & Davies 2007) and in the 1970s to early 1980s in New Zealand (Wilkinson 1999). Erosion control by means of riparian willow plantings have a long history in Europe (Evette *et al.* 2009). Preferences for willows are related to their easy vegetative propagation of rooted and unrooted cuttings, tolerance to flooding and periodically saturated soils, fast growth and formation of extensive fine-fibrous root systems capable of binding sediments (Wilkinson 1999).

1.1.2. Willow invasion

The same characteristics that made willow plantings so successful also provided potential for willows to become invasive. Rapid vegetative reproduction occurs through detached branches that are transported in the water and root on wet bare river margins downstream (Doody *et al.* 2011). Branches of crack willows (*S. fragilis*) are very brittle, hence this species and its hybrids are particularly prone to spreading this way (Cremer 2003). The potential for willows to spread more widely (up to a distance of 100 km) than within a river system is exacerbated via seed reproduction (Cremer 2003). Previously, it was believed that the production of viable seeds could be prevented by introducing only one gender of each species, but the possibility of hybridisation had been overlooked (Cremer *et al.* 1995). In New Zealand, 11 species and five hybrids have become naturalised, and three of these are considered the main problem taxa: crack willow (*S. fragilis*), grey willow (*S. cinerea*), and pussy willow (*S. x reichhardtii*) (Collier 1994). As a consequence of both vegetative and sexual reproduction (including those that were intentionally planted), willows today dominate many riparian habitats in New Zealand and Australia. For example, crack willows are the dominant marginal vegetation along New Zealand's Waikato River, but grey willows and weeping willows (*S. babylonica* and hybrids) are also widespread along and throughout the catchment (Champion & Clayton 2010). The two species, weeping and crack willow are prevalent in over a third of the River Murray's 830 km course below the Darling junction in South Australia (Schulze & Walker 1997; Doody *et al.* 2011). A national estimate of the total riparian area covered by willows in Australia is 21,015 ha with the main distribution in the south-eastern regions (Doody *et al.* 2011). No recent estimate is available for New Zealand, but a 1962 survey estimated that the total area of willows was about 41,000 ha, and that willows were the second most

common exotic trees after pine trees (Van Kraayenoord *et al.* 1995). Success of willows in spreading and out-competing native riparian vegetation may also be partly due to previous environmental change such as flow regulation (Poff *et al.* 1997; Schulze & Walker 1997) and to having less natural enemies and diseases than the natives (Cremer 2003). Even so, willows have acquired pest species along the way. For example, the larva of a voracious willow sawfly (*Nematus oligospilus*), first discovered in New Zealand in 1997 and in Australia in 2004, is known to defoliate several willow types (Ede 2006).

While most willows are reliant on wet bare ground for regeneration from seed and hence are confined to riparian habitat, grey willow is known to also establish on undisturbed sites and tolerate a range of soil conditions. This has extended its spread to National Parks and wet forests in Australia and large wetland areas in New Zealand (Cremer 2003; Beard 2010), where it is considered to be one of the top 10 environmental weeds in several Department of Conservation conservancies (Froude 2002). Furthermore, since willows are extremely tolerant to standing water and resistant to shear stresses during floods (Evette *et al.* 2009), willows are not confined to streambanks. They also encroach into shallow permanently-inundated streambeds (Doody *et al.* 2011) by layering of branches and toppling mature live stems taking root again (Cremer 2003). These willows can eventually block the stream channel and divert floods potentially causing erosion of floodplains, roads and bridges, and channel migration (Cremer 2003).

1.1.3. Willow management

Concerns about flooding, streambank erosion, damage to infrastructure, and willow invasions associated with potential impacts on biodiversity and ecosystem function prompted the listing of *S. fragilis* and *S. cinerea* as ‘unwanted organisms’ under the New Zealand Biosecurity Act 1993 in the National Pest Plant Accord (NPPA). The NPPA is an agreement between the Nursery and Garden Industry Association, regional councils and government departments banning sale, propagation and distribution of these plants in New Zealand. In addition, resource management agencies started to remove so-called ‘problem willows’ from invaded areas or earlier plantings in the 1980s.

However, willows other than the two NPPA-listed species and varieties believed to be non-invasive and sterile, have been and are still commonly used for soil conservation and streambank stabilisation by resource managers and land owners throughout New Zealand (Phillips & Daly 2009). Considerable effort has gone into research and breeding programmes of willow varieties that were specifically selected for their suitability in New Zealand river management since 1969 (http://www.poplarandwillow.org.nz/pages/breeding-&-research/; accessed March 2013). Important selection criteria were male sex to prevent seeding, rapid growth

rate, strong root system with many fibrous roots, and resistance to disease (Slui 1991).

Willows are seen as the most cost-effective vegetation for the front-line defense in reaches of higher-order streams modified by levees (stopbanks) and where active erosion is likely to undercut banks to a steep and unstable slope of more than 2 m high (Marden *et al.* 2005; Phillips & Daly 2009). In these rivers, the effectiveness of riparian restoration with New Zealand native plants, without prior installation of structural protection, is likely to be less effective due to their relatively shallow root systems (Marden *et al.* 2005). On the other hand, New Zealand natives have shown to be efficient in stabilising banks of lower-order streams (Marden *et al.* 2005), and are increasingly being used in streamside vegetation programmes. The driver for these programmes, however, generally is the need to increase biodiversity rather than streambank stabilisation (Phillips & Daly 2009). At the same time, willow planting on farms is still being promoted on some Regional Council websites for specific purposes: drought fodder and shelter for livestock, soil conservation in hill country, and also for streambank stabilisation (*e.g.* National Poplar and Willow Users Group 2007). This is despite some native species being known to provide good protection from erosion in a variety of settings (Slui 1991). The governmental Sustainable Land Management Hill Country Erosion funding scheme has recently supported a 'Poplar and Willow Breeding Programme' (Willow and Poplar Research Collective & Plant and Food Research 2009) aiming to breed new varieties that are suitable for erosion control and more robust to diseases such as the willow sawfly. The willow sawfly (*Nematus oligospilus*) has posed serious threats to willows providing important riverbank protection in New Zealand's Hawke's Bay region. This damage has resulted in multi-million dollar remediation works (Ede 2006).

Willow management is complex because it is taxon-specific and because there is a suite of arguments both for and against removal of certain willows. Both implementing willow removal programmes and promoting willow plantings by resource management authorities is certainly confusing to the public. This confusion may be resolved if:

- willow removal involved invasive taxa that constrict channel capacity or threaten other ecosystems by further invasions
- non-invasive willows were planted in places where they can provide an important erosion-control function that is unlikely being fulfilled by native vegetation, or where they provide other specific functions.

By contrast, it is not a consistent management strategy to:

- remove willows for ecological reasons, or promote any willow removal operation as being of ecological benefit
- widely promote willow planting, where native vegetation could also fulfill similar functions.

In contrast to New Zealand, willow management in Australia has undergone a paradigm shift. All *Salix* spp. except *S. babylonica*, *S. x calodendron*, and *S. x reichardtii* were listed as 'Weeds of National Significance' in 1999, which is a government initiative providing national strategic management for weed control. Development of a national strategic plan (ARMCANZ *et al.* 2001) involved assessment of the current spread and the invasiveness of the most common willow varieties, and publication of willow management guidelines (Holland-Clift & Davies 2007). Willow planting is not being encouraged anymore by Australian management authorities, most species are illegal to trade or distribute in all states and territories and control of certain species is legally required in some areas.

Willow removal techniques are manifold and range from hand pulling or use of machinery to stem injection or foliar spraying with herbicides (Holland-Clift & Davies 2007). Biological control measures have also been investigated, but have not yet been applied in New Zealand or Australia (Harman 2004; Adair *et al.* 2006; Holland-Clift & Davies 2007; Caron *et al.* 2011). The recommended removal technique depends on tree/shrub size, extent and location of invasion, potential environmental impacts on the site and downstream sites and on social impact (Holland-Clift & Davies 2007).

There is broad support for reach-scale willow removal by government agencies in Australia and New Zealand for social, economic and environmental reasons (ARMCANZ *et al.* 2001; Holland-Clift & Davies 2007; Phillips & Daly 2009). Resource managers need to know about costs and benefits incorporating social, economic and environmental values of stream and riparian ecosystems in order to make the most effective decisions. Whether the benefits outweigh the costs is largely dependent on the management goals of a specific project. Reach-scale willow removal and re-establishment of native vegetation has been suggested and implemented as a management action to improve stream health and the biodiversity of both instream and riparian communities. Here, knowledge of whether the ecological benefits outweigh the ecological costs is central although the effects on the socio-economic values also need to be considered. Particularly little is known about the ecological costs and benefits of such willow removal operations. Few scientific studies address the effects of willows on riparian and stream ecosystems and even less studies investigate the ecological effects of willow removal. Willow removal operations are underway but monitoring and reporting of their ecological effects are sparse (but see McInerney *et al.* 2010).

1.1.4. Controversy over willow removal

While the negative effects of certain willows and the need for control seem to be widely recognised (ARMCANZ *et al.* 2001), the removal of willows is very controversial (*e.g.* Tane 2010). In particular, reach-scale willow removal operations from along streams and rivers seem to be conflicting with the notion of conserving

riparian vegetation for its multiple important functions (Collier *et al.* 1995). Community concerns arise from people who believe that willows are crucial for good streambank protection, or those who do not want to see willows removed that have become part of the Australian and New Zealand landscape and possess aesthetic or heritage value (*e.g.* weeping willows, *S. babylonica*) and provide important nutrition for bees (Harman 2004; Holland-Clift & Davies 2007; Tane 2010). Willow removal is often criticised by anglers who believe that willows create habitat for trout and eel to thrive in (Caruso 2006; Leaman 2012; Mirfin 2012). But anglers and other recreationists such as kayakers, may also be in support of removal, as willows can obstruct both access to the river and the channel itself (Holland-Clift & Davies 2007; Phillips & Daly 2009). Conflicting opinions can also arise within the farming community. While generally farmers value willows as provision for stock feed during drought, others, in particular in the dry regions of Australia, would like to have them removed anticipating a net gain in irrigation water since willows remove large quantities of water (Holland-Clift & Davies 2007; Doody *et al.* 2011). In New Zealand, however, the removal of water through high evapotranspiration rates of willows has been valued for easing management issues in wet areas (Willow and Poplar Research Collective & Plant and Food Research 2009). And finally concerns arise because some willow management has gone wrong in the past due to the lack of re-vegetation, fencing or follow-up control measures (Holland-Clift & Davies 2007).

1.2. Aims

This report provides a review of the literature on the ecological effects of reach-scale willow removal incorporating knowledge from scientific studies and case studies with a view to informing resource management about the potential ecological benefits of such operations and the risks involved. Potential ecological benefits of willow removal are a result of mitigating their negative effects on streams and riparian zones; hence in Section 2, we review the effects of willows on these ecosystems. Section 3 is a review of the potential ecological effects of willow removal with a special focus on the risks involved. More specifically, this report aims at guiding management in formulating ecological management goals for willow removal programmes and to assess and minimise the potential ecological risks involved. This literature review also highlights the environmental variables and biological indicators that will be useful to include in monitoring programmes (pre- and post-willow removal) in order to evaluate rehabilitation success but also with a view to improving future resource management.

2. EFFECTS OF WILLOWS ON INSTREAM AND RIPARIAN ECOSYSTEMS

2.1. Overview

Willows can affect instream and riparian ecosystems because they possess several functional traits different from those of most native riparian plants in New Zealand and Australia. When compared with most native shrubs and trees, willows:

- are deciduous, thus provide dense shade during the growing season and less shade in autumn and winter, as well as provide potentially larger pulsed inputs of leaf litter of different quality to streams in autumn compared to evergreens, which may provide a more continuous energy input throughout the year
- have underwater roots providing instream cover, modifying banks and substratum, and affecting stream flow
- have high evapotranspiration rates, thus can considerably reduce stream flow
- have light wood that decays quickly and is more likely to be carried downstream resulting in lower quantities of resident large woody debris (LWD)
- are exotic and may be a poor link in the food chain (Cremer 2003; Holland-Clift & Davies 2007).

Shading and leaf litter input are well-known properties of riparian vegetation to have strong influences on stream communities and functioning (Allan & Castillo 2007). Shading typically lowers water temperature and hence increases oxygen content benefitting sensitive taxa, but it can also reduce instream primary and secondary production, since less food is available for macroinvertebrates that feed on algae, with further bottom-up effects on fish. Maintenance of cooler temperatures through shading also avoids direct thermal stress on sensitive species of invertebrates (such as larvae of mayflies and stoneflies) and fish (such as banded kokopu) (Quinn *et al.* 1994; Richardson *et al.* 1994). Leaf litter, on the other hand, is an important energy source to the stream food web, but timing and quality of the input are important determinants of availability to higher trophic levels. Leaf litter also serves as habitat but can reduce oxygen content when large amounts decompose in slow-moving water. The combined action of these factors and their relative importance, which is likely dependent on the nature of the willow stands (extent, density, species, age), stream size, geomorphology and catchment land use, will ultimately govern the impacts that loss of native riparian vegetation and replacement by willows have on biodiversity and stream ecosystem functioning at the local and regional level.

2.2. Instream effects of willows *vs*. native riparian vegetation

Few scientific studies have investigated the ecological impacts of willows in relation to the native riparian vegetation in New Zealand or Australia. Lester *et al*. (1994a) found lower macroinvertebrate densities in willowed (*S. fragilis*) compared to open tussock reaches in two small, 3 to 5 m wide, Central Otago streams in New Zealand. Because there was no evidence that shading by the trees reduced primary production and hence food resources, the authors concluded that lower macroinvertebrate densities were most likely related to a decrease in interstitial habitat as these spaces were filled by willow roots and fine sediment trapped within them. This assumption was supported by further investigation into the effects of differences in substrate and shade on macroinvertebrate communities in one of the study streams, but it also revealed that another, undetermined factor associated with willows must have contributed to the faunal differences (Lester *et al.* 1996). Lester *et al.* (1996) proposed that exudates from willow roots may have inhibited macroinvertebrate feeding. The increased amount of leaf litter input in autumn seemed to have no effect on shredder abundance (Lester *et al.* 1994a), although a stable carbon isotope study revealed that insect shredders derived over half, and their predators up to nearly half, of their total body carbon from willows at the willow-shaded sites. This indicates that willows can contribute considerably to the energy flow in stream food webs (Lester *et al.* 1995). Palatability of willow leaves was supported by a food preference experiment showing that detritivore larvae of *Olinga feredayi* (Trichoptera) preferred willow leaves (*S. fragilis*) over periphyton, but only after incubation in the stream for 56 days (not for 7 or 28 days) (Lester *et al.* 1994b). Similar periods of incubation (41 and 58 days) in two other New Zealand streams were reported for when willow leaves (*S. babylonica*) seemed most palatable as leaf bags were most densely colonised by invertebrates at that stage (Collier & Winterbourn 1986).

The majority of studies were conducted in Australia focusing on the effects of willows *vs*. the native riparian tree vegetation, most notably eucalypts. Willow leaves were palatable as shown by preference experiments with three common detritivore macroinvertebrate species (trichopteran *Notalina* sp., ephemeropteran *Koorrnonga* sp., and mollusc *Physastra gibbosa*) from south eastern Tasmania which preferred willow (*S. fragilis*) over eucalypt leaves (Yeates & Barmuta 1999). Two of these species also showed higher growth rates when being solely fed on willow leaves compared to being solely fed on eucalypt leaves. By contrast, shrimp *Paratya australiensis* slightly preferred native eucalypt over willow leaves (*S. babylonica*) (Schulze & Walker 1997).

A field experiment in the South Australian Murray River also showed that the soft willow leaves (*S. babylonica*) decomposed significantly faster than those of the native eucalypts, and this was independent of whether leaves were submersed in reaches lined with willows or eucalypts (Schulze & Walker 1997). In this study, however, macroinvertebrates did not play a major role overall in the breakdown process and

macroinvertebrate community structure did not differ between willow- and eucalypt-lined reaches. Perhaps, loss of native vegetation and replacement by willows exerts less of an impact on instream communities in larger rivers where the riparian vegetation is expected to be less influential than in smaller rivers or streams (Vannote *et al.* 1980). However, the authors note that this may be an underestimation of the impacts of willows since the River Murray, even though it has native eucalypt stands, did not provide a reference condition free of any other anthropogenic modification.

A similar field experiment in a small third-order stream lined by eucalypts found willow leaves to decompose considerably faster than eucalypt leaves (Pidgeon & Cairns 1981). Here, macroinvertebrates played a significant role in the breakdown process suggesting that abundance and community structure of macroinvertebrates in these streams may be altered as a consequence of changes in food quality and perhaps timing of when food becomes available. The authors note that even though willow leaves are palatable and can be easily assimilated by the native macroinvertebrate fauna, riparian willows on their own appeared unable to enhance secondary production relative to native evergreens because willow leaves are shed in autumn and are processed quickly, therefore available for too short an amount of time during the year (Pidgeon & Cairns 1981) and possibly during the wrong time of the year.

To investigate this assumption and consider factors contributing to potential impacts of willows on stream macroinvertebrate communities other than just leaf palatability, Read & Barmuta (1999) focused on the continuity of food resources and habitat alterations. They compared reaches lined with willows (*S. fragilis*) or native eucalpyt-dominated vegetation in nine small- to medium-sized (ranging from 2 to 15 m in width) south eastern Tasmanian streams and rivers in spring, summer and autumn. The most pronounced dissimilarities in macroinvertebrate communities between the two vegetation types were found in summer, when the fauna seemed to respond to differences in habitat and water quality. Total macroinvertebrate densities and taxon richness were lower in willowed reaches corresponding with reduced dissolved oxygen levels and increased levels of deposited fine sediment. Reduced oxygen levels and increased fines were likely a result of the willow root mats invading the streambed, slowing the flow and reducing it to nearly isolated pools. By contrast, riffles in native reaches mainly stayed intact despite low summer flows. Macroinvertebrate communities sampled from willow-root riffles and riffles free of willow roots in willow reaches, however, were similar. In autumn, willow reaches had higher densities and increased dominance of shredders and filterers relative to reaches lined with native vegetation likely reflecting the higher standing stocks of course and fine particulate organic matter, but the faunal response was not marked. In spring, however, no differences in macroinvertebrate communities were detected between the two vegetation types despite higher epilithic biomass and stream temperature in willow reaches. Read & Barmuta (1999) speculated that the effects of willows on streams smaller than the study streams are likely to be more pronounced changing the macroinvertebrate community structure permanently as increased spring

and autumn discharges may not offset the negative impacts willows have on water and habitat quality. And even smaller creeks may experience the largest impacts, turning into 'willow swamps' (Collier 1994) or drying out completely (Holland-Clift & Davies 2007) in the most extreme case, as willows can considerably reduce water flow via high evapotranspiration rates and via clogging of the channel with their thick roots that also trap sediment (Doody *et al.* 2011).

Wilson (2001) investigated organic carbon dynamics in willow-dominated (mainly *S. fragilis*) and native eucalypt stream reaches in Victoria, Australia, and found no significant differences in the timing as well as the amount of annual input of organic matter (litter-dominated) between the two vegetation types. Even though litterfall overall for willows and natives was greatest in summer and autumn, all streams received peak inputs in autumn when flow increased and mobilised accumulated leaves alongside the channel. Hence, Wilson (2001) suggested that timing of organic matter input may not be as an important difference between deciduous willow and native evergreen vegetation (as is typically believed), and that leaf quality is a potentially important factor driving changes in the instream fauna and stream metabolic processes. Another important factor may be the much larger amount of benthic organic matter retained in willow streams, which he noted as the most striking difference between the two riparian vegetation types. Benthic organic matter was retained by willow root mats but the mats themselves contributed largely to the standing stock. However, willow-lined reaches had half the amount of LWD than the eucalpyt reaches (Wilson 2006). The light willow wood decomposes quickly and is also more likely to be carried downstream resulting in lower quantities of LWD in willow-lined sections (Holland-Clift & Davies 2007), and higher quantities in native sections where eucalypt limbs sink, decompose slowly and provide structure (Schulze & Walker 1997). Considering the structural role of LWD in streams (Gurnell *et al.* 1995), loss of native riparian trees and replacement by willows may have significant effects on instream biota but no such samples were taken in Wilson's (2001) study.

2.3. Instream effects of willows *vs.* pasture

Because willows have been and, in New Zealand, are still being planted to stabilise the banks of degraded agricultural streams, it is also relevant investigating the ecological effects of willows relative to pasture sites. Streambank stabilisation and vegetation can be beneficial to benthic macroinvertebrate and fish communities via a decrease in fine sediment loads, increased input of leaf litter providing habitat and food resources, and shading of the streambed associated with control of temperature and algal proliferation (Tabacchi *et al.* 1998; Johnson *et al.* 2007). Glova & Sagar (1994) found higher standing stocks of brown trout, but not native fish, in moderately-willowed (*Salix* spp.) reaches compared with pasture reaches in small New Zealand streams. This is possibly because the former had deeper channels, overhead shelter and larger amounts of brown trout's preferred prey (Ephemeroptera) (Sagar & Glova

1995). The same study also reported higher benthic macroinvertebrate biomass and diversity associated with cooler water temperatures and reduced growth of filamentous green algae in the willowed reaches. This supports the conclusion that riparian willows at moderate density are beneficial to trout and benthic macroinvertebrates compared to their pastoral counterparts (Glova & Sagar 1994). Streams lined by dense willow stands, however, seemed to sustain lower densities and biomass of invertebrates than both the moderately-dense willow and the pasture sites, however definite conclusions cannot be drawn because the densely-willowed treatment was not replicated (Glova & Sagar 1994). Broad *et al.* (2002) found that the mean total length of longfin eels were largest in pasture, intermediate in pasture lined with willows, and smallest in native tussock reaches of Lee Stream (a 4th-order tributary of the Taieri River in New Zealand); but longfin eel condition or density were not influenced. Larger eel size in stream reaches lined with pastoral land, compared to reaches lined with native tussock grassland, was likely related to the elevated nutrient levels and boosted stream productivity. The smaller sized eels in reaches lined with willows compared to the pastoral reaches may tentatively be explained by increased shading (Broad *et al.* 2002).

Even though planted willows may have improved the stream ecological condition when compared to streams lined by pasture, the mitigating effects may over time be outweighed by new bank erosion, which occurs when further willow growth and regeneration causes channel constriction. In small rivers, willows can encroach into the streambed where their roots trap sediment and organic matter, reducing the channel's capacity to transport water. In this instance, during high-flow events, it forces the river to cut new channels and eventually create a shallower but wider braided river system with willow islands (Holland-Clift & Davies 2007; Pope *et al.* 2007). In bigger rivers, willows cannot encroach into the centre, but instead they trap coarse material, narrowing the channel and thereby increasing the likelihood and frequency of flooding and erosion (Holland-Clift & Davies 2007; Rutherfurd 2007). In most cases, where infrastructure is at risk, further river engineering work will be required. For this reason, willows can be considered invasive ecosystem engineers (Crooks 2002) that not only affect stream ecosystems locally due to differences in shading and food supply amongst others, but also have hydrogeomorphic impacts often facilitating further willow invasions (Crooks 2002) with broader-scale consequences on stream ecosystem structure and functioning (Tabacchi *et al.* 1998). The ecosystem engineering properties and predominance of willows in floodplain habitats, however, are not confined to Australia and New Zealand, but also prevail in areas where willows are native (Gurnell *et al.* 2001; Karrenberg *et al.* 2002).

2.4. Riparian effects of willows *vs*. native riparian vegetation

Willows change the riparian habitat, potentially affecting plants and animals native to that ecotone. The dense canopy of willows during the growing season allows less light to penetrate than the sparse and open canopy of native eucalypts in Australia, inhibiting native vegetation such as littoral macrophytes and terrestrial plant species, which are more diverse in the understorey of eucalypts (Schulze & Walker 1997). Bare banks underneath willows provide a limited amount of protection for frogs, lizards, snakes and water rats in Australia (Holland-Clift & Davies 2007), but no detailed studies of willow impacts on their populations were found. However, in two extensive surveys along a south eastern Australian stream, habitat structure, arthropod fauna and bird assemblages were compared between sections dominated by the invasive white-crack willow (*S.* x *rubens*) and sections with native vegetation (Greenwood *et al.* 2004; Holland-Clift *et al.* 2011). Generally, the native sections comprised a greater diversity of plants, were structurally more complex and had a richer terrestrial arthropod fauna as well as a richer avifauna (Holland-Clift *et al.* 2011). Willow-dominated sections hosted only approximately a sixth of the number of canopy arthropod taxa and a third or less of the total individuals that were hosted by the non-willowed sections; there was no difference found in the numbers of flying arthropods between 'willowed' and native sections (Greenwood *et al.* 2004). The depauperate arthropod fauna in willow-invaded areas may be explained by 1) the physical and biological simplification of the vegetation, 2) the specialist fauna of willows observed in their native ranges having been 'left behind', and 3) the native Australian fauna not having adapted to the exotic trees (Holland-Clift *et al.* 2011). Differences in the arthropod fauna, *i.e.* less food resources available to higher trophic levels, coupled with differences in habitat structure such as less numbers of logs and dead trees and lower percentage cover of shrubs and coarse litter in willow-invaded sections have likely contributed to lower records of birds, bird species and foraging guilds compared to those in the native vegetation sections (Holland-Clift *et al.* 2011). A reduction in terrestrial arthropod food resources may also affect instream food webs, which received, at least in one season, considerably less arthropods in the willow-invaded compared to the native sections (Greenwood *et al.* 2004).

Similar patterns emerged from a New Zealand study (Stanley & Ward 2003). Riparian willows (*S. fragilis*) had less abundant invertebrates and very different invertebrate communities than native riparian kanuka trees, independent of whether willows were surrounded by native forest or pasture. Willows also hosted fewer birds, less bird species and a higher percentage of exotic species in the community than kanuka trees. Fewer birds were observed foraging in willow trees across all seasons, consistent with less invertebrate food resources being available. In contrast to invertebrates, birds also responded at larger scales, with less native and endemic species found on kanuka trees surrounded by pasture than on those surrounded by native forest suggesting that native forest patches larger than riparian zones are needed to sustain rich and abundant native bird communities (Stanley & Ward 2003).

In his review, Collier (1994) summarised information from technical publications and personal communications with staff from New Zealand's Department of Conservation. This suggested that willows (particularly *S. fragilis*) have detrimental impacts on specialised bird-life of braided rivers in the Waitaki and Ahuriri catchments of the South Island, by decreasing nesting and feeding habitat for riverbed birds such as the banded dotterel and wrybill. Instead, willows on braided riverbeds favoured birds like waterfowl that prefer overhead cover and that can use willows for nesting, moulting and roosting (Collier 1994). In the lower Waikato, dense crack willow forest has been observed to provide nesting sites for shags, grey teal and the New Zealand shoveler as well as roosting sites for these and other bird species (Champion & Clayton 2010). Invasion of wetlands by grey willows (*S. cinerea*) in New Zealand resulted in higher terrestrial beetle abundance and species richness compared to native wetland vegetation (Watts *et al.* 2012); however, beetle communities of willow-dominated wetlands had an altered trophic structure and a lower proportion of native taxa compared to the native wetland vegetation.

Finally, platypus foraging activity in Australia was negatively related to the number of willow trees growing on the bank and the presence of willow roots and silt in the channel substrate although the substrate seemed not to be related to different densities of macroinvertebrates, the platypus' main prey (Serena *et al.* 2001). Overall, few studies look at willow effects on terrestrial consumers, but they consistently support that exotic willows are likely a poor link in the native food chain.

3. EFFECTS OF REACH-SCALE WILLOW REMOVAL ON STREAM ECOSYSTEMS

3.1. Overview

The expected ecological benefits of willow removal and subsequent re-establishment of native riparian vegetation are the reduction of the negative impacts of willows outlined in Section 2. However, the specific benefits to incorporate into a cost-benefit analysis would largely be dependent on the management goals. The majority of ecological benefits are likely to take effect in the longer term, because it takes time for the native vegetation to mature. The time for many New Zealand riparian shrub and tree species to provide an effective canopy is dependent on the environmental conditions and can take 7–10 years, but longer at high altitudes (Marden *et al.* 2005). In the shorter term, the destructive process of willow removal poses a risk to the instream ecological condition and values that management wants to protect. Resource managers need to know whether the risks and negative effects associated with reach-scale removal of willows are outweighed by the expected benefits following re-establishment of native riparian vegetation. Willow removal without the re-establishment of vegetation is widely accepted to be a poor management option (Holland-Clift & Davies 2007). One exception is willow removal on braided river systems where the reference condition is sparsely or non-vegetated shingle (see Section 3.3.3).

The effects of willows on stream ecosystems are complex, but more complex is the prediction of the potential effects of willow removal and re-establishment of vegetation (Zukowski & Gawne 2006). Complexity arises because:

1. There will be both short- and long-term effects
2. Reach-scale operations will change shading and the inputs of organic matter, nutrients and sediment, all being interacting factors important to the instream fauna and stream ecosystem functioning at, as well as downstream of, the removal site
3. Effects will depend on stream size, geomorphology, hydrology, catchment land use and associated stressors
4. Willows are ecosystem engineers and their removal can change hydrologic and geomorphic processes
5. Effects will depend on the removal strategy (timing, whether working from upstream to downstream or vice versa) and technique (mechanical, chemical), as well as the willow species involved
6. Effects will depend on the success of the re-established vegetation.

We are aware of only one Australian study (see section 3.3.1, Becker & Robson 2009) that has specifically investigated the effects of riparian restoration involving willow removal and re-established vegetation to support the potential effects they may have on water quality, geomorphology, as well as fish and benthic macroinvertebrates reviewed for the Australian stream environment elsewhere (Zukowski & Gawne 2006).

3.2. Risks of willow removal

Willow removal is a destructive process and will cause short- to medium-term effects that potentially pose risks to stream ecosystems. Some of the risks may be reduced by best management practices but others are inevitable. Risks are associated with 1) the removal of willows that have retained large amounts of fine sediment and organic matter, 2) the removal of willows that have modified their environment as ecosystem engineers, 3) the loss of important functions that riparian vegetation fulfils (Naiman *et al.* 2005) until the native vegetation is re-established, and 4) the removal process itself.

3.2.1. Mobilisation of fine sediment and organic matter

Willows have been planted for their ability to stabilise degraded streambanks and retain sediments. Hence, a major concern following willow removal is the mobilisation of fine sediment and organic matter, and of the nutrients contained within, when willow roots retaining these materials rot away (Wilson 2006). This process is predicted to last for at least five years (Holland-Clift & Davies 2007; Rutherfurd 2007). The negative impacts of fine sediment deposition and nutrient enrichment on stream ecosystems are well-known (Wood & Armitage 1997; Allan 2004). We are not aware of any studies that have quantified sediment and nutrient loads released after willow removal, but the volumes of material, particularly from agricultural streams, may be large and degrade downstream ecosystems (Wilson 2006).

3.2.2. Geomorphic modification

In Section 2, we described how willows are able to change original channel morphology and flow patterns, hence the reason they can be called 'ecosystem engineers'. Prevention of these changes is, in some cases, the major driver for their removal. However, in other cases well-established willows may have already significantly modified their environment, so that their removal may cause morphological changes that are now considered undesirable. This is because they can be associated with streambank erosion (Rutherfurd 2010) and threaten pool-riffle sequences (Boyer 2003; Wilson 2006), with consequences for the stream ecosystem, but also for the surrounding land and human infrastructure. For example, willow removal is expected to threaten pool-riffle sequences along the highly modified (gold-mining history, engineering works and urbanisation) Yarrowee River, Victoria, where willow root mats (in contrast to roots of the native vegetation) were found to bind

sediment into erosion-resistant 'weirs', which defined the downstream edge of pools (Boyer 2003). In another example, actual willow removal in combination with heavy grazing pressure caused Weminuche Creek, Colorado, to change from a stable, meandering, single-thread stream to a braided stream within a 2-year period (Rosgen 2009). After further channel succession and within a 12-year period, the original stream type (defined by entrenchment, width/depth ratio and sinuosity) was re-established, with obvious sedimentological, morphological and hydraulic changes to the original stream. This also resulted in severe losses of land and macroinvertebrate and fish habitat. More specifically, degradation of fish habitat was a result of; 1) excess sediment deposition and smaller particle sizes in the substrate, 2) decreased water depths and consequently reduced instream cover and pool quality, increased water temperature and predation from birds and terrestrial animals, and 3) reduced overhead cover provided by grasses compared to the willows (Rosgen 2009). Willow removal, however, will not always cause these drastic geomorphological changes as the sensitivity of streams to change in riparian vegetation is strongly dependent on stream type (Rosgen 2009). On the other hand, if re-establishment of a more natural, pre-willow stream geomorphology is one of the aims of willow removal, geomorphic modification is not actually a risk but rather the desirable outcome.

3.2.3. Loss of the functions riparian vegetation fulfils

Risks also arise because reach-scale removal of willows means loss of important functions of riparian vegetation to the instream biotic communities and ecosystem processes. These functions include provision of shade, organic matter, shelter (overhanging vegetation, undercut banks), and a buffer against agricultural runoff. In particular for small streams, canopy removal considerably reduces shade and litter input. Shade reduction leads to increased water temperatures (Rutherford *et al.* 1997), with maximum summer temperatures potentially exceeding upper thermal tolerances of sensitive invertebrate and fish species (Quinn *et al.* 1994; Richardson *et al.* 1994). An increase in water temperature is also associated with reduced levels of dissolved oxygen concentrations. Increased light levels, in particular coupled with elevated nutrient concentrations, can also increase primary production (Quinn *et al.* 1997) and change the periphyton community structure from palatable unicellular algae to prolific filamentous green algae and macrophytes (Bunn *et al.* 1999). Eutrophication is also associated with potentially toxin-producing cyanobacteria and reduced dissolved oxygen levels with negative consequences for macroinvertebrates and fish (Camargo & Alonso 2006). The risk of secondary invasions of aquatic weeds facilitated by clearance of willows, which has been shown for an invasive aquatic grass in south-eastern Australia (Loo *et al.* 2009), should also be considered.

Reduction in detrital food sources likely affects the instream fauna and stream metabolic processes (Bunn *et al.* 1999). Wilson (2006) expects the stream food web in low-order streams to shift from being reliant on external (allochthony) to being reliant on internal energy sources (autochthony). Fine sediment and nutrient loads can

initially increase because the newly-established riparian vegetation is likely to be less effective in buffering streams from agricultural run-off (Tabacchi *et al.* 2000), in particular because willows are efficient in the uptake of nutrients (Elowson 1999).

Finally, loss of overhanging vegetation and undercut banks can reduce suitable habitat for fish (Pusey & Arthington 2003). Willows have been observed to provide good fish habitat. For example, dense crack willow forests along the Waikato River banks provide cover and deep holes for New Zealand's longfin eels and introduced brown trout (Champion & Clayton 2010); undercut banks under willows along a creek in Victoria, Australia, were the major day-time refuge for River Blackfish, a nocturnal ambush predator (Khan *et al.* 2004); and willow growth in the Upper Taieri River had restricted channel capacity that led to seasonal lagoons and oxbows being permanently connected to the river, which provided a broad, shallow and productive environment for trout to thrive (Dons *et al.* 1988). Hence, willow removal has created commercial and recreational fisheries issues in New Zealand (Leaman 2012; Mirfin 2012). However, not much is known about the factors (or combination of factors) that caused the issues in these specific cases, and whether these issues could have been minimized using best management practices or will be resolved once the native vegetation has become established.

The relative importance of these factors and the risks involved, however, depend on each specific stream or river system. The risk of channel degradation is likely to be higher when willows are removed from larger rivers where flow can undercut banks to a steep and unstable slope, although smaller but high-energy streams are also at high risk to get further incised. Willow removal from larger rivers, where canopy cover provided by willows was less extensive, may have relatively less consequences for stream metabolic processes than removal from smaller streams, where willows can provide full canopy cover. Loss of overhanging vegetation, however, may adversely affect the local fish population in both large and small rivers.

Recovery from loss of the functions that riparian vegetation provides following the removal of willows is highly dependent on success of the re-establishment of vegetation, either through natural regeneration or re-vegetation. Hence, the risks and costs involved with vegetation re-establishment and the measures to minimize them, need to be considered. Overall, in higher-order streams that have been modified by flood banks and where flow likely undercuts the streambanks to a steep (~2 m) and unstable slope, New Zealand native riparian vegetation on its own is unlikely to provide the required streambank stabilisation (Marden *et al.* 2005). Here, additional structural materials at the toe of the bank and below the streambed, such as gabion baskets or riprap, may be needed to prevent erosion and protect the native vegetation (Marden *et al.* 2005). Native vegetation in lower-order streams, on the other hand, can be effective in providing streambank stabilisation, especially where channel form and slope, and hydraulic conditions resemble the unmodified condition before forest

clearance (Marden *et al.* 2005). Here, the selection of species is crucial to successful re-establishment of vegetation and the most important characteristics to consider are:

1. Rooting depths to be large enough to provide stability up to a certain required depth
2. Provision of year-round protection
3. Ability to establish under adverse soil conditions and to withstand hydraulic shear forces
4. Being long-lived and require minimum maintenance (Marden *et al.* 2005).

In places, where a seed source already exists, native vegetation would likely regenerate naturally and at little cost (Marden *et al.* 2005). Nevertheless, restoration success can be jeopardised by stock grazing, seedlings being washed away, plant diseases (Marden *et al.* 2005), drought, (which hindered re-establishment of vegetation following willow removal in an Australian project; Zukowski & Gawne 2006), secondary invasions by environmental weeds, or re-invasion by willows. Disposal of the removed willows is crucial to avoiding re-invasion and frequent weed control as well as stock exclusion is typically needed for successful establishment of woody riparian vegetation (Zukowski & Gawne 2006). However, the effort and cost involved in on-going maintenance may be too large to outweigh the benefits. For example, while removal programmes targeting female and seeding willows in rivers with low levels of flow disturbance may eliminate willow recruits, the same programme may prove unsuccessful in rivers of high disturbance levels because of on-going asexual willow recruitment (Stokes & Cunningham 2006).

3.2.4. Damage caused during removal operation

Immediate risks are associated with the removal technique such as damage to the banks and existing native vegetation by heavy machinery or effects of herbicides on the riparian and instream fauna and flora. Some of the risks and measures to minimize mechanical damage are described in willow management guides (*e.g.* Holland-Clift & Davies 2007), but the effects of different herbicides and chemical treatment techniques on stream ecosystems are largely unknown (Maloney 1995). These immediate risks are not reviewed here.

3.3. Case studies

3.3.1. Upper Gellibrand River Catchment, southern Victoria, Australia

Willow removal and re-vegetation with native plants was conducted in 3rd and 4th-order streams in a semi-rural catchment and enabled the study of recovery of macroinvertebrate communities after riparian restoration (Becker & Robson 2009). The study design comprised of six ‘treatment’ sites where re-vegetation works had

been completed 1, 3, 4, or 8 years prior to sampling, six willow-dominated ‘control’ sites, and six native forest ‘reference’ sites dominated by evergreen tree species (eucalypts, Australian blackwood and myrtle beech). The canopy cover was complete at the two sites where restoration took place eight years before sampling, but was incomplete at all other sites. Macroinvertebrate abundance and taxon richness did not significantly differ between treatment, control and reference sites, in both spring and autumn. Macroinvertebrate community composition, however, significantly differed between sites in autumn. Overall, the variability in taxon composition among sites within each vegetation type showed the clearest pattern. Native forest sites had the highest variability among sites in both seasons. In spring, communities at willow sites were more variable than those at re-vegetated sites, but in autumn, no difference could be discerned. Temperature was recorded as one potential factor affecting macroinvertebrate communities. Maximum temperatures exceeded 23 °C at the most recently re-vegetated sites, but never exceeded 19.5 °C at forest sites. Mean temperature at the two sites where canopy cover was complete (sampling eight years since re-vegetation) were comparable to that at the forest sites. The authors suggest that while willow removal increased stream temperature until canopy cover of the restored vegetation was complete, temperature increase in their study had little influence on macroinvertebrate community structure (Becker & Robson 2009). Full recovery of the variability in macroinvertebrate communities as seen in forest sites may be a matter of time and take longer than 8 years. For example, it may take longer for instream willow root mats, which have not been actively removed, to decompose and the benthic habitat to be restored to natural conditions; or take longer for the biota to recover from past history of human disturbance. On the other hand, stressors other than those redressed by riparian restoration may constrain full recovery to macroinvertebrate communities observed at reference sites.

3.3.2. Little Snowy Creek, Victoria, Australia

A de-willowed 600-m stream reach was monitored up to three years after the willow removal operation and compared to a willowed control reach, both surrounded by farming land. Key findings were:

1. Earth works likely caused bank erosion observed immediately after removal
2. Dissolved oxygen levels remained high at least during the spring and autumn sampling periods
3. Maximum summer temperature was often more than 5°C higher at removal sites reaching temperatures of up to 34.5°C
4. Despite high summer temperatures that were likely associated with reduced dissolved oxygen levels (not monitored), there was little difference in standard macroinvertebrate metrics (*e.g*. EPT taxon richness) or fish communities between treatment and control sites (Zukowski *et al.* 2009; McInerney *et al.* 2010).

However, at treatment sites, trout abundance seemed to be slightly higher but trout sizes smaller two years after removal (Zukowski *et al.* 2009). As with most restoration studies, low replication and, in this case, no replication at the reach-scale precluded statistical analysis and rigorous study of willow removal effects.

3.3.3. Restoration of riverbed habitat for native birds in a braided river in New Zealand

Mechanical and chemical removal of willows and exotic grasses from a 1.5 to 2.5-km long braided-river section of the Tekapo River in the Upper Waitaki Basin was undertaken in 1992 to restore habitat for native riverbed bird species; some of special conservation status. Here, vegetation was not re-established as bare shingle or sparse vegetation with grasses is the reference condition. Soon after the removal operation, four of the five monitored species (banded dotterel, pied stilt, black-fronted tern, South Island pied oystercatcher) used the cleared areas for nesting and foraging, and their densities were comparable to those in old riverbed habitat (Maloney *et al.* 1999). So it appears that willow removal has benefitted these native riverbed bird species. Long-term success will depend on the on-going maintenance to prevent the invasion of exotic grasses and herbs because flow regulation has altered the flow regime so that these areas are not naturally kept clear of vegetation anymore (Caruso 2006). Furthermore, control of introduced mammalian predators will also be necessary to increase the bird population in the long-term (Maloney *et al.* 1999). Aquatic invertebrates have not been formally monitored; but the assessment of trout habitat and abundance carried out by Fish & Game New Zealand, showed that the declining population of trout was probably due to factors other than willow removal (Heppelthwaite 1998; Brown & Sanders 1999).

4. CONCLUSIONS

4.1. Complexity of willow management

4.1.1. Invasive and non-invasive willows

In New Zealand and Australia, there is a multitude of willow species, hybrids and varieties. Some of them are invasive and their removal may be necessary, and in Australia is even legally required, to prevent further invasion by means of vegetative propagation or seeding or both. This includes removal of willows from earlier plantings or from areas that have been invaded. Eradication of these invasive species, however, is not an easy task and the risk of re-invasion and the associated costs for follow-up maintenance can be extremely high. Knowledge of the ecological requirements and the way these willows spread is crucial for successful control. For example, crack willow (*S. fragilis*) has brittle branches and spreads with its branches being carried downstream and becoming established. Hence, removal strategies such as working from upstream to downstream in the catchment and prioritising the removal of the pioneer willows rather than the dense and mature willow stands, will maximise willow control efficiency (Rutherfurd 2007). Grey willow (*S. cinerea*) spreads by seed and does not require bare ground. So the risk with this species is also its spread upstream and across catchments and into areas of potentially high conservation status, rather than just the riparian zones. Removal programmes targeting female and seeding willows in rivers with low levels of flow disturbance may eliminate willow recruits, while the same programme may prove unsuccessful in rivers of high disturbance levels because of on-going asexual willow recruitment (Stokes & Cunningham 2006).

4.1.2. Multiple values of willows

Willows have multiple values to multiple stakeholders. For example, farmers and resource managers value willows for their provision of erosion control, streambank stabilisation and as a buffer against agricultural run-off. Farmers also value willows as provision of fodder and shade for livestock. One the other hand, anglers appreciate the willows' aesthetic looks and that they can provide good fish habitat.

4.1.3. Current willow plantings

In Australia the planting of willows is no longer encouraged. By contrast, in New Zealand willows of non-invasive and sterile varieties are still being planted by resource managers and landowners for streambank stabilisation, soil conservation and other specific purposes on farms. Resource management authorities promote such willow plantings on their websites, but at the same time implement willow removal programmes. This is likely to cause confusion among the public, which can be resolved by informing the public how these new varieties differ from problematic willows. Further, in situations where native species are able to provide adequate bank

protection, and at the same time improve ecological values, promotion of native species should be considered.

4.1.4. Multiple reasons for willow removal

Willows have multiple values but willows, both invasive and non-invasive types, also have multiple disadvantages. Hence, the reasons for willow removal currently put forward by New Zealand and Australian resource management authorities are numerous and include the protection of ecological, economic and social values of streams and rivers and their riparian zones. However, since the use of willows have pros and cons, willow removal will not protect all these values at the same time. For example, willow removal may be necessary to protect economic values but it will not necessarily improve ecological condition although negative ecological effects need to be mitigated for. For that reason, it is important to state the specific goals for willow removal on a case-by-case basis. This ensures that 1) the public is informed about the reasons for intended management action, 2) the most appropriate removal strategy is being implemented, and 3) success in reaching these goals can be tracked.

4.2. Cost-benefit analysis of reach-scale willow removal

This review focussed on investigating reach-scale willow removal and re-establishment of native riparian vegetation as a stream rehabilitation measure. Hence, knowledge of the ecological effects of willows and of their removal is central to evaluating the potential benefits and negative ecological effects or risks (costs) of willow removal operations. However, knowledge of the ecological effects of willow removal is also relevant for when willows are to be removed for reasons other than the protection of ecological values.

Ecological costs are associated with the potential negative effects or risks of the destructive removal process on the ecosystem. The benefits, however, are strongly dependent on what ecological values management seeks to protect. In fact, evaluation of whether the expected benefits outweigh the costs is impossible without having set the goals, the latter of which is the first critical stage in successful stream rehabilitation projects (Ladson *et al.* 1999). In particular, because there may be positive effects for the riparian, but negative effects on the instream ecosystem.

Very few studies have formally investigated the ecological effects of reach-scale willow removal and riparian re-vegetation to provide strong evidence for or against such operations as a stream rehabilitation measure. Documentation of ecological condition before and after willow removal is equally scarce. However, this review summarised information from the literature on the effects of willows on ecosystems, from which potential benefits can be inferred, as these typically are the mitigation of

their adverse effects. This review also summarised the risks of willow removal based on knowledge of the important functions riparian vegetation fulfils and based on knowledge of the ability of willows to retain material and influence stream geomorphology.

A key finding of this review is that the ecological effects of willows and their removal are complex and highly context-dependent. Hence, the influence willows have on a stream ecosystem, the risks that are involved with the removal of willows, and the benefits that arise from when native riparian vegetation is fully re-established will all be highly specific to each particular situation. Stream size and geomorphology, hydrology, catchment land use and associated stressors, and the extent of willow growth and species will all play a role.

For example, the risk of channel degradation is likely to be high when willows are removed from larger rivers where active erosion undercuts banks to a steep and unstable slope (Marden *et al.* 2005), although smaller but high-energy streams are also at high risk to get further incised (Rutherfurd 2010). While it may be possible to provide the necessary bank stability if structural measures are installed in addition to re-establishment of native riparian vegetation (Marden *et al.* 2005), the ecological benefits for the instream biota and ecosystem functioning may be small and the monetary costs of such operations too large to make the rehabilitation cost-effective. Conversely, willow removal with the intention to improve instream values may be more effective in small streams where riparian vegetation has a relatively larger influence compared to bigger rivers. Rehabilitation may be particularly effective in streams where improvement of local stream condition, as a consequence of reach-scale riparian management, is not constrained by land-use impacts at larger-scales, as here more intensive measures, such as channel and instream habitat modification, are not needed (Greenwood *et al.* 2012).

4.3. Potential ecological benefits of willow removal and re-establishment of native riparian vegetation

Potential ecological benefits of willow removal as a stream rehabilitation measure relate to the mitigation of the adverse effects of willows. Overall, review of the literature showed that willows compared to the native riparian vegetation:

1. Are likely to provide less suitable habitat for macroinvertebrates due to the dense willow roots and their ability to trap fine sediment
2. May not sustain equally productive macroinvertebrate communities due to the shorter availability of leaf organic material during the year
3. Can increase water temperature and epilithic biomass during the seasons when deciduous leaves are young or shed and hence provide less shade

4. May degrade water quality by reducing levels of dissolved oxygen as a consequence of increased temperature or decomposition of large amounts of retained willow leaves
5. Can substantially reduce flow due to high evapotranspiration rates
6. Retain lesser quantities of LWD because light willow wood is prone to be carried downstream and decays quickly
7. Trigger erosion, channel widening or migration if willows reduce channel capacity due to their extensive root growth
8. Sustain less diverse native terrestrial arthropod and bird communities, amongst others.

4.4. Recovery from adverse effects of willows and evaluation of rehabilitation success

There is a multitude of potential benefits that may arise from willow removal and re-establishment of native riparian vegetation. Evaluation of rehabilitation success, however, is dependent on the ecological values management seeks to protect. These can be broadly categorised into instream ecosystem values and values of riparian ecosystems although streams and their riparian zones are intimately connected. These values can be further specified, for example into water quality, healthy/diverse stream or riparian biotic communities, and ecosystem functioning/services. Specification of values guides appropriate selection of a set of indicators required to evaluate and track rehabilitation success after completion (Parkyn *et al.* 2010).

In some cases, recovery from adverse effects of willows may be quick and successful. For example, native riverbed birds recolonized the braided section of the Tekapo River, New Zealand, soon after the willow removal operation, although on-going maintenance may be required (see section 3.3.3; Maloney *et al.* 1999); and Watts *et al.* (2012) observed that willow removal from wetlands was effective for restoration of terrestrial beetle communities. However, in most cases, expectations of riparian rehabilitation should be tempered with knowledge of the temporal and spatial limitations (Parkyn *et al.* 2003). Long recovery times can be expected because it takes time for the re-established vegetation to provide the necessary structure. For New Zealand native riparian vegetation to mature and provide complete canopy cover it takes 7-10 years, but more at high altitudes (Marden *et al.* 2005) and at larger stream widths (Quinn & Wright-Stow 2008). For riparian vegetation to recruit LWD, however, it takes at least 100 years (Erskine & Webb 2003; Meleason & Hall 2005). Full recovery from the adverse effects may further be hampered by spatial limitations. For example, reach-scale riparian rehabilitation may not result in recovery to good or excellent stream health if human land-use impacts operate at a larger spatial scale; the re-established native riparian vegetation may not provide suitable habitat for native bird species in pastoral catchments if birds respond to scales larger than the

riparian zone (Stanley & Ward 2003); and there may be spatial or temporal barriers to recolonisation with native and sensitive species (Parkyn & Smith 2011). Identification of barriers to recovery assists management to maximise the positive outcomes of rehabilitation (Robson *et al.* 2011).

4.5. Potential risks and negative effects

Review of the literature showed that potential risks of reach-scale willow removal are related to the influence willows have on geomorphic processes and the consequences of their removal. These include changes to the stream channel, pool-riffle sequences or channel migration associated with streambank and floodplain erosion with further consequences for stream biota. Furthermore, mobilisation of large amounts of sediment, organic matter, and the nutrients that are contained within them, from the rotting roots that retained these materials, are of particular concern in heavily degraded agricultural catchments. In these cases, willow removal may cause more damage to the stream ecosystem than willows cause when leaving them intact (Rutherfurd 2010). In fact, willows may even be beneficial in re-filling deeply incised high-energy streams in agricultural catchments providing an argument against willow removal, at least in the medium term (Wilson 2006; Rutherfurd 2010). On the other hand, if geomorphological change following willow removal reinstates channel dynamics and a riparian ecosystem more similar to the natural condition at a larger scale, then these values need to be weighed up against the potential loss in values of the local aquatic ecosystem. The potential conflict that initially arises between restoration of riparian and that of aquatic ecosystems has been described before and stresses the importance to clearly define restoration aims (Richards *et al.* 2002).

The review also showed that risks of willow removal are associated with the loss of the important functions riparian vegetation fulfils and include increase in water temperature, sediment and nutrient levels, decrease in dissolved oxygen levels, organic matter input, shade and shelter, changes in periphyton community structure and stream metabolism, and eutrophication with direct negative effects on sensitive macroinvertebrate and fish species or indirect food-web mediated effects.

Management strategies to potentially reduce the risks of willow removal have been suggested. These strategies include either staged replacement of willows by natives (Holland-Clift & Davies 2007) or planting of native seedlings alongside and under willows and letting succession take its course (Wilson 2006). In both cases, willows can still perform their erosion-control function and provide canopy cover until the native vegetation has matured. The slow transition between willows and native riparian vegetation may prevent further drastic ecosystem changes that a wide-scale willow removal operation might cause. Australian willow management guidelines suggest that a planned project over several years of gradual willow removal and

replacement with native vegetation is more costly than an operation in one go, but more likely to be successful (Pope *et al.* 2006).

4.6. Research needs for the New Zealand context

There are various questions arising from this review specific for the New Zealand context:

Invasion

- What is the status of willow invasion and what is the risk of further spread in relation to willow species or hybrids?
- How can further invasion be effectively prevented?
- What species and habitats are threatened by riparian willows?

Removal strategies

- What are the best willow removal and native re-vegetation strategies at the reach scale balancing the protection of ecological values and cost-effectiveness?
- Are the following strategies effective management options and what is the influence of stream channel type on effectiveness:
    - staged removal and replacement with native vegetation
    - understorey willow removal and native vegetation replacement leaving the willow canopy intact until establishment of a native canopy
    - natural regeneration from planting natives next to or amongst riparian willows?
- For example, are these strategies effective for spring-fed streams with U-shaped channels receiving few floods?
- Do certain invasive species require special consideration and different strategies to be effective?

Costs

- What is the effort and cost of managing invasive riparian willows?
- What is the effort and cost (in the short and long-term) of establishing and maintaining native plants *vs*. that of non-invasive willow varieties currently planted for streambank protection?
    - For example, natives may be more costly to establish than willows but cheaper to maintain and hence be more cost-effective than riparian willows provided they equally fulfil the desired functions.

Native riparian plant species

- Building on the research by Marden *et al.* (2005), further information is needed on the suitability of native riparian plant species or mix of species for replacement of the various functions willows fulfil (particularly in regards to streambank protection) specific to soil types, geologies, channel morphologies and hydraulic characteristics of streams. This is important knowledge for projects involving willow removal and re-vegetation but also for re-vegetation programmes where traditionally exotics have been planted but native species would be equally well suited.

4.7. Management recommendations

This literature review identified the following management recommendations concerning willow removal operations:

- Know the pros and cons of willows
- State the goals for willow removal
- Know the ecological risks of willow removal
- Seek and apply best management practice for the local context.

The goal of willow management is not to eradicate all willows but to decide why, where, when and how to manage them (Holland-Clift & Davies 2007). Knowledge of the pros and cons of willows, that is, the values of willows and the impacts of willows on values incorporating social, economic and ecological aspects is important. These will vary with the willow taxa involved as there are invasive as well as non-invasive species and hybrids. Equally important is knowledge of the ecological risks of willow removal. The pros and cons of willows and the risks associated with their removal will be context-dependent and can vary widely amongst the individual situations. It is crucial for resource management to state the goals for willow removal, so that; 1) a cost-benefit analysis incorporating social, economic and ecological values can be undertaken before its implementation, 2) areas can be prioritised both at the regional and catchment scale, 3) the appropriate steps can be taken to reach these goals, 4) success can be evaluated in reaching these goals, and 5) the stakeholders and public are made aware of the intentions of such costly and often controversial operations.

The goals are manifold and mainly relate to:

1. Flood management and the protection of downstream infrastructure
2. Reduction of costs involved with ongoing willow management
3. Reduction of risk of further invasions
4. Increase in water yield for irrigation purposes or instream biological communities

5. Increase in recreational values including angling and kayaking
6. Increase in riparian and/or instream ecological values.

Cost-benefit analysis and the steps to be taken to reach these goals will vary vastly. For example, if invasive species are involved, knowledge of the ecology and spread of the species is important and specific removal strategies should be implemented to maximise control efficiency, such as working from upstream to downstream in the catchment for species spreading vegetatively or targeting multiple populations at the regional level for seeding willows; if increase in water yield is the goal, removal should target those individuals that remove substantial amounts of water. Some of the goals may require removing all willows at a site while others may only require for some to be removed. Best management practices are available to minimize some of the risks associated with willow removal and to maximise effectiveness of rehabilitation through re-vegetation with the most appropriate native species. The manual 'Willows National Management Guide: current management and control options for willows (*Salix* spp.) in Australia' (Holland-Clift & Davies 2007) provides guidance based on published information, existing research and experience with willow management. The authors, however, specifically mention that this manual is meant to evolve as new information and research becomes available and new experience with willow control is gained. Therefore, feedback on the manual's presentation and management recommendations including sharing of information on the successes and failures of willow control operations to build a data bank of case studies in Australia is highly appreciated. In New Zealand, no such substantial manual exists although some guidance on willow control management can be found on Regional Council websites, for example:

- 'Eradicating Crack Willow and Grey Willow' in 'The Waitakere Best Practice Guidelines for Bush and Riparian Restoration'[1],
- 'Mechanical vegetation removal – willows and other plant pests' in 'Best Practice Guidelines for Vegetation Management and In Stream Works'[2],
- Willow removal section in the 'Living Streams handbook'[3].

A compilation of best management practices specific to the New Zealand stream environment and a databank of New Zealand case studies would also be of great benefit to willow control management.

[1] http://www.waitakere.govt.nz/cnlser/pw/greennetwk/pdf/willow-control-best-practice.pdf (accessed March 2013)
[2] http://www.waikatoregion.govt.nz/PageFiles/5677/tr0741.pdf (accessed March 2013)
[3] http://ecan.govt.nz/GET-INVOLVED/LOCAL-PROJECTS-COMMUNITY-GROUPS/LIVING-STREAMS/HANDBOOK/PART-2/Pages/removing-willows.aspx (accessed March 2013)

This review focused on willow removal as a stream rehabilitation measure where the goal is to enhance riparian and instream ecological values. Hence, the following specific management recommendations are

- State the specific goal for willow removal, such as increase in water quality, riparian or instream biodiversity, increase in invertebrate or fish habitat, *etc.* taking into account spatial limitations and that long timespans for recovery can be expected. There are multiple indicators that can be used to monitor and evaluate restoration success and the management goals will guide which indicators to use (*e.g.* dissolved oxygen, invertebrates, fish, birds, habitat, ecological processes, *etc.*) but success also depends on whether the restored stream ecosystem is compared to the pre-willow removal or to a potential pristine reference condition.
- Prioritise riparian management where it is most needed within a catchment or a region and most effective for a specific goal. For example, in order to maximise ecological outcomes from stream rehabilitation efforts, it is recommended that 1) planting of native riparian vegetation should be prioritised at pastoral sites before proceeding to streams where willows need to be removed first, unless the willows are invasive and threaten other ecosystems, 2) willow removal should be prioritised for streams where the native riparian vegetation can fulfil an erosion-control function on its own and where the expected benefits are maximised, which is likely the case in smaller streams.
- In each case, evaluate what are the adverse effects that willows currently have and what are the expected benefits from rehabilitation.
- Evaluate the potential negative effects and the risks involved that are associated with 1) loss of important functions riparian vegetation fulfils: change in shading, temperature regime, *etc.*, 2) issues with mobilisation of sediment, organic matter and nutrients and geomorphic effects, and 3) the removal process itself. Here, knowledge of the system is extremely important.
- Given the potential ecological risks and negative consequences that are involved with willow removal in some cases, it is not recommended 1) where willow roots retain large amounts of fine sediment and organic matter that will be mobilised and threaten downstream ecosystems, and 2) where removal will lead to undesirable changes in geomorphology and flow patterns.
- Watch out for threatened plant species among the willowed area.
- Remove most invasive willow species/hybrids first, as this prevents potential impacts on stream or wetland ecosystems not yet invaded by willows.
- Consider alternative strategies to wide-scale willow removal, such as staged removal and replacement with native vegetation or clearing of small willows and replacing with natives in the understorey leaving the willow canopy intact until the native vegetation is established.

- Willow management would improve if handled more consistently in New Zealand. For example, it makes little sense to remove willows and re-establish native riparian vegetation in agricultural catchments for reasons to increase biodiversity and stream health when at the same time new willows (even if non-invasive) are being planted on streambanks where native riparian vegetation could provide the same functions that willows fulfil (stabilisation, canopy cover, buffer *etc.*) but also positively contribute to biodiversity and stream health.

5. ACKNOWLEDGEMENTS

We thank John Quinn and Paul Franklin (NIWA) and Colin Stace (Waikato Regional Council) for their useful comments on our draft report.

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