Survival & Growth of Sandbar Willow, *Salix interior,* in Bioengineering Projects, and the Implications for Use in Erosion Control in Manitoba

By

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Abstract

Willow bioengineering is an alternative erosion management technique that includes the use of living and inert willow material. It is successfully used across North America, Europe and Asia but, due to lack of public awareness of the technique or concerns about its effectiveness, it is currently used only occasionally in southern Manitoba. To provide insight into possible biological limitations upon the use of willows to prevent erosion a combination of field experiments and observational studies of new bioengineering sites was carried out across southern Manitoba.

The results indicate that first year willow cutting survival is likely to be below 50% unless planted within 100cm of fall low water level. Using taller cuttings may improve survival as they develop greater numbers of shoots early in the growing season, but taller cuttings have a greater chance of being cut down or even pulled from the ground by beaver. Flooding had a negative effect of shoot numbers during the first year after planting, although it did not impact survival. In 2012 flood levels were lower at the majority of sites than the long term mean; more extensive flooding may have a more negative effect upon the cuttings. Maximum shoot length was reduced by high water levels, but was improved by cutting proximity to low water later in the summer. More research is needed to better understand the effect of high water levels on long term survival.

Combining live willow with erosion blanket helps reduced substrate loss during establishment and also prevented willow bundles from being removed by beaver reducing the potential of project failure.

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1 Introduction

1.1 Stream Bank Erosion

Stream bank erosion is a natural process that is responsible for the sinuous nature of rivers and the formation of river valleys (Hooke 1979). Although erosion is a geologic process it is often possible to observe bank erosion in real time. Accelerated erosion is often associated with anthropogenic modification (Brookes 1988): changes to the slope and cross section of the channel, or modification to the volume and pattern of flow, will destabilise the relationship between water and soil.

The area close to rivers is often in high demand for development. It is used for agriculture, transport corridors and in more recent years for housing (Parker 1995, Colby and Wishart 2002, Cook 2010) so that financial consequences of erosion are also high. The impact of bank erosion has been particularly great in Manitoba with extensive damage reported each spring as water levels recede (Fernando 2007). Loss of bank stability at or around transport infrastructure may cause sudden collapse, often with wider effects on communities in addition to the costs of replacement such as loss of access to services or damage to cultural sites.

Riverside development or agriculture can, deliberately or otherwise, cause damage to natural vegetation that would otherwise act as a protective layer against erosion (Thomas 1986, FISWRG 2001). Riparian vegetation also acts to buffer watercourses against pollution by absorbing nutrients through their roots (Osbourne and Kovacic 1993), binding soil particles that carry nutrients and also filtering windblown soil that would otherwise enter the watercourse. Silt washed into streams is harmful to fish and aquatic invertebrates and smothers gravel spawning areas (Wood and Armitage 1997). Phosphate, adsorbed by the silt particles (Mihara and Ueno 2000), contributes to eutrophication with increased macrophyte and algae growth and consequent de-oxygenation as well as toxic effects from blue-green algae (Correll 1998).

The widespread natural habitat loss across farmed landscapes makes riparian corridors vitally important to wildlife (Bennett 1999, Naiman *et al*. 1993, Virgos 2000). As well as acting as habitats in their own right (Maisonneuve and Rioux 2001, Boutin *et al.* 2003), they allow animals to move between areas of higher diversity (Burbrink *et al*. 2004, Hilty and Merenlander 2004, Machtans *et al*. 2001), increasing the functional size of the population and permitting recolonisation of impacted areas. Erosion is a particular problem in these areas because natural recovery is prevented by human actions.

Rivers and streams with high quality riparian vegetation also have greater value for recreation, both on the water, for canoeing and kayaking, and for fishing, hiking trails or informal recreation areas on land (Lant and Roberts 1989). The economic cost from channels and reservoirs that fill with silt, impeding flood management, navigation or power generation can also be substantial (McNeely 1987). Disposal of dredged materials may also create environmental impacts if spread without adequate planning.

1.2 *Methods of Stream Bank Erosion Prevention*

The most common method of erosion prevention is to spread graded stone across the river bank or lakeshore. This material, known as rip-rap, is good at preventing erosion and in most situations requires little in the way of additional skill to install (Li and Eddleman 2002). High banks and unstable lacustrine clays in the Red River valley have presented greater problems for river bank engineers. Stone is used to construct deep columns or shear keys down to stable material below the clay layers preventing further slippage of the bank layers (Alfrolo *et al* 2009).

The properties that make rip-rap so good at preventing erosion also have an impact upon biodiversity. Rip-rap can reduce native species diversity and allow non native species to gain a foothold (Canaille *et al*. 2010, Geiger and Best 1980, Long and Walker 2005). In some circumstances the impact upon the ecosystem may last for many years (Hurst *et al* 1980). There is strong evidence that rip-rap may have negative impacts on fish and wildlife communities principally because it reduces heterogeneity and removes or inhibits the recovery of aquatic and riparian vegetation (Quigley and Harper 2004). Mining for stone to produce rip-rap also has negative impacts, as does the transport of the material to the site. In some instances rip-rap can have impacts upon banks adjacent to the repaired site by accelerating flows, reflecting wave energy and increasing erosion along unreinforced sections (Li and Eddleman 2002). Additionally, the access required for heavy machinery often extends the impacts of the work out into the terrestrial habitat.

An alternative to hard engineering would be the wide variety of techniques that rely upon the structure of marginal aquatic or riparian plants to reduce erosion (Schiecthl and Stern1997). This is mainly accomplished by creating a living buffer between the soil and water, absorbing energy and increasing the cohesion of the soil structure (Polster 2002, Jarvis and Richards 2008).

These techniques, collectively known as bioengineering, provide a number of advantages over harder techniques:

- Use of renewable, often locally sourced materials (Jarvis And Richards 2008)
- Reduced construction impacts (Jarvis And Richards 2008)
- Improved habitat for fish and other wildlife (Sudduth and Meyer 2006, Maisonneuve and Rioux 2001)
- Local improvements to water quality through nutrient filtration (Elowson 1999)
- Reduced costs compared to hard defences (Allen and Leech 1997)

Of the various materials in use living willow is likely to be most suited to the extremes of climate found in Manitoba due to its rapid growth and ability to withstand inundation (Amlin and Rood 2001, Li and Eddleman 2002). It has been used for erosion protection across Europe and Asia for over 1000 years in a variety of ways, each adapted to local situations (Evette *et al*. 2002). A number of reports have been published in the USA (Allen and Leech 1997, Sotir and Fischenich 2001,2007) and western Canadian Provinces (Polster 2002, Skirrow 2006), that provide information on using living willow, but relatively little in the way of academic research has been published.

Investigations have found that the potential of living willow has not been explored in Manitoba to the extent that it has been in the USA or Europe;

there are brief reports describing the limited use of live willow, but this has been principally to establish vegetation cover within rip-rap.

The conflict between the safety factor of stone protection and environmental impacts requires, that where the safety factor provided by stone is not necessary or where risk of environmental impact are greatest, we should look to alternative solutions. Rip-rap and other stone techniques are effective at preventing erosion, but do little to replace the biodiversity that is lost when riparian corridors are degraded, and may actually be damaging to native habitats. Willow bioengineering potentially has the capability to meet both demands but guidance appropriate to Manitoba is needed to ensure the technique is used most effectively.

1.3 Purpose and Objectives

The purpose of this thesis was to discover, through a series of field investigations, whether physical conditions in Manitoba allow bioengineering to be used to repair eroded stream banks and shorelines.

The objectives were:

1. *To determine the potential to use taller willow cuttings in Manitoba bioengineering projects to reduce the effect of inundation during spring flooding.*

Successful bioengineering projects depend upon good survival and growth of willow materials. Extended flooding is believed to cause high mortality of cuttings. Increasing the height of cutting above the soil surface should increase the potential for the top of the cutting to remain above flood level, but may increase the potential for desiccation in the period before the root system becomes established.

2. *To review five bioengineering projects from southern Manitoba and identify how the techniques used may have contributed to survival and growth of willows during the first growing season following installation.*

Bioengineering protection increases in strength over time as live material becomes established, but damage in the first year after installation would inhibit successful development. Early identification of failure to grow or other damage allows remedial works to be carried out at relatively low cost and would help to identify which bioengineering techniques are suitable for use in Manitoba.

3. *To make recommendations on the use of willows in bioengineering in Manitoba and identify additional research that may be required to develop effective use of willow bioengineering in Manitoba.*

2 Review of Literature Relating to the Use of Willow Bioengineering in Manitoba

2.1 Stream bank failure

2.1.1 Stream bank failure as a natural process

Stream bank erosion is an entirely natural process that has always determined the shape of landscapes although it has only become a significant field of study in the past fifty years (Lawler 1993, Simpson and Smith 2001).

Erosion was described by Hooke (1979) as corrosion, collapse or slumping, caused by different mechanisms. Corrosion was most likely to take place during periods of high flow (Hooke 1979) and at the outside of meanders where flow velocity was greatest (Ackers and Charlton 1970), whereas collapse or slumping would occur once peak flows had passed. How erosion occurred could be related to the cohesive ability of the soil structure (Thorne 1991) that made up a particular section of river (a reach) whilst the extent and rate of erosion was linked to the level of moisture within the soil (Hooke 1979, Simon and Collison 2001). Less cohesive soils, described principally as having a larger grain size, show erosion that takes place at the level of individual grains (Thorne 1991). Simpson and Smith (2001), working on the Milk River in Alberta, found that reaches with a bank composed of a silt clay mix had narrow incised channels whereas reaches with a predominantly sandy structure were up to three times wider, due to the increase in lateral erosion as opposed to a meandering form taken by the river through the more cohesive sediments.

Plate 1 Erosion of coarser grained (sandy) soils showing typical concave stream bank surface, Rat River, Manitoba. July 2011

Collapse was identified by large blocks of sediment shearing away from a steep bank (Hooke 1979), resulting either from saturation of a vertical layer at the face of the bank during high water level or from percolation of water from above along a plane parallel to the bank face (Thorne 1991). Slumping is categorized by Thorne (1991) as occurring in cohesive soils when they become saturated with water and may even reach a fluid state. This was the principal method of failure described by Schwert (2003) along riparian areas in the Red River Valley due to the extreme plasticity of the fine grain sediments when saturated by water. In contrast to unsaturated conditions, where both air and water are present and the remaining film of water helps to bind the particles together (Karube and Kawai 2001), the water maintains separation between particles of soil that allows them to move relative to one another (Simon and Collison 2002). Large scale slumping may be caused by water seepage down through the soil some distance away from the stream until it meets an impermeable layer from where it flows toward the toe of the bank creating a plane along which the mass of soil can move (Fox *et al.* 2007). If the water is flowing through a non-cohesive layer such as sandy soil it can transport soil particles creating a void that further weakens the bank by creating tension cracks that increase the rate of water infiltration (Shields *et al.* 1995).

Plate 2 Slumping and subsequent erosion of cohesive soils, Tourond Creek, Manitoba. June 2011

2.1.2 Effect of Ice on Bank Erosion

Most early studies (Hooke 1979, Wolman 1959 in Thorne 1991) were carried out in milder climates that do not experience the extended freezing that occurs in Manitoba, so concentrated upon the impact of high water levels or rainfall to saturate banks; however, Lawler (1986) determined that, once frozen banks had thawed, they were more susceptible to erosion due to a loss of cohesion. Zaimes *et al*. (2006) observed increased susceptibility of thawed soil to erosion and found rates of erosion at medium flows were equivalent to those they had previously measured during out of bank conditions in milder conditions. Along with the expansive power of ice, the layer of ice forming along the margin of rivers can reduce the rate of groundwater drainage, leading to greater levels of soil moisture (Eteema 1999). Ice plays a separate role by physically increasing the erosive power of the stream as it becomes entrained within the flow, scraping along stream banks shearing away soil (Uunila 1997, Eteema 1999). It can also contribute to mass failure. Sections of bank attached to marginal ice may be torn away as spring break up occurs (Eteema, 1999 and Prowse and Culp 2003). These observations have made on larger river systems such as the Mackenzie and Peace Rivers, so a gap exists in the literature on the scale of ice effects upon vegetation in lower order streams.

2.1.3 Contribution of Riparian Vegetation to Stream Bank Stabilisation

The property of vegetation to prevent or limit erosion of stream banks has been widely recognised (Hickin 1984, Smith 1976, Thorne and Lewin 1979 and Gray and MacDonald 1989 both cited in Ott 2000), and now forms a key tool in the management of riparian areas. Study of the scale of the effects of riparian vegetation and the mechanisms of bank stabilisation seem to have been generally overlooked for many years in favour of hydraulic and sediment investigations. It has been suggested that perhaps this reflects the training of engineers of the period, but may also indicate the tendency to work upon simple systems that could be modelled in a laboratory (Hickin 1984).

2.1.4 Effect of Trees on Channel Stability

Trees are generally considered to reduce stream bank erosion, though studies by Trimble (1997) and Davis-Colley (1997) attributed channel widening in small streams to a dense forest canopy, which prevented other vegetation from growing beneath the tree cover and also increased amounts of large woody debris that increased turbulence. Trimble (1997) proposed that forest cover should be removed in favour of herbaceous vegetation. Davis-Colley (1997) warned that aforestation of small streams may actually result in a period of increased sediment loads if shading removes ground cover species. A more recent study by Sweeney *et al.* (2004) found that though wider and despite localised erosion, forested channels were more stable and supported a greater diversity of fish and invertebrates. The greater stability is likely due to the distribution of larger roots from woody species (Wynn and Mostaghimi 2006) compared to herbaceous species that had a smaller root volume and fewer larger roots.

2.1.5 Trees on Large Rivers

Studies of trees have mostly worked on smaller rivers. At the other end of the river continuum scale, Gatto (1984 cited in Ott 2000) did not find any relationship between riparian vegetation type and channel erosion when working on the Tanana River, a large river in Alaska. River banks were high enough that erosion was taking place below the depth of the root zone, so once the bank had begun to erode trees actually may increase erosion due to their weight upon the bank. Depending on soils and morphology, this may not be the case for all large rivers. Hicken (1984) describes the role live and dead trees play in forming rivers throughout British Columbia and vegetation has been successfully used in Europe to mitigate erosion on large rivers (Schiechtl and Stern 1997, Evette 2009)

2.1.6 Mechanical Effect of Roots

Research by Smith (1976) found that root systems bind soil, increasing shear strength, and that exposed roots growing within the channel created a zone of slower water, reducing the erosive potential of the flow by a factor of 20,000. The latter property was also regarded as a negative attribute for engineers wishing to maximize channel conveyance. Thorne (1990 cited in Burckhardt and Todd 1998) and Simon and Collison (2002) describe riparian root systems as being mostly confined to the upper 1m of soil, but Smith (1976) recorded them several metres down into the soil. He attributed this to the process of silt continually being deposited around actively growing scrub willows and coarse grasses. Other studies of willows have found roots down to over three metres (Stone and Kalisz 1991). Abernethy and Rutherford (2001) tested the tensile strength of different root systems of riparian trees in Australia, and found fine roots grow at a much greater density within the soil and so produce a greater cumulative resistance to shearing than smaller numbers of larger roots. Simon and Collison (2002) conducted a series of detailed studies into the erosion preventing properties of trees and grasses that concluded that the beneficial effect of larger roots should not be ignored. They found that large deep roots were key to preventing large scale failure as only they were capable of penetrating deeply enough into the soil. Grasses had greater root density but they were shorter than trees, so they did not prevent collapse as much.

2.1.7 Hydraulic Effect of Roots

The strength of many soils is linked to soil moisture levels (Hooke 1979) so the ability of vegetation to reduce soil moisture levels via transpiration plays an important role in improving bank stability. At the peak of the growing season, the hydraulic effect can provide even more strength than the mechanical effects of roots (Simon and Collison 2002). Vegetation can have a negative effect on bank strength by increasing the rate of water infiltration. To reduce the rate of surface water run-off grass buffer strips are often promoted for this very purpose, but compared to trees, may have limited capacity to then remove water from the soil via their root system (Simon and Collison 2002).

2.1.8 Anthropogenic acceleration of stream bank failure

The contribution of human activity to accelerated rates of bank erosion has been widely reviewed, both in terms of direct modification to channels and alteration to the wider watershed (Allan 2004, Brookes 1988, Macklin 1999, Sickle *et al*. 2004 and Walling 1999). A model to explain the cycle of events following human intervention in geomorphological processes was proposed by Schumm *et al*. (1984, cited in Zaimes *et al.* 2006). They described the channel moving from a phase of dynamic equilibrium to become deeper, causing bank collapse. As sediment levels increase, the channel stabilises once more at a new equilibrium.

Modification to the morphology leads to instability of river channels and erosion (Brookes 1988). In many cases channels are straightened to increase the rate of discharge or to more easily accommodate transport crossings. The increased power of the stream, proportional to discharge times slope (Booth 1990), may exceed the threshold for the particle cohesion of bank or bed in the reach (Hooke 1979). This results in an increased rate of erosion, and depending on sediment type, channel widening or rapid migration of meanders across the floodplain.

Enlarging channel capacity to accommodate greater peak flows reduces water velocity at low and median flows. This can result in greater sediment deposition and may result in greater channel braiding (Brookes 1988). Structures such as low head dams, sluices and hydro-electric stations can result in localised high velocities and areas of bank erosion, while at the same time selectively reducing longitudinal transport of coarser sediments required for more stable meander construction.

The degradation of river systems associated with human alteration of watersheds is reviewed by Allan (2004). Patterns of development may be described as progressing from natural vegetation with lowest rates of run-off through conversion to pasture then arable and finally to urban area (Sickle *et al*. 2004, Walling 1999). At each stage there tends to be reduced floodplain storage, less infiltration of water to the ground and more rapid run-off with greater peak stream flows. Removal of native vegetation (Macklin 1999,) and later, agricultural practices that leave large areas of bare soil, particularly on hill slopes, can increase the amounts of sediment entering streams (Walling 1999, Zaimes *et al.* 2004). This reduces capacity and often creates a demand for channel modification to overcome perceived inadequacies in channel capacity. Livestock trampling has the potential to damage soil structure, particularly when soil moisture levels are high, increasing sediment inputs or reducing soil permeability (Kaufmann and Kreuger 1984). Trimble and Mendel (1995) contrast the preference of cows for riparian zones, with sheep that prefer dryer areas, potentially resulting in greater impact even at low stocking densities.

Wolman (1967) proposed that as watersheds become urbanized this tends to reduce the amounts of sediment produced, though he did identify construction works as producing by far the greatest volumes of sediment. This may account for the findings of Lenat and Crawford (1994) who found much greater suspended sediment levels in urban streams than either agricultural or forested areas. Urban watersheds generate greater and more pronounced peak flows due to the paving of the soil surface preventing infiltration (Paul and Meyer 2001, Randall 1988, Wolman 1967) with consequent increases in bed and bank erosion as flows exceed the capacity of the sediment to withstand the imposed shear stress (Ackers and Charlton 1970, Booth 1990).

2.1.9 Effects of Riparian Vegetation Removal

Removal of riparian vegetation is a major focus of the literature relating to the human contribution to erosion. Vegetation may be removed either as a by-product of channel modification or through changes to adjacent land use (Brookes 1988). When riparian vegetation is removed erosion increases, precipitating Schumm's (1984) model of channel instability and change. Wholesale channel modification inevitably results in the removal of vegetation, and although regulations usually require mitigation for loss of habitat, alternatives to hard engineering are not given prominence in Manitoban guidelines. Where vegetation is restored, poor understanding may result in the use of inappropriate or non native species not suited to local riparian conditions (Schiecthl and Stern 1996). In urban areas there is a tendency to domesticate the riparian zone (Moffat *et al.* 2004) or attempt to establish mature trees with inadequate root systems unable to survive high flows.

Vegetation is most frequently lost as an indirect consequence of changes to riparian land use. Loss of vegetation due to the impacts of browsing animals upon bank side vegetation has been extensively studied. Wildlife herbivory is a significant factor in many natural riparian areas (Opperman and Merelander 2000), but browsing by livestock, and cows in particular, has been shown to have negative impact upon vegetation cover and structure (Kaufmann *et al.* 1983, Miller *et al*. 2010, Schulz and Leininger 1990). Studies agree that cattle browsing modifies the streamside community (Kaufman and Kreuger 1984) although there is disagreement as to the extent this results in increased channel erosion. Zaimes *et al.* (2006) and Kaufmann and Kreuger (1984) found significantly greater amounts of soil lost to bank erosion on Iowa rivers with cattle browsing than where there was a forested buffer alongside the stream; on the other hand, Buckhouse *et al*. (1981) found no increase in erosion rates on banks browsed at 3.2 cattle/ha., although there were changes to the plant community due to browsing.

2.2 Impact of Stone Based Erosion Protection Techniques on Biodiversity

Rip-rap is the most widespread erosion protection material in use across North America (Fischenish 2003), but there are a wide variety of studies showing that its use results in reduced aquatic and terrestrial biodiversity. The impact upon salmonid fisheries is particularly widely studied. Sections of streams with banks protected by rip-rap were found to have lower fish densities than sections containing large woody material (Knudsen and Dilley 1987 and Peters *et al*., 1998) an effect which was linked principally to the loss of overhead cover and removal of small scale variation in bank morphology.

Plate 3 Stone rip-rap applied to from the bank toe to the top of channel, Red River, St Aldophe, Manitoba.

Studies dealing with other fish assemblages are less frequently reported. The loss of aquatic vegetation and reduced bank side heterogeneity in rip-rapped sections affected the type and number of fish species present in European lowland rivers, favouring lithophilic species such as bitterling *Rhodeus sericeus* (Pallas) over phytophils like pike *Esox lucieus* (Juradja

1995). A similar negative effect was found of lakeshore rip-rap on Wisconsin pike populations (Margenau 2008). In studies on the Hawkesbury-Nepean River in Australia, numbers of fish associated with vegetated banks were up to thirteen times higher than on banks with stone protection (Growns *et al.* 1998). Fish communities at River Danube sites were altered by rip-rap but there was no significant loss of species richness (Erős *et al.* 2008) suggesting that the rip-rap provided additional habitat type more favourable to some of the fish species present. This was also the case along the Winnipeg River where fish and invertebrate communities at armoured sites were found to be locally different from those recorded in un-armoured sections. In contrast to the Danube study, armoured sections had communities more closely resembling the “natural” population of the river, perhaps reflecting the degraded status of the un-armoured sections as a result of high water levels impounded for hydro-electric power generation (Long and Walker 2001).

Negative impacts also extend to invertebrate species, with lower macro-invertebrate biomass and density on rip-rapped sections compared to banks reinforced with woody material (Sudduth and Meyer 2006). Cavaille *et al.* (2010) found a gradient of plant and invertebrate diversity decreasing with level of rip-rap coverage. Sites with a combination of rip-rap and woody material had species diversity part way between natural and completely modified sites. They also found that numbers of invasive species were greatest in the highly modified areas. The effects of rip-rap are likely to be greatest and longest lasting on smaller streams (Kimball and Kondolf 2002) where the riparian zone makes up a greater proportion of the habitat and the stream is likely to lack the energy to recreate habitats lost during the engineering works.

For aquatic species of invertebrates the impact of rip-rap will not necessarily be negative, particularly where waterways are already degraded and lack heterogeneity (Fischenish 2003, Litvan *et al.* 2008). Where other large material has been removed rip-rap can increase available substrate for fish and invertebrates. Long and Walker (2005) found greater biotic integrity on stretches of the Winnipeg River that had been armoured with rip-rap. In this instance water levels had been raised by generation dams above the previous rocky littoral zone to create a new shoreline on the clay soil above.

2.3 Willow Bioengineering

2.3.1 History of Willow Bioengineering

The history of using live willow to reinforce and repair stream banks dates back many thousands of years (Schiechtl and Stern 1997) but was largely set aside in favour of more formal structural engineering techniques in the 20^{th} century (Evette *et al.* 2009). The US Army Corps of Engineers published a review of stream bank engineer techniques (Keown 1977) that briefly mentions the use of vegetation to reduce surface erosion, but describes fascine mattress techniques as obsolete due to high labour costs and lack of raw materials.

Many of the pre-20^{th} century applications for live material were simply reforestation of degraded riparian areas to slow erosion (Schlüter 1984 in Evette 2009), a technique still widely used today (Bentrup and Hoag 1998). Bioengineering has developed in sophistication over time to provide levels of erosion protection often in excess of rip-rap due to the increasing strength of living structures as they take root into the bank (Schiechtl and Stern 1997).

Bioengineering has become a widely practised technique in many parts of the world. Fripp *et al.* (2008) have suggested that bioengineering techniques be reclassified into two different styles: treatments that either seek to work with natural processes, accepting that rivers are dynamic systems that change over time, or those that seek to fix the form of the channel, preventing all future erosion. They acknowledge the structural and environmental benefits from incorporating vegetation into hard engineering projects where valuable infrastructure is threatened, but where there is space for natural river processes to take place projects should lean more towards a wholly vegetation based solution with greater benefits to ecology. This discussion could be seen to reflect the debate between systems theory and mechanistic science that has also taken place in other areas of natural resource management. The holistic approach can be taken further by controlling development close to rivers and shorelines, to allow an “erodible corridor” where natural processes can take place (Piégay *et al.* 2005), reducing the need for the high degree of protection provide by rip-rap.

2.3.2 Rooting property of willows

The underlying principle behind the use of woody species to stabilize and reinforce stream banks is the ability of cut stems to produce roots once in contact with water. Potential roots, root primordia, develop within stems as they grow on the tree, reaching maturity by the end of the first growing season (Carlson 1938). Root primordia remain inactive unless the stem is separated from the parent plant. It is likely that changes in levels and ratios of cytokinins and auxins in the cutting are responsible for initiating root growth (Blakesly *et al.* 1991). This shooting ability permits even small sections of willows to colonize habitats subject to frequent disturbance such as flooding (Karrenberg *et al.* 2002) that otherwise do not offer suitable conditions for seedling propagation.

In common with many other plant species, willows undergo a period of dormancy from early winter until early spring though only the first 30 days of this period should be described as a true dormancy (Saunders and Barros 1987). Plants subsequently responded to increasing temperature by re-commencing growth (Pop *et al.* 2000, Sennerby-Forse 1986). Both experimental and field data show that rooting ability of willow cuttings is lowest during the peak growing season (Houle and Babeaux 1993, 1998). Cuttings taken prior to bud break had greater numbers and longer roots than those taken later, although summer cuttings had a similar rate of rooting. Numbers of roots rose again in the fall, a pattern which appeared to be inverse to the rate of stem growth. This is likely to affect survival of the cutting due to reduced ability to take up water and may also affect how the cuttings contribute to bank stability.

Rooting ability in both dormant and growing periods can be enhanced with soaking prior to planting (Pezeshki *et al.* 2005,). For dormant cuttings of black willow *Salix nigra*, soaking for 10 days prior to planting improved rooting and survival compared to soaking for 3 days that had no significant improvement over un-soaked cuttings (Schaff *et al.* 2002). Both peach leaf willow and sandbar willow showed improved root and shoot biomass following fourteen days of soaking compared to no soaking (Tilley and Hoag 2009). For non-dormant black willow, soaking for seven days was beneficial, though increasing the soaking period to 15 days was found to reduce survival. No significant benefit was found from soaking if the water levels at the planting site were at or above ground level (Pezeshki *et al.* 2005).

2.3.3 Flood tolerance of willows

Alongside their ability to grow from cuttings, tolerance of periodic or even extended flooding allow willows to be used for riparian reclamation (Pezeshki *et al.* 2005). Other species also produce adventitious roots as readily as willows; none are able to match the performance of willows when planted on saturated or inundated soils (Gill 1970). Comparing distribution of floodplain tree species along the lower River Rhine in the Netherlands, Vreugdenhil *et al.* (2006) found that levels and duration of inundation could explain the distribution of the various species. Oak *Quercus robur*, Ash *Fraxinus excelsior* and Hawthorn *Crataegus monogyna* declined with increasing inundation while *Salicacae* increased in frequency with increased inundation duration. For the *Salix* species, average length of inundation event best explained the distribution. Location in the riparian zone is likely to be linked to the ability to produce adventitious roots in response to flooding (Krazny *et al* 1988). Sandbar willow, *Salix interior Rowlee,* growing by the Tanana River in Alaska produced the greatest number of adventitious roots per plant, compared to balsam polar, *Populus balsamifera that* only produced a mean of two adventitious roots over the growing season.

A study of willows growing on gravel bars in Japanese rivers found density and crown size were controlled by total annual inundation (Nakai and Kisanuki 2007). Highest densities occurred at around 165 days of inundation while crown size was greater with more frequent inundation, even where in some years the soil surface was completely submerged for the whole year. The reduction in willow density at very high flooding frequency is related principally to seedling survival (Karrenberg *et al.* 2002, Mcleod and MacPherson 1973), but more mature plants are able to withstand greater levels of inundation, both through greater resistance to mechanical forces and by an ability to continue with limited respiration even while underwater.

Mature stems typically develop additional root systems close to the water surface and develop hypertrophied lenticels to enable gas exchange (Kozlowski 1984). Prolonged flooding has been shown to reduce growth and increase mortality; though, there is much variation between and within species (Gill 1970, Good *et al.* 1992). Pezeshki *et al.* (1998) carried out a study on the effect of flooding on cuttings of black willow *Salix nigra* which found reduced growth under flood conditions, but not increased mortality. Their study may have only limited applicability to Manitoba conditions because their experiment took place in the south western USA where air and presumably water temperatures, were greatly elevated, encouraging growth, stimulating bacterial decomposition and reducing the oxygen content of water. Manitoba flooding tends to occur with snow melt, prior to bud break and also at much lower air and water temperatures. In reviewing the available literature on flood tolerance in plants, Whitlow *et al.* (1971) cite studies by Silker (1948) and Broadfoot (1967) which propose that flooding during the dormant season has little or no effect on growth and survival of trees. A Minnesota experimental study found willows growing in saturated conditions showed the greatest increase in biomass when water levels were raised to flood the root crown for increasing durations up to a maximum of 60 days during the growing season (Ohmann *et al.* 1990). When water levels are raised to continually inundate willows for several years, mortality does eventually occur, often suddenly. (Hall 1955). If unsaturated soil is available, willow roots will spread into this material to take advantage of the oxygen available (Krazny *et al.* 1988, Schiechtl and Stern 1997). This enables willow cuttings to even be placed at the toe of the bank where the base is underwater for much of the year.

2.3.4 Willow bioengineering techniques

Planting willow cuttings is the most frequent bioengineering technique described in the available literature, although by itself this technique is often inadequate to stabilize actively eroding banks that may lack other vegetation (Hoag 2007, Schiechtl and Stern 1997). Much of the erosion in the Red River Valley and the area that previously formed the base of Lake Agassiz is due to slumping caused by saturated, poorly cohesive soils (Rush 2007, Fernando 2007). If the willow poles are planted deeply enough they may provide some immediate resistance to shearing effects in a way similar to living roots, although on high banks soil movement will be taking place too far below the surface for this to be practical.

Where erosion is principally due to corrosion at the water-soil interface, willow cuttings are able to play a greater role once established (Schiechtl and Stern 1997). To prevent continued loss of bank material they must be combined either with alternative forms of willow engineering or with other erosion resistant materials such as geotextiles, or most commonly with rip-rap (Allen and Leech 1997, Bentrup and Hoag 1998, Schiechtl and Stern1997).

2.3.5 Selection and treatment of willow cuttings

The predominant consensus of advice on the use of willow materials is that cuttings should be taken from dormant plants (Schiechtl and Stern 1997, Bentrup and Hoag 1998, Hoag 2007) though there is evidence that non-dormant cutting survival can be improved if soaked for seven days before planting into areas with sufficient but not inundated soil water levels (Pezeshki *et al.* 2005). Soaking increases root and shoot growth and improves survival. Black willow *Salix nigra* posts soaked for ten days performed significantly better than un-soaked or three day soaked posts (Schaff *et al.* 2002) and soaking was found to provide the greatest benefit to posts planted higher up the bank where drought stress was most likely (Martin *et al.* 2005). Soaking before planting is thought to stimulate the transition of root primordia into roots. Cuttings taken during the dormant period can be held in artificial cold storage or buried in snow until access to planting sites becomes available (Cram 1982 in Morgenson 1992, Bentrup and Hoag 1998). As temperature at planting time increases, survival of cold stored willow cuttings decreases (Li, M. *et al.* 2005) to a level close to that achieved by Pezeshki (2007) with freshly planted, non-dormant, late spring harvested cuttings.

Willow rooting potential has been indentified as greatest at or around bud break (Densmore and Zasada1978, Houle and Babeux 1993 &1998) but late fall planting may actually produce better field results. Tilley and Hoag (2009) compared fall and spring planting success for both peachleaf willow, *Salix amygdaloides,* and coyote (sandbar) willow, *Salix exigua,* and found greater biomass of roots and shoots following fall planting for both species. Soaking for 14 days prior to planting was also beneficial in both species and for both planting periods. They also suggest that cutting survival may also be enhanced by sealing the top of each cutting with a latex based paint. This also has the added benefit of making sure that cuttings are inserted the correct way up into the ground (Hoag 2007). Other guidelines published by the USDA (Darris 2006) recommend a maximum of seven days of soaking and that painting does not aid survival, though they agree that cuttings should be painted if only to ensure correct orientation. Differences in published guidelines highlight the difficulties for field workers who may not have access to the most current advice.

2.3.6 Size of cuttings

Willow stem cuttings for stream bank projects are generally described as either whips of less than 2.5 cm, poles, up to 7.5 cm and posts for larger material (Crowder 1995, Hoag and Fripp 2002). Cuttings with a greater diameter are believed to offer greater survival, principally because they hold greater reserves of carbohydrate (Hoag 1995). A clear relationship was found by Tilley and Hoag (2009) between cutting diameter and survival, with 100% survival being reached at approximately 2cm diameter. Larger cuttings are also better suited to withstand mechanical forces during inundation (Hoag 1992). Complexity of planting increases with very large diameter cuttings but large diameter posts may enable bio-engineering to be used on larger, more energetic rivers or lakeshores (USDA 1996).

Cutting length is widely described as critical if the base of the cutting is to reach far enough into the soil to make contact with the water table (Conroy and Vejcar 1991, Watson *et al.* 1997). A number of projects have used cuttings 500mm long or less (Carriere 1976, Hoag 1992, Jackson *et al.* 1995, Schaefer 2000). Whilst this is common practice in horticulture or to establish biomass plantations, (Morgenson 1992) because it was easier to produce a large number of cuttings from fewer trees, this may have led to a lower success rate of bio-engineering projects. There may be little biological benefit from using very long cuttings if the water table is close to the ground level, particularly on clay or silty soil. Working on a stream in Mississippi Pezeshki and Shields (2006) found reduced root growth on cuttings placed in permanently inundated stream banks. They found significantly lower survival in silt-clay soils than sand soils which they attributed to lower oxygen levels in ground water.

By leaving more of the willow pole above ground, taller cuttings are better placed to withstand competition from grass species or other plants that may be growing adjacent to the cutting (Hoag 1992).

2.3.7 Planting techniques

Small cuttings may be simply pushed into wet soil by hand, but as cuttings increase in diameter and length this becomes impractical (Darris 2006). Some texts suggest using a soft hammer to drive the stakes into the soil or using a metal bar to pre-form the hole. With larger poles the arm of a hydraulic excavator may be used (Allen and Leech 1997, Bentrup and Hoag 1998), but these techniques risk damaging the top of the cutting, leading to reduced survival (Hoag 1992). A major advance over previous techniques was first described by Oldham (1989 in Hoag *et al.* 2001), using high pressure water to drill the hole which then closes around the stem after it has been inserted. Complete instructions for constructing a water drill are provided in Hoag *et al.* (2001) though simpler variations on this system work effectively in

Manitoba soils (author *pers. obs*.). Holes as deep as 2m have been successfully planted using this method. For larger posts Hoag (2007) suggests using a rotary auger to cut a hole, filling any voids with a soil and water slurry to remove air pockets around the stem.

2.3.8 Willow engineering

Willow cuttings alone are insufficient to protect actively eroding banks or to immediately stabilise bare soils (Allen and Leech 1997). Attempts to establish willow cuttings along a reservoir shoreline failed when 200-250mm of soil was washed away from around the cuttings by wave action (Hoag 1992). Where bank erosion was occurring as a result of channel down-cutting, even large willow posts were insufficient to prevent further erosion (Shields *et al.* 1995).

More complex levels of material placement are needed to provide surface protection, prevent soil movement within the bank and at the toe and to fill voids. The emphasis placed on each of these aspects is determined by the nature of the watershed, particularly soil types (Bentrup and Hoag 1998, USDA 1996). It is common for many of the techniques to serve one role once installed then serve a second purpose as the willows grow, an aspect seen as a major benefit of bio-engineering systems. For example, surface protection systems help to prevent soil movement as roots develop or a soil movement anchor would help to protect surface soils as new branches grow (Schiechtl and Stern 1997).

2.3.9 Surface protection techniques

Prevention of corrosive erosion can take place either by separating soil and water with an armoured layer or by reducing water velocity at the soil interface to below the threshold for particle entrainment.

A layer of willow branches laid vertically to cover the bank slope is generally described as a “brush mattress” (Schiechtl and Stern 1997, Bentrup and Hoag 2002), though Li *et al.* (2005) term this a “brush layer” that term is usually applied to another technique. Once placed the branches are anchored in place with live or dead stakes and held with a network of wire or rope. To enable rooting the branches are covered with soil and ideally the stump end of the branches is placed below normal water level. Coverage of at least 80% of the soil surface is recommended by Schiecthl and Stern (1997) for protection to be effective. A brush mattress deployed on the Yangtze estuary at Shanghai airport was used to cover a newly constructed river bank. After 10 months of growth the brush mattress had increased soil strength by a factor of ten compared to bare soil (Li *et al.* 2005).

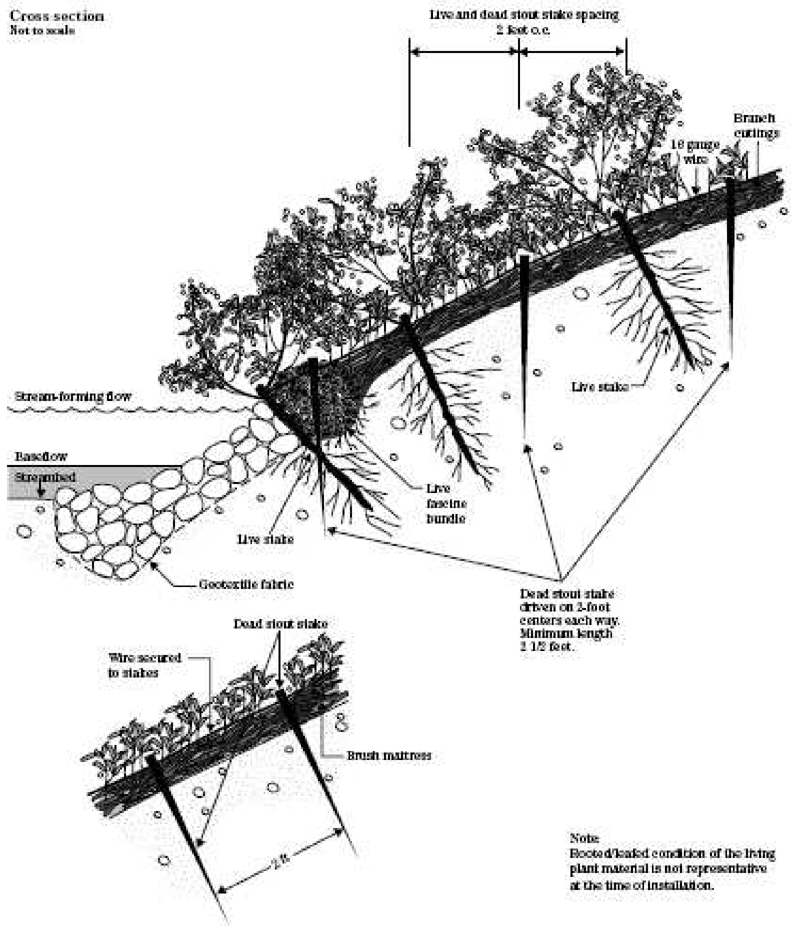

Figure 1 Standard design for willow brush mattress (reproduced with permission USDA 1996)

Brush mattresses are limited to slopes no steeper than 3:1(USDA 1996). If steeper the bank must be graded to the correct angle, which may harm existing vegetation at the top of the slope. Alternatively “willow spiling” may be used to develop a series of terraces on steeper slopes or used to raise the toe of the bank sufficiently for a shallower grade to be established on the slope above. Although commonly used in Europe, particularly in the UK, (Anstead and Boar 2010), spiling is not discussed in any depth in the North American literature. Polster (2002) describes the use of wattle fences in slope stabilisation but uses only loosely placed branches behind large live posts rather than the woven fill characteristic of spiling and which provides additional strength to the structures (Anstead and Boar 2010).

Plate 4 Willow spiling during installation at Minnedosa, October 2011 showing woven cuttings laced horizontally between vertical posts

Care must be taken to ensure good soil contact behind the wall if the willows are to survive and be an effective control measure (www.btcv.org.uk). Given the frequent use of spiling in the UK where labour costs are also high, claims by Sotir (*pers. comm.* cited by Anstead and Boar 2010) that the technique is not used in North America due to the high labour requirement seem unfounded.

Erosion may also be reduced by lowering the velocity of the water close to the bank surface. Willow bundles, mostly described as fascines but also called wattles by Allen and Leech (1997), can be used above or below water level either alone or in combination with other willow engineering. Cut material placed underwater is unlikely to grow effectively so may be composed of other woody species if that is more readily available. Sotir and Fischenish (2001) describe the increased resistance to shearing effects if the bundles are set at 45° to the angle of slope instead of at 90°. To enable the bundles to root into the bank they must be set into a shallow trench and backfilled with soil.

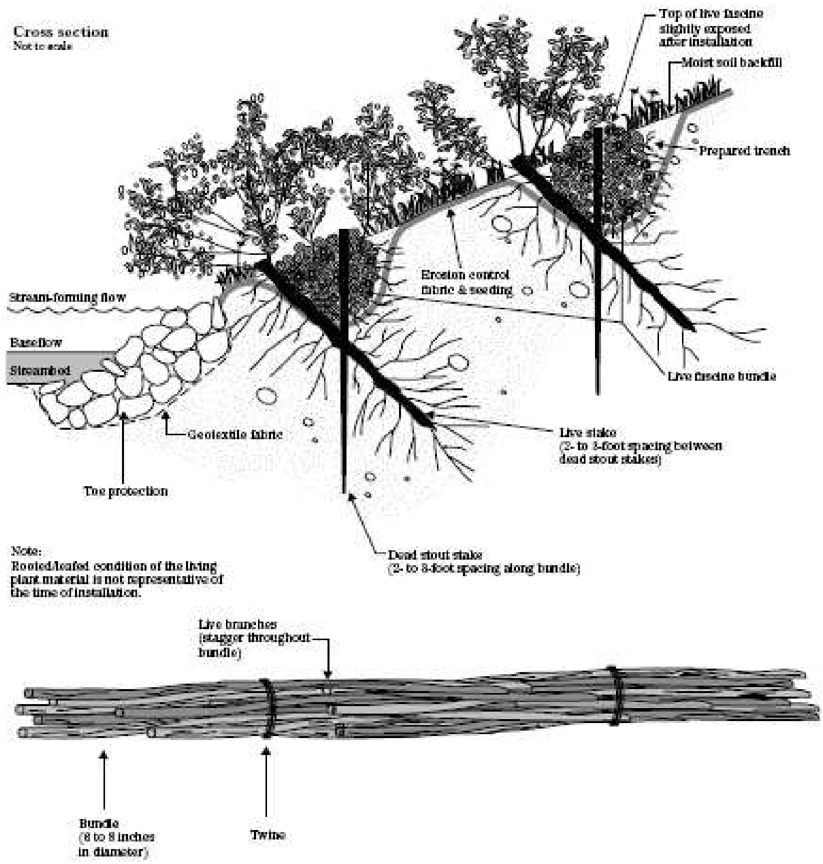

Figure 2 Standard design for willow bundle protection (reproduced with permission USDA 1996)

Hoag (2009) describes vertical bundles set in line with the slope that helps the willows to survive greater variation in water levels as the top of the willow pole is more likely to be above the water surface. As with conventional live willow planting, greater soil to stem contact improves survival. Using smaller diameter bundles of only a few branches increases the amount of growth due to greater willow to soil contact (Hoag 2009).

A complex surface lattice grid of willow branches to protect against erosion is described by Schiechtl and Stern (1997) and shown in widespread use in the European Alps by Evette *et al.* (2009), although this method was apparently very effective it fell out of use as mechanised plant became available and labour became relatively more costly.

2.3.10 Soil stabilization methods

Techniques to prevent soil movement aim to increase the shear strength of the stream bank soil, either through direct mechanical reinforcement or reduction in soil moisture (Schiechtl and Stern 1997). Methods to stabilize soils are described by Schiechtl and Stern (1997), Allen and Leech (1998) and require live willow to be incorporated into the bank in a variety of configurations. These include live bundles, brush layers and, where large voids require filling, branch packing. Bundles and layers are usually set at 90° to the slope to resist the shearing forces down the bank and to capture water moving down the slope, though placing at 45° helps control water drainage more effectively (Sotir and Fischenich 2007). Spacing of willow bundles depends on slope angle and soil cohesiveness. On less cohesive soils with steeper slopes up to 3:1 Sotir and Fischenich (2007) advise a spacing of 900mm whilst on cohesive, shallow slopes a spacing of 2500mm would be suitable. Although brush layers are designed to stabilize deep into the soil they advise against using brush layers on new fill that can often settle after placement.

Where a bank profile is being restored with new fill Schiecthl and Stern (1997) and Hoag and Fripp (2002) recommend a method described as brush packing, alternating layers of live willow branches with soil to create a more stable structure. Branches should be laid at varying angles to provide greater tensile strength, mimicking the large diameter roots of mature willows. To enable growth the tops of the branches should protrude above the soil surface.

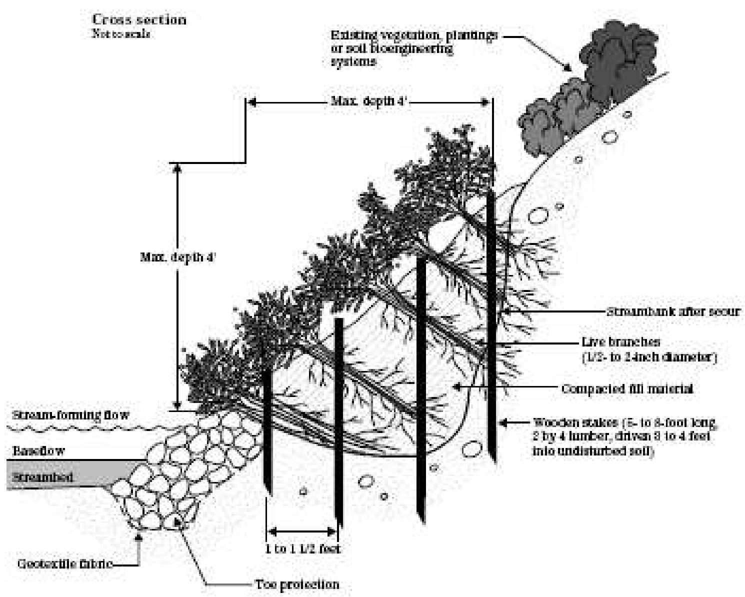

Figure 3 Standard design for willow branch packing (reproduced with permission USDA 1996)

2.3.11 Companion materials

Amongst the most commonly recommended combination is to use rip-rap at the toe of the bank with willow based techniques above summer water level (Allen and Leech 1997, Beaver *et al.* 1998). Because stability of the bank toe is critical to successful erosion protection (Shields *et al.* 1995) many river engineers are unwilling to risk using wholly biological based solutions (Li and Edleman 2002), although inert bundles of locally cut woody material have traditionally been used in many places where stone has not been commonly available (Schiecthl and Stern 1997). Whereas stone provides permanent protection against erosion, inert bundles' principle role is to provide time for vegetation planted higher up the bank to establish. Inert bundles cut from hawthorn, *Crataegus monogina*, have traditionally been used to reinforce drainage channels in the east of England, lasting upwards of twenty years before showing signs of decomposition (author *pers. obs*). Reduced flow velocities within inert bundles causes sediment to gather and provides protection against wave action until living roots take on this role (Sotir and Fischenich 2001).

In rivers with higher gradients and greater flows such as mountain areas, or where there is critical infrastructure immediately adjacent to the watercourse, it may be necessary to extend rip-rap above the normal summer water level (USDA 1996). Willow can be incorporated within the rip-rap without compromising its protective capacity and helps to prevent water filtering through the bank from undermining the rock structure (Shields 1991, Schiechtl and Stern 1997). This can be carried out after rip-rap installation (Hoag 2008), but it is far better to place the willow cuttings as bundles into the soil at the same time as the rock is laid to ensure that the cuttings make good contact with the soil below (Hoag and Sampson 2007).

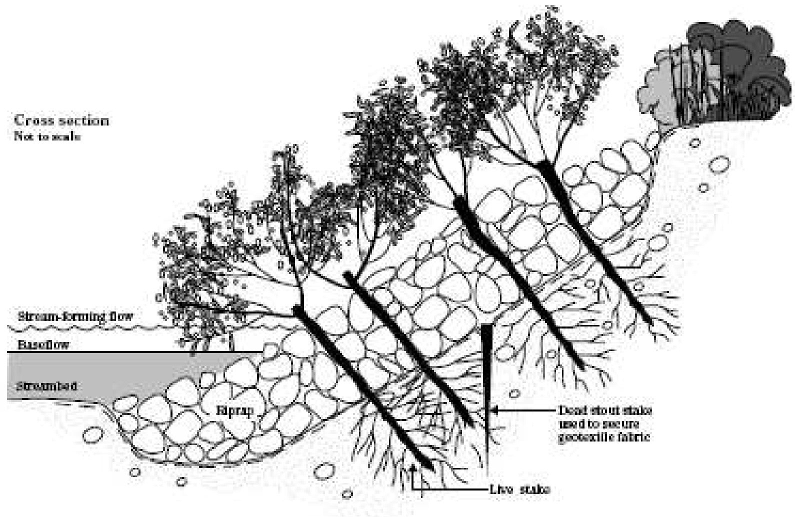

Figure 4 Standard design for willow planting through rip-rap (reproduced with permission USDA 1996)

By enclosing the stone in wire or rope baskets (gabions) smaller stone than would be needed for rip-rap can be used (Freeman and Fischenich 2000). Live willow cuttings can be incorporated within or between the baskets that increases bank stability over that provided by the gabions alone (Gray and Sotir 1996, Schiechtl and Stern 1997).

Care should be taken as to which species are used within gabions. Freeman and Fischenich (2000) caution that larger tree species may cause damage to the integrity of the baskets if toppled by extreme flows or high winds. This can be prevented with the European technique of coppicing, where riverbank trees are cut back to reduce the overall height of the tree while preserving the living root mass (Gray and Sotir 1996). Cutting back the tree stems to a stump on a regular basis can extend the life of the tree, and particularly on smaller streams, can enhance native biodiversity due to reduced shading (Broadmeadow and Nisbet 2004). Brunet and Shuey (2003) installed vegetated gabions on the Merrimack River in New Hampshire, lining each basket with a coir (coconut) fibre blanket to retain sediment within each gabion. Although they originally intended to use live staking, a bald eagle's nest delayed installation and required the use of pre-rooted plants.

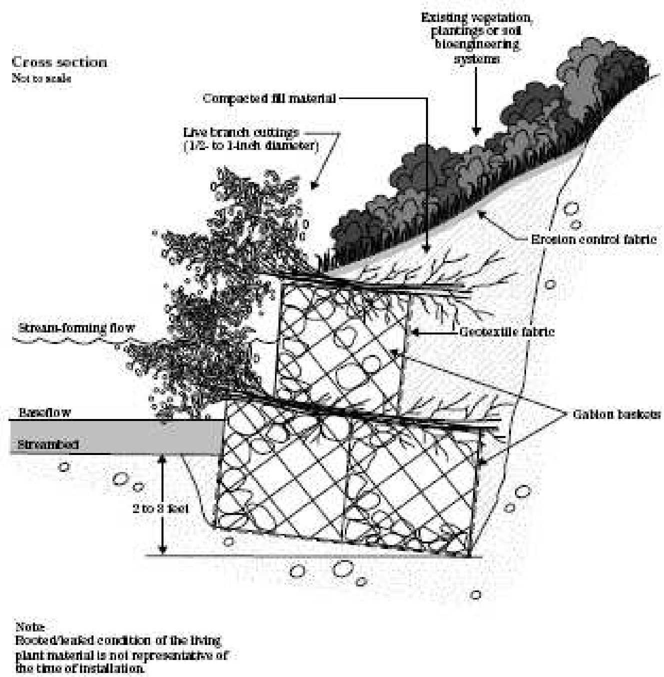

Figure 5 Standard design for vegetated gabions (reproduced with permission USDA 1996)

Engineering fabrics, collectively called geo-textiles, are increasingly used in conjunction with willow engineering, often replacing some of the more labour intensive methods such as brush mattresses and branch packing. Geo-textiles are available in biodegradable materials such as coir or jute, or from longer lasting materials such as polypropylene. Delivered to site in large rolls, geo-textiles are laid across a levelled surface and staked into place. Willow cuttings are easily driven through the textile into the soil below (Sotir and Fischenich 2007). Geo-textiles do help to retain soil moisture but care must still be taken to ensure the base of the cuttings reach deep enough into the soil to contact the water table.

To provide deep stabilization of soils, large geo-textile bags may be formed in situ to create a stepped slope or filled away from the river and lifted into place. These are termed “vegetative geogrids” by Allen and Leach (1997) or Vegetated Reinforced Slope Systems (VRSS) by Sotir and Fischenich (2003). Live willow material is placed along each of the horizontal layers within the grid, rooting into the bags and the soil behind the reinforced bank.

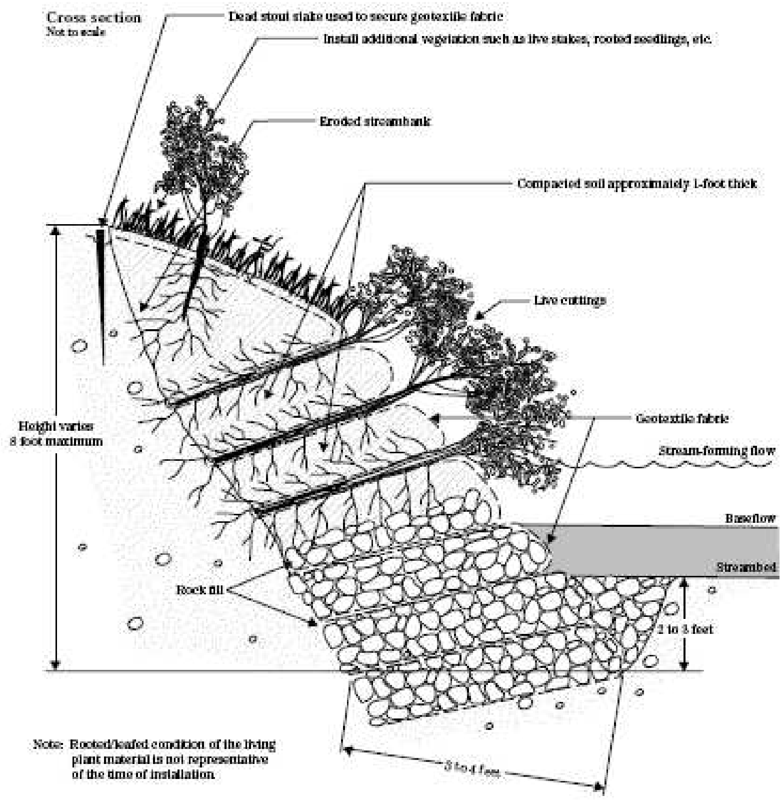

Figure 6 Standard design for a vegetated geogrid (reproduced with permission USDA 1996)

Although resistant to erosion, care must be taken to reduce water infiltration behind the grid reinforcement and undercutting at the toe and ends of the structure (Sotir and Fischenich 2003). Karle *et al.* (2005) observed geogrids had failed at sites in Alaska due to ice that abraded the geotextile, spilling the contents of the cell. This is potentially a problem in Manitoba, particularly on larger rivers and lakes. One solution would be to use a higher specification textile than would normally be required in areas exposed to mobile ice (Artieres and Lombusto 2010). The ability of vegetated geo-grids to resist mass failure on high banks this system would be a favourable candidate for further investigation into its potential on the larger rivers of Manitoba

2.4 Relative Costs of Willow Bioengineering

The cost of bio-engineering is closely linked to the complexity of the applied solution and will also vary between sites (Hoag 2000). Although bio-engineering is less costly than equivalent hard engineering solutions (Jarvis and Richards 2008), on large sites requiring extensive soil excavation costs will be of the same order of magnitude as using stone reinforcement. Gray and Sotir (1996) provide costs, as of 1994, for simple willow stake planting as between $1.50 and $3.50 per stake through to $12- $30 per linear foot of vegetated geogrid. Instead of providing monetary values for the costs of various types of bio-engineering, a number of authors have compared costs in terms of hours/linear metre (linear ft) of reinforcement (Allen and Leech 1998, Schiechtl and Stern 1996, and Hoag 2000). Simply planting willow cuttings is the least costly at less than one hour /metre whilst the most complex techniques such as fascine bundles and crib walls may be up to ten hours/metre. Li and Edleman (2002) adapted an earlier cost-strength matrix developed by Landphair and Li (2001) to visually depict relative costs versus stabilisation capabilities of the various bioengineering techniques. Live stakes are described as low strength and low cost while complex structures such a live crib walls and vegetated geogrids are both high cost and high strength.

2.5 Limitations on the Use of Bioengineering

Failure of Bioengineering projects described in the literature relate either to a poor survival of the materials or to the forces causing erosion exceeding the ability of the material to withstand them. Although the latter is a problem shared with traditional hard engineering materials, the variability in performance brought about by the former is unique to bio-engineering.

2.5.1 Biological limitations

Water levels are identified by a number of authors as key in determining the survival of bioengineering projects. The most commonly reported problem is water stress during the first and second growing seasons when cuttings have not acquired a fully developed root system. Despite initially encouraging observations of growing shoots, cuttings of Bebbs willow *Salix bebbiana* suffered 100% mortality when planted on a dry eroding hill slope (Schaeffer *et al.* 2005). Pezeshki and Shields (2006) and Pezeshki *et al.* (2007) describe a study of bioengineering projects along streams in Mississippi, USA, involving the planting of over 20,000 black willow poles of which less than 50% survived into the following growing season and long term survival of less than 10%. On free draining, less cohesive soils, depth to the water table proved critical to survival due to reduced rate of rooting and inability to support transpiration losses as leaves grew over time (Pezeshki *et al.* 1998).

Results from the same Mississippi study also demonstrated the effect of elevated water levels on survival and growth of black willow. Provided oxygen levels in the soil water remained positive, willows growing closest to river level showed the greatest growth, but prolonged flooding and reducing conditions led to a reduction in growth rates over the duration of the study (Pezeshki *et* *al.* 2007). Similar issues were found on the Turtle River in North Dakota where black willow posts placed at or below summer water level showed lower survival than those planted higher up the bank (Watson *et al*. 1997). Investigations into the effects of complete submersion on willow cuttings are very limited. Submersion of 30cm cuttings of European *S.purpurea* and *S.viminalis* continued to grow whilst completely submerged. Those that grew sufficiently to emerge from the water developed new shoots and leaves while others that remained fully submerged died after three months (Good *et al.* 1992). Slightly greater periods of inundation in Nevada reservoirs killed over 80% of cuttings submerged for 105 days (Tallent-Halsell and Walker 2002). In both papers the authors suggest that survivability would be much greater in plants tall enough to remain only part submerged.

As pioneer species willows are generally described as shade intolerant, disappearing as riparian woodland matures (Walker and Chapin 1986). There is some indication that shade principally impacts upon seedling establishment (Sacchi and Price 1992) preventing re-generation of willows within stands of other trees, though Bryant (1987) suggests another mechanism whereby shading reduces the levels of tannins in willow leaves and twigs, making them more palatable. If browsing is sufficiently heavy carbohydrate supplies can become exhausted, leading to death of the young tree or re-sprouting stump. Tall grasses and invasive Kudzu vine were a problem on sites in Mississippi (Shields *et al*. 1995) though Watson *et al*. (1997) found no significant effects of shade on another willow post scheme.

The biological differences between willow species have sometimes been overlooked by some bio-engineering practitioners, often with generic references to willows, that has the potential to impact upon the success of projects (Schiechtl and Stern 1997). As well as differing tolerance to drought and inundation, reduced rooting ability of some species may reduce survival of plantings (Amlin and Rood 2001, 2002). Evidence from experimental flooding has also shown wide variations within species in timing and rate of growth when waterlogged (Good *et al*. 1992), suggesting that success would be enhanced by securing willow material from local sites and similar habitats.

2.5.2 Engineering limitations

All engineering methods and materials have physical limitations on their ability to prevent erosion and stabilize stream banks. Data on the shear stresses that various engineering treatments are able to withstand were complied by the US Army Corps of Engineers (Fischenich 2001) showing a wide range of strength for bio-engineering techniques that in the most complex forms can equal the protection provided by rip-rap.

Table 1 Stability thresholds for various bank stabilization techniques (from Fischenich 2001)

Technique	Shear stress (lb/ft)	Velocity (ft/s)	Ref.
Rip-rap, 6”	2.5	5-10	1
Rip-rap, 12”	5.1	10-13	1
Live stakes	2.1-3	3-10	2,3,4
Brush mattress (initial)	0.4-4.1	4	5,2,6
Brush mattress (grown)	3.9-8.2	12	5,2,6,7,3
Brush layering (initial-grown)	0.4-6.25	12	2,6,3
Live fascine	1.25	6-8	7,2,6,8

1. Norman, J. N. (1975), 2. Gray, D.H., and Sotir, R.B. (1996), 3. Fischenich (2001), 4. USACE (1997), 5. Florineth. (1982), 6. Schiechtl, H. M. and R. Stern. (1996), 7. Gerstgraser, C. (1998), 8. Schoklitsch, A. (1937).

The difference between initial values and strengths once established indicate one of the most notable challenges of using bioengineering techniques. A number of authors describe failures in the period prior to establishment and the need to allow for monitoring and remedial action if damage occurs is noted (Anstead and Boar 2010, Beaver *et al.* 1998, Simon and Steinmann 2000).

The ability of bioengineering to combat the type of rotational slumping present on the soils of the Red River would be dependent on both the mechanical and hydrological stabilisation of the soils. Brooks (2003, 2005) and Schwert (2003) describe layers of soil several meters thick moving down the bank slope toward the river, often carrying large trees rooted within the mass. Although Abernethy and Rutherford (2000) concluded that the trees planted on the bank crest moved the failure plain back away from the river, decreasing the risk of failure, the trees were not able to remove it altogether. In combination with techniques such stone reinforcing at the toe of the bank or Vegetated Reinforced Slope Systems (Sotir and Fischenich 2003) bioengineering may offer sufficient protection even where costs of bank failure are very high.

The benefits to bank strength from hydraulic reinforcement by tree roots (Simon and Collison 2002) are dependent upon timing of flooding: until leaves emerge there is very little reduction in soil pore water through transpiration, reducing the ability of simpler bioengineering techniques to prevent slumping.

2.6 Gaps in Current Knowledge

A number of studies have been published that relate to the use of willow to stabilize stream banks, but little of the work and subsequent guidance is directly transferrable to Manitoba. Variations amongst species as well as differences in geography have the potential to render methods developed elsewhere less successful.

Studies of willow biology have been carried out across North America and Europe (Amlin and Rood 2001, 2002, Carlson 1938, Houle and Babeaux 1993, Karrenberg *et al.* 2002, Krazny *et al.* 1988, Talbot *et al.* 1987) but investigations into bioengineering techniques have been driven first by United States Army Corps. of Engineers (and then later the United States Dept. of Agriculture Natural Resource Conservation Service). Many of the studies have been carried out using black willow *Salix nigra*, a species not native to Manitoba. The locations described in the literature often feature a longer growing season and greatly elevated spring temperatures compared to Manitoba. Flooding experiments have taken place in greenhouses at temperatures over 20°C, decreasing the oxygen content of flood water and increasing the level of bacterial activity responsible for tissue breakdown. The soils described have generally been coarse, non-cohesive, that although applicable to soils in the Lake Agassiz escarpment are very different to much of the lower parts of both Red and Assiniboine watersheds.

The uncertainty created by these differences reduces the likelihood that river managers will select bioengineering over more “traditional” forms of bank stabilization with further loss of riparian habitat as a result. Research is required to understand whether current techniques can be applied successfully, whether and how they should be adapted to make bioengineering a practical proposition or whether some techniques are impractical in Manitoba.

3 Methods

3.1 Objective 1: The Use of Taller Cuttings to Mitigate the Effects of Spring Inundation

3.1.1 Research hypothesis

Prolonged inundation due to elevated water levels potentially reduces survival and retards growth of newly planted willow cuttings. The impact of flooding may be mitigated by using taller cuttings to decrease likelihood and the period of immersion; alternatively longer stems could lead to negative impacts when water is less available in summer due to moisture loss from the exposed stem.

3.1.2 Study design

Stem cuttings 1.5m-2m long, basal diameter between 20-25mm were cut in October/November 2011 from stands of sandbar willow *Salix exigua* located in riparian areas south of Winnipeg. To reduce the potential for disease or chemical contamination to impact the results of the study, cuttings were taken from three separate locations. Before planting the cuttings were soaked horizontally in water at air temperature for 14 days in a 2.5m by 1.2m by 0.5m deep tank, Soaking has been shown to increase root and shoot biomass in the subsequent growing season (Tilley and Hoag 2008). The cuttings were then randomly assigned to study sites by mixing them during storage to remove any potential for variation amongst source stands to affect the results.

To reduce the potential for the planting to be completely lost due to an unforeseen event, five separate locations were planted with cuttings across several watersheds. This also helped to avoid confounding effects due to local variation in environmental conditions at the study locations that could favour a particular cutting height.

Table 2 Location of willow cutting trial sites

Site	Local Watershed	UTM Co-Ordinates (14U)
St Pierre	Joubert Creek	649584.00 m E 5477525.00 m N
Dufresne	Seine River	663308.00 m E 5511017.00 m N
Otterburne	Rat River	641672.00 m E 5484489.00 m N
Riverton	Icelandic River	640313.00 m E 5650683.00 m N
Brandon	Assiniboine River	440676.00 m E 5520572.00 m N

Map showing location of sites removed for copyright reasons.
Details of sites are shown in Tables 2 & 5

Figure 3.1 Distribution of willow cutting trial sites (●) and bioengineering projects (●) across agro-Manitoba

At each study site two rows of a minimum of twenty cuttings (forty cuttings total) were inserted into the bank using a water-jet stinger (Hoag *et al*. 2001) at approximately 1m spacing. Dependent on local topography, the lower row was inserted approx. 0.5m above water level and 0.5m vertically into the soil, while the upper row was placed approximately 1m higher up and 1m into the bank face to improve contact with the water table. As well as providing a wider variation in water levels by planting cuttings at two elevations it was hoped that some cuttings would survive even if the sites were affected by extremes of flooding or drought.

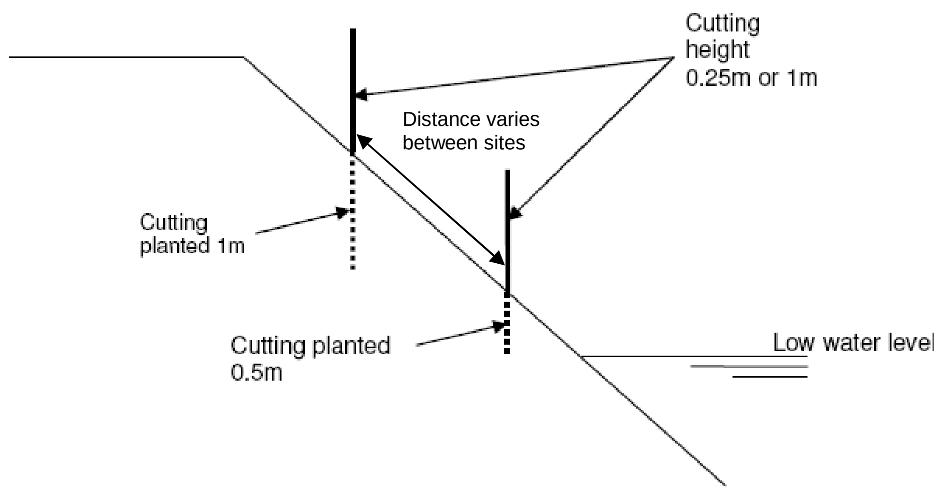

Figure 3.1 Arrangement of willow cuttings at study sites

Plate 5 Otterburne willow cuttings showing typical placement of cuttings in rows

The cuttings were then trimmed using manual loppers, half to 0.25m above ground, half to 1m. At each site the position along the row for each cutting height was allocated using a random number table. The willow cuttings were then marked with flagging tape to aid relocation and differentiate them from other willow cuttings planted on the site (Plate 5). Vegetation for a radius of 50cm around each cutting was cut to ground level immediately prior to the first measurement of shoot growth in late July to allow the shoots to be located and measured.

3.1.3 Sampling methods

Sites were visited monthly between May and September 2012 to assess survival, level of insect damage and browsing. Additional detailed observations on the number and length of individual shoots took place on two occasions first at the end of July/ beginning of August and for a second time in September. Percentage survival is a widely reported statistic in bioengineering studies indicating the overall success of the project (Schiechtl and Stern 1996). Destructive sampling has been used frequently to compare growth rates, principally enabling measurement of shoot and root biomass. However, unless the number of cuttings is very large this reduces the potential for repeat sampling and could also negatively impact the success of the scheme being monitored. As an alternative to destructive sampling, number and length of shoots were measured. Shoots emerging from the cutting were measured to the nearest 0.5cm from the cutting to where the apical leaves emerged or to the end of browsed stems.

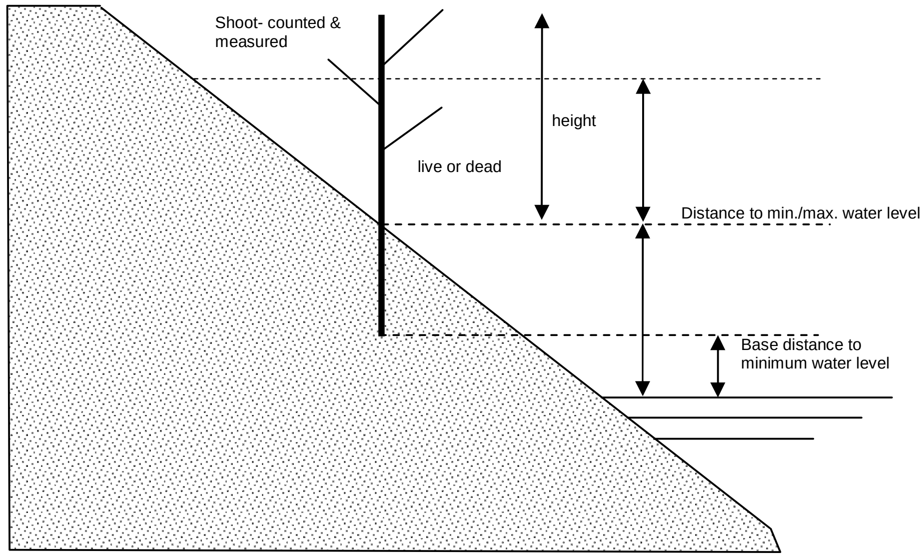

Figure 7 Detail of measurements collected for willow cuttings

Cutting diameter at 0.1m above ground level was also recorded at the initial visit as this has also been found to have an impact upon growth and survival (Tilley and Hoag 2008, Watson *et al*. 1997). Where cuttings had been browsed by beavers below this height the measurement was made immediately below the cut end.

Table 3 Timing and type of sampling occurring at each visit to willow cutting study sites

Sample event	Survival	Cutting Length
May/June	X	
June/July	X	X
July/August	X	
August/September	X	X
September/October	X	

3.1.4 Environmental Monitoring

To enable comparison amongst sites, data on the environmental factors that could potentially affect growth and survival of the cuttings were also collected.

Weather Data

Data of daily temperatures (max. and min.), precipitation and where available soil temperature for closest weather stations were obtained for the period March to October 2012 from the Manitoba Agricultural Weather Program (www.tgs.gov.mb.ca)

Table 4 Location of weather stations used as sources of data for each willow cutting study site.

Site	Weather Station
Brandon	Carberry
Otterburne	St. Pierre-Jolys
St. Pierre-Jolys	St. Pierre-Jolys
Dufresne	Dugald
Riverton	Arborg

Shading

As an early colonizer of bare ground, willows are widely held to be intolerant of shade (Karrenberg 1992). To compare light levels among sites and rows an estimate was made of the percentage of open sky to the south and overhead of the plot that was obscured by adjacent vegetation and topography. The estimate was made with recorder prone to take better take account of bank profile and over head vegetation.

Vegetation Cover

An estimate was made to the nearest 5% of the proportion of ground covered by vegetation growing within a 1 metre by 1 metre quadrat centred on each willow. Estimates were made in July to allow time for annual seeds to germinate.

Vegetation present was categorized as either grasses, broad leaved herbs or a mixture of herbs and grasses.

Soil Water

To compare soil water levels among sites a shallow tube well was inserted into the stream bank at the centre of the plot. A hole was drilled with an auger down to 1.8 meters. At Riverton the depth was reduced to 1.2m due to stones within the soil. A perforated plastic tube enclosed with a porous fabric was inserted leaving approximately 20cm above ground. Dry sand was then poured around the tube up to within 150 mm of ground level to fill any space around the and then wet clay was packed around the tube to prevent direct surface water infiltration.

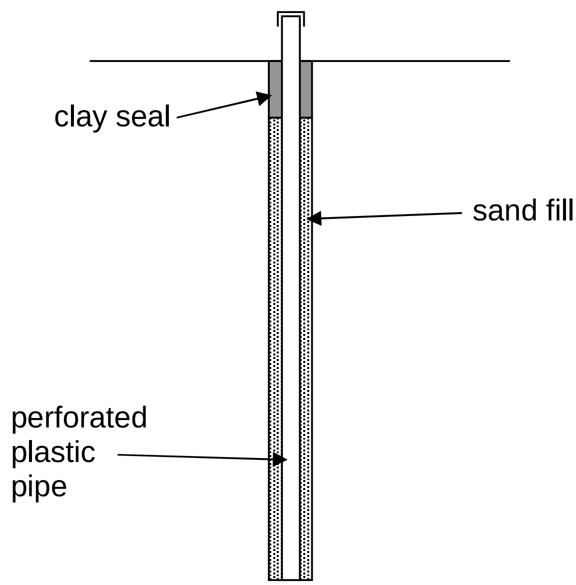

Figure 8 Cross section of typical shallow pipe well installed at each willow planting sites

Further information on soil water was also collected at each site using a Stevens Hydraprobe™. The Hydraprobe™ uses an electromagnetic signal to determine the electrical permittivity of a known volume of soil around four stainless steel pins from which soil water levels can be calculated (Stevens Water Monitoring inc. 2007). Soil water was sampled at three points along each row of cuttings on a minimum of two occasions through the summer. At Otterburne and Dufresne soil conditions were too dry later in the summer to allow the probe to be inserted into the ground, limiting the number of samples taken.

Soil Characteristics

Some initial indication of soil type was gained during the installation of the shallow wells. This provided information on a coarse scale as to the general nature of the soils in the riparian area. More detailed information was obtained from soil cores taken along the rows of cuttings. Cores were obtained using a JMC Backsaver (www.jmcsoil.com) soil sampler. Cores were taken to a depth of 100cm but at Brandon and Riverton high soil water caused the samples to fall from the sampler preventing cores being taken to the full depth so particle size analysis was restricted to the upper 40cm of the core. Soil samples could not be collected at Dufresne as the soil had become too hard to insert the auger.

Analysis was carried out using a combination of filtration and sedimentation to determine the fraction of sand, silt and clay in each unit of soil. Samples were sieved to remove any material larger than 2mm after which a sub-sample was taken for analysis. This material was then mixed with distilled water and hydrogen peroxide to remove any organic material to leave only sand, silt and clay in suspension. The sand fraction was collected by passing the suspension through a sieve. Proportions of silt and clay were estimated by allowing the suspended material to settle in a large measuring cylinder. Sedimentation rates are dependant upon particle size, so by taking sub-samples immediately and then after eight hours the proportions of silt and clay present in the sample could be estimated. For more details of the technique see Kroetsch & Wang (in Carter & Gregorich 2008).

3.1.5 Statistical Analysis

The relationship between survival and growth of the willow cuttings and the environmental variables was modelled using Generalized Estimating Equations (GEE). This technique was developed from Generalized Linear Models (GzLM) to create regression models with confidence intervals adjusted to take account of correlated data (Liang & Zeger 1986 *in* Hardin & Hilbe 2003). In this study the GEE was used to allow for correlation between cuttings within the same site, and overcomes the need to pool results from each site to prevent pseudo-replication. Without taking account of correlation among cuttings at the same site there would be greater potential that associations between variables will be found where none exists (Lennon 2000).

To reduce the number of parameters used to develop the model the effects of variables upon willow performance was explored graphically to identify those most likely to be associated with cutting performance. Selecting model parameters from an appropriate pool avoids using an arbitrary significance level to decide whether variables should or should not be included in the model (Anderson *et al.* 2000). SPSS provides corrected QIC (QIC_u) values (Pan 2001) for the GEE to compare between models. As with likelihood-based information theory scores, lower QIC_u values indicate a model with better fit to the data. Survival data were modelled using binary logistic regression whilst a negative binomial model with log link was used for shoot number and maximum shoot length.

With only five clustering sets (sites) Hardin & Hilbe (2003) suggest that the model may be best fit without adding an additional correlation parameter, but still using an estimate of variance that is robust to within cluster correlation. They also state that where there are justifiable reasons for selecting a particular correlation type, such as the wide separation of sites used in this study, these should be used to guide model selection. Where data are spatially correlated, rather than correlated over time, applying a common correlation parameter to each cluster is generally recommended, termed an "exchangeable" correlation.

How well the model discriminated between planting conditions likely to result in survival and those where cuttings would likely die was evaluated by comparing correctly predicted survival against correctly predicted mortality using a 2 x 2 confusion matrix (Pearce & Ferrier 2000).

The threshold between predicted survival and mortality was determined using a Relative Operating Characteristic curve (ROC) (Pirotta *et al*. 2011). ROC curves were originally developed to evaluate observer accuracy and have been adopted in medicine and to a lesser extent in ecology to evaluate the fit of models that describe the effect of independent variables upon binary response data (Fielding & Bell 1997, Pearce & Ferrier 2000, Zweig & Campbell 1993).

Models developed to explain variations in the number and maximum length of shoots were evaluated using diagnostic graphs, comparing distribution of residuals and observed versus predicted performance for willow cuttings at each site to identify lack of fit (Hardin & Hilbe 2003).

3.2 Objective 2: Review of Bioengineering Projects and Techniques

3.2.1 Bioengineering Installation

Five small bioengineering projects were installed in Manitoba rivers in fall 2011/ spring 2012 in partnership with local Conservation Districts. The objective was to increase bank stability by reducing erosion and re-vegetating the bank area to increase soil strength. The projects varied in complexity, incorporating combinations of bioengineering techniques including live staking, willow bundles, woven willow spiling and willow brush grids. Two sites simply used willow material, two sites added erosion control blanket and at the other stone rip-rap was incorporated to protect the toe of the bank. The projects provided the opportunity to observe the effect of seasonal changes in water levels, with potential for ice damage, lengthy inundation and receding water tables upon willow survival and growth.

<u>Pembina River, Killarney</u>

The stream bank toe at this site was stabilized with rip-rap and the bank above re-profiled then covered in coir fibre erosion control blanket. Willow bundles were buried both on top of and under the erosion blanket with live willow cuttings planted through the blanket. Beaver were very active at Killarney. During construction willow cuttings that had been soaking in the Pembina River were removed by beaver so had to be replaced with new material.

<u>Little Saskatchewan River, Minnedosa</u>

The eroded stream bank was re-profiled to a 1 in 3 slope. The toe of the bank was protected using wooden posts and woven willows (spiling). Coir fibre blanket was laid across the slope and behind the spiling to prevent soil loss prior to vegetation becoming established. Willow cuttings were inserted through coconut erosion blanket to a depth grater than 1.2m using a water jet planter.

Icelandic River, Riverton

Bundles of willows cuttings were secured along the stream bank toe with additional live willow cuttings planted at water level and along the slope of the established dyke. Large bundles of willow were secured below water level, anchored by wooden posts driven into the river bed. These bundles were intended to dampen wave action and speed the re-growth of emergent macrophytes.

Rat River, Lake St. Malo

Bundles of 8-10 willow cuttings were secured with wooden stakes in shallow trenches along a 30 metre section of the eroded shoreline of the artificial lake. Excavated material was then used to fill the void between willows within each bundle.

Joubert Creek, St. Pierre- Jolys

Planting was carried out in October 2011 with the second adjacent section planted in May 2012. Both areas were planted with live cuttings at the toe and part way up the heavily eroded stream bank. Bundles of five willow cuttings 2.5m long were buried in trenches cut vertically into the stream bank with one bundle buried horizontally at water level during the spring planting.

Table 5 Locations and engineering techniques used in bioengineering projects

Site	Local Watershed	Bio-Engineering Method	UTM Co-ordinates (14U)
St-Malo	St.Malo Lake/ Rat River	horizontal bundles	651221.00 m E 5464135.00 m N
St Pierre	Joubert Creek	Live stakes & vertical bundles	647601.00 m E 5477894.00 m N
Riverton	Icelandic River	Live stakes and horizontal bundles	640305.00 m E 5650664.00 m N
Minnedosa	Little Saskatchewan River	Willow spiling, live staking & erosion blanket	438726.00 m E 5567023.00 m N
Killarney	Pembina River	Vertical bundles, rip-rap & erosion blanket	442177.00 m E 5449270.00 m N

3.2.2 Observations

Visual assessment has been incorporated into previous studies (Anstead and Boar 2010, Beaver *et al*. 1998), to describe the type and location of bioengineering failure and forms a key part of the project cycle, allowing for remedial works to correct minor failure during the establishment phase (Schiecthl and Stern 1996). Karle *et al*. (2005) used a similar visual assessment to accompany a post event modelling of channel flows to better understand reasons for structural failure of bioengineering projects in Alaska.

Bioengineering projects rely upon vigorous vegetation growth for much of their strength, so assessment of vegetation performance is important to predicting success. A minimum level of growth to delineate success was set at 60% survival of live willow stakes and more than 10 live shoots per metre of willow bundle (Schiechtl and Stern 1996).

Each site was visited soon after high water levels had receded in the spring and throughout the growing season with observations made of the condition of the bioengineering treatment.

Biological Failure

- Presence of insect damage and browsing.
- No. of shoots per metre. on spiling, or bundles
- % of live stakes showing live growth at the end of growing season.

Indications of physical failure were also noted.

Physical Failure

- Erosion around the bioengineering materials
- Soil lost from around the protective material
- Damaged or missing bioengineering components

3.2.3 Analysis

Because the lack of replicates and the individual nature of each design prevented the information from being analysed quantitatively, relationships between bioengineering condition and environmental variables were explored qualitatively and used in combination with the study into the effect of cutting height and flooding to suggest key factors to take into account with future use of bioengineering in Manitoba.

4 Results

4.1 Study to Evaluate the Use of Taller Cuttings to Mitigate the Effect of Spring Inundation

Seven of the two hundred planted cuttings died over the winter and did not produce any shoots. Possible reasons for this include poor handling during the harvesting/planting process or desiccation over the winter. Ten cuttings could not be relocated at St. Pierre-Jolys and were suspected to have been removed by beaver though this could not be confirmed. At Brandon the entire lower row of cuttings was pulled from the ground by beaver, leaving holes where the cuttings had been and footprints along the river bank. At all sites, except for Riverton, a proportion (Figure 11) of the cuttings were bitten off by beaver (see Plate 6) at some time between fall 2011 and spring 2012 leaving a cutting of reduced height and potentially influencing the outcome of the study by changing the range cutting heights at each site.

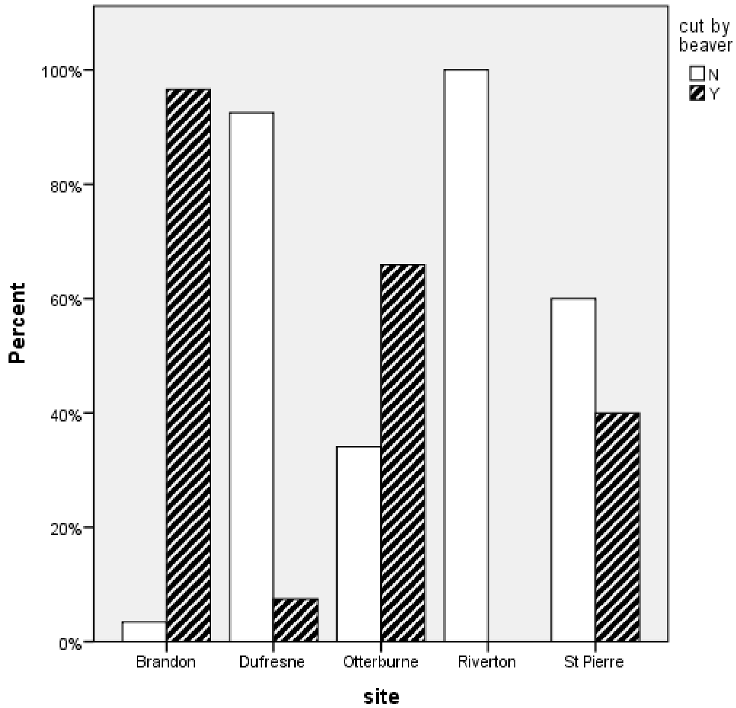

Figure 9 Proportion of willow cuttings planted in 2011-2012 to evaluate the effect of cutting height which were cut short by beaver.

Plate 6 Example of a willow cutting with top cut off by beaver showing subsequent emergence of shoots.

4.1.1 Selection of Cuttings by Beaver and the Possible Effect of Beaver Grazing on Cutting Survival

Beaver showed a preference for the taller cuttings and also targeted cuttings that were flooded during spring. There was however, no evidence that the cuttings trimmed by beaver had a lower probability of survival than those left intact.

Tall cuttings (100cm) were approximately five times more likely to be taken (β=-1.632, P= 0.011) than short (25cm) cuttings. Holding cutting height constant, the chance of cuttings being eaten by beaver increased by 0.5% for each 1cm increase in maximum water level (β= 0.005±0.0013, P<0.001) so that cuttings at lower relative elevations and greater inundation had more chance of being eaten (Table 6).

This model was 73.4% successful at predicting whether a cutting would be eaten by beaver, but was limited in that it did not include the likelihood that beaver were present at all locations and at similar densities.

The fit of a model for cutting survival incorporating beaver trimming and elevation above minimum water level was a poorer fit to the observed data than a simpler one including only elevation (Table 7). Complete removal of a cutting would have resulted in the cutting dying; however, the majority of beaver grazing resulted only in a shortened cutting. For the cuttings that were eaten but remained as stumps there was no evidence that beaver grazing had any impact upon survival (β= 0.366±0.695, P=0.598) (Table 8).

Table 6 Parameter estimates, robust standard errors, Wald χ^2 values and significance for the effect of original cutting height and relative distance to maximum water level upon the chance of planted cuttings at sites in Manitoba being eaten by beaver in 2012

Parameter	Estimate	Std. Error	Wald χ^2	P
original cutting height				
short (25cm)	-1.632	.6431	6.442	.011
tall (100cm)	0			
relative distance to max. water level	.005	.0013	12.968	.000

Table 7 Comparison of fit for combinations of parameters using relative QIC_u to survival of cuttings, September 2012, Manitoba

Parameters	ΔQIC_u
relative distance to minimum water level	0
Beaver trimming + relative dist. to minimum water level	6.24

Table 8 Parameter estimates, robust standard error, Wald χ^2 values and significance for the effect of trimmed by beaver and distance to relative minimum water level upon the chance of survival to September 2012 for willow cuttings planted at sites in Manitoba.

Parameter	Estimate	Std. Error	Wald χ^2	*P*
trimmed by beaver				
yes	.366	.695	.278	.598
no	0			
relative distance to minimum water level	-.025	.0046	30.544	.000

4.1.2 Chance of Cutting Survival

Mean proportion of cuttings surviving fell from 96.2±0.09% in July to 69.1±0.63% by mid-September. Mean percent surviving in upper rows was 34.1±1.0%, while 69.65±1.3% of cuttings planted at the lower elevations were alive by mid September.

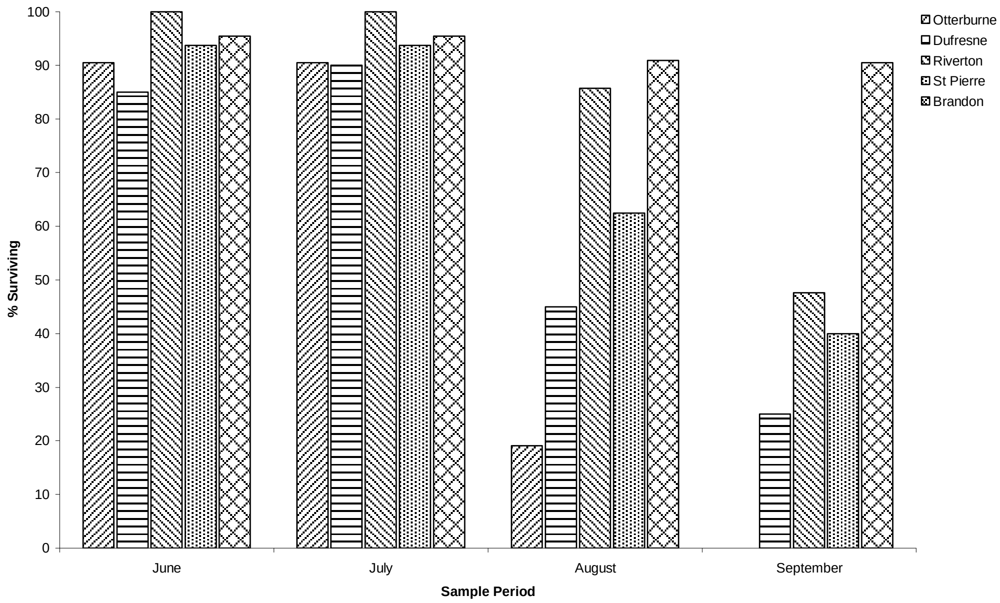

Figure 10 Bar chart showing proportion of willow cuttings surviving at each site along the upper row at each monthly visit during 2012. A total of 20 dormant cuttings, were planted in each row at each site in November 2011 with half trimmed to 25cm and half trimmed to 100cm from ground to top of cutting.

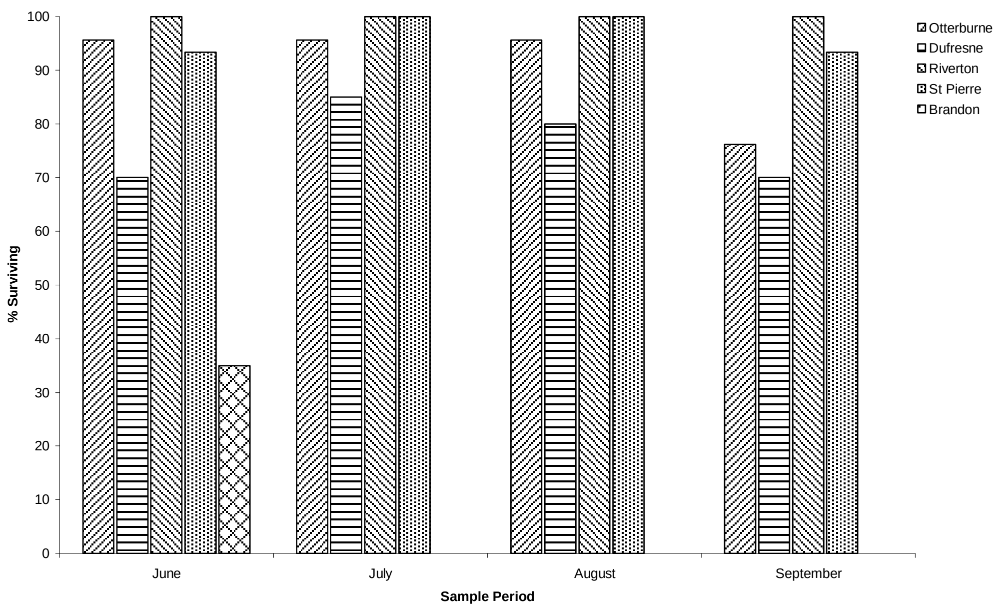

Figure 11 Bar chart showing proportion of willow cuttings surviving at each site along the lower row of planting at each monthly visit during 2012. A total of 20 dormant cuttings, were planted in each row at each site in November 2011 with half trimmed to 25cm and half trimmed to 100cm from ground to top of cutting. All lower row cuttings at Brandon had been pulled from the ground by beaver by the July site visit.

The best fit of parameters to the variability of willow cutting survival was obtained from the vertical distance of planting location to August water table combined with number of shoots growing on the cutting in July. The effect of some parameters that could have potentially influenced survival e.g. precipitation and soil texture could not be included within the model because there were only a small number of sites and these parameters were constant at the site level.

Table 9 Comparison of fit for combinations of parameters using relative QIC_u to chance of survival for willow cuttings planted in fall 2011 at sites in Manitoba, September 2012.

Parameters	ΔQIC_u
distance to August water table + number of shoots, July shoot number	0
distance to August water table + cutting height	16.212
distance to August water table + cutting height + cutting diameter	17.581
distance to August water table	18.558
distance to August water table + animal browsing	21.012
Flooding extent + July shoot number	47.449

Table 10 Proportion of observed cutting mortality and survival to September 2012 correctly predicted from distance from August water table and cutting height for willow cuttings planted in fall 2011 at sites in Manitoba,. A chance of 0.69 was used as a cut off between of survival and mortality.

Site	% of Observed Mortality Correctly Predicted	% of Observed Survival Correctly Predicted	Mean % of Cutting Status Correctly Predicted by Model
All Sites	72.5	81.1	77.7
• Dufresne	100	55.6	79.5
• Riverton	72.7	80.0	78.0
• St Pierre	100	90.5	93.3
• Brandon	0.0	100	90.5
• Otterburne	92.3	83.3	88.6

Table 11 Parameter estimates, robust standard error, Wald χ^2 values and significance for the effect of distance from August water table and number shoots, July upon survival to September 2012 for willow cuttings planted in fall 2011 at sites in Manitoba.

Parameter	Estimate	Std. Error	Wald χ^2	Sig.
distance from August water table	-.032	.0039	68.683	<0.001
number of shoots, July	0.089	0.021	18.082	<0.001

4.1.3 Effect of Distance to Water Table

Distance of planting location above estimated water table ranged from 50cm to 205cm above August levels. Each 1cm increase in planting elevation above the water table reduced the mean chance of cutting survival by 2.7% (β=-0.027±0.0046, P<0.001). Planting cuttings no higher than 100cm above August water table gave a mean estimated probability of survival greater than 0.6 whilst planting cuttings at elevations approaching 200cm from water table reduced mean probability of survival to close to zero.

4.1.4 Effect of July Shoot Number upon Cutting Survival

Number of live shoots recorded upon individual cuttings in July ranged from 0 on dead cuttings, to 82 on the most vigorous. Mean number of shoots on cuttings in July was 16.78±1.15. Each unit increase in July live shoot number was estimated to increase the mean chance of cutting survival by 9.3%.

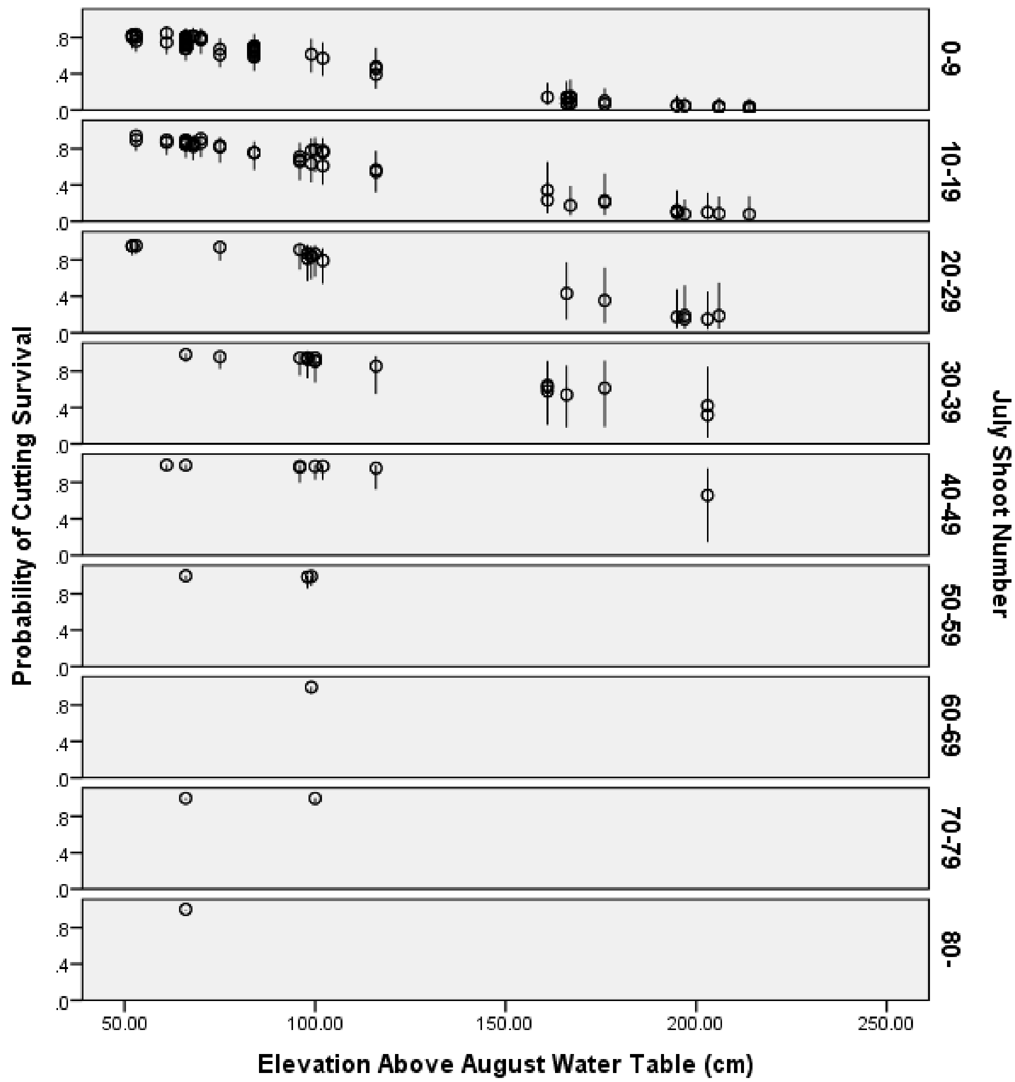

Figure 12 Scatter plot showing mean estimated probability of survival to September 2012 for willow cuttings planted at sites in Manitoba, fall 2011. 95% confidence limits shown. Survival declined with increased elevation of planting location above August water table (*P*<0.001). Cuttings that had produced greater numbers of shoots by July had increased probability of survival (*P*<0.001)

4.1.5 Number of Shoots on Live Cuttings

Mean number of shoots on surviving cuttings in July was 19.15±0.11 but had declined to a mean of 10.01±0.06 shoots per cutting in September. By September lower row cuttings had a mean of 10.58±0.07 shoots while those in the upper row had only 9.05±0.09 shoots per cutting. Mean ratio of shoots in July to shoots in September was 2.37±0.22, the least decline was at Brandon (1.71±0.37) the largest at St Pierre-Jolys (2.91±0.80).

The pattern of variation in number of shoots on cuttings in July was best fit by a model containing cutting height and relative distance to maximum water level. The model was unable to provide an accurate estimation of the number of shoots on the one cutting at Dufresne that had been trimmed short by beaver, estimating five times more shoots than actually observed.

4.1.6 Effect of Cutting Height upon Number of Shoots

Heights of surviving cuttings ranged from 0.5cm to 100cm with a mean height of 40.73 ± 2.54cm. Density of shoots (no. of shoots cm^{-1}) declined as cuttings increased in height up to 25cm. Cuttings at 25cm and 100cm had a similar number of shoots per cm. The model estimated that the number of shoots on live willow cuttings in both July and September would increase by 1.5% for each 1cm increase in the height of cuttings used ($\beta = 0.015 \pm 0.0014$, $P<0.001$).

4.1.7 Effect of Water Level upon Number of Shoots

High water levels of 2012 had a very small negative impact ($\beta=-0.001$, $P=0.034$) upon the number of shoots produced by the cuttings by July. The model estimated that for each 1cm increase in maximum water level the number of shoots produced would reduce by 0.1%.

The distance of the cutting above August water table had a negative impact upon the number of shoots remaining on the cuttings by September ($\beta= 0.007$, $P= 0.001$); each 1cm increase in distance to water table would cause the decline in number of shoots on a cutting from July to September to grow by 0.7%.

Table 12 Comparison of fit using relative QIC_u for combinations of parameters to number of shoots on live willow cuttings in July.

Parameter	ΔQIC_u
relative maximum water level & cutting height	0
cutting height	2.465
relative maximum water level	3.346
relative minimum water level	6.023
relative maximum water level, cutting height & relative maximum water level by cutting height	7.302

Table 13 Parameter estimate, robust standard error and significance for the effect of cutting height and relative maximum water level upon number of shoots upon live willow cuttings, July.

Parameter	Estimate	Std. Error	Wald χ^2	Sig.
cutting height	.015	.001	217.254	<0.001
relative maximum water level	-.001	<0.001	4.471	0.034

Table 14 Comparison of fit using relative QIC_u for combinations of parameters to number of shoots upon live willow cuttings, September.

Parameter	ΔQIC_u
cutting height	0
diameter & cutting height	2.969
distance to min. water level, cutting height, diameter	3.264
absence of grazing, cutting height, diameter, soil water content	4.308
absence of grazing, cutting height, diameter	4.613
soil water content, cutting height, diameter	4.953
distance to min. water level, cutting height, diameter, soil water content	5.260

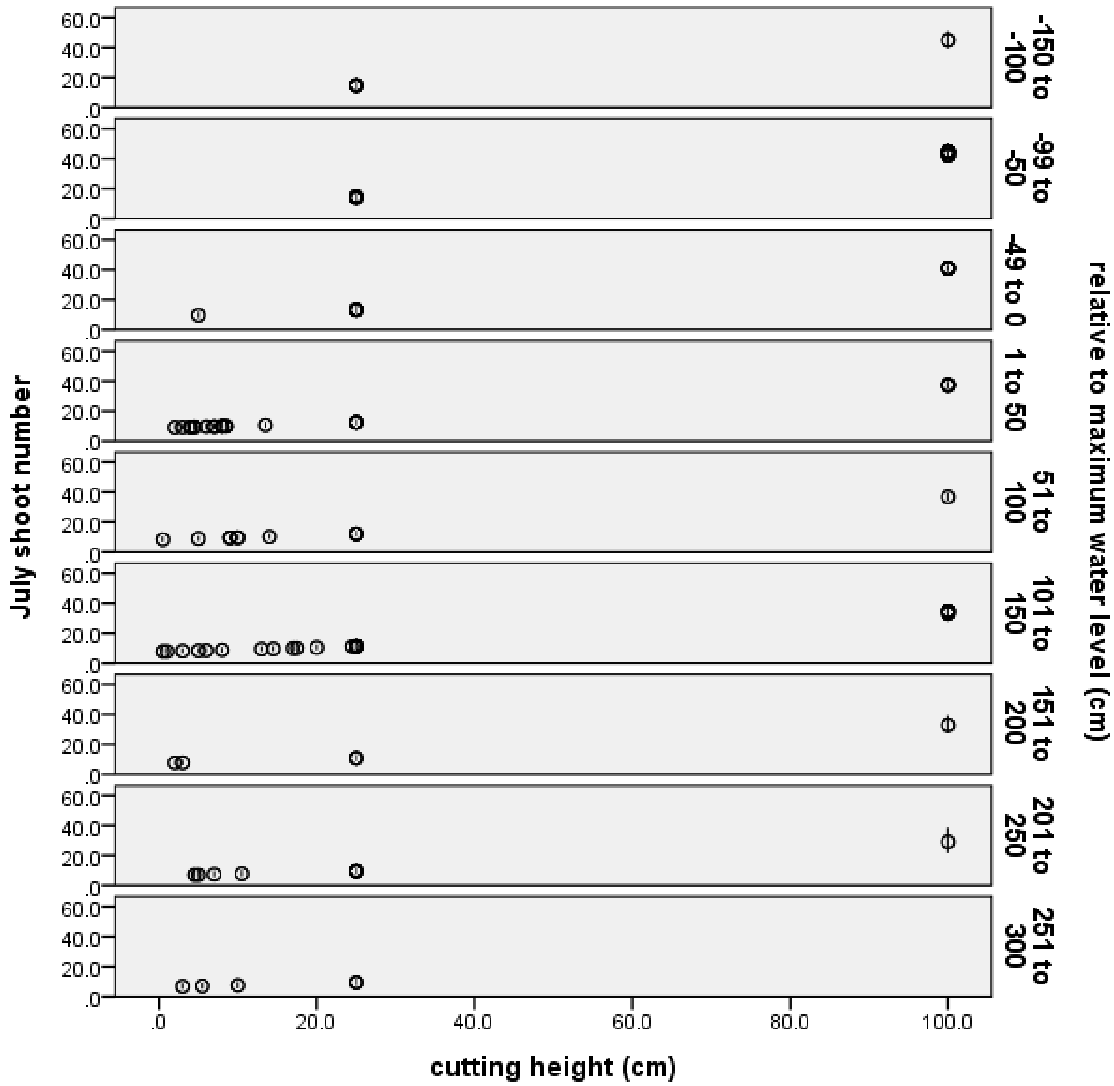

Figure 13 Scatter plot of mean estimated number of shoots in July 2012 for willow cuttings planted in Manitoba, fall 2011. 95% confidence limits shown. Estimated number of shoots on cuttings increases with height of cutting. Increasing relative maximum water levels has a negative effect upon number of shoots.

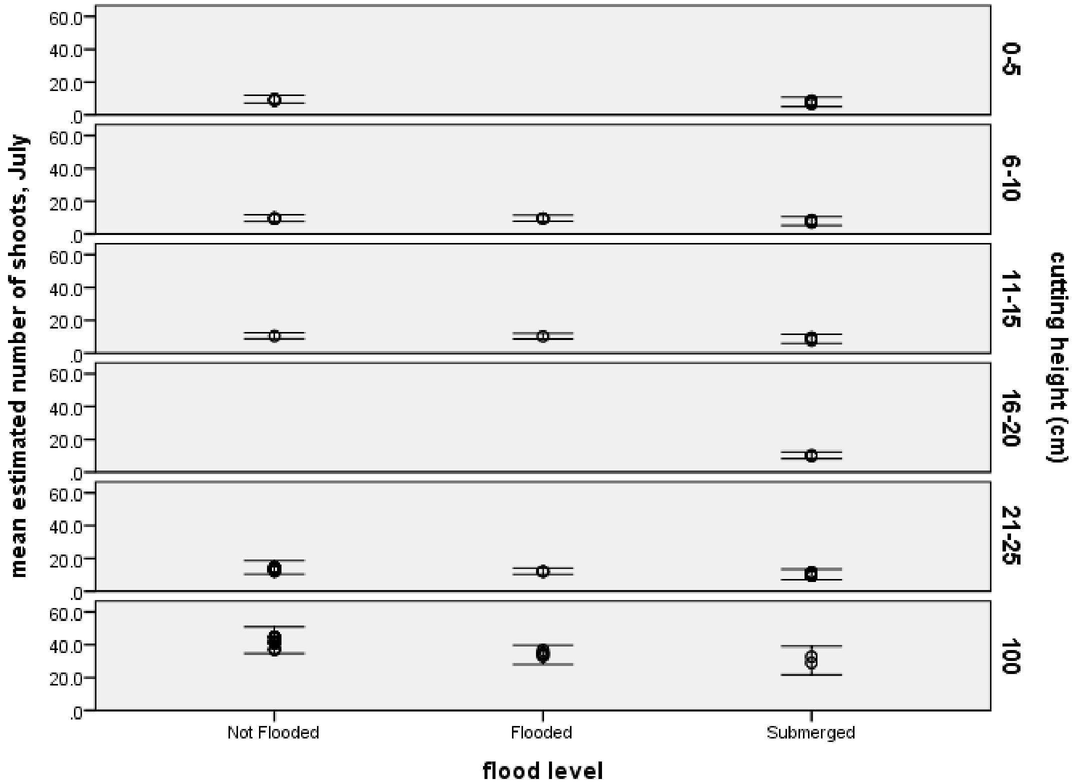

Figure 14 Scatter plot of mean estimated number of shoots in July 2012 for willow cuttings planted in Manitoba, fall 2011. 95% confidence limits shown. Estimates are shown for differing levels of inundation.

Table 15 Parameter estimate, robust standard error and significance for the effect of cutting height upon number of shoots in September 2012 on willow cuttings planted fall 2011.

Parameter	Estimate	Std. Error	Wald χ^2	P
cutting height	.016	.001	477.269	<0.001

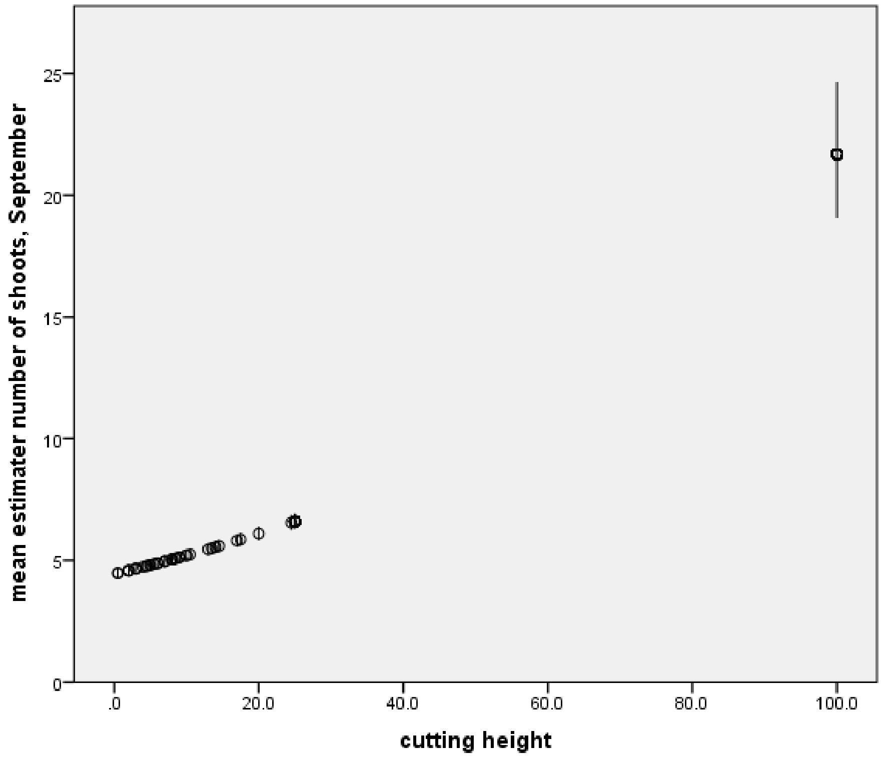

Figure 15 Scatter plot of mean estimated number of shoots in September 2012 for willow cuttings planted in Manitoba 2011. 95% confidence limits shown. Mean number of shoots on live cuttings in September increases with cutting height.

4.1.8 Maximum Shoot Length on Cuttings

The maximum shoot length recorded on any of the cutting still living in September was 107cm, though the overall mean of maximum shoot length was 43.0±0.14cm. Shoots on cuttings in upper rows had a mean maximum length of 40.3±0.22 cm and mean maximum length of shoots upon lower row cuttings was 45.4±0.18 cm.

Proportion of vegetative ground cover and relative distance to minimum water level were the best fit to the variation in maximum shoot length (Table 16). The model including relative minimum water level and vegetation cover had the lowest value of QIC_u and the model residuals were found to offer the best fit of predicted to observed data across all sites.

4.1.9 Effect of Vegetation Cover

Maximum shoot length was found to vary with the amount of plant cover. Maximum shoot length was significantly greater (*P*=0.006) in areas with a 75% plant cover than for areas with a 95% plant cover. Cuttings planted in areas with 50% cover had significantly longer maximum shoots than cuttings surrounded by only 5% vegetation.

Table 16 Comparison of fit using relative QIC_u for combinations of parameters to maximum shoot length (MSL), September 2012 for live willow cuttings in planted in fall 2011, Manitoba.

Parameters in Model	ΔQIC_u
plant cover & relative min. water level	0
relative max. water level & soil water content	10.665
relative max. water level	10.994
relative min. water level & soil water content	11.702
soil water content, relative max. water level & cutting height	11.726
cutting height & diameter	12.134
relative max. water level & relative min. water level	13.091

Table 17 Parameter estimates, robust standard errors and significance for the effect of relative minimum water level & density of plant cover upon maximum shoot length, September 2012 for live willow cuttings planted in fall 2011, Manitoba,.

Parameter	Estimate	Std. Error	Wald χ^2	Sig.
Level of Plant Cover				
95	.176	.2661	.440	.507
75	.834	.3054	7.465	.006
50	.420	.1392	9.086	.003
25	.212	.1081	3.839	.050
5	0			
distance to relative minimum water level	-.006	.0030	3.397	.065

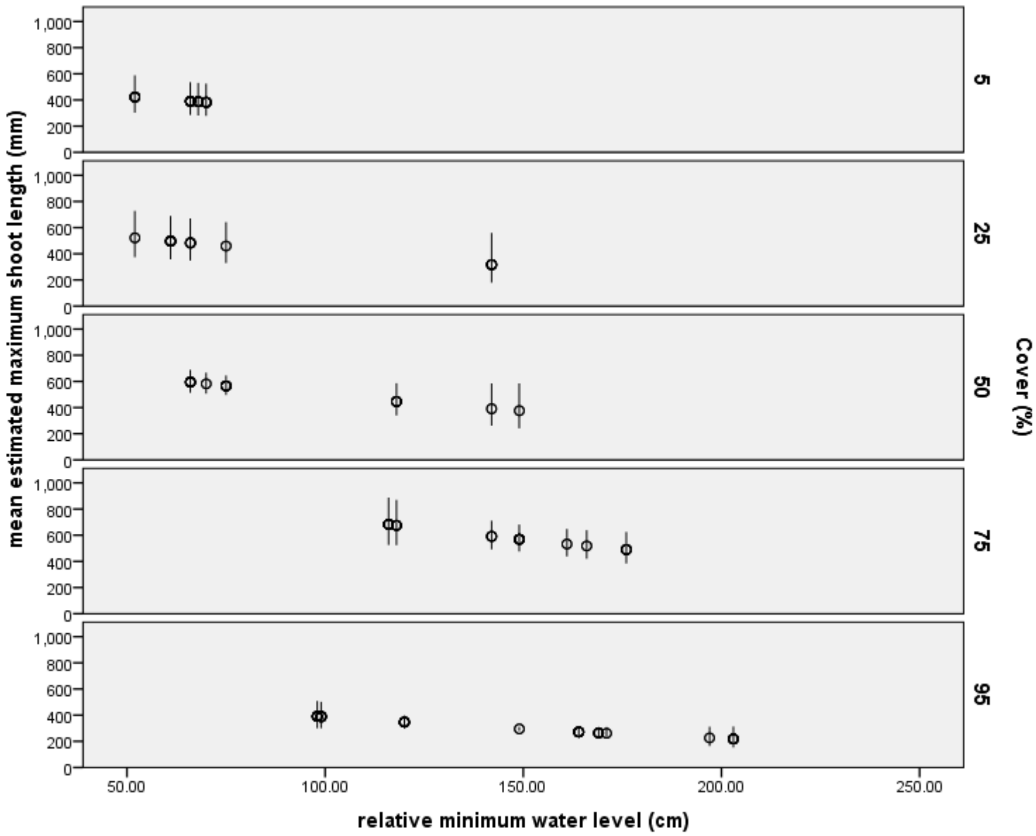

Figure 16 Scatter plot of mean estimated maximum shoot length, September 2012 for willow cuttings planted in fall 2011, Manitoba. 95% confidence limits shown. Effect of increased planting distance above minimum water level upon maximum shoot length on first year willow cuttings was not significant (*P*=0.065). Cuttings in areas of intermediate of vegetation cover had greater maximum shoot length than those planted in very low or high levels of plant cover.

4.2 Review of Bioengineering Projects and Techniques

4.2.1 Pembina River, Killarney

Willow bundles that had not been covered by erosion control blanket were removed by beaver. More than 90% of the remaining bundles and live stakes showed good survival and growth but the longest shoots were repeatedly cut back by browsing animals. Water level was retained by a beaver dam downstream of the site. Sampling found loam soils at Killarney with high organic matter content. There was some soil slumping beneath the erosion blanket at the downstream end of the site in an area that had not been planted with stakes.

Plate 7 Shoots from vertical willow cutting bundle emerging through erosion blanket at Killarney, July 2012

4.2.2 Joubert Creek, St. Pierre-Jolys

Snow was still present at this site in late May 2012 and covered a third of the cuttings that had been planted in fall 2011. By late September cutting survival was below the 60% target, even at lower elevations, and declined noticeably with increased distance above minimum water level. Survival of the vertical bundles was also low with no bundle exceeding the target value of 10 live shoots per visible by the end of September.

Soil texture varied widely within the site. There were areas of sand, silt and clay within the stream bank. Soil at low bank elevations had a higher clay content. Soil moisture varied with soil texture as well as decreasing with increased elevation above low water level.

4.2.3 Rat River, St. Malo Lake

The horizontal willow bundles were completely inundated from when the lake thawed until June when water levels began to recede. Bundles at one end of the site had been damaged by human activity due to the location at a picnic site and boat launch. Spring planted bundles had more and longer shoots than those planted in the fall of the preceding year. Loose soil that had originally been placed on top of the bundles was no longer present leaving the bundles of cuttings exposed. Small roots (approx. 3cm long) were initially visible on some of the spring planted willows but these had disappeared by the following site visit. The majority of the new shoots died as water levels receded later in the summer. Few stems survived to the fall so that differences between spring and fall planted bundles were considerably reduced. Bundles that had been damaged by humans or beaver required re-securing to prevent the remaining material from being lost.

Plate 8 Growth on horizontal willow cutting bundles at St Malo bioengineering project, July 2012. By September more than half of the new shoots had died.

4.2.4 Little Saskatchewan River, Minnedosa

The lower part of the Minnedosa site was submerged by high water levels from spring until August 2012. The woven willow spiling was submerged completely and the lower cuttings were flooded to above the root crown. Cutting survival was lowest in the area that had been flooded though still exceeded 50%. Above the level of summer flooding approximately 95% of cuttings were surviving in September. High water levels had also prevented grass from establishing in the flooded zone.

The uppermost rows of willow spiling had been removed from the spiling by beaver at some point between construction and the first site visit of 2012. When the spiling emerged from the flood waters in August small numbers of live shoots were visible from only the upper rows of the remaining spiling. Normally all parts of the spiling structure would have been expected to grow.

Plate 9 Minnedosa bioengineering project immediately after construction in November 2011, showing woven willow spiling at bank toe and coir erosion blanket covering slope

Plate 10 Minnedosa bioengineering in September 2012 showing damage to spiling by beaver leaving bare coir blanket. The live and dead willow cuttings at bottom of slope can also be seen.

4.2.5 Icelandic River, Riverton

Survival and growth of individual willow cuttings was highest (>75%) close to water level, but was less than 25% for cuttings more than 1m above minimum water level. All willow bundles developed numbers of new shoots In a number of cases maximum shoot length exceeded 100cm by late September 2012. Water levels at Riverton did not follow the same pattern as at other sites in this study. They are determined by levels in Lake Winnipeg so tend to rise slightly during the summer as lake levels increase, fluctuating according to wind direction, before declining again in the fall. Soil around the willow bundles remained in place around the cuttings. Wire holding the bundles of inert willow at the toe had loosened or broken, requiring replacement before the next winter.

Plate 11 Riverton bioengineering project, shortly after installation in November 2011, showing inert bundles at 90° to bank toe placed to absorb wave energy

Plate 12 New shoots produced by willow bundles at Riverton grew to > 100cm during 2012.

Table 18 Negative effects observed at each bioengineering project and whether proportion of willows surviving was greater than 60%

Site	Acceptable Survival	Observed Impacts: Lost willow material	Animal browsing	Other physical damage	Slumped soil	Lost Substrate
Pembina River, Killarney	Y	Y	Y	N	Y	N
Joubert Creek, St. Pierre-Jolys	N	N	N	Y	N	Y
Rat River, Lake St. Malo	N	Y	Y	Y	N	Y
Lt. Saskatchewan River, Minnedosa	Y	Y	Y	N	N	N
Icelandic River, Riverton	Y	N	N	Y	N	N

5 Discussion

5.1 Survival and Growth of Sandbar Willow Cuttings

5.1.1 Effect of Water Level

The objective of this thesis had been to focus upon the negative effect of flooding: instead, I found that drought had a much greater impact upon the willows. The negative effect of low water levels limited the likelihood of cutting survival and negatively impacted growth.

There is a substantial body of evidence that many species of willow are able to flourish despite extended flooding, particularly during the dormancy phase. More than a month of submersion may be required before the most resilient willow species are impacted (Hosner 1958, Good *et al*. 1992). The local distribution of many riparian willow species is dependant upon their ability to withstand longer periods of flooding (Francis *et al*. 2006, Nakai & Kisanuki 2007), so given the limited period of high water occurring in 2012, sandbar willow, *S. interior*, would not have experienced flooding long enough to have a negative impact upon survival. For example, willow cuttings at Riverton completely escaped inundation during 2012, whilst at other sites only willows planted at the base of the bank were flooded and then for only a few days.

Compared to cuttings that were not flooded, full submersion had a negative effect upon the number of shoots produced. Two potential mechanisms may be responsible for this, but data establishing the contribution that each may have made to the reduction in number of shoots was not collected as part of this thesis. Flooding of dormant willow cuttings in spring will break dormancy and stimulate growth. When sandbar willow cuttings are soaked for several days they produce large numbers of adventitious roots from the stem below the water surface (Kuzovkhina et al 2004, Tilley & Hoag 2008). The production of adventitious roots enables branches, and even whole trees, torn free by flood water to colonise areas of stream banks that would otherwise be unsuitable for seedlings (Densmore & Zasada 1978, Francis *et al.* 2006); however, the hormones that initiated root formation, principally ethylene and auxins, also suppress the production of lateral shoots and may have been sufficient to negatively impact the number of shoots developed (Davies 1987).

Flooding may also directly impact the formation of new shoots or cause pre-existing shoots to rot due to lack of oxygen and increased concentration of toxic chemicals (Good *et al.* 1992, Talbot *et al.* 1987). How this impacts dormant cuttings is not clear; in previous studies, such as those by Kuzovkhina *et al.* (2004) and Talent-Halsall and Walker (2002), cuttings have been allowed to develop roots and shoots before being flooded. Further investigations using dormant cuttings and more precisely controlled water levels are required to reveal how inundation and shoot emergence are linked.

Each of the sites in this study experienced a pattern of flooding and drought unique to its watershed and local topography, but common to all sites, cuttings planted in the lower rows would have had greater exposure to periods of high water and, more importantly it seems, would have been less subject to moisture stress later in the year when rainfall declined. When soil moisture levels were consistent across elevations Schaff *et al*. (2003) found no significant relationship between elevation and cutting survival. In this study I found only the lowest elevations above minimum water levels had sufficient water available for cutting survival later in the growing season. Studies of natural recruitment have found that seedling and cutting survival is greater at lower stream bank elevations. Water table decline is the dominant source of willow seedling mortality (Karrenberg *et al*. 2002) and *S. interior* is more sensitive to rapid water table decline than some other willows (Amlin & Rood 2001). Vegetative fragments of willow deposited at lower elevations along sand bars are more likely to survive than those higher up where distance to water is greater (Francis 2007, Nakai & Kisanuki 2007).

Planting closer to minimum water levels also mitigated against the loss of shoots between July and September. The sufficiency of soil water at the lower elevations would have enabled cuttings to allocate resources to shoot growth rather than to extending roots downward to seek water (Amlin & Rood 2001, Li *et al*. 2005). The elevation above minimum water level where optimal growth occurs will vary due to site conditions and climate. Cuttings at lowest elevations may be subject to poorly aerated soils due to continuous saturation (Schaff *et al.* 2005, Watson *et al.* 1997); however, if planted higher up drought may negatively impact growth and as found in this study, the risk of planting failure will be much more likely (Francis 2007, Pezeshki *et al.* 2007, Sacchi & Price 1992).

Radtke *et al.* (2011) noted a decline over a period of eight weeks in number of shoots on first year willow cuttings and concluded that competition for light lead to more shoots being lost, although did not include the effect of declining water level. The decline in number of shoots recorded on cuttings between July and September may be evidence of an adaptive response by sand bar willows to drought. Rood *et al.* (2000) suggest that the loss of branches by poplar trees during drought was “branch sacrifice” to prevent the whole tree from succumbing to the effects of water scarcity. Newly formed shoots are small in diameter so would be vulnerable to air pockets (cavitation) within the xylem. By dropping shoots transpiration rates would be reduced in response to reduced water availability.

Differences between flooding tolerance of various willow species will also affect the position for optimal planting, so that lack of availability of cuttings from suitable willow species may impact project success. *S. nigra* has been described as more tolerant of waterlogged soil than *S. exigua* used in the current study, though both are riparian willows and more resilient to flooding rather than more generalist species such as *S. discolor* (Karrenberg 1992, Amlin & Rood 2001).

5.1.2 Effect of cutting height

Two heights of willow cuttings were originally planted in this study, although a proportion of the cuttings were reduced in length by beavers soon before the start of measurement. The objective was to determine whether taller cuttings were more resistant to flooding. I did not find that increased cutting height had an effect upon survival; nevertheless increased cutting height did have a positive effect on the number of shoots being produced by cuttings across all water levels.

Guides to willow planting widely suggest that, to prevent desiccation and maximise survival, no more than one third of the cutting should be left exposed to the air (Platts *et al.* 1987, Sotir & Fischenish 2001) so that empirical studies of the effect of increasing cutting height are rare.

Large willow cuttings planted into perennially wet grassland grew well even with only 15% of their length inserted into the soil (Stolarski *et al.* 2011); however, no studies of willows have been identified that attempted to make comparisons as to how well cuttings of different heights perform under similar conditions. A study into the use of poplar cuttings by DesRochers *et al.* (2004) found that tall (>30cm) cuttings had significantly better survival than those with only 1 or 2cm above ground.

I did not identify the mechanism behind the increase in shoot numbers. It may simply be that taller cuttings have a greater number of buds available than short cuttings. Verwijst *et al.* (2012) found that in addition to being correlated with length, number of shoots was correlated with cutting diameter and also clonal type. Length of the cutting may contribute to cutting performance but this study found that height was key to how many shoots were produced. Taller cuttings may also be more vigorous because photosynthesis occurs in stem as well as leaf tissue, so taller cuttings have more opportunity to build carbohydrate reserves prior to buds emerging (Aschan & Pfanz 2002).

Cuttings with more shoots had a greater chance of survival. Increased cutting length is thought to improve the probability of survival because a larger pool of carbohydrates would improve the capacity for survival (Francis 2007, Verwijst *et al.* 2012), so it is likely that increased shoot number benefits survival in the same way. The leaf area from the additional shoots on tall cuttings would enable more rapid replacement of carbohydrate reserves used during root development.

5.1.3 Vegetation Cover

This study revealed significant differences in maximum shoot length (MSL) amongst willow cuttings growing in areas with different densities of surrounding vegetation. Interaction with neighbouring vegetation negatively affects willow cutting growth (Garau *et al*. 2008). Plant cover immediately around newly planted cuttings and seedlings is generally regarded as having a negative effect on growth due to competition for resources (Davies 1985, Labreque *et al*., 1993, Welham *et al*. 2007). Where below ground resources, such as water, are not limiting, access to light and space will be the main source of competition (Sage 1999, Radtke *et al.* 2011). Willows are typical of shade-avoidant plants that respond to competition for light through stem elongation and reduction in branching (Vandenbussche *et al*. 2005). Shade may result in a reduction in overall biomass, but coppiced willows grew taller shoots when surrounded by grasses and herbs (Sage 1999). Even where surrounding vegetation does not overshadow the cutting, changes to the wavelength of reflected light can be sufficient to stimulate the competition response (Vandenbussche *et al*. 2005). This study found that planting willows in areas of medium density ground cover had a significant positive effect on MSL compared to full ground cover. The highest levels of plant cover were found at the upper elevations along the stream bank, so that competition would have been mainly for water, particularly later in the summer when water levels are very low.

The explanation of the negative effects of low vegetation densities is more difficult to determine. Where there were even fewer plants surrounding the cuttings MSL should have increased due to the lack of competition for resources (Radtke *et al.* 2011); instead, MSL declined with decreasing vegetation density. Surrounding vegetation can also create benefits for newly established plants such as increased humidity, reduced evaporation from the soil surface and protection from herbivores (Berkowitz *et al*. 1995, Connell & Slatyer 1977, Holmgren 2000). Willow seedlings are extremely vulnerable to high temperatures on exposed areas of bare soil and this may also be the case for cuttings (Sacchi and Price 1992).

A more likely explanation for the observed reduction in growth may be that density of cover is a proxy for the effects of flooding. Stream bank vegetation reflects the frequency and scale of the disturbance caused by episodes of high water level (Dixon 2003, Francis *et al.* 2007). The depth and duration of flooding experienced creates progressively less favourable conditions for long term establishment of terrestrial plants from high to low elevation (Kozlowski 1984). Shoots did not emerge from the flooded willows until water levels had receded. Willow cuttings in the areas of bare soil would have likely experienced the longest level of flooding. This would have delayed the onset of shoot production, limited the length of the growing season and reduced the opportunity to replenish carbohydrate reserves.

There was no evidence that the high water levels encountered resulted in increased mortality during the first growing season; however, duration of flooding was shorter in 2012 than normally experienced. It is possible that very long periods of flooding would reduce survival. Talent-Halsall & Walker (2002) described mortality rates over 80% for *Salix goodingii* cuttings submerged for a month, although, their study used rooted cuttings and took place in a much warmer climate. Where temperatures remain low enough to maintain dormancy there seems to be no negative effects from submersion of unrooted cuttings (Tilley & Hoag 2008).

The reduction in growth may also have implications for longer term survival of willow cuttings at the lowest elevations. These cuttings may not develop sufficient carbohydrate reserves to enable over winter survival and to initiate new growth in the following spring.

5.1.4 The effect of beaver cutting

Beaver are naturally distributed across all of North America and may potentially be found wherever there is a suitable food and habitat. They are often regarded by ecologists as having a mutually beneficial relationship with riparian willows, maintaining the health of natural stands and increasing overall productivity (Peinetti *et al.* 2009). Despite the effect this species has upon riparian woody species it has not been investigated in relation to bioengineering. This is likely due to its absence from areas where bioengineering was widely practised. The Eurasian beaver (*Castor fiber*) became extinct in the UK in the 16th century while in Europe the population was reduced to only 1200 pairs (Nolet & Rosell 1998). North American beaver (*Castor canadensis*) were also widely extirpated from many local ecosystems in North America so that it may have not been present in areas where bioengineering was re-introduced. Where beaver are still present they are often poorly tolerated (Hood 2011), so that any beaver would probably have been killed before any impact to the willow structures was felt.

Cuttings at four of the five sites in this study showed evidence of being trimmed by beaver between planting in the fall of 2011 and first site visit in 2012. All of the lower row cuttings at Brandon were completely removed before shooting commenced; all but one of the upper row cuttings were cut close to ground level. Beaver had a preference for tall cuttings, probably because of their greater food value. Because the same effort was required to cut the taller cuttings they represent greatest energy intake for least feeding time (Schroener 1979 in Jenkins 1980).

Beaver harvested willow from the planting sites during the period of spring flooding when they are closer to refuge from predation (Gerwing *et al.* 2013). In areas where the supply of willows is limited they may be more prepared to forage further from the water's edge to obtain the tall cuttings, but data on the presence of nearby willows was not gathered as part of this study. Sites lacking in riparian woody vegetation are often selected for bioengineering treatment, this could make beaver herbivory more likely as the only willows present are the new planting. All of the sites studied had previously been subject to clearance or grazing that had removed riparian willows.

I found no evidence to support a hypothesis that beaver browsing reduced the probability of cutting survival; there was no difference in number of shoots on trimmed and un-trimmed cuttings. Willows quickly recover following early season stem removal similar to the type encountered in this study (Kindschy 1989). Animal browsing during the growing season has been shown to harm willow cuttings (Li *et al*. 1985); in contrast, I did not identify the presence of browsing damage as an important factor in determining cutting performance. This could have been due to the low intensity of the browsing. Browsing was usually selective, taking only some of the shoots present on each cutting.

From a practical viewpoint if beaver cannot be prevented from trimming the new cuttings it reduces the potential to use tall cuttings and effort directed at planting longer material may be better targeted at increasing the overall number of cuttings planted.

5.1.5 Effect of Soil Texture

Soil texture has been found previously to have significant effect upon cutting survival (Martin & Stephenson 2006, Schaff *et al.* 2003, Pezeshki *et al.* 2007), but because soils were strongly correlated to site, the effect of soil texture upon cutting performance could not be quantified in this thesis (Hardin & Hilbe 2003). The earlier investigations into the factors affecting willow cutting survival have often produced different conclusions. Schaff *et al.* (2003) found increased survival and better growth in the most coarsely textured soil while Pezeshki *et al.* (2007) concluded that there was significantly lower survival for “coarse” compared to “fine” and “medium” soils and Radtke *et al.* (2011) found cuttings grew more vigorously on finer loam soils than on coarser sand. Francis *et al.* (2006) found that, although *Salix* seedlings grew more vigorously on sandy soils, soil type had no overall effect upon cutting performance. Soils with a very high proportion of sand have improved percolation, ensuring that rainfall reaches root systems, but coarse particle size reduces water retention and also reduces the distance that water is drawn up through the soil profile from the water table. Fine textured soils hold more water than coarse soils, but due to the effects of surface tension a greater proportion of that water is held too strongly for plants to access; the cuttings begin to wilt even when soil moisture levels appear sufficient to sustain growth (Brady & Weil 2008, Martin & Stephenson 2006).

By limiting the ability of the cutting to access resources soil texture has also been found to affect the number of shoots found on cuttings (Schaff *et al.* 2003) with more than double the number of shoots on cuttings grown in "coarse" soils compared to "fine".

At Dufresne, Otterburne and Riverton soils were too hard by August to collect sample cores and by September could not be sampled with the Hydraprobe. Gas transfer is mostly dependent upon the presence of large pores found in aggregated or coarsely textured soil (Kozlowski 1999). Even in soils with 37% sand, anoxic conditions can develop in saturated soils, restricting willow root development below 0.6m. (Pezeshki *et al.* 2007) The low levels of sand (<20%) found at the sites in this study with clay soils are likely to have had an even greater effect upon soil aeration. Riparian soils with a high percentage of clay are extremely prone to slumping when saturated with water, so that the soil structure would have been poorly suited to cutting establishment (Kozlowski 1999). As these clay soils dry they compact and become too hard for roots to penetrate, slowing or even preventing the development of effective root systems.

Hardened and compacted clay soils also prevent water from moving freely through the soil matrix. (Taylor & Brar 1991, Whalley *et al.* 1995). Rainfall penetration is much slower and often confined to surface cracks so that on steeply sloping stream banks rainfall will have very little effect on soil water levels (Kozlowski 1999). The soil at Riverton and Otterburne were both predominantly clay, but the soils at Riverton site incorporated far greater amounts of stones than found at other sites. Stones increase hydraulic conductivity and limit soil compaction (Chow *et al.* 2007). Both these properties would have the penetration of rainfall in July at Riverton beyond the surface layers more quickly than had the soil been of a more uniform texture.

5.2 Review of Survival and Growth Willows used in Bioengineering Projects

5.2.1 The Effect of Local Conditions upon Survival and Growth

Water levels at each site played a noticeable role in how well bioengineering performed at each site. Despite being inundated for approximately three months (from May until the end of July) at Minnedosa willow cutting survival in the flooded area remained above 60%, high enough to be considered successful (Schiechtl & Stern 1996). For most of the flooding duration the willows were within 10-20cm of the water surface so light and oxygen levels may have been sufficient to maintain life (Armstrong & Armstrong 2005). A greater depth of water, increased turbidity or stagnant water would all likely have resulted in a higher mortality rate (Good 1992, Kozlowski 2002).

At both St Malo and Riverton the bioengineering was submerged by 10-15cm of water early in the summer; however, at St Malo water levels declined rapidly from mid-summer onwards leaving bundles perched above the water table. As water levels fell, willow cuttings were unable to develop roots sufficiently quickly to prevent them from drying out (Amlin & Rood 2002).

Accumulated snow in the shaded areas of St Pierre-Jolys would have created a localised micro-climate, keeping air and soil temperatures low enough to prevent shoots from emerging. Delayed onset of growth would reduce the ability of the cuttings to take to take advantage of optimum growing conditions such as higher soil moisture early in the summer (Sennerby-Forsse 1986).

Differences in soil texture between sites would have also contributed to variation in performance, modifying the ability of the willows to develop a root system capable of accessing both water and nutrients. The lower end of the bundles were placed close to minimum water levels, but clay soils at lower elevations of St Pierre-Jolys compared to the loam at Killarney would have formed a barrier to root development (Kozlowski 1999). Martin & Stephenson (2006) found that, compared to *S. viminalis* growing in sandy loam soil, cuttings planted on Oxford clay were unable to develop a root system capable of taking up sufficient nutrients for shoot growth.

Compared to hard engineering, soils play a dual role, both providing mass and form to the engineering, but also providing a growing medium for the plant material that ultimately determines the success of the project. Loss of soil from around bioengineering during establishment has been identified as a common reason for failure (Anstead & Boar 2010, Karle 2005), although Schiecthl and Stern (1996) note that planning for erosion control projects should always allow for the need to make repairs and adjustments during the first year after installation. Loss of back fill from willow spiling (used at Minnedosa) in the UK accounted for failure at a 3 of 15 sites assessed between 1989 and 2009 (Anstead & Boar 2010). This did not happen at Minnedosa, despite extended high flows, so suggests that the addition of coir blanket behind the willows prevented this from occurring.

Differences were seen in how easily soil of different textures was washed from between the cuttings. Soil along the shoreline at St Malo was a mixture of sand and gravel, while at Riverton it was predominately clay and much more cohesive, so at Riverton was less susceptible to being washed from the bundles.

Willows at Killarney were subject to greater levels of browsing than other sites although this did not appear to be impacting survival. Compared to studies using simulated browsing, for example those by Li *et al.* (2005) and Kindschy (1989) where all shoots were cut back, the browsing appeared to target the largest of the new shoots. Deer are very selective in how they browse young trees and may target longer shoots due to their higher nutrient value or because they prefer to feed on shoots closer to head height (Gill 1992).

There was no evidence that beaver browsing reduced survival of individual cuttings, but beaver damage had strongly negative impacts at bioengineering sites. As well as removing large amounts of living material, browsing is likely to have reduced the strengths of the engineering by loosening the formerly secure structures. It was not possible to tell whether the bindings had been cut by beaver or broken during the act of material removal. Securing with wire rather than natural cord would be considerably stronger but would not prevent beaver from cutting either side of the binding.

The bioengineering structures used longer cuttings, up to 2.5m long and 5cm basal diameter, than deployed in the cutting trials. This would have made them particularly desirable for food caching (Novarski 1967). Bundles were positioned at or just the normal water level surface making the live material more accessible to beavers. Woven willow cuttings at Minnedosa suffered damage exclusively along the upper edge. This would have normally been above water level, but would have been easily accessed when the willow was mostly submerged by flood water.

The risk of damage by beavers to new bioengineering projects may be affected by the timing of the works. Fall installation of bioengineering coincides with the time when beaver switch from a predominantly herbaceous diet to one concentrating on woody material (Brenner 1962 in Henker 2009, Kindschy 1985) to sustain colonies over the winter.

Wrapping bundles with coir erosion blanket at Killarney appeared to protect them from serious damage by beaver. This may suggest that beaver made an initial selection of food materials based on visual recognition of potential food items. It is possible to chemically deter beaver from eating valuable woody species, although this may only be effective if alternative food sources are available (Kimball & Perry 2008). In the United States a repellent, Ro-Pel™ containing the proprietary compound Bitrex™ is available to deter beaver and other rodent damage though this is not currently licensed for use in Canada.

From the slumping that was seen at Killarney it can be inferred that the density of willow cuttings used was inadequate to support the shear stresses experienced within the newly established bank profile. Collecting sufficient willow cuttings to meet the requirement of the technique used can often exceed the labour required for the installation (Schiechtl & Stern 1997). At Riverton, St Pierre-Jolys, St. Malo and Minnedosa a team of volunteer labour enabled large numbers of cuttings to be collected in only a couple of days but this assistance was not available at Killarney so that a much smaller quantity was collected.

5.2.2 Effect of Bioengineering Techniques upon Survival and Growth

5.2.2.1 Live Staking

Despite many of the cuttings being planted at low enough elevation that the base of the cutting would have been very close to or below late summer water table this did not, as is commonly stated (Bentrup & Hoag 1998, Rossi 1999), appear to increase the chance of survival. The benefit of deep planting is likely because deep staking requires that a longer cutting be used with larger reserves of carbohydrate rather than any increased proximity to the water table (Francis 2007, Verwijst *et al.* 2010). In fine textured soil aerobic conditions suitable for root growth may only be present close to the surface of the soil (Pezeshki *et al.* 2007), so that even though the base of the cuttings was close to the water table, cuttings at Riverton and St Pierre-Jolys were unable to develop an adequate root system.

The process of re-profiling the stream bank at Killarney and Minnedosa potentially contributed to the increased survival at higher bank elevations. Cuttings were planted into soil that had been mechanically disturbed in the process of recreating a more stable bank profile. Disturbance would have reduced competition from other vegetation (Vandenberghe *et al*. 2006) and would have reduced any natural compaction assisting both water and air movement through the soil (Martin & Stephens 2006, Whalley *et al.* 1995). At both sites erosion control blanket was used. Its primary purpose was preventing soil loss before vegetation became established, but it would also helped to maintain soil moisture and increased plant growth compared to bare soil (Davies 1985, Vishnudas *et al.* 2012).

5.2.2.2 Horizontal Bundles

Loss of substrate from around the bundles of horizontally laid cuttings was a problem on sandy soils exposed to wave action. For projects constructed in the fall this would have made the cuttings susceptible to drying out over the winter. Although willow cuttings may be successfully harvested and stored in “snow caches” over winter, care must be taken to avoid exposure to wind (Crowder 1995, Verwijst *et al*. 2010). Once temperatures rose in the spring loss of substrate would have limited opportunities for the cuttings to produce roots. Exposure to light prevents cuttings from developing roots even when submerged in water (Eliasson & Brunes 1980).

Survival and growth of the willows used to create the woven spiling at Minnedosa was very low indicating a pattern of flooding beyond the tolerance of the sandbar willows used (Good *et al.* 1992, Ohmann *et al.* 1990). Shoots emerged once water levels had declined and then only from the uppermost row of cuttings.. The willows in the upper rows were the last to be inundated and first to be exposed as water levels fell perhaps explaining why these willows survived. Close to the water surface, light and oxygen levels would have been sufficient to prevent decomposition during flooding, enabling cuttings to commence growth once water levels fell (Gill 1970, Good *et al.* 1992).

5.2.2.3 Vertical Bundles.

The primary purpose of using bundled willow cuttings buried vertically up the stream bank face is to increase the likelihood of cuttings surviving during prolonged high water levels; however, neither of the sites where this was used experienced extended flooding. Survival and number of stems produced by vertical bundles at Killarney was good whilst at St Pierre-Jolys bundles performed poorly. Soil moisture levels at the two sites were similar but loamy soil at Killarney would have allowed willows to develop a larger root system than the heavy clay soils at St. Pierre-Jolys.

6 Summary, Conclusions and Recommendations

6.1 Summary

The purpose of this thesis was to reveal the extent to which physical conditions in Manitoba limit the survival and growth of willows used in bioengineering to repair eroded shore lines and stream banks.

Sandbar willow cuttings, 25 and 100cm tall, were planted in fall 2011 along riparian areas at five locations across southern Manitoba. Measurements were made of survival and growth from May until September 2012 to determine the potential for using taller cuttings to reduce the negative effect of inundation during spring flooding upon survival and growth.

At the same time, bioengineering projects were designed and installed at five locations across the same geographical area using a range of techniques taken from the available literature. Survival and growth of sandbar willows used at each site were recorded and possible causes for failure to survive or grow were identified.

The performance of the bioengineering techniques used was reviewed and methods of failure were highlighted. Particular attention was paid to the effects of beaver browsing upon the bioengineering projects as this has not been previously described in bioengineering literature.

6.2 Conclusions

The study of planted willow cuttings did not show any reduction in cutting survival due to the effects of flooding in spring 2012; consequently, it was not possible to determine the potential for cutting height to mitigate the effects of flooding. Due to lower than average flows spring in 2012 the level of inundation was much less than had been anticipated and peak flows occurred earlier in the year than was typical.

Spring flooding had a negative effect upon number of shoots although the reason for this was not determined. No difference was found between the numbers of shoots on partly or fully submerged cuttings, but cuttings that were not flooded had more shoots. If flooding levels had had been higher or for longer the effect upon shoot number would have been more pronounced and could result in reduced survival.

Taller cuttings did produce more shoots than short cuttings; cuttings with more shoots had increased chance of survival. Cuttings with more shoots would have a greater rate of moisture loss, but this negative effect is outweighed by the benefits of increased photosynthetic surface area. The investigation also revealed, that whilst there may be potential to increase survival by using taller cuttings, where beaver are present these cuttings are unlikely to be left intact.

The review of bioengineering projects found that establishment can be greatly enhanced through use of companion materials. Adding a covering of erosion control blanket helped to retain substrate and also deterred beaver damage. Using rip-rap along the bank toe provides protection where willows cannot grow. The partnership of living and inert materials to improve effectiveness distinguishes bioengineering from simple riparian planting.

The willows used in all bioengineering techniques were found to survive and grow well when installed close to low water levels, but like simple cuttings, survival rates fell dramatically away from the stream. Horizontally laid willows may be particularly vulnerable to prolonged inundation during the growing season, so projects using this technique are best suited to lake shorelines where water levels may be less variable.

6.3 Recommendations

As a result of the findings of this thesis, to prevent cuttings from becoming desiccated, it is recommended that willow bioengineering projects are undertaken once water levels have receded sufficiently to enable planting close to minimum water level. In most cases this restricts the optimum window to the fall when water levels are most likely to have fully receded and source willows have once again entered dormancy. For some projects it may be possible to use large scale refrigeration to store spring harvested willow until water levels have receded, but this entails additional costs. The potential in southern Manitoba for storing willow cuttings in traditional snow caches would appear limited due to the risk that water levels may remain elevated for some time after temperatures have risen, preventing the material from being used.

Where rip rap is used for bank stabilization planting should occur concurrently to ensure cuttings can be planted close to minimum water levels, improving survival and overall benefits of the stabilization project.

Because this thesis was unable to fully address the effect of flooding on live willow cuttings, further research is required into the effect of reduced shoot numbers over successive growing seasons.

Techniques for ameliorating the negative impacts of low water level, such as solar or wind powered irrigation, should be explored to evaluate whether they can be cost effective for small bioengineering projects.

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Appendices

Appendix I. Willow Cutting Performance Data

Extent of Beaver Cutting

Table I-i Proportion of willow cuttings at each willow planting site trimmed short by beaver

Site	N	% of total number of cuttings trimmed
Brandon	28	96.4%
Dufresne	3	7.7%
Otterburne	29	65.9%
Riverton	0	0%
St Pierre	12	22.6%
Total	71	39.0%

Table I-ii Proportion of willow cuttings of each height and row trimmed short by beaver

Height	Row	Beaver Cut
S	Lower	5
	Upper	9
	Total	14
T	Lower	27
	Upper	31
	Total	58
Total	Lower	32
	Upper	40
	Total	72

Cutting Survival

Table I-iii Proportion of all cuttings surviving to end of growing season by row

Live?	Row	N	%
N	Lower	11	14.1%
	Upper	57	58.8%
	Total	68	38.9%
Y	Lower	67	85.9%
	Upper	40	41.2%
	Total	107	61.1%

Number of Shoots

Table I-iv Summary of number of shoots on all live cuttings at each willow planting site by row

Site	Row	Median	Minimum	Maximum
Brandon	Upper	5.00	2	11
	Total	5.00	2	11
Dufresne	Lower	8.00	2	34
	Upper	8.00	1	8
	Total	8.00	1	34
Otterburne	Lower	3.50	1	27
	Total	3.50	1	27
Riverton	Lower	14.50	2	32
	Upper	16.50	1	45
	Total	16.50	1	45
St Pierre	Lower	6.00	2	22
	Upper	7.00	1	15
	Total	6.00	1	22
Total	Lower	6.00	1	34
	Upper	6.50	1	45
	Total	6.00	1	45

Shoot Length

Table I-v Length (cm) of live shoots by site and row- all cuttings

Site	Row	Median	Minimum	Maximum	Mean	S. E. of Mean
Brandon	upper	15.00	0.50	107.00	25.50	2.60
	Total	15.00	0.50	107.00	25.50	2.60
Dufresne	lower	20.00	0.50	84.50	24.02	1.41
	upper	23.00	8.50	73.50	33.48	4.59
	Total	21.00	0.50	84.50	25.08	1.36
Otterburne	lower	11.00	0.50	82.00	16.10	1.67
	Total	11.00	0.50	82.00	16.10	1.67
Riverton	lower	13.00	0.50	75.50	16.50	0.71
	upper	10.00	0.50	51.00	11.83	0.62
	Total	11.50	0.50	75.50	14.82	0.51
St Pierre	lower	25.00	1.50	99.50	28.72	1.79
	upper	10.00	0.50	45.50	12.76	1.40
	Total	19.00	0.50	99.50	23.85	1.43
Total	lower	15.00	0.50	99.50	20.25	0.62
	upper	11.00	0.50	107.00	17.08	0.95
	Total	14.00	0.50	107.00	19.17	0.52

Appendix II. Soil Water Content

Table II-i Mean soil water content (by volume) by willow planting site and row for July/August 2012

Site	Row	N	Mean	S. E. of Mean
Brandon	Middle	3	.4095	.02488
	Upper	3	.1548	.01384
	Total	6	.2822	.05837
Dufresne	Lower	3	.5400	.00500
	Middle	3	.4740	.01550
	Upper	3	.4953	.02484
	Total	9	.5031	.01296
Otterburne	Lower	3	.4758	.12559
	Middle	3	.1762	.04765
	Upper	3	.1546	.01138
	Total	9	.2689	.06481
Riverton	Lower	3	.4256	.00164
	Middle	3	.3093	.04843
	Upper	3	.3747	.01573
	Total	9	.3699	.02235
St Pierre	Lower	2	.3000	.06071
	Upper	3	.0471	.00417
	Total	5	.1483	.06489
Total	Lower	11	.4476	.03991
	Middle	12	.3423	.03738
	Upper	15	.2453	.04430
	Total	38	.3345	.02710

Table II-ii Mean soil water content (by volume) by willow planting site and row in August/September 2012

site		N	Mean	S. E. of Mean
Brandon	Lower	3	.4190	.01090
	Middle	3	.1218	.02076
	Upper	3	.0897	.02009
	Total	9	.2102	.05317
Riverton	Lower	1	.2046	
	Upper	2	.1760	.01331
	Total	3	.1855	.01224
St Pierre	Lower	3	.3750	.05616
	Middle	3	.3433	.07035
	Upper	3	.0121	.00860
	Total	9	.2435	.06362
Total	Lower	7	.3695	.03595
	Middle	6	.2326	.05941
	Upper	8	.0822	.02526
	Total	21	.2209	.03469

Appendix III. Results of soil texture analysis

Table III-i Proportions of sand, silt and clay for combined samples 0-40cm for each sample location by willow planting site.

Site	Location within site	mean % sand	mean % silt	mean % clay
Riverton	d/s	22.5	36.5	41.0
Riverton Lo	d/s	30.3	37.9	31.8
Riverton	mid	31.4	27.3	41.3
Riverton	u/s	11.7	29.7	58.6
Otterburne	d/s	17.1	41.5	41.4
Otterburne	mid	15.3	38.9	45.7
Otterburne	u/s	23.2	42.7	34.1
St. Pierre-Jolys	d/s	86.9	6.5	6.6
St. Pierre-Jolys	mid	89.1	5.3	5.6
St. Pierre-Jolys	u/s	87.4	3.9	8.7
Brandon	d/s	56.9	28.0	14.8
Brandon	mid	61.6	24.1	14.3
Brandon	u/s	55.1	28.6	16.3

Appendix IV. Comparison of 2012 Water Levels with Long Term Values at Willow Planting Sites

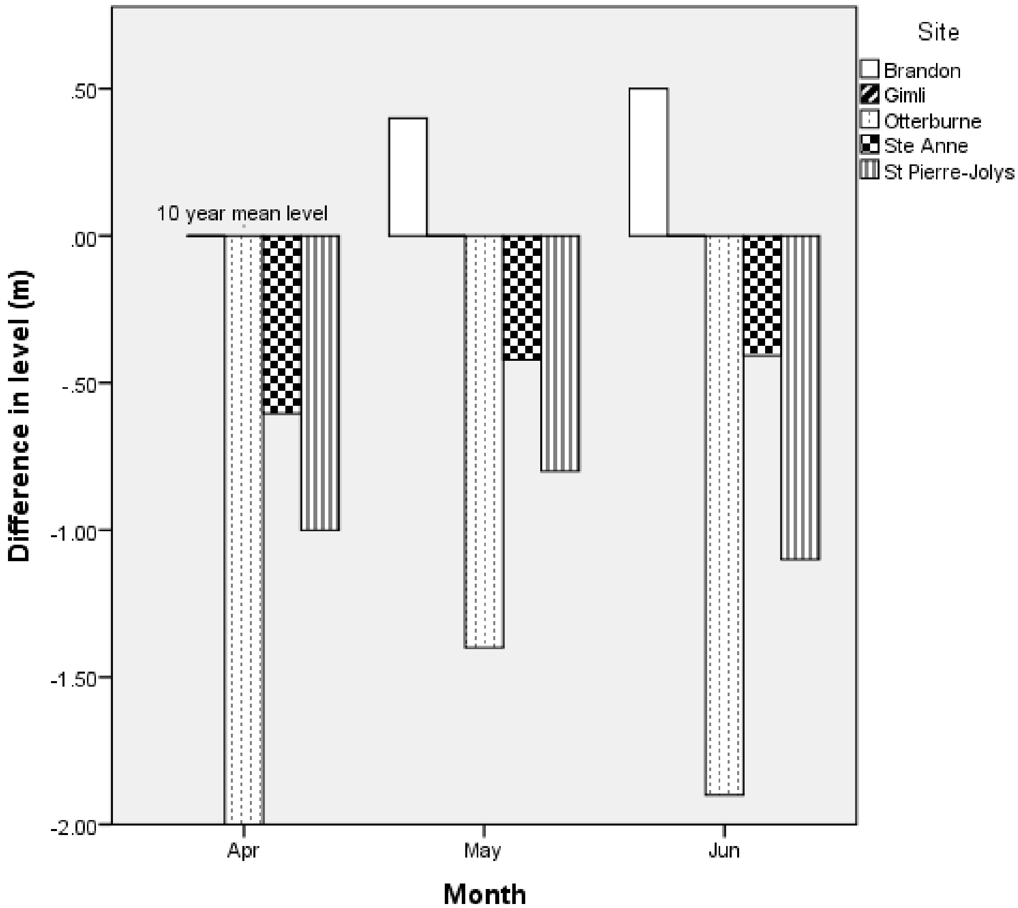

Figure 17 Difference between 10 year mean monthly water levels and 2012 monthly level for each willow planting site. Data was taken for the nearest Environment Canada station.

(Data downloaded from Environment Canada- *http://www.wateroffice.ec.gc.ca)*