Rough & loose reclamation

NATURAL PROCESSES:

RESTORATION OF DRASTICALLY DISTURBED SITES

DAVID F. POLSTER

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RESTORATION OF DRASTICALLY DISTURBED SITES

NATURAL PROCESSES ARE SLOWLY ESTABLISHING VEGETATION ON THE FRANK SLIDE DEBRIS IN SW ALBERTA, CANADA.

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1.0 INTRODUCTION

Natural processes have been revegetating naturally disturbed sites since the advent of terrestrial vegetation about 400 million years ago. Glaciers, volcanoes, floods, landslides, fires, sea level changes and the activities of animals, including humans, all create un-vegetated land. Natural processes, however, ensure these areas do not stay bare for long (Polster 2009). How does this happen and can we use these processes to restore sites we disturb? This manual looks at how ecosystems are put together naturally and how they unravel when they are degraded. The manner in which ecosystems naturally assemble can provide clues to the development of effective restoration strategies. The filters or constraints to natural recovery will be investigated. This will provide the foundation for exploring the steps we can take to restore drastically disturbed sites.

Ecological restoration is defined by the Society for Ecological Restoration (SERI 2004) as the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed. This definition suggests that the best we can do is to assist in the recovery of ecosystems, we cannot make ecosystems recover; this happens naturally outside of our control. There are, however, things that we can do that prevent recovery. These may be well intentioned, but none-the-less, provide a barrier to the recovery processes. There are also natural events and conditions that can prevent recovery. Restoration activities can anticipate these and can provide actions that will allow recovery to continue. The use of natural systems in the design of restoration efforts is gaining acceptance (Higgs 2003).

Ecosystems are complex (Loreau 2010) and operate in many ways that are still being explored. Ecosystems come together and repair themselves in specific ways, many of which we do not fully understand (Temperton et al. 2004). In general, bare areas are colonized by pioneering species (Walker et al. 2007) but what allows these pioneering species to establish? Conversely, what conditions prevent these species from establishing? Pioneering species facilitate the establishment of later successional species (Polster 1989). Understanding the natural processes that occur to provide an initial cover of pioneering species on a glacial outwash plain or a recent lava flow (Hobbs and Suding 2009) can help in the design of restoration programs for drastically disturbed sites such as large mines and industrial sites. In addition, understanding how this initial cover may promote the establishment and

growth of later successional species can be helpful in the design of restoration systems.

Theories of ecosystem assembly, of competition and facilitation and how natural successional processes operate to create ecosystems may be useful in defining restoration strategies (Temperton et al. 2004; Hobbs et al. 2006; Hobbs and Suding 2009). However, it is often the practical issues that make the difference between a successful project and one that fails to meet expectations. Practical solutions to common restoration problems may help to overcome deficiencies and can assist in meeting deadlines and staying within budgets. Restoration is conducted in the real world so theories must be tested on real sites or they remain just published papers gathering dust on a shelf.

Building a sense of connection with the sites being restored may be the most important part of ecological restoration. This is the land ethic that Aldo Leopold speaks of (Leopold 1949). A new understanding of the importance of such a connection is emerging (Louv 2006). It is the reason why people engage in restoration and the reason that gaining community support for significant restoration projects is essential for success (Clewell and Aronson 2007). Restoration provides an excellent way to build the connection between people and the land.

2.0 ECOSYSTEM COMPOSITION

Ecosystems and ecosystem processes are complex (Loreau 2010) and our understanding of them is in its infancy. Understanding how ecosystems operate and how they are composed and compiled can help in restoring them. It is useful however, to look at the factors that contribute to the species and structures of ecosystems. In this chapter we will look at one model of ecosystems as a means of discovering what we need to consider when we restore them.

2.1 BIOGEOCLIMATIC TRIANGLE

Ecosystem classification is the system of grouping ecosystems based on shared elements; in most cases plants are used as the defining characters of ecosystem classification systems. However, plants comprise only one element in the broad array of factors that come together to make an ecosystem. Phytosociology is the study of the characteristics, classification, relationships, and distribution of plant communities. Phytosociological techniques have been used to define ecosystem units in British Columbia and elsewhere in the world. In British Columbia, modified Braun-Blanquet methods (Mueller-Dombois and Ellenberg 1974) have been used to define a biogeoclimatic ecosystem classification system (BEC system) that has been used to classify the diverse ecosystems of the Province (Pojar et al. 1987). This system is based on the three ecosystem elements that are considered most important in determining the distribution of the plants and animals that make up the ecosystems of the Province. The BEC elements can be used to describe the things that are important in making ecosystems function or conversely those elements that are important to consider when restoring ecosystems. These can be arranged as the sides of a triangle (Figure 2-1) with each side representing one of the three elements.

Understanding how each of the three BEC elements contributes to how ecosystems arrange themselves on the land provides a foundation for designing recovery systems for restored ecosystems. For instance, soils that are basic (high pH) will support a different assemblage of plants and animals than soils that are acidic (low pH). Different bedrock geology produces soils that are either basic or acidic. The limestone of the Rocky Mountains supports a different alpine flora than the alpine flora of the Selkirk or

Purcell Mountains with an igneous/metamorphic geology right next door (Polster 1977). Similarly, the vegetation growing in the lee of the Coast Range Mountains is completely different than the vegetation growing on the windward side of the mountains. The following sections describe how these three BEC elements influence the natural vegetation and in turn influence the restoration treatments.

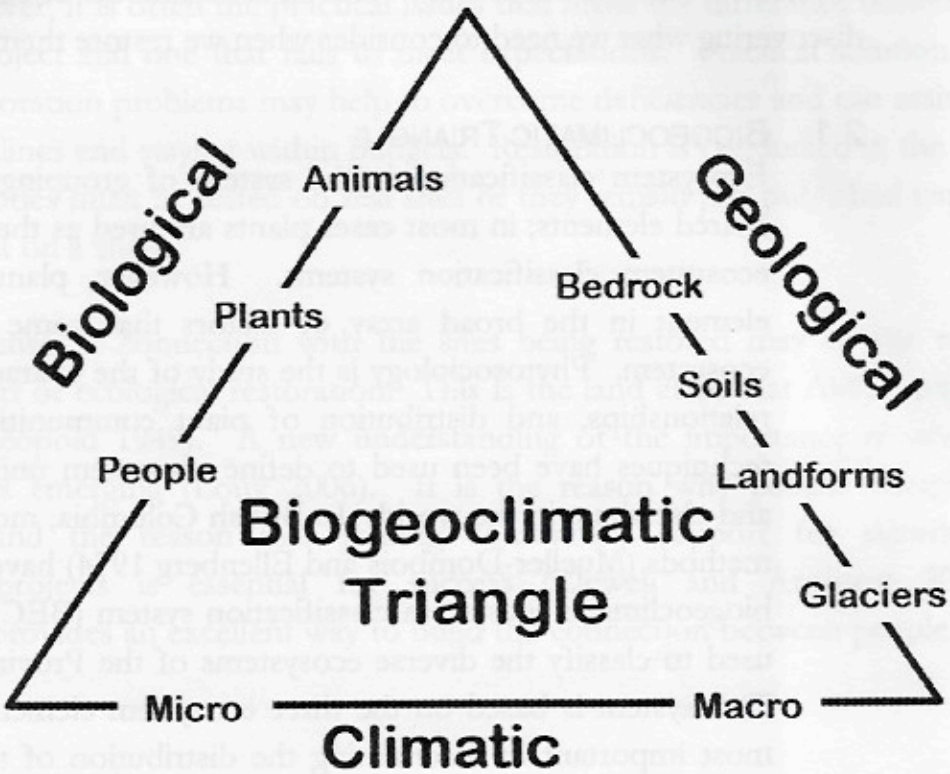


Figure 2-1. Biogeoclimatic triangle showing the elements that are needed for effective restoration planning.

2.1.1 Climatic Contributions

Climatic conditions are the dominant predictor of vegetation patterns and form one side of the biogeoclimatic triangle (see Figure 2-1). Climatic characteristics for a variety of sites throughout British Columbia are given in the Environment Canada Canadian Climate Normals (Environment Canada 1993). The Canadian Climate Normals are now available on-line as well (http://climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html). In addition, the field guides for site identification for various forest regions such as Green and Klinka (1994), DeLong et al. (1993) and Braumandl and Curran (1992) provide summaries of the essential climatic features for the various biogeoclimatic units.

+ microclimatic conditions

Precipitation and temperature are critical to the development of effective restoration programs. Figure 2-2 provides an example of a climate diagram, in this case, for Prince George, BC. Climate diagrams can be used to define the best times for undertaking restoration work as follows:

PRECIPITATION LEVELS AND TIMING

Planting schedules must be developed to so that the freshly planted vegetation is provided with sufficient moisture to become established to the point where periods of dry weather will not result in death of the planted vegetation. If restoration work was contemplated in the Prince George area of BC, then by looking at Figure 2-2 one could determine that planting in April and May might be fine in terms of frost, but limited moisture might be a problem for new plants. Although there is a burst of rain in June, the temperatures are also going up so the relative moisture availability might be lower than in August where there is also an increase in moisture and there is a decrease in temperature so the moisture may be more effective. Climate Normals would also provide an indication of extreme rainfall events so one could be prepared to have exposed soils protected in some way to prevent erosion.

TEMPERATURES, INCLUDING EXTREMES

Temperature can be an important factor in determining where some plants will establish. Frost can kill seedlings and may prevent susceptible species from establishing on a site. Where planting work is being considered, the work must be scheduled to ensure that tender young plants will not be subjected to killing frosts before they can harden off. This is particularly true of legumes that can be easily killed by an early frost. Conversely, extreme high temperatures can "cook" young seedlings, resulting in excessive mortality. Moderate temperatures following vegetation establishment will promote suitable growth. Cool, moist weather can help maintain viability of stem cuttings used in soil bioengineering treatments (discussed below) but may prevent the germination of seeds causing the seeds to rot rather than germinate. Understanding the susceptibility of the vegetation that is being considered to temperature extremes can allow decisions on timing and species to be made with some assurance of success.

High temperature can be a factor on south facing slopes (Northern Hemisphere) where soils are dark such as at coal mines.

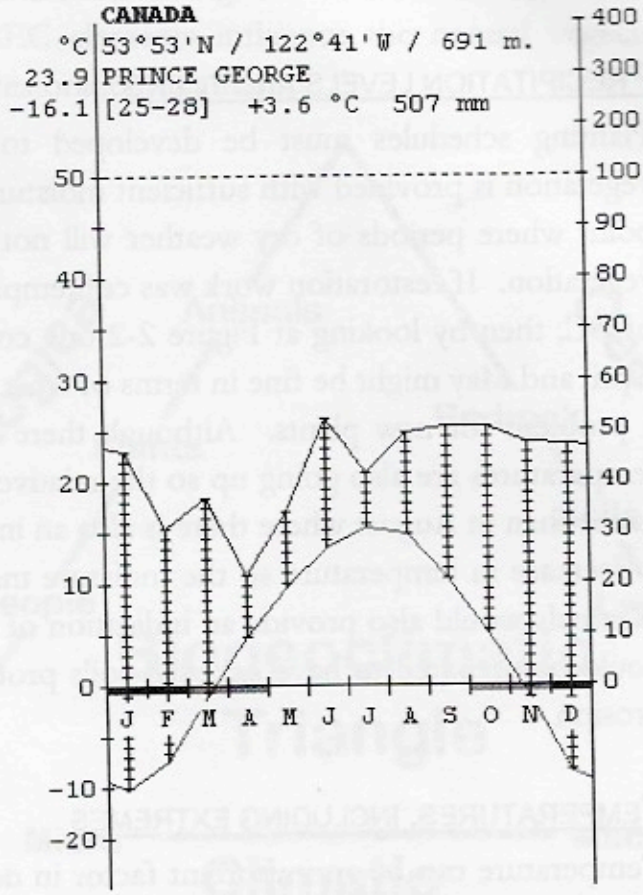


Figure 2-2. Climatic diagram for Prince George BC. The upper blue line shows the average monthly precipitation (scale in mm on right) while the lower red line shows the mean monthly temperature (scale on left). The zero line shows the days below freezing all day (solid bar) the times when there is frost part of the day (blue bars) and the frost free period (clear bar)

Temperature extremes can sometimes cause problems with restoration programs. Species that may be doing well during periods of normal temperature may succumb during periods of extreme weather – an early frost may catch plants before they have hardened off. Similarly, a period of prolonged cold weather may cause frost damage for plants that are normally hardy. Understanding extremes can be an important contributor to project success.

2.1.2 Geologic Contributions

Geologic conditions underlie and influence all terrestrial ecosystems. The mineral component of soils is derived from rock so the geology of an area has a profound influence on the soils that develop and in turn, the plants that grow in that soil. Most of Canada was glaciated so understanding the glacial landforms that have resulted can be important to the vegetation that is being established as well as the conditions that will be experienced as the restoration work is being undertaken.

The identification of landforms and an understanding of the underlying substrates associated with those landforms can assist in the design of restoration programs (Holland 1964). For instance, recognition that a disturbed site is located on an alluvial fan may suggest that the underlying soils will be granular and may be prone to drought, while a lacustrine (lake derived) terrace may suggest silts that may be highly erosive. Consideration of the potential erosion of a site will influence the design of the restoration system. Restoration designs that include immediate erosion protection such as the use a rough and loose surface configuration will be more suitable than those that rely on the growth of seeded vegetation to create the erosion protection.

Natural Soil Classification

Soils form the foundations of plant communities. Understanding the characteristics of the soils of an area can provide an excellent foundation upon which to develop reclamation programs. Published soils reports such as Jungen (1985) give information on the soils in an area including parent materials, textures, generalized nutrient characteristics and other useful information. Soil classification in Canada is governed by the Canadian Soil Survey Committee (Canada Department of Agriculture 1974) and although specific classification of soils associated with a restoration project is not needed, this document provides additional information on the soils of a site. In particular, issues such as calcareous cements, layers of clay accumulation and other such features can be critical to the development of an effective restoration program.

Disturbed Site Soils

The soils associated with disturbed sites may vary considerably from those on the pre-disturbance site (SEAM 1979). The use of natural soils in the restoration of disturbed sites can provide a significant benefit (Ziemkiewicz et al 1980). In some cases sites such as roads and landings can be effectively reclaimed by replacing the "topsoil" on the loosened landing or road (Curran and Dykstra 1997). The native soil may contain seeds and other propagules what will re-establish a suitable native species cover on the disturbed site while the native soil micro-organisms (fungi, bacteria, viruses etc.) can contribute substantially to the recovery of the ecosystem. In many cases, however, the original soils have been lost from the disturbed site and the substrates bear little resemblance to the original soils. Landslide sites may have "soils" piled at the bottom of the slide, while the slopes are left with "D" horizon materials or rock (Walker and Shiels 2013). Characteristics of the "soils" that will need to be restored need to be evaluated in light of plant requirements. Details of the essential soil features are presented below.

Essential Soil Features

Soils must provide moisture and nutrients to the plants to sustain growth (SEAM 1979). Many pioneering plants have the ability to grow in situations where nutrient levels are very low and where moisture may be limited for at least part of the year. Selection of species (see 4.0) that can grow in the conditions that exist on the site will serve to overcome site-limiting features. The following soil features are important to the development of an effective reclamation program (Buchman and Brady 1969):

Soil Texture

Fine textured soils will hold moisture and will tend to be less droughty than coarse sands and gravels. However, fine sands and silts can be prone to erosion and special consideration needs to be given when working with these soils to protect against erosion. Soil texture also influences nutrient retention. Clays serve to hold nutrients for subsequent plant use while coarse sands and gravels will tend to be low in available nutrients. Soils with about 20% passing a 200 mesh screen will provide a suitable rooting medium for most pioneering plants.

Soil Organic Matter

Organic matter content is important to plant growth. Rich dark soils with 15 to 20% organic matter (measured by loss on ignition) will hold moisture and nutrients better than a similarly textured soil without the organic matter. Many restoration sites have little or no soil organic matter and it is the initial pioneering vegetation that will serve to build organic matter. The restoration of peatlands is becoming increasingly important (Laberge et al. 2013; Sottocornola et al. 2007) so a knowledge of peatland biology is essential (Rydin and Jeglum 2013).

Soil compaction

Bulk density, porosity and permeability play a role in the way plants grow. A dense basal till may preclude root penetration while a loose friable loam will provide a good rooting medium. Typically, compacted sites should be loosened to a depth where roots are expected to penetrate (generally 1 m or more) prior to restoration. The rough and loose treatment described below provides an effective way to reduce compact and create conditions that will foster invasion by native pioneering species.

Soil colour

A dark shale substrate on a south facing slope may get very warm and could prevent seedling growth. Light coloured substrates may be slow to warm up in the spring, causing growth problems. Mulching may serve to reduce the heat absorption characteristics of a dark substrate sufficiently for plant establishment. Similarly, mulching may help darken light substrates. Making sites rough and loose creates north and south facing slopes with different temperature regimes.

Drainage

Soil drainage can influence the design of restoration programs. Sites that are poorly drained or sites that drain too freely will require specific restoration designs and treatments and may need species that have been selected for their abilities to address the conditions of the site.

Consideration must be given to the characteristics of the site and to the essential soil features in the design of a restoration program. Features such as root permeability, moisture holding capacity, nutrient availability as well as aspect, elevation and exposure all influence the design of restoration programs. Understanding the interactions between soils and plants can help make restoration projects a success.

2.1.3 Biotic Contributions

Biotic elements provide an important contribution to ecosystems. It is the biotic contributions that we see and name. The biotic component can be broken into heterotrophs and autotrophs. Heterotrophs derive their food either directly or indirectly from autotrophs while most autotrophs obtain energy from the sun to produce carbon based organic molecules. Green plants are autotrophs while the deer and cougars that eat the deer are heterotrophs and the invertebrates and micro-organisms that breakdown the body of the dead deer are also heterotrophs. Both are important in the development of ecosystems. In most restoration projects, however, plants are most important. Herbivory, discussed in Section 4.2.1 can be a major problem at restoration sites.

Vegetation

Plants are one of the major components of ecosystems providing the "food" for other ecosystems elements. Plants provide most of the structure of ecosystems. They hold the soils in place and moderate the climatic extremes. They can be used stabilize slopes, change the course of rivers and provide shade for streams. Through their growth, plants can significantly modify ecosystem conditions, creating new substrates (rotting logs) and providing habitats for animals. As important ecosystem elements, plants will be the focus of much of this course manual.

2.2 Interactions

The interplay between ecosystem elements is where the action happens. Trees rooted in the soil blow over, bringing up fresh soil thus replenishing nutrients for new growth. Mosses soak up rainfall maintaining moisture on the forest floor long after the rain stops. Animals carry seeds to new

locations as does the wind. The interactions between ecosystem elements can be considered to be the "grease" in the ecosystem "wheel".

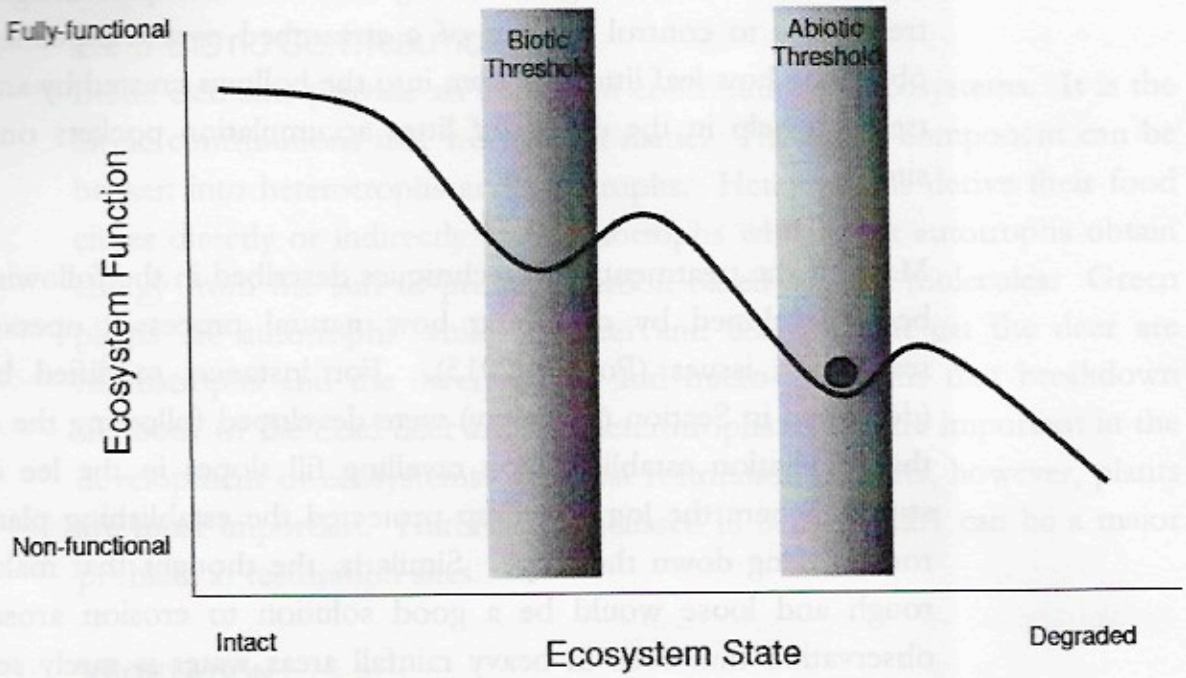
Observing how ecosystem elements interact can help design restoration programs that work with these interactions. For instance, watching how water flows across a gravel bar and how those flow patterns change when a log and root mass is lodged on the gravel bar can help us design restoration treatments to control erosion of a streambed over a pipeline. Similarly, observing how leaf litter is blown into the hollows created by an overturned tree can help in the design of litter accumulation pockets on restoration sites.

Many of the treatments and techniques described in the following text have been developed by observing how natural processes operate to solve restoration issues (Polster 2013). For instance, modified brush layers (described in Section 6.4 below) were developed following the observation that vegetation established on ravelling fill slopes in the lee of logs and stumps where the log or stump protected the establishing plant from the rocks rolling down the slope. Similarly, the thought that making a slope rough and loose would be a good solution to erosion arose from the observation that even in heavy rainfall areas water is rarely seen running across the surface of the ground. It soaks into the soil and re-appears as springs in the streams that drain the region. Observing how natural systems solve these and other restoration problems can lead to effective strategies for the restoration of difficult sites.

3.0 Ecosystem Degradation

Understanding how ecosystems are degraded can help us restore them by allowing us to control or modify the degrading processes or elements. The following section looks at common ecosystem degrading processes. Hobbs and Suding (2009) have proposed a model of degradation that has thresholds defined as either biotic or abiotic (Figure 3-1). Their idea is that ecosystems cross these thresholds during degradation and that getting them back to a fully functional, intact state is very difficult as the ecosystems have the tendency to fall back into the degraded state very easily. Anyone who has tried to restore an invasive species infested

meadow, a compacted mine waste dump platform, or a motor bike plagued mountain trail will understand the concept that is being presented. This model has likened restoration of these degraded sites to the task of Sisyphus, the cruel king of Corinth who was condemned for eternity by the gods to roll a huge boulder up a hill only to have it roll back down just as it reached the top.



Modified from Hobbs and Suding, 2009

Figure 3-1. This model for ecosystem degradation suggests ecosystems pass through thresholds, biotic and/or abiotic that can be difficult to overcome during restoration.

The suggestion is that restoring ecosystems to a fully functional, intact state is a futile task in our modern world where invasive species and other anthropogenic changes, including changed climates, have created conditions that will prevent the effective recovery of the degraded ecosystems. From this idea comes the concept that novel ecosystems arise from these degraded states (Hobbs et al. 2006). This model however, does not provide for natural ecosystem recovery processes and suggests that ecosystems must remain in a degraded, non-functional state; a condition we know is not true. However, it may be that the ecosystem never again recovers to the point of being identical to the pre-disturbance ecosystem. Since ecosystems are not static entities, i.e. they are always changing (Walker et al. 2007),

the question of returning to the same condition that was left when the ecosystem was disturbed may be a moot point. Seeking to return pre-disturbance ecosystem functions and processes may be a more effective restoration goal for drastically disturbed sites than trying to re-establish the same species composition. The following sections explore the ways ecosystems are degraded.

3.1 THRESHOLDS

Ecosystems can cross (or be driven across) thresholds from which they cannot recover to their original state without extensive efforts. When feedback is between degrading forces (drivers) and the ecosystem elements, the drivers are said to be "internal" while if the changes (degradation typically) in the ecosystem comes from outside the ecosystem and has no feedback to the ecosystem, then the drivers are said to be "external" (Hobbs and Suding 2009).

Four major feedback systems that can cause degradation if disrupted have been identified (Hobbs and Suding 2009):

1. Changes in species composition. The example of Cheatgrass, (*Bromus tectorum*) in the Interior grasslands where the Cheatgrass causes a change in the fire return interval thus maintaining the Cheatgrass domination is an example of this type of species compositional change that shifts the ecosystem (crosses a biotic threshold).

2. Trophic interactions can also cause ecosystem degradation that is hard to cross over. The loss of cougars in some areas, particularly island ecosystems, has resulted in an explosion of deer populations that causes severe impacts on the ecosystems (Martin et al. 2011). Treatments would entail removal of most of the deer, re-introduction of cougars or fencing to keep the deer out of the most sensitive areas.

3. Loss of landscape level connectivity can also cause ecosystem degradation.

4. Changes in climate or changes in other abiotic factors such as hydrology (Hobbs and Suding 2009) cause ecosystem changes. Big

bulldozers and other excavating equipment are a major abiotic degrading element.

The following sections provide information on the types of degrading factors that influence ecosystems. Understanding the degrading elements that are at play in an ecosystem provides the first step in designing recovery processes.

3.1.1 Biotic

Biotic (biologically based) intrusions (thresholds) can cause significant shifts in ecosystems. Some invasive species such as Scotch Broom (*Cytisus scoparius*) can create substantial shrub layers in ecosystems such as Garry Oak ecosystems where there were no shrub layers previously. In addition, the nitrogen fixing ability of bacteria associated with the Scotch Broom can enhance the growth of agronomic grasses such as Orchardgrass (*Dactylis glomerata*) thus further moving the ecosystem away from its historic condition. Removal of the Scotch Broom may not be all that is needed to restore these ecosystems to their pre-invaded state. The alien invasive grasses may maintain a novel ecosystem, which, although it possesses many of the attributes of the former ecosystem, is different. Herbivory, discussed more fully below, can be a major biotic degrading force (Gonzales 2008).

3.1.2 Abiotic

Direct habitat alienation or alteration is the major cause of degradation of natural systems (abiotic = non-biological). Mining, urban expansion, industrial logging and agriculture all cause major abiotic changes to ecosystems. However, changes in climate may become the most significant abiotic degrading factor associated with the loss of natural ecosystems. It may be that striving to restore former ecosystems in the face of climatic shifts will be impossible and we will have to content ourselves with re-establishing functioning ecosystems that provide the former ecological services rather than re-establishing the exact suite of species associated with the former ecosystems.

3.2 Modified Disturbance Regimes

Substantial ecological degradation has occurred as a result of modifications to natural disturbance regimes. The control of fire in fire maintained ecosystems such as the Ponderosa Pine – Bunchgrass ecosystems of the Interior of British Columbia (Photograph 3.2-1) and other related ecosystems have caused major ecological changes (Friederici 2003). Harvesting in beetle killed Lodgepole Pine stands is another example (Lindenmayer et al. 2008) Changes in flooding regimes due to large dams have also caused major ecological degradation (Ligon et al, 1995). Sorting out the ecological tangles associated with large dams and resulting reservoirs may be an impossible task, requiring acceptance of novel ecological systems in place of the former riparian ecosystems. Many of the changes to natural disturbance regimes cannot be addressed by simply returning the disturbance element (Friederici 2003). In the case of fire, the build-up of fuels associated with decades of fire control would result in much hotter fires that would cause further ecological changes. Similarly, simply removing dams would not restore the former riparian ecosystems as sediment deposition, wave sorting of shoreline materials and a host of other ecological changes will prevent a direct recovery of these ecosystems.

4.0 Filters to Recovery

Many of the ecosystem degrading elements act as filters preventing the effective recovery of the degraded ecosystem. As with the degrading elements, filters can be classed as either biotic or abiotic. Most drastically degraded ecosystems such as major mines or hydroelectric developments have been caused by abiotic changes to the ecosystem. Similarly, the major filters or constraints to recovery are primarily abiotic sometimes with biotic changes overlying these changes. For instance, a compacted mine waste dump platform may have developed a cover of weedy species that are preventing recovery of the ecosystem. It is the compaction that is the underlying constraint or filter, not the weedy species, although the weedy species may become a more significant problem once the compaction has been dealt with. The following sections provide a discussion of the major filters operating in drastically disturbed ecosystems. Polster (2015) lists eight abiotic and six biotic filters.

4.1 Abiotic Filters

Abiotic filters are the most common filters operating on drastically disturbed sites. Erosion associated with steep, unstable slopes is the primary cause of restoration failure at major mines (Photograph 4.1-1). Details of erosion processes are discussed below. Compaction can be another significant factor preventing the recovery of drastically disturbed sites (Photograph 4.1-2). Compaction issues often interact with erosion because of the failure to establish an effective vegetation cover on severely compacted sites. In many cases, compacted sites end up with weedy vegetation covers or with no vegetation at all. Toxic wastes can be a major issue at some mine sites (Morin and Hutt 1997). Excessively high metals levels may prevent or limit vegetation growth while the generation of acid due to the oxidation of sulphide minerals may work in combination with high metals to prevent or limit plant growth (Photograph 4.1-3). The details of acid rock drainage (ARD) are beyond the scope of this manual, although treatment considerations that influence the revegetation of these sites are provided below.

4.1.1 Erosion

Processes of Erosion

Erosion is the act of wearing away a surface and comes via the French "*éroder*" from the Latin *erodere* meaning to "gnaw away". Erosion is generally considered to be a gradual process. Erosional processes have been at work on the earth's surface since the earth was formed. The removal of rock and soil through erosion shapes and reshapes the landscape in a never ending process. Erosion, therefore, is a process that cannot be stopped. However, anthropogenic (human caused) erosion (Lengelle 1976) can and should be minimized since the impact on natural recovery processes, other resources as well as human structures can be significant. Natural erosion rates of 5 to 7 $Mg/km^2/year$ (Mg = metric tonne or 1,000 kg.) can be increased to 20 to 50 $Mg/km^2/year$ through human activity (Gray and Leiser 1982).

There are two principle agents that cause erosion: water and wind while gravity plays a part in all erosional processes. Energy from the initial agent (water/ice or wind) loosens and/or lifts the material being eroded while gravity acts to move the material down slope. Erosion may also be classified as being either single particle erosion or mass movement. Soil erosion is a form of single particle erosion, while slumps, rock falls and even creep is considered to be mass movements (Chatwin et al 1994). A variety of terms are used to describe erosion. Table 4.1-1 presents the agents / processes and types of erosion. These are further discussed in the following paragraphs.

Water is the dominant agent responsible for erosion whether as liquid water or as ice. From the slow drip, drip, drip of water dripping onto a rock surface; a raging torrent of a large river carving a canyon or the slow grinding of massive glaciers shaping the land, water plays a major role in erosion. **Solution** is the simplest form of water's attack on the landscape. Soluble rock such as limestone is dissolved by water and weak organic acids and slowly eroded. In most cases, human activities have little bearing on rates of solution erosion although where industrial activities such as smelters result in acidic precipitation, solution erosion can be a significant factor. **Rainsplash** (or raindrop) erosion occurs as the impact of raindrops on a wet soil surface launches the upper soil particles into the air. As much as 37 Mg/ha of soil can be "lifted" by rainsplash erosion into the air. Protection of the soil surface is the solution to raindrop erosion.

Once the soil is in the air due to rainsplash erosion, it can easily be washed from the slope as **sheet** erosion. In addition, the movement of water over the surface of the soil can move soil particles along. Soil particles on the surface will be buoyed up by a force equal to the weight of the water displaced by the particle. Therefore, small particles that are entirely submerged by the sheet of water will tend to "float" away with the water. This is particularly true of organic soil components that may be significantly less dense than either mineral soil particles or water.

As water moves down slope it coalesces into small channels known as **rills**. Rill erosion is a complex process composed of down-cutting the base of the rill, undercutting the sides of the rill with subsequent collapse of the sides and "head walling" at the top of the rill. At the top of the rill, water flowing from the surface into the rill results in waterfall erosion and regression ("head walling") of the rill up the slope. In some materials, saturation of the soils adjacent to the rill results in this material "flowing" into the rill. The base of the rill is eroded by the water passing over it, deepening the rill. The sides of the rill are undercut or liquefied by the water. Slumping of the over-steepened sides or flowing of the liquefied material and the washing away of this material serves to widen the rill. Eventually, the rill is deepened and widened to the point where it becomes a **gully**. Rills are defined as erosional features that are small enough to be reshaped using normal agricultural equipment (disk, harrows, ploughs, etc.) while gullies require construction equipment (bulldozers, excavators, graders, etc.) for repair. Gully erosion processes are similar, although on a larger scale, to rill erosion processes. Flow in gullies, and therefore erosion, is related to rainfall and / or snowmelt events. Large amounts of material can be removed in a very short time where gullies cross easily eroded materials such as silts and fine sands. Preventing movement of water across the soil surface is the solution to sheet erosion and rill/gully erosion. A discussion of soil erodibility is presented in the following section along with a discussion of the Universal Soil Loss Equation.

Once flow in a gully is continuous throughout at least part of the year, the flow is considered a stream and the erosion processes are those of **stream channel** erosion. Stream channel erosion is similar in nature to both rill and gully erosion. That is, erosion occurs on the stream bed through down-cutting and along the banks through undercutting and sloughing. Streams, and therefore stream channel erosion, can range in size from small flows in stable channels with very low rates of erosion to large rivers in active channels where erosion rates can be significant. Slowing flow velocities can help reduce stream channel erosion. Where water bodies are large enough so that waves are generated by wind (or boats), the wave action that results can cause significant erosion. **Wave**

erosion occurs as a result of a variety of processes. As the wave crashes onto the shore, the energy of the water falling from the crest of the wave to the beach is dissipated in part through erosion of the shore. In addition, the flow of water back and forth over the beach can loosen and remove particles. Damping waves with shoreline vegetation or other materials can reduce the impacts of wave erosion. Flows along the shore of a water body can carry soil particles over great distances in a process known of as **longshore drift**. Longshore drift can be an important process in shoreline erosion.

Table 4.1-1
Agents / Processes and Types of Erosion
(Modified from Gray and Leiser (1982) and Chatwin et al (1994))

Agent or Process	Type of Erosion
Water	Solution Rainsplash Sheet Rilling Gullying Stream Channel Wave Action Groundwater Piping
Ice	Solifluction Frost Action Glacial Scour Plucking
Wind	There are no different types of wind erosion
Mass Movements	Falls (rock) Creep Slumps and Earthflows Debris Avalanches Debris Flows Bedrock Failures

When groundwater exits the ground to become surface water, it can carry soil particles with it in a process known as **piping**. Piping can be a significant factor in erosion as the loss of soil through the piping action can cause upslope materials to collapse in a mass movement event. In some cases, piping at the toe of an otherwise stable slope can destabilize the entire slope. The transition from groundwater to surface water can

be problematic where unconsolidated material (soils) overlies bedrock and the groundwater is travelling along the bedrock surface. Piping can be the underlying cause of stream bank instability as groundwater often exits the soil at the topographic low point in the terrain.

Ice, in the form of glaciation, has played a major role in shaping the land and in presenting surficial materials that provide significant stability challenges. **Glacial scour** continues to erode alpine and northern areas. **Solifluction, plucking** and **frost action** are all erosional processes associated with ice. The enlargement of soil pore space, when pore water freezes, can result in soil instability as the moisture within the soil thaws. Surface phenomena associated with the freezing and thawing of moisture sensitive (fine textured) soils can result in soil flows. Frost may also prevent seepage of moisture from a slope resulting in increased pore water pressure and subsequent slope failure. The loss of soil strength as the frost comes out of the ground during spring break-up is well known. This loss of strength can result in mass movements such as earthflows.

Wind can be a major erosive force in some areas and with some soil types. Fine silts and sands can be easily eroded by wind when the weather is dry. There are no different types of wind erosion as there are for water, only different degrees of severity. Wind-blown ice crystals can scour soil and deposit an ice/soil mixture known as "snirt" (snow + dirt). Loess deposits (wind-borne materials) often associated with the terminal areas of continental glaciation are prone to wind erosion (Frazier et al, 1983) as are fine lacustrine sediments. Control of wind erosion typically involves reducing the effective fetch such as by providing wind breaks and/or providing an erosion protecting cover such as vegetation on the susceptible soils.

Mass movements account for a substantial loss of soil in areas of steep terrain and intense precipitation (Chatwin 1994). The mountains of coastal British Columbia provide the steep terrain while the orographic uplift of the prevailing west winds provides the abundant moisture. Mass movements come in a variety of types. **Falls** (typically rock) occur

when a steep slope collapses in a manner where the material falls through the air. Rocks pried lose by frost action may form rock falls with resulting talus slopes below the rock face. **Creep** is the slow downslope movement of soils. Soil creep may be seen in the formation of harp shaped tree trunks. In some cases, creep may be the precursor to more rapid soil movements. **Slumps** and **earthflows** originate from a circular/concave slip surface and result in movement of materials downslope either as a liquid-like flow or as a series of blocks. Where slump blocks remain in place trees tend to be leaning upslope. Where flows have occurred, the trees tend to be lying on the slope with the root mass downslope. Open slope failures typically include **debris avalanches** and **debris flows**. Debris avalanches and flows originate from shallow slip surfaces where shallow soils contact bedrock or an underlying impermeable layer. Loss of root strength associated with decomposition of the less than 2 mm roots coupled with periods of heavy precipitation and an increase in weight of the slide material are typically causal factors in debris avalanches and debris flows. The volume of water associated with the slide mass dictates whether it will be termed an avalanche (dry) or flow (wet). Debris flows or debris avalanches can become **debris torrents** if they move into steep gullies or valleys during periods of high flow. In many cases a small debris avalanche along the side of gully will become a major debris torrent as it moves down the gully gathering whatever materials are in the gully. Debris torrents can scour out a gully so that only bedrock or compacted till remains, depositing wood, rocks and soil in a jumbled mass at the bottom of the slope. Debris fans at the toe of the slope are evidence of a history of debris torrents.

Universal Soil Loss Equation

Quantification of erosion rates has been a problem, particularly for single particle erosion. Soil erosion is often a critical feature in the design of restoration programs. If a site is actively eroding, then the first step in the restoration process must be to control erosion. Single particle soil erosion has been described empirically by the ***Universal Soil Loss Equation*** (USLE) (Wischmeier and Smith 1965). The USLE suggests that erosion is the product of a number of factors as follows:

$$X = R \cdot K \cdot L \cdot S \cdot C \cdot P$$

Where: X = Soil Loss

R = Rainfall factor (index)

K = Soil erodibility index

L = Slope length factor

S = Slope gradient factor

C = Cropping or vegetation factor

P = Erosion control practices factor

The rainfall factor (R) is the factor (sometimes called the rainfall index) that incorporates the energy associated with a storm as well as the intensity. The rainfall factor can be calculated from the following equations:

$$R = EI/100$$

Where: R is given in foot tons/acre/hour (= 1.735 metre tonnes/ hectare/hour

E is the kinetic energy of rain and

I is the maximum 30 minute rainfall intensity in the area in inches/hour

The kinetic energy of the rainfall can be calculated as follows:

$$E = 916 + 331 \log i$$

Where: E = kinetic energy of rain (ft.-tons/acre-in)

(1 ft.-ton/acre-in = 26.38 J/m^3)

i = the rainfall intensity in inches per hour

1 inch/hr. = 25.4 mm/hr.

The records from individual storms are summed over a given time interval (week, month or year) to give the cumulative R values for that

time period. Typically when erosion rates are presented, they are given as a weight (Mg) per unit area (ha) per time interval (usually one year). It is the cumulative R value that determines the time interval. Iso-erodent maps for the United States (R values) have been provided by Israelsen et al. (1980 from Wischmeier and Smith 1965) showing values ranging from 800 foot tons/acre/hour (= 1,388 metre tonnes/hectare/hour) in central Mississippi to 9 foot tons/acre/hour (= 15.6 metre tonnes/hectare/hour) in the Okanagan area of Washington. Although these maps only show values for the United States (including Alaska), values for Canadian sites can be estimated from comparable sites in the United States. For instance, values of 280 foot tons/acre/hour (= 486 metre tonnes/hectare/hour) given for upper elevation areas on the Olympic Peninsula might be comparable to upland areas on the southern coastal area of British Columbia. Values of 20 foot tons/acre/hour (= 35 metre tonnes/hectare/hour) are given for various prairie sites east of the continental divide and might be comparable to similar sites in Alberta. Without extensive rainfall intensity / duration data, calculation of the R value for sites in British Columbia will be both difficult and uncertain. Estimates, however, can be used to provide approximations of R.

Soil erodibility (K) is an important part of determining potential soil loss. Clearly, a non-cohesive fine silt soil is far more erosive than a very coarse granular soil. A nomograph (Figure 4.1-1) has been developed to determine the value of K given the percent of silt and fine sand (0.002 – 0.10 mm fraction), the percent sand (0.10 – 2.0 mm fraction), the percent organic matter, the soil structure and permeability (Wischmeier et al 1971). It should be noted that knowledge of the coarse fragment content or the clay content is not needed to calculate K.

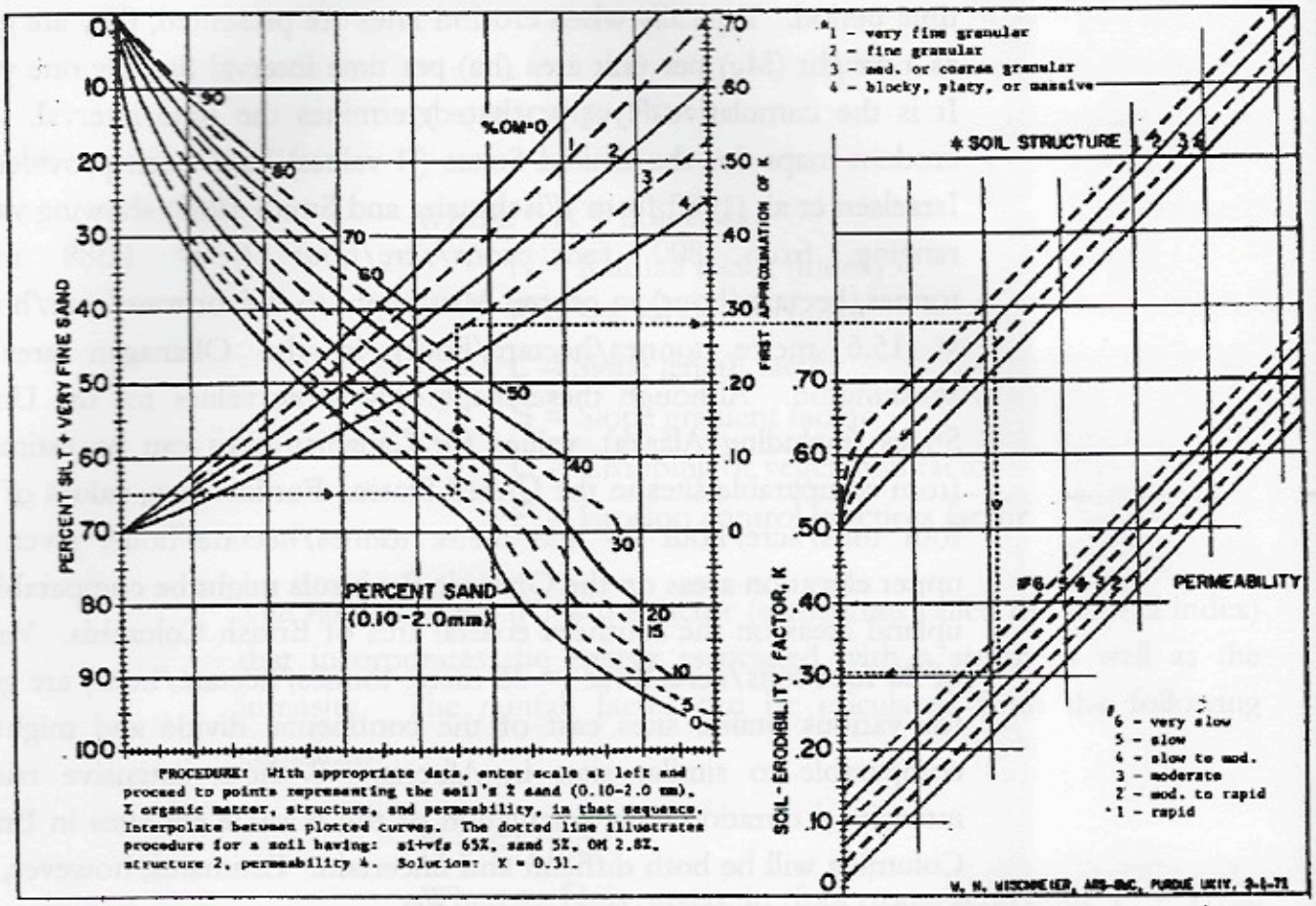


Figure 4.1-1. Nomograph for calculation of K given percent silt and fine sand, percent sand, percent organic matter, soil structure and permeability from Israelsen et al (1980), originally from Wischmeier et al (1971).

Slope gradient and slope length are important determinants in the prediction of erosion rates. Clearly long steep slopes will lose more soil to erosion than short flat slopes. Together, the slope gradient and slope length factors are known as the "topographic" factor. The topographic factor is the ratio of soil loss per unit area from a given site to that from a unit plot having a 9 percent slope and a 72.6 foot length (22.13 m). A graph (Figure 4.1-2) giving values for the topographic factor (LS) is presented below.

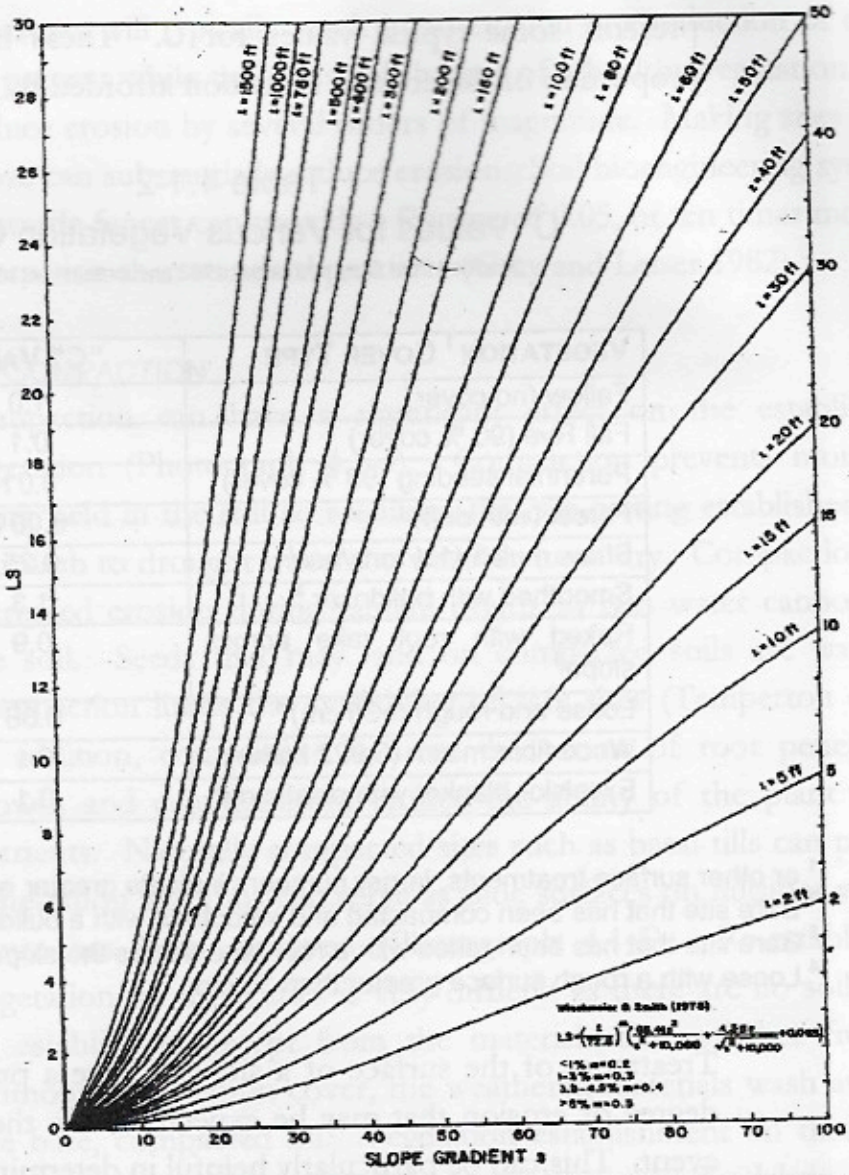


Figure 4.1-2. Graph for determining topographic factor (LS) from Israelsen et al (1980), originally from Wischmeier et al (1971).

The cropping factor, C, provides a measure of the ability of various vegetation covers to reduce erosion. It is clear that different vegetation covers protect the soil surface differently. For instance, a cover of fall rye that may appear to be fairly dense in transverse view may provide little protection from rainfall or from surface erosion. The single stems of the fall rye simply do not provide erosion protection. Values for C for a 90% cover of fall rye are reported to be 0.1 while for a 90 % cover of perennial grasses and legumes the value for C is 0.01. Table 4.1-2

presents some typical values for C. These have been derived as a proportion of the erosion reduction afforded by the vegetation cover.

Table 4.1-2
"C" Values for Various Vegetation Covers
(Modified from Gray and Leiser 1982 and Israelsen et al 1980)

VEGETATION [1] COVER TYPE	"C" VALUE
Fallow (no cover)	1.0
Fall Rye (90 % cover)	0.1
Perennial seeding (90 % cover)	0.01
Forest (with duff)	0.001
Straw mulch (1½ tons/acre)	0.25
Smoothed with bulldozer [2]	1.3
Raked with root rake across slope[3]	0.9
Loose and rough (>30 cm) [4]	0.08
Wood fibre mulch (3,922 kg/ha)	0.1
Excelsior blanket with plastic net	0.1

[1] or other surface treatments, larger numbers indicate greater erosion
[2] Bare site that has been compacted and smoothed with a bulldozer or scraper
[3] Bare site that has been raked with a root rake across the slope
[4] Loose with a rough surface greater than 30 cm

Treatment of the surface of a site can have a profound impact on the degree of erosion that may be expected from the site given an erosion event. This can be particularly helpful in determining surface treatments to be applied to a site. It is clear from the values given in Table 4.1-2 that careful grooming of a slope by machine operators actually contributes to erosion and that leaving the slope rough and loose will reduce erosion rates. Simple measures such as making sites rough and loose and the application of coarse woody debris can provide a significant benefit in terms of erosion reduction.

The erosion control practices factor, P, is included in the USLE to allow for treatments such as contour ploughing, strip cropping, check dams, silt fences, flumes, water ladders and other erosion controlling practices. The purpose of these practices is to reduce erosion. However, they are generally not particularly effective. Application of major erosion control

measures will typically result in an erosion rate reduction of only about 50 percent while timely establishment of a healthy vegetation cover can reduce erosion by several orders of magnitude. Making sites rough and loose can substantially reduce erosion. Soil bioengineering systems such as wattle fences can provide a P value of 0.05, or ten times more erosion protection than standard practices (Gray and Leiser 1982).

4.1.2 Compaction

Compaction can have a significant effect on the establishment of vegetation (Photograph 4.1-4). Compaction prevents moisture from being held in the soil so seedlings that are getting established will often succumb to drought when the weather turns dry. Compaction results in increased erosion during rainfall events as rain water cannot soak into the soil. Seeds that may land on compacted soils are washed away. Compaction limits the availability of safe sites (Temperton et al 2004). In addition, compaction reduces the extent of root penetration and growth and can therefore reduce the ability of the plant to take up nutrients. Naturally compacted sites such as basal tills can prevent root penetration and thus can serve as slide surfaces on hillsides where forest cover has been removed (Photograph 4.1-5). Re-establishment of vegetation on these sites is very difficult as there are no soils for plants to establish in except from the materials that weather from the till. Without a vegetation cover, the weathered materials wash away, leaving the bare, compacted till. Vegetation establishment on these sites may require some additional structure such as woody debris to trap the weathered soil materials and allow pioneering vegetation to establish. Modified brush layers (see below) can be used to initiate successional processes on bare basal till sites.

4.1.3 Toxic Wastes

Toxic wastes can limit the establishment of vegetation. Sites with acid generating rock (ARD) can prevent the growth of vegetation for many years (Photograph 4.1-6). High metal content of soils can have adverse effects on vegetation, slowing growth or even killing the vegetation (Photograph 4.1-7). A substantial body of literature has developed on the treatment of ARD and high metals. A review of this material is

beyond the scope of this manual. However, when dealing with drastically disturbed sites associated with mining and/or smelting, the possibility of ARD and high metals levels must be considered.

Salt (NaCl) can create toxic soils and prevent plant growth. Saline soils can occur due to a number of causes. Salt may be encountered during drilling for hydrocarbons. Salt may also occur due to continued irrigation with slightly saline water. Since salt can be moved in solution with water, allowing water movement down in the soil can help move salt below the rooting zone. High sodium (Na) levels can cause problems for plant growth as well. Sodic soils (with an exchangeable sodium content above 15%) can lose structure and become very difficult to work with. Again, moving the sodium down into the soil through deep ploughing or otherwise loosening the soil can help.

4.2 Biotic Filters

Biotic elements can prevent the recovery of damaged ecosystems. In some cases, simply removing the biotic filter is all that is needed to allow the ecosystem to recover. The following sections discuss common biotic filter.

4.2.1 Herbivory

Herbivory can be a significant feature influencing the development of ecosystems (Gonzales 2008; Martin et al. 2011). Herbivory associated with invertebrates can change the establishment rate of some species. Slugs may eat seedlings preventing the growth of those plants. Similarly, various insects (Photograph 4.2-1) can influence the development of ecosystems by selectively reducing the vigour of some species relative to others.

Vertebrate herbivores can play an adverse role in the recovery of ecosystems (Photograph 4.2-2). Where predators have been removed, hyper-abundant populations of prey species such as deer and rabbits can significantly shift the vegetation, removing much of the understory and preventing recruitment of overstory species. Browsing may shift the vegetation towards species that are less palatable, including alien invasive species.

4.2.2 Competition

Competition is a major influence on the species composition and dynamics of ecosystems (Loreau 2010). Competition associated with dense stands of seeded grasses and legumes (Photograph 4.2-3) can prevent the establishment of woody species (see also section 5.4 Priority Effects below) (Polster 2015). Competition can create successionally stagnant stands (Kimmins 1987) that prevent the normal successional changes in the vegetation. In some cases, small mammal populations can thrive under the dense thatch created by seeded agronomic grasses and legumes. These then girdle and kill woody species preventing establishment of these species (Green 1982). Although this can be seen as an herbivory effect, it is the competitive effects of the dense cover of seeded species that allows the small rodent populations to expand. Seedling suppression can be a significant factor in the establishment of some species and can prevent the establishment of these species where the density of competing species is excessive. Competition can, however, be used to control alien invasive species (see below).

5.0 Assembly Rules

Understanding how ecosystems assemble can be a powerful tool when we go about putting them back together once they have been destroyed (Temperton et al. 2004). One of the most effective models for the assembly of ecosystems is succession (Polster 1989; Walker et al. 2007). How succession works and how it can be used in the restoration of drastically disturbed sites has been the topic of study in some circles (Polster 1991; Walker and del Moral 2003; Walker et al. 2007; Caners and Lieffers 2014; Swanson et al. 2014). Information on the structure of natural plant communities can help in the design of restored ecosystems with appropriate structure. Similarly, the manner in which species use safe sites as they assemble to form ecosystems and the influence of priority effects can play a role in the design of restoration systems for drastically disturbed sites. Understanding how some species, notably pioneering species facilitate the establishment of other species can be helpful. The idea that historic natural successional processes may

not operate in the same manner in the context of the current ecological situation has led to the idea that new pathways may emerge. The concept of novel ecosystems and ecosystem processes is gaining acceptance in the treatment of damaged ecosystems (Hobbs et al. 2006). The following sections discuss these elements of ecosystem recovery more fully.

5.1 Succession

Succession is the process of replacement of one suite of species by another. Historically (Clements 1936) succession was considered to be an orderly progression of species leading to a climax community that remained static. However, recognition that no communities are immune to natural disturbance elements (fire, wind, flooding, etc.) as well as the slow accumulation of organic matter or the slow changes in nutrient status suggests that there are no static endpoints to succession so the idea of climax communities has been set aside (Walker and del Moral 2003). The debates about later successional processes and endpoints continue and the study of succession provides a fascinating backdrop to restoration ecology.

Stochastic (by chance, non-deterministic) events such as the establishment of an individual species such as a tree due to some rare combination of physical conditions have been seen to be a player in the manner in which succession proceeds. Events such as a wet spring or a mid-summer rainy period or the death of an animal at the site that contributes nutrients can influence the species that establish on a site and thus the manner in which the ecosystem develops. Seed rain is not uniform and species with seeds that can be blown onto distant sites may establish preferentially to those with large seeds that are moved by gravity or animals. Similarly, the movement of animals, notably birds, can influence the establishment of species. Species with fruits that are favoured by birds may be found under perch sites and not on open bare areas. The manner in which species establish on a site changes the way succession proceeds.

Pioneering species play an important role in the initiation of succession on a site. Establishing pioneering species on a drastically disturbed site can start the successional processes that re-establish the successional trajectories operating in a region (Photograph 5.1-1 and Photograph 5.1-2). The use of

pioneering species in restoration of drastically disturbed sites allows successional processes to provide the cover that is appropriate for the site if the seeds of these species are available and there are no filters preventing the establishment of these species. Pioneering species are used in soil bioengineering treatments and thus fit well within the successional approach to the restoration of drastically disturbed sites (Photograph 5.1-3).

5.2 Community Structure

1The structure of plant communities is an important part of ecosystem assembly as it influences the functions and processes associated with the ecosystem. Rebuilding appropriate community structure in restored ecosystems is an important consideration in the design of restoration programs. The structure in natural ecosystems changes as the ecosystem changes. Generally, older ecosystems (Photograph 5.2-1) tend to have more structure than younger ecosystems. In ecosystems disturbed by natural events such as fires and landslides, structure in the form of snags and downed woody debris from the previous ecosystem may remain as the new ecosystem establishes.

Large, drastically disturbed sites such as many mines generally lack structure. In these cases, structure can be built through the creation of rock piles (Photograph 5.2-2) or brush piles (5.2-3). These artificial structures can greatly enhance local biodiversity by providing habitat for small mammals and perching sites for birds. Trees with attached root wads can be established with the root wads turned up to provide sites for Osprey nesting (Photograph 5.2-4). Scattering woody debris (100 m^3/ha) can provide significant benefits for the restoration of ecosystems (Craig et al. 2014; Vinge and Piper 2012).

Physical modifications of the substrate such as occurs with the creation of rough and loose surface treatments (see Photograph 5.1-3 and 5.2-5) creates ecosystem structure that can be used by different species. Rough and loose surface treatments create different aspects relative to sunshine as well as different moisture regimes. In addition, as organic matter collects in the hollows, different species can exploit these sites.

5.3 Safe Sites

Safe sites are essential for the establishment of vegetation. Seeds need to be trapped in a location where the requirements for germination and growth are met. Many pioneering species have established specific mechanisms for ensuring these conditions are met. Willow (*Salix* spp.) and poplar (*Populus* spp.) seeds are carried on the wind by tufts of fluff. When these fruits fall into puddles or open water, they are blown to the margins where wet soil allows effective germination and growth (Photograph 5.3-1). Safe sites may also allow some species to establish and not others, or species may preferentially establish in certain sites and not in others. Pioneering species on rock cliffs such as Broad-leaved Stonecrop (*Sedum spathulifolium*) can establish in small crevices in rock faces where other species are precluded (Photograph 5.3-2). Understanding the safe site requirements of the species that are desired on a restoration site can contribute to the success in encouraging these species to establish.

5.4 Priority Effects

The ability of already established species to facilitate (see below) or constrain (filter) the establishment of subsequent species may be associated with the order in which the species arrive at a site. Priority effects (Temperton et al. 2004) is the term used to describe the influence previously established species have on newly arriving species. Priority effects can be important determinants where filters such as excessive herbivory are suddenly removed. The timing of removal may benefit some species growing on a site and not others. For instance in a mixed grass and forb meadow area removal of herbivory late in the growing season when the forbs have completed their annual growth (and it has been largely consumed) but before the grasses have finished growing and setting seed for the season will benefit the grasses to the detriment of the forbs. Conversely, removal of herbivory early in the season before the start of their seasonal growth may provide a competitive advantage to the forbs as their unconstrained growth may suppress the later growth of the grasses.

Species that can produce a dense shading cover quickly may prevent the growth of shade intolerant species if the shade producing species can get

established first. Similarly, species such as Himalayan Blackberry (*Rubus discolor*) or Giant Knotweed (*Polygonum sachalinense*) that are shade intolerant can prevent the establishment of other species if they grow first. Both of these species are non-native invasive species in British Columbia and can create conditions of successional stagnation (Kimmins 1987) if they get established before shade producing native species such as Red Alder (*Alnus rubra*) can establish. In some cases such as traditional grass and legume seeding on disturbed sites, the early establishment of a dense cover of seeded species can prevent the establishment of other species for many years.

5.5 Facilitation

Some species, often pioneering species, may assist in the establishment of other later successional species. The shade or organic matter produced by the pioneering species may provide conditions that are appropriate for the establishment and growth of the later successional species (Photograph 5.5-1). Early successional pioneering species are often deciduous. By establishing a canopy of deciduous species the cool, moist, conditions under the canopy produced by the transpiration of water by the deciduous species allow the understory conifers to grow better than if they were out in the hot summer sun. Some deciduous species are associated with nitrogen fixation such as with Alder, and in these cases the understory species get the benefit of the enhanced nitrogen in addition to the improved moisture and temperature conditions.

Facilitation can also occur with abiotic as well as biotic elements. Providing perches for birds can help establish species where the fleshy fruits are eaten by birds (see Photograph 5.2-2). Similarly, spore catching branches of trees can encourage the establishment of ferns and fungi when the spores are washed to the ground with rain. The role of facilitation within the context of natural successional processes can be very important and may help offset the impacts of competition on the establishment of some species.

5.6 Novel Ecosystems

Increasing influence of humans in the ecosystems of the earth, either intentionally or unintentionally, is creating conditions where combinations

of species are occurring that have never occurred before. These have been termed novel ecosystems or emerging ecosystems (Hobbs et al. 2006). It can be argued that the restoration of drastically disturbed ecosystems always results in the creation of novel ecosystems. Sites where mining and other significant disturbances have substantially altered the physical attributes of the ecosystems that are being restored can be considered to be novel ecosystems. Using this concept, the goal of restoration becomes one of re-establishing the ecological processes and functions (not specific species assemblages) that operated on the landscape prior to disturbances, not trying to re-establish the exact ecosystems.

A successional model for the restoration of drastically disturbed sites provides a good framework for success in the re-establishment of processes and functions on drastically disturbed sites (Polster 1989). By understanding how ecosystems are initiated on sites that are naturally disturbed (see photograph on title page), we can create successional trajectories that produce novel ecosystems that provide the processes and functions that existed prior to disturbance.

6.0 Natural Solutions to Common Filters

Natural systems have established a whole series of methods to re-establish functioning ecosystems on sites that have been naturally disturbed. By understanding how these natural systems operate, the emulation of these natural methods can be used to restore drastically disturbed sites. Reference ecosystems (undisturbed ecosystems that are thought to be similar to the disturbed site prior to disturbance) have been considered in restoration ecology for many years but have been recognized as providing an unclear pathway for restoring disturbed sites (Temperton et al. 2004). Looking at the pathways that natural ecosystems follow in the recovery process may be more effective than looking at an endpoint, which may, in fact, not be an endpoint at all. This section explores the natural solutions to common filters that constrain recovery. The application of these solutions for the restoration of anthropogenic disturbances may provide the most effective treatments for assisting the recovery of drastically disturbed sites.

6.1 RESILIENCE

Resilience is the ability of ecosystems to recover from disturbance and rebound in an essentially un-impacted state (Holling 1973). One of the primary goals of restoration is to develop ecosystems that are resilient. Disturbance elements (fires, floods/erosion, insect attack, etc.) may be more common in restored ecosystems than in natural, undisturbed ecosystems. It is therefore important when considering restoration options to think about how the ecosystem in its restored condition will respond to stresses. Creation of resilient ecosystems is an essential part of ecological restoration.

Riparian ecosystems can serve as a good example of sites where the restored ecosystem may be subjected to increased stress. Riparian restoration is often conducted on sites where human activities have degraded or destroyed the natural riparian conditions (see Photograph 6.1-1). Streams in agricultural areas where natural riparian vegetation has been removed often suffer from excessive streambank erosion and nutrient loading. The loss of woody vegetation on the banks weakens the bank structure resulting in susceptibility to erosion during high flow conditions. In addition, upland clearing increases the prevalence of flashy flows. Restoration of riparian areas under these conditions must consider how to create enhanced bank stability as well as an ecosystem that is capable of addressing the new stream flow conditions.

Pioneering vegetation that is adapted to establishing and growing under the extreme conditions of a bare site will perform much better than later successional vegetation that is adapted to growing under relatively stable conditions associated with later successional ecosystems. In Western Canada species such as Willows (*Salix* spp.), Alders (*Alnus* spp.) and Poplars (*Populus* spp.) are common pioneers of disturbed ecosystems. The adaptations of these species to the rigours of establishing on bare sites are shown in Table 6.1-1. The use of pioneering species for the restoration of drastically disturbed sites allows these adaptations to disturbance to be incorporated into the restored ecosystem, creating resilience in the newly established ecosystem. In addition, these species provide the conditions needed for later successional species to establish, thus initiating appropriate successional trajectories.

Table 6.1-1
Adaptations of Common British Columbian Woody Pioneering Species

Species	Adaptations
Willows (many species)	Regrow readily from root crowns; stems can be buried (layering); will send out new shoots when browsed; can be easily grown from dormant stem cuttings.
Balsam Poplar (*Populus balsamifera*)	Will send up suckers from roots and root crowns when main stem cut; stems can be buried; can be easily grown from dormant stem cuttings.
Aspen (*Populus tremuloides*)	Will send up suckers from roots and root crowns when main stem cut; can be grown from root cuttings (will not grow from stem cuttings); establishes readily from seed on appropriately prepared sites.
Red Alder (*Alnus rubra*)	Associated with nitrogen fixing bacteria; regrows readily from root crowns; establishes from seed on appropriately prepared sites.
Green Alder (*Alnus viridis* ssp. *crispa*) and Sitka Alder (*Alnus viridis* ssp. *sinuata*)	Associated with nitrogen fixing bacteria; regrow readily from root crowns; establish easily from seed on appropriately prepared sites.

6.2 Rough and Loose Surface Configurations

Erosion and compaction are some of the most common filters found on drastically disturbed sites. Creation of a rough and loose surface configuration is one of the simplest treatments for these conditions. The rough and loose surface configuration is modelled on the condition that is created when trees blow over (see Photographs 5.1-3, 5.2-5 and 6.2-2) bringing a fresh supply of non-mobile nutrients to the surface. Rough and loose surface configurations can be achieved by using a large excavator to open holes on the site, dumping the material that is generated from the holes in mounds between the holes. The excavator, using a digging bucket (not clean-up), takes a large bucket full of soil and places it to the left of the hole that was just opened, half a bucket width from the hole so it is half in and half out of the hole. A second hole is then excavated half a bucket width to the right of the first hole. Material from this hole is then placed between the first and second holes. A third hole is now opened half a bucket width to the right of the second hole, with the excavated soil being placed between the second and third holes.

Care should be taken when excavating the holes to shatter the material between the holes as the hole is dug. The process of making holes and dumping soil is continued until the reasonable operating swing of the excavator is reached. The excavator then backs up the width of a hole and repeats this process, being sure to line up the holes in the new row with the space between the holes (mounds) on the previous row.

Creation of rough and loose surface treatments provide structure to the ecosystems being restored (see Section 5.2 above). By providing a diversity of conditions, rough and loose surface treatments provide the opportunity for a diversity of species to establish. When rough and loose surface treatments are created in combination with the application of large woody debris, diversity is greatly enhanced. Rough and loose surface treatments provide a simple, inexpensive erosion control technique as well as creating a variety of other ecosystem enhancements that are unavailable to traditionally created smooth soil surfaces (Photograph 6.2-3). Creating a diversity of conditions in the physical environment can help produce a diversity of plant life resulting in an increase in the productivity of the site (Loreau 2010).

6.3 VEGETATION ESTABLISHMENT TECHNIQUES

Establishment of vegetation on drastically disturbed sites can be difficult. Once the filters to recovery (Section 4.0 above) have been addressed there may be a need to assist with the establishment of vegetation. There are three principle ways of establishing vegetation: by seed; from rooted seedlings; and vegetatively. These are discussed in the following sections. Table 6.3-1 provides a listing of the restoration related characteristics of some common Western Canadian species, including establishment techniques and seed numbers. Understanding the autecology of potential restoration species can help in determining the most effective manner of establishing these species on a specific restoration site.

6.3.1 ESTABLISHMENT FROM SEED

Seeding appropriate species on the restoration site can be a very effective method of establishing vegetation (see Photographs 5.1-1 and 5.1-2).

Seeding with agronomic grasses and legumes has been the historic means of treating drastically disturbed sites (see Photographs 4.1-1 and 4.2-3). In most cases, seeding sites with agronomic grasses and legumes has proven to be a problem that has locked many restoration sites into a successional dead-end. Seeding woody species or native grasses and forbs can be an effective way of establishing these species. Seed predation can be a problem with direct seeding and care must be taken to ensure carefully collected native seeds do not just become bird feed.

6.3.2 Establishment from Rooted Seedlings

Planting rooted seedlings of restoration species is commonly used to stretch limited seed resources to produce growing plants (Photograph 6.3-1). Tree planting is well established in forestry circles and effective strategies have been developed. A wide variety of species can be grown from seeds in nurseries and planted on restoration sites. Planting rooted seedlings requires that the seedlings that are suitable for the site being treated are available. This may require planning several years in advance of the actual planting as there may be a need to collect seed from the local area and to grow the seedlings. There are a variety of excellent references on the growth of native species (Pettinger and Costanzo 2002; Rose et al. 1998; Kruckeberg 1996).

Table 6.3-1
Some Useful Characteristics of Pioneering Woody Species[1]

Species [2]	Seed Numbers/Kg. (X 1,000)	Site Preferences (N Fixing)	Establishment
Acer macrophyllum	6.8	Moist, rich	from seed & rooted stock
Acer glabrum	28 - 44	Mesic	from seed & rooted stock
Alnus viridis ssp. *sinuata*	2,514	Mesic – moist, N fixing	from seed & rooted stock
Alnus rubra	1,468	Mesic – moist, N fixing	from seed & rooted stock
Amelanchier alnifolia	99 - 180.7	Mesic - dry	from seed, rooted stock & cuttings
Arctostaphylos uva-ursi	59 - 128	Dry	from seed, cuttings and layering
Betula papyrifera	1,300 - 9,100	Moist - mesic - dry	from seed & rooted stock
Ceanothus sanguineus	Unknown	Dry, N fixing	from seed & softwood cuttings
Ceanothus velutinus	282 - 291	Dry, N fixing	from seed & softwood cuttings
Cornus stolonifera	30 – 58 (380.6)	Moist, riparian	from seed, cuttings & rooted stock
Crataegus douglasii	47 - 52	Moist, riparian	from seed & root cuttings
Dryas drummondii	Unknown	Riparian gravel bars, N fixing	from seed
Elaeagnus commutata	7.5	Dry, well drained, N fixing	from seed & stem cuttings
Gaultheria shallon	10,670 [3]	Mesic - dry (varies)	from seed & stem cuttings
Holodiscus discolor	11,772	Mesic - dry	from fresh seed, poor from cuttings
Lonicera involucrata	50 - 105	Mesic to moist	from seed & cuttings
Populus balsamifera	6,684 [4]	Dry to wet	from seed & cuttings
Populus tremuloides	7,936	Mesic to dry	from seed & root cuttings
Prunus virginiana	12.8	Mesic	from rooted stock
Quercus garryana	0.1	Dry to very dry	from planted seed
Rhamnus purshiana	26.5	Moist to wet	from seed & cuttings
Rhododendron albiflorum	4,000 - 13,000	Moist to wet	from seed
Rosa spp.	62	Varies	from seed & cuttings
Rubus idaeus	723	Mesic	from seed, root cuttings & dividing clumps
Rubus parviflorus	unknown	Mesic to moist	from seed, root cuttings & dividing clumps
Rubus spectabilis	315	Moist	from seed, root cuttings & dividing clumps
Salix spp.	4,400 - 6,600	Mesic - moist - wet	from cuttings
Sambucus racemosa	575 - 630	Moist to wet	from seed & cuttings
Shepherdia canadensis	90 [5]	Mesic to dry, N. fixing	from seed & rooted stock
Sorbus sitchensis	145 - 385	Mesic to dry	from seed & rooted stock
Spiraea douglasii	4,400 ?	Moist to wet	from seed & cuttings
Symphoricarpos albus	165	Dry to very dry	from seed & root cuttings
Vaccinium spp.	unknown	Varies	from seed & rhizome cuttings
Viburnum edule	30 6	Mesic to moist	from seed, rhizome cuttings& stem cuttings

[1] Information derived from Comeau et al (1989); Dick (1974); Hardy BBT (1989); Haeussler and Coates (1986); Klinka et al (1989); Marchant and Sherlock (1984), USDA. (1948). Unless otherwise noted, cuttings refer to hardwood cuttings.
[2] Nomenclature following Douglas et al 1998 - 2002.
[3] Seed number for the related G. procumbens.
[4] Seed number for the related P. grandidentata.
[5] Seed number for the related S. argentea.
[6] Seed number for the related V. opulus.

6.3.3 VEGETATIVE ESTABLISHMENT

Some species can be established using vegetative techniques (Hartmann and Kester 1975; Haeussler and Coates 1986). Willows (*Salix* spp.), Red-osier Dogwood (*Cornus stolonifera*) and Balsam Poplar (*Populus balsamifera*) are common species in much of Canada that can be easily grown from cuttings (Photograph 6.3-2). Many of the soil bioengineering techniques discussed below require that the plants used for the structures root readily from dormant stem cuttings. Cuttings should be collected while the plant is dormant. Cutting woody vegetation in the fall and winter results in the maximum amount of growth. At this time of year, carbohydrates (stored photosynthates) are at their highest level in the plants. This allows the cutting to provide fresh growth in the spring without the benefit of further photosynthesis. Cutting woody plant stems in the fall and winter allows all of this stored energy to be expended in the growth of new roots and shoots during the spring and early summer before leaves have had a chance to develop.

New roots and shoots on the cuttings develop either from buds that developed in the axils of the leaves (axillary buds), or from other tissues in a process termed dedifferentiation. Buds arising from these are termed "adventitious" buds (Hartmann and Kester 1975). Axillary buds result in the growth of new shoots and roots from sites where there were leaves on the plant in the past, while adventitious buds result in the growth of new shoots and roots from either axillary locations or from other areas on the plant such as the cut end of the cutting. The growth of shoots that develop from axillary buds can be maximized by maximizing the number of such buds on the cutting. Always trimming a cutting above a fork in the cutting will help to maximize the number of such buds on the cutting. The encouragement of adventitious bud formation can be enhanced in some cases by wounding the stem. Callus tissue typically forms when plants have been wounded (cut), and may develop from the vascular cambium (just under the bark) or even the epidermal tissues. Although adventitious roots often appear to arise from under this callus tissue, the formation of callus and the formation of roots are generally independent (Hartmann and Kester 1975). Adventitious buds may therefore form at any location where these

tissues are present, (Easu 1960). In some species, such as willows, that are very easy to root, pre-formed (latent) bud initials are formed as the stem develops initially. These species have a variety of adaptations that allow them to function well as early pioneers. The presence of pre-formed root initials is one such adaptation, and allows these plants to regrow effectively after being buried.

Control of bud initiation and growth is maintained by plant hormones (auxins, cytokinins and gibberellins) released by the apical meristems (growing shoot tips) and other tissues of the plants. Removing these apical meristems results in development of axillary and adventitious buds, thus removing some of the hormonal influence provided by these tissues and allowing the subsequent development of roots, shoots and other plant structures (Salisbury and Ross 1969). Some artificial plant hormones can be helpful in encouraging the cuttings to develop roots, particularly in species that may otherwise be difficult to root. These are available commercially. Hartmann and Kester (1975) provide a detailed account of the influence of plant hormones and growth regulators in the initiation of root development.

Scheduling of restoration projects where cuttings are to be used to coincide with optimal collection periods allows the cuttings to be planted soon after collection, thus avoiding problems associated with storage of the cuttings. If cuttings are to be stored, they should be kept moist and at temperatures that minimize respiration (-1° to –4° C). Willow cuttings collected in February were successfully stored in a commercial cold storage unit and used at the end of June, well after the local flora had flushed (Polster 1992). Storage of willow cuttings buried in sawdust over the winter in Cranbrook did not change their rooting patterns compared with cuttings collected and planted immediately. Cuttings that are to be stored or transported for any significant distance should be left in as long pieces as possible. This will minimize moisture loss through cut surfaces. Similarly, small branches and twigs should be trimmed so that the stems can be easily handled. Where a significant number of cuttings are to be collected, it is suggested that the highest quality tools

(saws, clippers and loppers) available be obtained for use as the cost of these will be offset by improved productivity and reduced fatigue.

Stem cuttings may be hand pushed into very soft soils prior to flushing of the cutting species in the local area. Protection during sticking of cuttings may be provided through the use of "welder's gloves". Small rubber mallets, such as are used for automobile body work, can be used for driving cuttings into holes that have been opened in the soil using large steel planting bars. Cuttings should be inserted so that approximately three-quarters to seven-eighths of the cutting is buried in the soil. Stem cuttings that are approximately 50 to 60 cm long, up to 4 or 5 m and no less than 2.5 cm in diameter are most effectively used in restoration projects. In many cases, slipping the cuttings in at an angle can provide effective burial. The soil around the cutting should be in contact with the cutting so that moisture can be absorbed through the bark and the cut end of the cutting while the roots form and grow.

Cuttings that are collected from healthy, moderately rapidly growing parent plants will perform better than those collected from decadent, senescent stems although the tips of stems should be avoided. Marchant and Sherlock (1984) report that cutting material with low nitrogen/high carbohydrate reserve will root better than "exceptionally vigorous, "sappy" wood". Where significant amounts of restoration work is to be conducted in an area over several years, hedging of parent plants (cutting the parent plant and using the re-sprouts) can provide cutting stock. In many cases, local logging sites or power-line rights-of-way will provide an abundance of healthy pioneering woody plants that can be used for cuttings. Willows, for instance, may be found growing on the side cast side of roadways and on skid trails where mineral soils have been exposed. Power-line, pipeline, railroad and road rights-of-way often provide ideal sites for the collection cuttings as the vegetation in these areas is often maintained in an early seral state. Permission from the land owner must be obtained prior to collecting cuttings from any site. In the case of Crown Land, local Ministry of Forests officers can provide advice on appropriate locations for the collection of cuttings. Care must

be taken in the collection of cuttings to avoid environmentally sensitive sites such as stream banks or areas of heavy ungulate use.

Collected cuttings should be soaked for approximately 10 days prior to use (Schaff et al 2002). This removes rooting inhibitors and ensures the cuttings are fully hydrated prior to use (Shields 2000). The cuttings can stay in the water for up to a month depending on the temperature of the water. Roots will start to form on cuttings that have been kept in the water for extended periods. As these tend to be very fragile and break off when the cuttings are handled, development of roots on cuttings prior to installation is not desirable.

Direct planting of root cuttings may be used for the establishment of some species (Table 6.3-1). Although the collection and use of root cuttings is significantly more difficult than using stem cuttings, there are cases (e.g. Aspen) where root cuttings provide the best results and stem cuttings are not effective. As with stem cuttings, healthy, moderately rapidly growing roots that are one half to one centimetre in diameter will work most effectively. These should be collected during the dormant period of the parent plant when the parent plant has stored food reserves contained in the roots. Collections should be made well before any flushing of the parent plant in the spring (Hartmann and Kester 1975). Collection of root cuttings during clearing operations can provide an efficient means of collecting large quantities of suitable roots. Where the need for such cuttings is known in advance, opportunities to collect the cuttings can be used to good advantage. In most cases, root cuttings can be collected without interruption of the land clearing operation. Cuttings should be 5 to 15 cm long and at least 0.5 cm in diameter. Root cuttings must be planted with the proximal end (end towards the parent plant) up, or horizontally (Hartmann and Kester 1975). Root cuttings should be planted 2.5 to 5 cm deep (Hartmann and Kester 1975) to 5 to 7.5 cm deep (Dick 1974). As it may be difficult to determine which is the proximal and which is the distal end of a root cutting, Hartmann and Kester (1975) suggest cutting one end with a straight cut while the other end is cut on a slant, keeping in mind which

is which. Root cuttings should be kept moist, and planted at the restoration site as soon as weather conditions allow.

Layering is where a branch from a living plant that is still attached to the parent plant is laid down on the soil, maybe dug in under the soil or held down with a rock and then grows roots and shoots to become a new plant. Western Redcedar (*Thuja plicata*), Junipers (*Juniperus* spp.) and Kinnikinnick (*Arctostaphylos uva-ursi*) in addition to Willows, Red-osier Dogwood and Balsam Poplar can be established by layering. Vegetative treatments can be effective means of establishing plants on restoration.

6.4 SOIL BIOENGINEERING TREATMENTS

Soil bioengineering is the use of living plant materials to perform some engineering function (Schiechtl 1980), whether it be erosion control through the establishment of emergent aquatic vegetation along a shoreline, or installation of live pole drains to control sub-surface moisture or a variety of other treatments. Soil bioengineering is therefore a hybrid between the traditionally utilized hard engineering solutions and the more conventional reclamation sciences. Soil bioengineering is particularly useful as a tool in the development of effective restoration projects on difficult sites. Soil bioengineering is used to overcome some of the filters such as steep, unstable slopes that prevent natural recovery of drastically disturbed sites. Soil bioengineering can be used to re-establish successional trajectories on disturbed sites. The following sections provide details of the plant species that are useful in the development of soil bioengineering projects, timing of soil bioengineering works, key elements for success of projects and some specific techniques. For a detailed treatment of soil bioengineering, the reader is referred to N.K. Horstman's translation of Schiechtl (1980) and the more recent books by Schiechtl and Stern (1996 and 1997).

Soil bioengineering fits neatly into the framework of successional reclamation (Polster 1989; Polster 1991; Walker et al. 2007; Walker and del Moral 2003) and thus is an ideal approach in the restoration of

degraded or damaged sites. The science of soil bioengineering is in its infancy in North America, and there are many opportunities for restoration practitioners to be creative in the design and development of soil bioengineering solutions to restoration problems.

Soil bioengineering projects are typically undertaken where site conditions preclude the use of more standard approaches to reclamation. Sites such as slides and slumps, eroding streams and watercourses, sites that have been buried by erosion from adjacent sites, and habitats that have been damaged due to industrial activities, are all candidates for the use of soil bioengineering techniques. Soil bioengineering can be used to address common filters such as erosion that are preventing natural recovery. The pioneering plant species that naturally establish on disturbed sites can be used for soil bioengineering.

Woody pioneering species, some of which are suitable for soil bioengineering projects are listed in Table 6.3-1. In addition to the species listed in Table 6.3-1, there are a wide variety of herbaceous species and later successional species that may be applicable to use in certain soil bioengineering projects. Defining suitable species for all such projects is therefore of limited value. A wetland sedge that might be used in the re-establishment of a wave protecting cover on the shores of a lake that have been damaged by cattle, will be of little value in the establishment of a suitable vegetation cover on debris left after a landslide. The following discussion focuses on the role the plants are to play in the project rather than the specific species. The appropriate species are selected on the basis of their role in the soil bioengineering project, and from their presence in the local flora.

Many soil bioengineering projects entail the development of stout, structural elements, such as retaining walls or drains that require the use of strong woody vegetation. In addition, if the plants used in the soil bioengineering are to grow and thus make the constructed structure stronger with age, they must be able to do so within the context of the soil bioengineering system. There is no point in selecting a species that requires 2 months to initiate root development if the shoots, and

therefore significant moisture loss, start to develop in a week; the plant would just die due to moisture stress.

Willows (*Salix* spp.) are ideal for use in many soil bioengineering projects. Willows sprout both roots and shoots rapidly due to preformed buds that lie dormant under the bark (see Section 6.3.3). These plants are early pioneers on many disturbed sites, and the adaptations that make them successful as pioneers also make them useful for soil bioengineering work. Many willow species grow straight strong stems that can be used to build soil bioengineering structures, the exceptions being the dwarf alpine species and some of the upper elevation shrubby species. Willow stems can be easily collected in large quantities for use in soil bioengineering systems without significant damage to the stand. This is because they will readily sprout and grow new stems to replace those harvested for the soil bioengineering. In some cases, it may be advantageous to actually culture willow stands for future soil bioengineering projects by trimming back older stems and allowing new stems to develop. Willows can be used to provide an initial stabilizing cover on a drastically disturbed site that as the plants age, allows later successional species to establish. Thus willows can fulfil both the structural and ecological role required in many soil bioengineering projects.

Willows lack associations with nitrogen fixing bacteria (as far as we know) and do not contribute to improved soil fertility. Species such as alder (*Alnus*) are associated with nitrogen fixing bacteria but do not have the ability to sprout from stem cuttings. Selection of species for soil bioengineering projects should be made on the basis of what these species can contribute to the site or to other species that might move into the site. Association with bacteria (and other groups) that can "fix" nitrogen and make it available for plant use is an attribute that many pioneering species share. It may be prudent to select such species for use in soil bioengineering projects where nutrients are limited and where the ability to fix nitrogen will enhance the nutrient status of the site and allow other plants to establish.

Balsam Poplar (*Populus balsamifera* L.) and Red-osier Dogwood (*Cornus stolonifera* Michx.) are useful species for soil bioengineering projects. Balsam Poplar can be found in many areas with limited moisture, although it is commonly found in riparian areas. Red-osier Dogwood does well in shady locations such as along streambanks and under forest canopies. Both of these species can complement the use of willow in the development of soil bioengineering treatments.

Alder is a particularly useful species that is associated with the nitrogen fixing Actinomycetes (filamentous bacteria). The bacterial genus *Frankia* removes atmospheric nitrogen and "fixes" it, thus making it available to the alder that in turn provide a suitable environment for the *Frankia*. Alder is often one of the first woody species to invade disturbed mineral soils. Red alder (*Alnus rubra*) can form dense stands on old logging roads, in gravel pits and on landings (Pojar and MacKinnon 1994). Although this species may compete with conifers initially, enhancement of the nutrient status of these sites is sufficient to allow conifers to grow well on sites once occupied by alder. Reports of improved conifer growth associated with Alder are found in the literature (Comeau et al 1989). Haeussler and Coates (1986) report nitrogen accretion rates of from 45 to 335 kg/ha/year. This may be sufficient to "carry" coastal forests through the long (+/- 1,000 years) natural rotations. Sitka alder (*Alnus viridis* ssp. *sinuata*) has been used as "nurse crop" for conifers in the British Columbia Interior on sites that have been drastically disturbed by industrial activities (Polster 1987). In this case, the alder was used to provide nitrogen, enhance site nutrient status and to provide a suitable micro-site for conifer growth. The alder, which is deciduous, allows soils to warm in the early spring while later in the season, the cover of alder reduces transpirational losses and enhances photosynthesis by providing protection from the extremes of direct exposure to sun and wind. Alder may enhance the development of nutrient cycling in the restored ecosystem through nitrogen enrichment and the establishment of greater diversity of micro-sites. Alder in fresh cut-blocks may assist in the breakdown of old conifer roots that might otherwise transmit pathogens to young conifer trees.

In soil bioengineering, alder can be used as a secondary species once the work of the primary species, such as the structural willows, has been completed. Planting of rooted alder stock or seeding in alder on stabilized slide areas and other mineral soil sites can set the stage for the successional advancement of sites by providing nutrients and additional stability. Red alder seed has been successfully mixed with the grass and legume seed and applied to landslides in the Clayoquot Sound area of British Columbia while Sitka alder has been successfully seeded onto steep rock cuts in the Rogers Pass area of the Province. Both of these treatments would have been more effective if the grasses and legumes had not been included with the alder seed. Alder densities must be managed so that further successional advancement of the site can proceed. Alder densities of from several hundred to several thousand per hectare will provide the beneficial effects of the alder while not limiting further successional advancement. Alder can play a significant role in the amelioration of adverse conditions in damaged ecosystems and on soil bioengineering projects.

There are a variety of other woody species that are associated with nitrogen fixing bacteria (Table 6.3-1) and that are therefore useful as secondary species in the development of soil bioengineering solutions to restoration problems. Species such as *Ceanothus, Dryas, Elaeagnus* and *Shepherdia* can be established on soil bioengineering sites to aid in the further successional development of the site. Species that enhance the site conditions and encourage successional advancement of the vegetation on the site are found in the pioneering vegetation of all ecosystems. These should be sought and developed for use in soil bioengineering projects.

In addition to plants that encourage greater phyto-diversity, plant species that will enhance the invasion and use of the site by a diversity of other organisms will assist in the re-establishment of the functions of the ecosystem. The tendency of contractors and owners to neatly "clean up" sites and to reduce site diversity in the process should be curbed in the development of soil bioengineering solutions. Incorporation of a diversity of substrates, including old stumps and logs as well as rocks, in

the soil bioengineering project will encourage the invasion of the site by a diversity of both plants and animals. In many cases, seeds and propagules contained in stumps and roots masses will assist in the establishment of additional species. These will in turn, encourage the establishment of a variety of other organisms. Plants that provide foods and habitat for vertebrates should also be considered for soil bioengineering sites as these will help to re-integrate the site into the surrounding ecosystem webs. Shrubs such as *Shepherdia* that fix nitrogen and provide wildlife food can be a useful addition to dry site restoration projects, while species such as *Typha latifolia* can provide both the structural elements for a wetland shoreline restoration project (wave protection and energy damping) and habitat for wildlife. Increasing the diversity of both plants and animals that inhabit a soil bioengineering site will enhance the ecological stability and productivity (Loreau 2010) of the site.

Soil bioengineering projects are most effectively conducted when the site being treated is fresh and new. In most cases where soil bioengineering will be used to aid in the restoration of drastically disturbed sites, conditions of the site will worsen over time, and damage to adjacent ecosystems will increase the longer the site is left untreated. For this reason, restoration projects that involve soil bioengineering solutions should be conducted as soon after the disturbance initiating event as possible. For instance, on a site where excess soil moisture has caused a fill slope failure along a logging road, rapid repair of the site will conserve fine textured soil materials, thus aiding in the revegetation of the slope and preventing additional materials from eroding. Erosional processes will cause the loss of fine textured soil materials and will result in the development of a "stone pavement" on the soil surface. In addition, some soils surfaces become increasingly compacted as they age after a disturbance as moisture slowly drains and the fine textured particles move downward in the soil profile. This makes the installation of cuttings and other soil bioengineering structures difficult and reduces the probability of success.

Active erosion should be treated as soon as possible to minimize the impact of this erosion on both the site and adjacent ecosystems. Slumping over-steepened cut slopes may regress significant distances up the slope over the years as the site ages, resulting in an increase in the area requiring restoration and often an increased difficulty in access. Eroding gullies will deepen as time progresses, making repairs that much more difficult. Slopes and other sites that are eroding pose a threat of additional damage to adjacent ecosystems. Downslope movement of fine textured soil materials can bury adjacent sites and eventually enter water courses with subsequent damage to aquatic systems. It may be prudent to incorporate some immediate erosion protection measures, such as scattering leaf litter, in with the design of soil bioengineering projects to avoid these negative impacts. Abiotic methods for temporary control of erosion will be specific to the site being treated. Consideration should be given to using living materials for erosion protection. Living plant materials can be placed with rock or large organic debris to protect eroding sites. The use of living plant materials to protect actively eroding sites can have the added benefit of providing additional growth in subsequent years. Placement of large quantities of full plant cuttings in erosion gullies can act to slow active erosion as well as providing living materials from which new plants can grow. These can then be incorporated into the soil bioengineering designs when the period of active erosion passes. Prompt action on the part of the restoration practitioner can serve to minimize the damage and start the process of restoration.

Soil bioengineering projects are typically conducted at times of the year when weather conditions are poor relative to human comfort. Plant materials such as willow cuttings are most effectively taken and used during their dormant period that generally coincides with periods of inclement weather. These conditions, however, provide the best results for the cuttings as cool, moist weather reduces moisture stresses and slows metabolism. Willow stem cuttings will typically develop large shoot volumes relative to roots soon after planting. This imbalance can lead to moisture stress in the new planting if soil moisture levels are low.

Planning programs to be conducted during the dormant period of the plants will minimize the stress on the plant materials.

Soil bioengineering work should be undertaken when local climatic conditions will be most favourable for growth of the living materials. Climatic records, available as climatic normals from the Atmospheric Environment Service of Environment Canada website, should be consulted to determine the best times for conducting the work proposed. Consideration should be given to the types of weather patterns that might be anticipated during the period when the soil bioengineering work is to be conducted. For instance, steep slope work that is undertaken during periods when intense rain storms are expected might result in a significant loss of materials. Work on the same steep slopes during a time when gentle drizzles are the norm and when temperatures are appropriate for the growth of the planted species will have a far greater chance of success. There will be situations where, after determining the optimum time for conducting soil bioengineering work, abnormal weather patterns result in conditions that would be adverse. At these times, it may be best to delay the proposed program until more favourable weather conditions return. Checking with the forecasters at Environment Canada can aid in determining the appropriate course of action during periods of adverse weather.

Timing constraints can sometimes be ameliorated by techniques such as watering planted materials, cold storage of rooted stock and cuttings and holding rooted stock in nurseries until favourable weather occurs. Plant materials that are manipulated in these ways to accommodate external timing constraints will be adversely affected and may be prone to disease and poor growth patterns. It is advisable to avoid such situations where possible.

Soil bioengineering projects typically stretch the limits of disturbed site solutions that can be achieved using vegetation. Sites that could be restored using conventional hard engineering solutions can, in many cases, take advantage of the environmentally compatible soil bioengineering techniques and thus be restored using methods that will

enhance the future productivity of the site. There will be situations where soil bioengineering solutions fail to provide the stability required for further integration of the site into the natural successional pathways. In these cases, the advice of qualified engineering personnel should be sought.

Restoration practitioners are encouraged to incorporate diversity in the development of soil bioengineering projects, as the greater the diversity incorporated into the design of a project the greater the chance that appropriate ecosystem elements will be available for the natural processes of site healing to take over the work of restoration. Methods that enhance the diversity of a soil bioengineering site will depend on the site and the circumstances of the restoration project. However, inclusion of materials such as old stumps, rocks, and rotting logs as well as a variety of living materials, in the design for a project can aid in the encouragement of diversity. For instance, where a steep slope is topped by an overhanging mat of forest duff, stumps and roots, the soil bioengineering design may require that this mat be cut off so that the crest of the slope can be rounded and future sloughing can be minimized. The duff mat should then be incorporated into the face of the slope below the crest so that the benefits of this material (i.e. seeds, organic matter, micro-organisms, etc.) can be exploited in the restoration of the slope. Such use of the duff mat would mimic the natural restoration of the slope, although the use of the mat may cause the site to "look untidy". By incorporating measures of diversity in the design for restoration, natural restoration processes can be enhanced.

The following sections provide details of soil bioengineering systems that have been used in Canada for the stabilization and treatment of difficult sites.

6.4.1 WATTLE FENCES

Wattle fences are short retaining walls built of living cuttings (Figure 6.4-1). These walls take up the vertical component of the slope, reducing the effective slope angle and allowing vegetation to become established (Photographs 6.4-1 and 6.4-2). In addition, the living cuttings sprout

and grow, thus further strengthening the structure. Wattle fences are used where site moisture conditions will allow the living cuttings on the face of the fence to sprout and grow. Sites where fine textured soils can provide ample summer moisture or where seepage of groundwater provides moisture are suitable for wattle fence installations.

Wattle fences provide breaks in the slope and can therefore reduce the impact of rolling materials on vegetation growing lower on the slopes. In many cases, vegetation will have difficulty in becoming established where it is being constantly bombarded by materials from above. Wattle fences can protect vegetation growing lower on the slope and can assist in the revegetation of the sites through protection from rolling rocks and sliding debris.

Wattle fences are used to reduce the effective slope of over-steepened areas without actually changing the overall slope (Photograph 6.4-3). They are most effective where moisture is plentiful and where the cuttings used to construct the fences will not dry out. In this regard, backfilling the fences with fine texture materials will assist in providing moisture during dry summer periods. The first year of fence growth is the most critical as it is at this time that the cuttings may show significant amounts of shoot growth with little supporting root growth. This causes summer desiccation. Wattle fences provide rows of growing vegetation. Willows can continue to grow when buried and therefore provide a good plant material for wattle fences where falling materials are expected to bury vegetation growing lower on the slopes.

Wattle fences can provide support for small (up to 30 cm deep) translational soil slumps or where excess soil moisture results in small (1 2 m deep) rotational failures of surface materials. In these cases, the wattle fences allow moisture to drain through the face of the fence while the soils are retained behind the fence. Where slumps are particularly soupy, the branches and twigs may be retained on the cuttings to provide additional support of the wet soils. Wattle fences can be used in combination with live pole drains (see below) to support the slumps while the live pole drains provide drainage of the excess moisture.

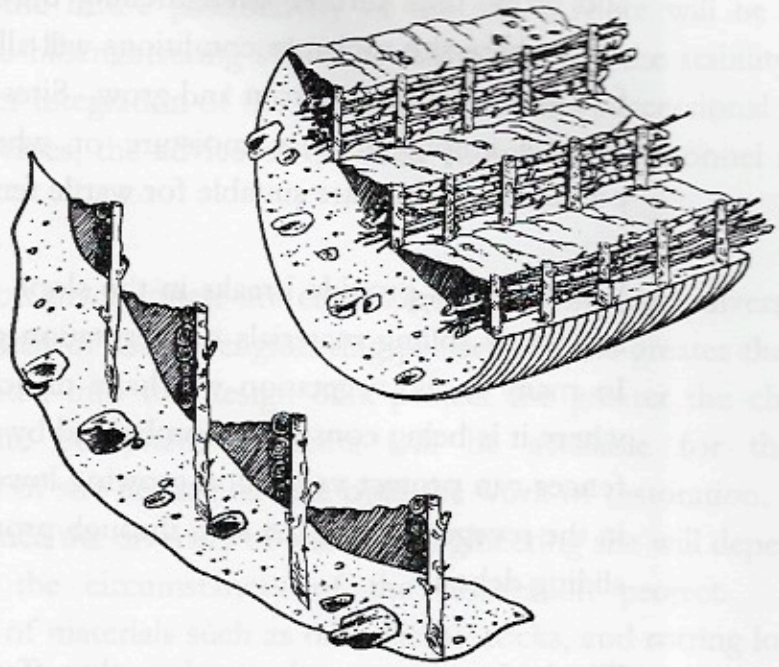


Figure 6.4-1. Wattle fences are short retaining walls constructed of living cuttings. They are used to provide slopes that will support plant growth where over-steepened slopes are preventing plant establishment. On steeper slopes, wattle fences are constructed closer together. Wattle fences have been successfully used on slopes that are as steep as 70 degrees (see Photographs 6.4-1 and 6.4-2).

Wattle fences are constructed by establishing the supporting cuttings in a row in the ground and placing the cuttings behind these supports. It is useful to start with all the butt ends of the cuttings at one end of the wattle fence as these can be organized to be fairly tight together while the soil is added (see Photograph 6.4-4). Soil materials are then backfilled behind the cuttings and additional cuttings are added moving down the fence to increase the height of the fence. Additional soil materials are backfilled behind these cuttings until the final height of the fence is reached taking care to pry the tip ends of the cuttings up against the posts so a tight fence is made. Wattle fences should be no higher than about 30 cm as toppling can occur due to the weight of the soil backfilling the fence. Resloping behind the fence should be conducted to create a slope of about 2:1 or less between the top of the fence and the bottom of the fence above. Wattle fences are constructed from the bottom of the slope up the slope so that workers may have a place to stand while additional fences are constructed.

6.4.2 LIVE POLE DRAINS

Live pole drains are constructed of bundles of living cuttings and are used to provide stability to sites where excess soil moisture results in soil instabilities (Photograph 6.4-5). The bundles of cuttings are placed in shallow trenches in such a manner that they intersect and collect the moisture. The bundles are then lightly buried with local materials, taking care to avoid over-burial. Careful trimming of the cuttings is not required, although the bundles should be as tight as possible. The plants used to form the bundles sprout and grow, with the moisture continuing to drain from the lower end. Sites where excess soil moisture results in site instability can be treated with live pole drains. Traditional engineering solutions often entail the installation of "French drains" or loading the face of the slope with rock. However, live pole drains can be used to drain excess moisture from the site and provide a cover of woody vegetation. The growth from the live pole drains forms the initial cover on the seepage site, allowing other species to invade. As with other soil bioengineering techniques, live pole drains must be designed to suit the specific conditions of the site.

Live pole drains act to provide a preferred flow path for soil moisture. The moisture moves into the drain bundle and runs down the cuttings to the end of the drain. Numerous bundles can be fitted together to make long drains. The drains immediately start to drain the slope. The drains shown in Photograph 6.4-5, installed in 1985 continue to drain moisture from this slope. As the roots of cuttings used to construct the drain grow out from the bundle into the surrounding soils, the cavity provided by the drain is preserved even when the original cuttings have been lost over the years (Photograph 6.4-6 and 6.4-7).

A variety of different shapes can be used for the drains depending on the site conditions. A "Y" pattern of the drains can be used to collect moisture from a diffuse seepage zone while a linear pattern can be used where a discrete seepage site exists. The objective in design of the drains is to collect all of the moisture to drain away as quickly as possible. The drains grow into a dense stand of hydrophytic vegetation, which is exactly what nature would produce given enough time. This technique

fits into the successional restoration scheme better than conventional "French" drains would. In addition, live pole drains can be installed without machine access and at fraction of the cost of traditional hard engineering solutions. Soil slumps such as those that occur the first spring after road construction or deconstruction operations can be stabilized using live pole drains.

Figure 6.4-2. Live pole drains can be used to stabilize slumping soils. This view shows the layout of live pole drains in a slump with the covering soils removed for clarity. The section shows a typical covering (1 - 2cm). Some twigs from the bundles should be left above ground.

Live pole drains are constructed by excavating a shallow trench from the site of seepage down the slope and away from the problem area. A bundle of cuttings is placed in the trench and lightly backfilled with local materials. The bundle is composed of cuttings with tips and butts alternating. The bundle is tied with degradable bailing twine or mechanics wire as tightly as possible. Twigs and branches down to pencil sized twigs should be kept on the cuttings where possible as long as this does not result in too loose a bundle. Avoid retaining any twigs with buds on them as these will produce shoots before the roots have a chance to grow. Sites that are particularly wet may require rocks to hold the bundles down in the trench. In these cases, it may not be possible to

actually excavate the trench, and the bundles can be inserted by standing on them and pushing them down into the mud. The key to live pole drain construction is to establish the drains in the area of seepage so that the drains provide a controlled alternative for the moisture to escape from the bank. In some cases where the flow capacity of the soils are low (high clay content) it may not be possible to drain a site using live pole drains. Where this occurs, live staking (see 6.4.8) can be used as a dense root system will draw moisture from the site.

6.4.3 Modified Brush Layers

Modified brush layers are essentially a brush layer (Gray and Leiser 1982) supported on a short (2 m long), small log or board. The use of a log or board for support of the brush layer provides the initial added advantage that the small terrace that is created can serve to "catch" rolling rocks rather than allowing them to roll down the slope, gathering speed and damaging vegetation. Although the log will eventually rot, the cuttings will by that time have grown to the point where they are stabilizing the slope. As the cuttings that are used in the brush layer grow, the wall of plants will also serve to trap rocks and soil and prevent movement of materials down the slope, thus further protecting vegetation on the slopes. Modified brush layers can be used on sites that would be too dry for effective wattle fence growth but where some form of additional support is needed for stabilization of the slopes (Photograph 6.4-8).

Logs (about 30 cm in diameter) or boards (5 cm by 25 cm (2" by 10")) approximately 2 m in length are used for the modified brush layers. This allows a large number of modified brush layers to be established on the slope rather than one or several long ones. This has the advantage of providing separate, independent structures so that if a very large rock comes down and destroys one of the modified brush layers, there are still others to do the work. Many soil bioengineering systems use this "strength in numbers" concept.

Live cuttings are used to hold the modified brush layers in place. Stakes that are about 1.25 m long have been found to be best for support of modified brush layers. Willow or Balsam Poplar cuttings are used for

the modified brush layers. These are collected locally. Logs, if selected, can often be collected from the cut blocks adjacent to the slides or from slash piles in the local area. In many cases however, the costs associated with collection of local logs is significantly greater than the cost of buying a comparable cedar board (5 cm by 25 cm or 5 cm by 30 cm rough cut). In shady areas, Red-osier Dogwood can be used for the stakes and shade-loving plants like Swordferns can be planted on the benches.

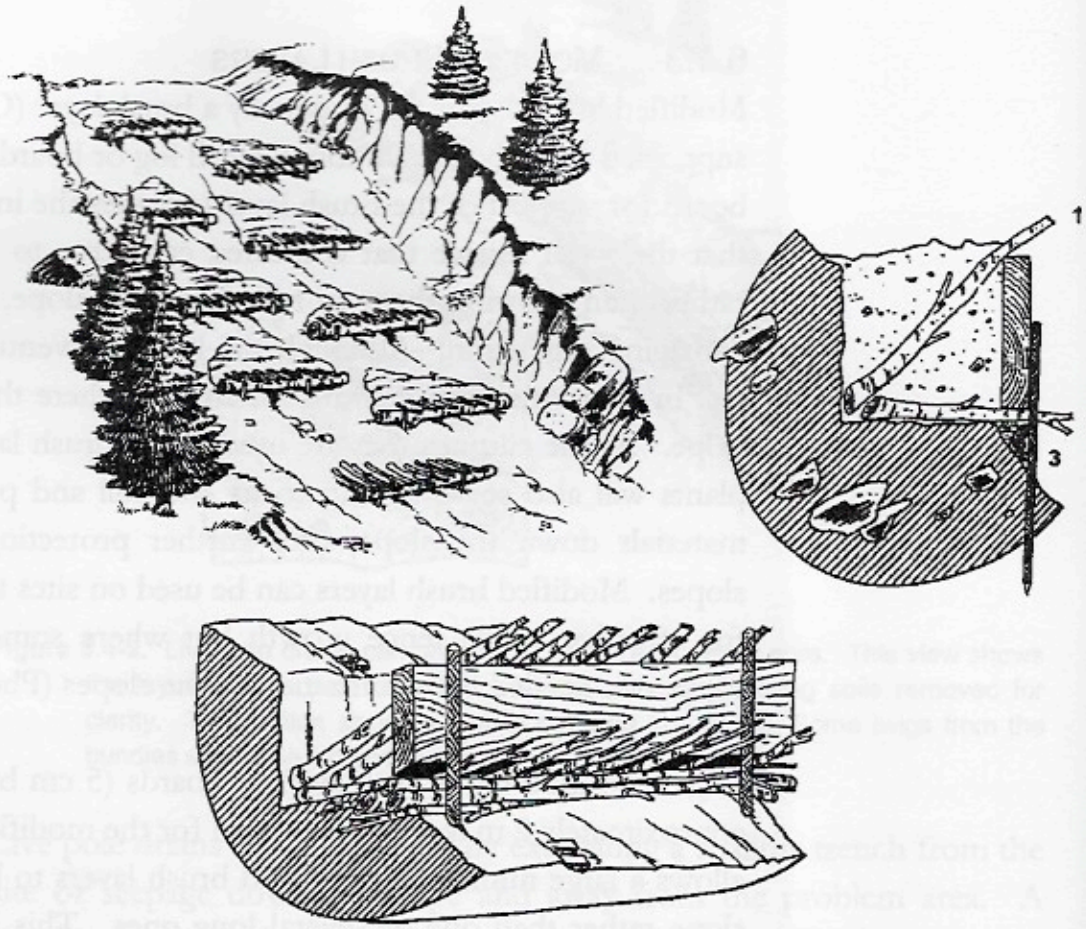


Figure 6.4-3. Modified brush layers should be staggered across the slope (left). Three different positions for placement of cuttings are shown in the diagram on the right. Boards or logs can be used for support. On mesic sites, modified brush layers should be built with the cuttings above the board or log ("1"). On dry sites, the cuttings should go below the board or log (2), while on very moist sites a small wattle fence can be installed below the board or log (3) to provide drainage.

The modified brush layers are constructed by initially establishing the stakes in the ground. The stakes should be placed one-quarter of the way in from the ends of the board as this provides the position of least

stress (zero moment). The log or board is then placed above the stakes on the slope, and an initial bench is created by back filling behind the log or board. The cuttings are then placed on the bench and backfill is pulled down to cover the cuttings. Stakes can be driven into holes that have been created using large steel bars with pointed tips. On most slopes, the modified brush layers are established in a staggered pattern about 2 to 3 meters apart. However, on steeper slopes, the distance between the structures should be reduced. Like wattle fences, modified brush layers should be built from the bottom of the slopes to the tops thus proving places for the workers to stand as they construct additional structures.

Variations of the modified brush layer designs, as shown above, have been used successfully in a variety of locations. Cuttings can be placed below the board or log, poking out from under the wood ("2" in Figure 6.4-3). This is useful where moisture may be limiting. In places where there is ample moisture, a few willow cuttings can be laid below the board against the supporting stakes, much like in a wattle fence ("3" above) to provide drainage. Cuttings can also be place out the ends of the structure and in the backfill behind the structure. The key is to provide the bench to control movement of material on the slope and to provide living plants to take over the function of catching falling material once the board or log rots away. As with most soil bioengineering systems, once there is an understanding of the principles associated with the system, a wide variety of specific designs can be used.

6.4.4 Brush Layers

Brush layers are horizontal rows of cuttings buried either in a fill (pulled back road) or cut (in-situ materials) such as the scour zone of a slide. Brush layers in fills are particularly useful where roads are being deactivated and the fill materials must be placed on steep (1.5:1 or steeper) angles due to the geometry of the site. They can also be used around culverts where fills are over-steepened. In these cases, cuttings (1.5 to 3 or 4 m long) can be inserted into the fills as they are constructed and can assist in creating a cohesive mass from the fill material. The cuttings can act like the bands placed in reinforced earth

structures and can give significant mechanical strength to the fill even before they start to grow. As the living cuttings sprout and take root, this strength increases. The cuttings act to increase the shear resistance of the soil and therefore reduce the possibility of rotational or translational failures.

Rooted plants such as alder can be added to the brush layer to create a hedge brush layer (Schiechtl and Stern 1996). This has the advantage of adding a nitrogen fixing species to the site. Other rooted stock such as native roses or elderberry can be added to brush layers to provide specific functions.

The development of brush layers in fills may be particularly useful in situations where local over-steepening of the fill is required and incorporation of brush would be useful. Sites such as where gullies cross roads that are being deactivated are candidates for incorporation of brush layers in the pulled back fill. In these cases, the brush layers will provide stability to the fill and will eventually result in the development of shrubby vegetation along the gully. Scheduling requirements for the use of cuttings may dictate that machine work be organized for these sites at times when cuttings can be used. The use of excavators to assist in the establishment of brush layers in a fill can greatly expedite production. Brush layers can be used to provide strength to backfilled or re-contoured gullies where the water that originally caused the gully has been removed.

In cuts or native ground, brush layers are constructed by digging a trench or bench across the slope and placing the cuttings perpendicular to the trench. These are built from the bottom of the slope so that the second excavation can be used to backfill the first and so on up the slope. Brush layers in cuts add little to the stability of the cut as no significant bench is created by the brush layer as in a modified brush layer and the cuttings are not deep enough to provide substantial mechanical stability as in a brush layer is built into a fill. Modified brush layers are easier to build and provide more immediate stabilization than brush layers on a cut.

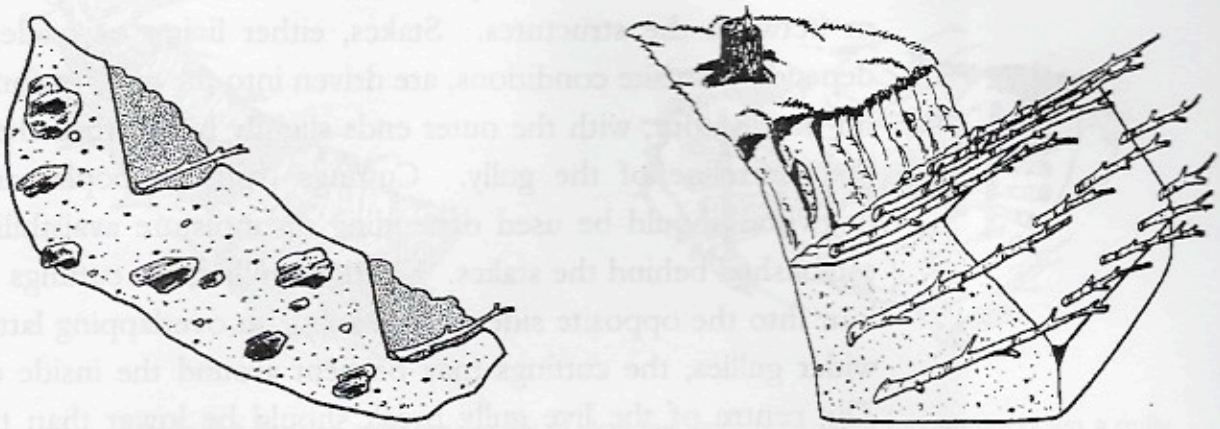


Figure 6.4-4. Brush layers can be used on a cut slope (above left), to treat a slump (Photograph 6.4-9) or a fill slope (above right). When used in a fill, full-length cuttings can be used and can act as soil reinforcement.

6.4.5 Live Gully Breaks

Live gully breaks are large wattle fences built in gullies to control the initiation of debris torrents. Where gully torrents originate from minor collapses of gully sidewalls, live gully breaks can assist in reducing the potential for torrents to initiate. Live gully breaks act by controlling the initiation of torrents rather than attempting to control the torrent once it gets moving. As this is the case, the live gully breaks must be established high in the channel where torrents are initiated. Live gully breaks can be helpful in the revegetation and stabilization of gullies that have already experienced debris flows by providing sites where materials may be trapped and where vegetation can become established. As with any soil bioengineering system, live gully breaks will strengthen with age. Broad (5 m) live gully breaks can be used to hold flowing silts on slopes. In this case, the live gully breaks are shaped like smiles (see 6.4.10 Live Smiles) on the slope, with the ends about 1 m above the centre of the structure. Backfill in these cases is left level so that flowing material may be caught on the bench.

Live gully breaks can be established in smaller gullies where torrenting has occurred or is expected to occur. Working from the bottom, the breaks are established at intervals up the gully. Spacing of the live gully

breaks depends on the steepness of the channel but ranges from 5 to 10 m between the structures. Stakes, either living or made from rebar depending on site conditions, are driven into the gully to form a crescent on the contour, with the outer ends slightly higher than the stakes near the centreline of the gully. Cuttings (willows, poplar and red-osier dogwood should be used depending on moisture availability) are then established behind the stakes. For tight gullies, the cuttings may need to butt into the opposite side wall, forming an overlapping lattice while on wider gullies, the cuttings may be bent around the inside of the gully. The centre of the live gully break should be lower than the wings to prevent water from flowing out along the wings and creating a problem. The gully breaks may be backfilled with local materials. In some cases, it is useful to provide a rock drain in the centre of the gully break to allow water to flow through, although care must be taken to provide fine textured materials for most of the backfilling. Backfilling should create a small terrace in the gully that will trap additional materials.

Live gully breaks will act to trap materials that would otherwise serve to initiate a debris torrent. The physical structure of the live gully breaks will serve this purpose initially while the growth of the cuttings and the establishment of rows of willows will provide long term control of materials. Willows will continue to grow even when deeply buried and will reinforce the soil through the growth of roots. Roots from the willows used in the live gully breaks will provide substantial reinforcement of the soils. Root tensile strengths of birch (expected to be similar to willow) have been measured to be 464 kg/cm^2 for root sizes less than 2 mm (Gray and Leiser, 1982), while spruce - hemlock roots were found to have a strength of 102 kg/cm^2 for root sizes less than 2 mm (Gray and Leiser, 1982). Coastal Douglas-fir roots were found to have a tensile strength of 578 kg/cm^2 for root sizes less than 2 mm (Gray and Leiser, 1982). Creation of large reinforced wedges of material in the gullies through the establishment of live gully breaks will assist in the control of debris torrents and the subsequent deterioration of downstream aquatic habitats. Live gully breaks act by creating numerous small structures high on the slopes rather than creating massive engineered structures to trap debris down below.

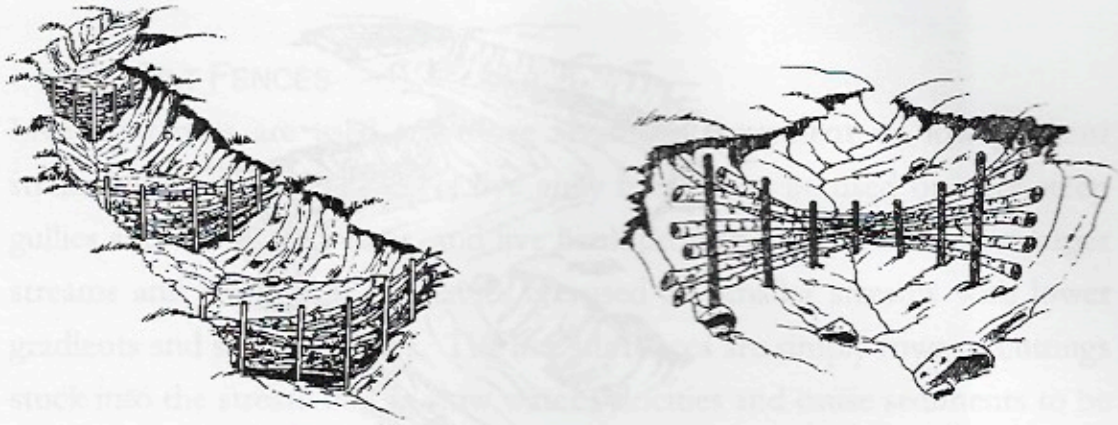


Figure 6.4-5. Live gully breaks act to slow the velocity of water movement down a gully and thus to trap sediments. Debris flows can be controlled by establishing live gully breaks in the trigger zone of a gully. In narrow gullies (above right) the cuttings are crossed at the back of the gully with the tips higher than the centre while in wider gullies (below right and photo) the structure is more like a "U" shaped wattle fence.

6.4.6 LIVE BANK PROTECTION

Live bank protection provides a means of stabilizing stream sides that may have become destabilized. Live bank protection structures are wattle fences (see above) built to protect the bank from the scouring action of streams. The typical arrangement for live bank protection provides the structure on the bends of the stream where undercutting is occurring or may develop. The structures are arranged so that the upstream ends are located at the tangent point between opposing curves. The ends should be tucked well into the bank to avoid "catching" the flow and causing more erosion. The structures are backfilled with local materials, taking care to avoid large cobbles and boulders that will tend to be dry in the summer. Where a large fluctuation in water levels occurs, several rows or tiers of live bank protection can be installed (Photograph 6.4-10). As these form steps up the bank, they allow for greater flow volumes to pass at each stage of the water. As with wattle fences, building the live bank protection with all the butt ends at the downstream end of the project will provide a tighter structure and help the water to flow past without damage.

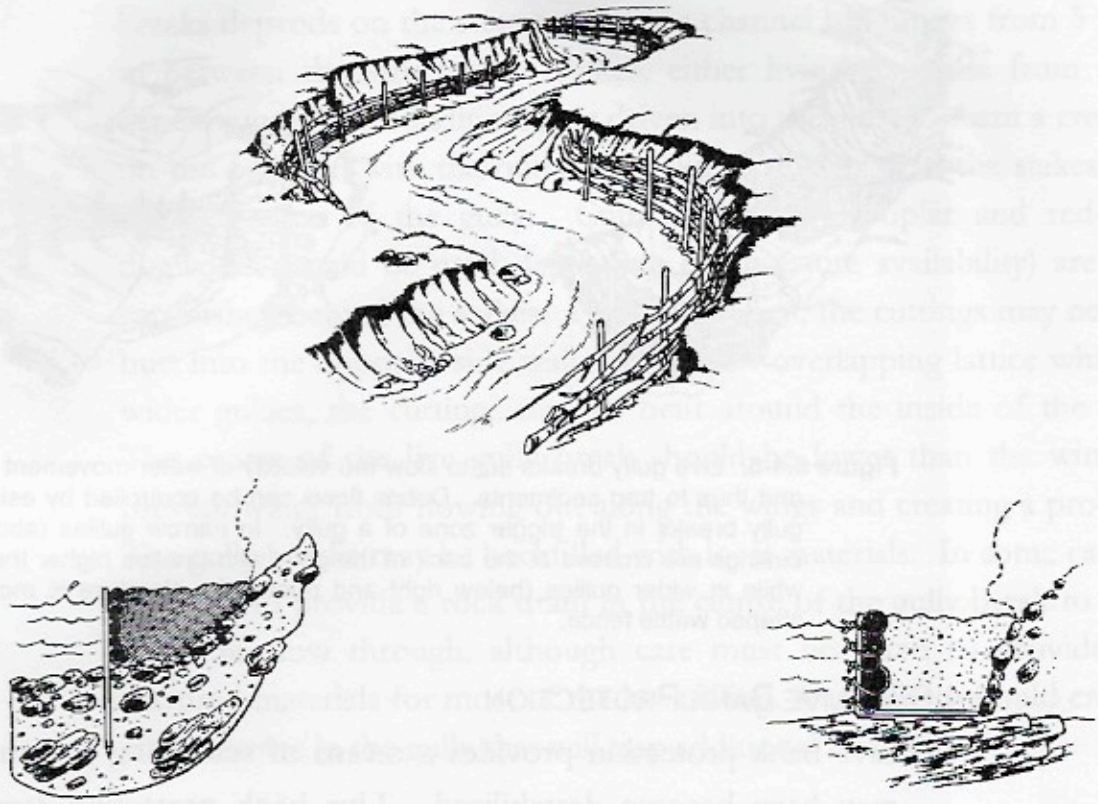


Figure 6.4-6. Live bank protection can be used to control erosion on the outside of curves. The backfill has been removed in this drawing (top) for clarity. The sections show the re-sloped undercut bank. Treatments where the streambed consists of unconsolidated material are shown in the top right drawing while bedrock controlled channels treatments are shown in the bottom right drawing.

Growth of the live bank protection structures provides a cover of riparian vegetation along the streams. The willows, red-osier dogwood and balsam poplars used in the structures provide a strong network of roots that help to hold the stream bank in place. Stabilization of the stream bank reduces the amount of material moving with the water and therefore reduces the erosive power of the water. In addition, live bank protection systems can be used where streams are cutting the toe of steep banks that feed material to the creek. By doing so, the live bank protection systems can reduce the amount of sediment moved from the site and can stabilize the over-steepened bank. Live bank protection systems work best where fine textured soils are being eroded. These can be effectively protected using live bank protection systems.

6.4.7 LIVE SILT FENCES

Live silt fences are used to reduce sediment movement on low gradient streams (Figure 6.4-7). Where live gully breaks can be used on very steep gullies and seasonal streams, and live bank protection can be used on larger streams and rivers, live silt fences are used on smaller streams with lower gradients and seasonal flows. The live silt fences are simply rows of cuttings stuck into the stream bed to slow water velocities and cause sediments to be deposited. The rows of cuttings also serve to trap floating debris that further slows water velocities (Photograph 6.4-11). Once the cuttings grow, the water flows between the stems of the growing cuttings, creating a brushy, swampy area characteristic of natural seepage areas and small streams.

Willow, red-osier dogwood and balsam poplar cuttings are particularly useful for live silt fences as these species will continue to grow when their stems are buried. Live silt fences can be established in swales and small drainage channels that exist at the toes of many of the landslides

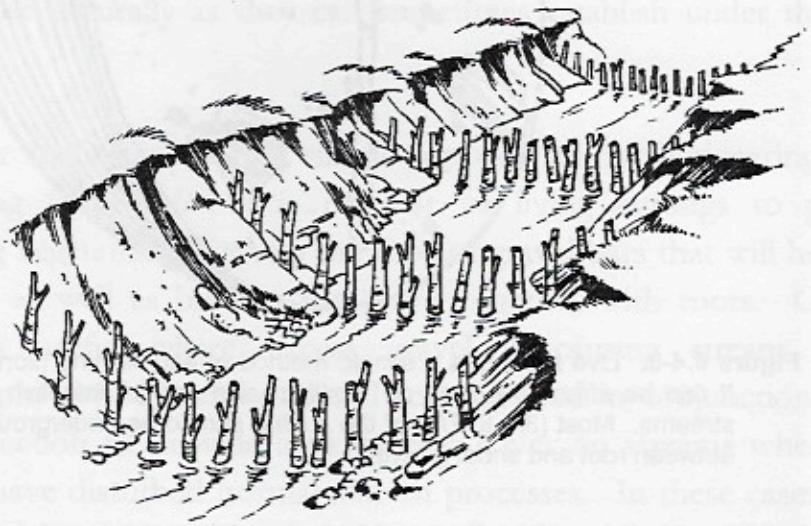


Figure 6.4-7. Live silt fences can be used to provide a willow coppice in smaller, slow moving streams and ditches. They act by slowing the velocity of the water and allowing sediments to settle out. The cuttings can be either in single rows (as shown in the drawing) or multiple rows in each band (as shown in Photograph 6.4-11). Note the use of live bank protection on the right bank in the photograph.

and torrented gullies. These will assist in restoring the sites so that rather than continuing to erode, these small channels can act as sediment traps and provide clean water to downstream sites. The natural filtering ability of deciduous shrub lands can be recreated using live silt fences on the small drainages and seepages.

6.4.8 LIVE STAKING

Live staking (see Photograph 6.3-2) is perhaps the simplest form of soil bioengineering. Live staking is the use of living cuttings (willow, balsam poplar, red-osier dogwood, etc.) to stabilize slumping materials or to "pin" sods to a slope. Live staking is particularly useful in silty materials that tend to flow down the slope in the spring. In these cases, the cuttings are inserted into the soft materials in the spring and as the cuttings grow over the summer, the roots serve to bind the unstable materials and to prevent further flows.

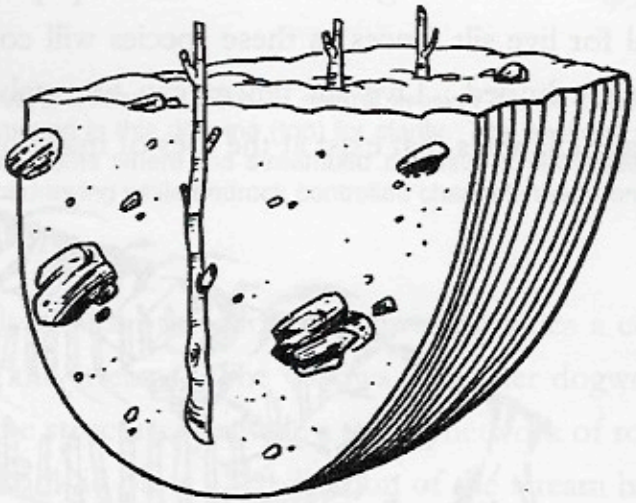


Figure 6.4-8. Live staking is a simple method of establishing pioneering woody vegetation. It can be effectively used on "flowing" silts and to establish riparian vegetation along streams. Most (3/4 to 7/8) of the cutting should be underground to establish a balance between root and shoot growth.

The cuttings used in live staking should be inserted into the soil so that at least 3/4 of the length of the cutting is underground. On drier sites, 7/8 of the cutting should be inserted. Cuttings need not be planted vertically (as shown) but can be slipped into the soil diagonally, as long as the cutting will

remain moist over most of its length. A large steel bar with a pointed tip can be used to provide a pilot hole for the cuttings as long as the soil is packed firmly around the cutting once the cutting is in the ground. Wearing heavy gloves such as welder's gloves can be helpful in pushing cuttings into the soil. Rubber auto body mallets can also be used to drive in cuttings. Where difficulty is encountered, cuttings may be trimmed to maintain the 3/4 or 7/8 burial, as long as the cutting is at least 60 cm long.

6.4.9 Gravel Bar Staking

Excess gravel in many stream channels can be attributed to upslope erosion and subsequent bank erosion due to increased material in the stream channel. Natural successional processes on gravel bars eventually leads to the establishment of pioneering vegetation on the top of the bars. This slows the water flow across the bar, resulting in deposition of fines and further elevation of the bar surface with a concurrent deepening of the thalwag. Prior to this deposition of fines, establishment of vegetation by seed on the bar surface is limited due to harsh dry conditions during the summer. However, once the fines have accumulated, species such as red alder and conifers can seed in. The key to starting this successional process is the initial establishment of the pioneering species. Willows often serve this purpose naturally as they can sometimes establish under these harsh conditions.

Gravel bar staking is another simple form of soil bioengineering. Gravel bar staking (Figure 6.4-9) is the use of living cuttings to provide a pioneering vegetation cover on the tops of gravel bars that will help collect sediments as well as binding the gravel together with roots. Gravel bar staking is useful where excess gravel is causing stream instability (Photographs 6.4-12 and 6.4-13). It can be used in conjunction with live bank protection to provide a pioneering cover on streams where human activities have disturbed normal alluvial processes. In these cases, cuttings from 1.25 m to 1.5 m long are inserted into the gravel in the early spring. As the cuttings grow over the summer, the roots serve to bind the gravel materials and reduce flow velocities and thus reduce erosion during periods of subsequent high flows.

The cuttings used in gravel bar staking should be inserted into the gravel so that at least three-quarters of the length of the cutting is underground. On higher bars and therefore drier sites, seven-eighths of the cutting should be inserted. Cuttings should be slipped into the gravel diagonally with the tips pointing downstream. It is important that the cuttings remain moist over most of their length. Cuttings should be planted with the distal (top) end up. It may be useful to leave short stubs of branches on the cutting (as shown) so that the top of the cutting will be known when the cutting is planted. The spacing between cuttings will vary depending on the materials, but can be as little as 5 cm. An excavator is used to open holes for the cuttings to be planted in. Five cuttings are planted in a clump using one bucket hole. This recreates the clumps of vegetation seen on bars where natural processes have established willows.

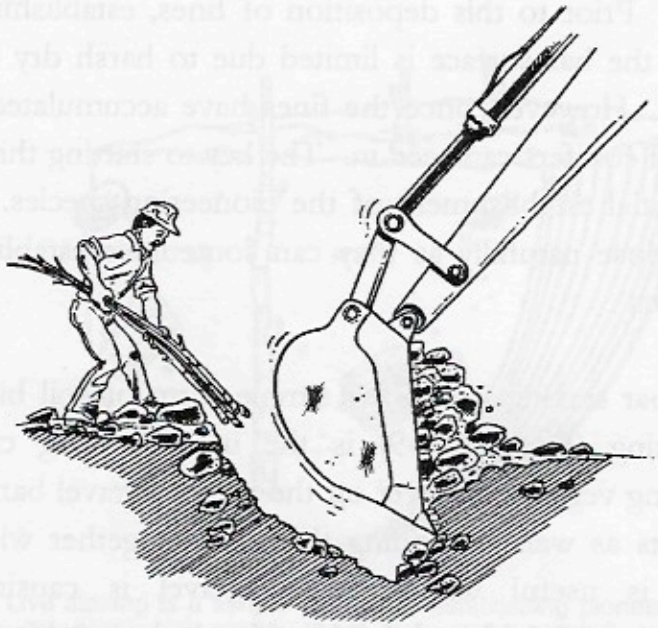


Figure 6.4-9. An excavator is used for gravel bar staking. With the machine backing up-stream, the holes opened for the cuttings will cause the cuttings to be angled downstream. Angling the cuttings downstream allows large woody debris to pass over the cuttings without getting snagged. This will allow the cutting to offer little resistance during the early years with the new shoots developing to slow the flow. This is a simple method of establishing pioneering woody vegetation on the tops of gravel bars where excess gravel is causing stream instability. It can be effectively used in these cases to establish riparian vegetation along streams and initiate successional advancement. Gravel bar staking changes the water flow across the bar during high flows, allowing deposition of fine sediment and thus encouraging invasion by other species. Significant volumes of sediment can be captured using live gravel bar staking.

The cuttings used in gravel bar staking should be collected from willows or balsam poplar growing in similar conditions. Species such as Sitka Willow (*Salix sitchensis*) that are commonly found on gravel bars in the area are ideal for use in gravel bar staking. Sandbar willows (*Salix exigua* and *S. sessilifolia*) are reported as being effective stabilizers of sand and gravel bars due to their ability to spread from creeping rhizomes (Brayshaw 1996). Other species such as red osier dogwood and balsam poplar can be used where these species are found in the surrounding alluvial forests. The cuttings must be inserted well down in the gravel as the upper surface of most gravel bars dries considerably during the summer. In coastal situations where high flows correspond to winter rains in November and December, it is best to conduct gravel bar staking in the early spring so that the plants can get established prior to the high winter flows. In Interior locations where spring snow melt corresponds with high flows planting work can be conducted in the autumn. Work in streams such as gravel bar staking may be subject to permission from fisheries agencies. Such permission must be obtained prior to conducting such work.

6.4.10 Live Smiles

Flowing soils with high silt content can create a significant surface instability problem. Treatment with brush layers, modified brush layers or wattle fences often fail under these circumstances due to an inability to hold the flowing materials. In many cases, the weight of the flowing mud causes structures such as modified brush layers or wattle fences to collapse (toppling failure) while brush layers may be swept from the slope or may not control the flow of the mud and thus do not solve the problem. Live smiles make use of the tensile strength of the cuttings to support the mud and thus are significantly stronger than wattle fences or modified brush layers. Establishment of the cuttings in a bowed configuration transfers the load from a toppling load to one where the cuttings are under tension. Most plant materials are extremely strong under tension and thus the live smiles can hold far more mud than a traditional wattle fence or modified brush layer. Photographs 6.4-14 and 6.4-15).

Live smiles are porous and thus serve to drain the flowing silts, increasing the strength of the soil itself. Saturated silts have very little strength and thus flow easily. However, as these materials dry, they can develop significant strength and thus can stand at much steeper slopes. In addition, the flowing silts tend to provide a good contact between the soil and the cuttings, thus allowing roots to develop readily. Live smiles can be an effective treatment for flowing silts as they help to drain the moisture causing the silts to flow and eventually developing a strong root system in this otherwise weak material.

Live smiles should be between 2 and 5 m wide depending on the nature of the slope and the size of the cuttings available. On steeper slopes or with thinner cuttings, the smiles should be smaller while on flatter slopes or with larger cuttings the smiles can be wider. They can be up to 40 cm high in the middle, tapering at the ends as shown in the drawings. The stakes supporting the live smiles should be firmly established in the underlying in-situ material. Spacing between stakes should be 50 to 60 cm to provide a firm foundation for the structure. The live smiles should be spaced in such a manner that there is no area on the slope where a significant amount of flowing mud can accumulate. As with most soil bioengineering systems, numerous live smiles will provide the best results.

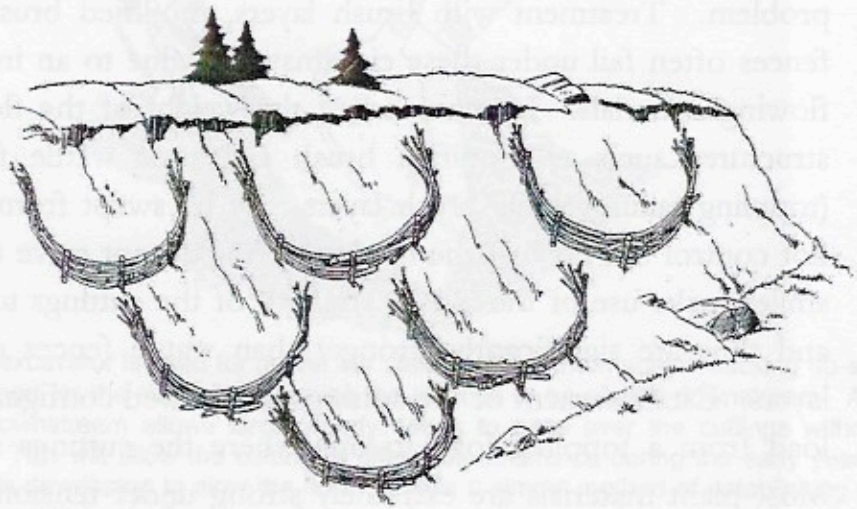


Figure 6.4-10. Live smiles can provide an effective treatment for flowing silts. The catenary curve allows the cuttings to act in tension for increased strength while the porous face of the structures provides drainage. The cuttings should be tightly tied to the rebar at the tops while any required splices should be tightly joined.

6.4.11 Live Reinforced Earth Walls (LaREWs)

Areas of piping failure create a particular problem in terms of slope stability. Backfilling these under-cut areas must be completed in such a way that the loose fill material does not slump. Live reinforced earth walls are wattle fences with long cuttings inserted in the face of the fence. The cuttings reach to the back of the over-hanging area and hold the face in place as well as providing shear resistance to prevent circular failure. Live reinforced earth walls are similar in concept to mechanically stabilized earth structures or reinforced earth walls except that the members of the structure are living and will sprout and grow. Roots from both the wattle fences on the face and the cuttings going into the slope will knit the backfill material together and cause it to act as a cohesive unit. Where piping is causing a significant amount of moisture to discharge from the slope, live pole drains can be used to drain the area and the live reinforced earth walls can be used for resloping. Live reinforced earth walls have been used successfully to treat cavities as large as 3 m deep by 3 m high by 5 m wide. In most cases, the seepage water associated with the piping failure allows excellent growth of the cuttings used in the soil bioengineering structures.

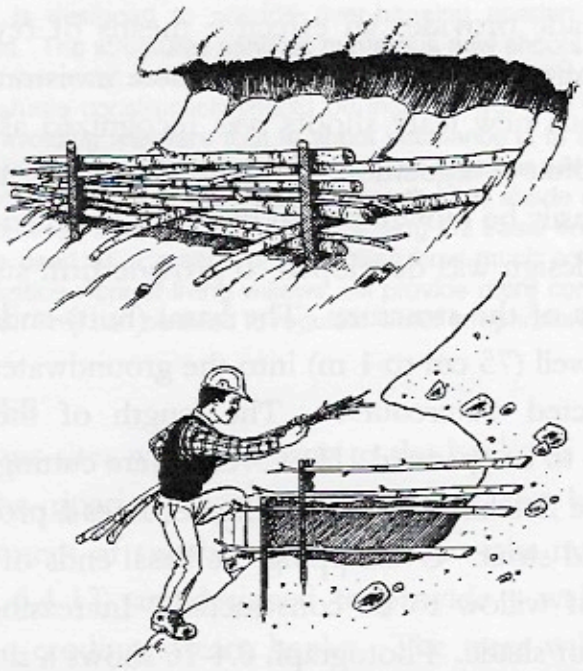


Figure 6.4-11. Live reinforced earth walls can provide an effective means of treating overhanging slopes. The face holds the backfill in place while the long cuttings inserted to the back of the cavity prevents rotational failure of the backfill. Backfill material is generated by resloping the overhang.

6.4.12 LIVE SHADE

Live shade was developed in response to the need for vegetative cover on newly constructed fish habitat. In many cases new habitats for fish is created in back channels and off channel areas as part of watershed restoration programs or as compensation for industrial activities that compromise fish habitat in other areas. This new habitat often involves excavations into the groundwater table to create permanent ponds and channels. In some cases, sufficient flow is available and new spawning habitat can be created as well. Construction of this new habitat clears large areas and generates a significant amount of spoil material that must be disposed of. The new habitat is then located in an area where significant riparian vegetation is lacking. Regulatory agencies, recognizing the need for shade and litter fall, request large planting stock. However, large stock is expensive and in many cases difficult to obtain and to plant and often grows poorly due to damage to root systems during transplanting. Even with large planting stock, shade over the channels and waterways depends on the orientation of the site relative to the path of the sun. Where hundreds of meters of new channel have been created, the cost of revegetation using large stock can easily exceed the cost of the initial channel construction. Live shade provides an effective means of revegetating these areas. The ability of willows to root readily where moisture is available and to send up numerous new leafy shoots was recognized as a potential solution to the fish habitat revegetation problem. However, unsupported willow cuttings could easily be blown over in the wind or be knocked down under snow. A tripod design was developed to provide firm support for the above ground portions of the structure. The basal (butt) ends of the cuttings need to be placed well (75 cm to 1 m) into the groundwater table adjacent to the newly constructed watercourse. The length of the cuttings depends on the channel to be spanned. However, where cuttings are greater than about 4 m long, the flexibility of the cutting becomes a problem unless the cuttings are large and stout. Overlapping the basal ends of the cuttings allows a dense lattice of willow to be constructed. Increasing the overlap increases the density of shade. Photograph 6.4-16 shows a site where live shade was used in combination with other riparian restoration treatments to restore a newly constructed fish channel.

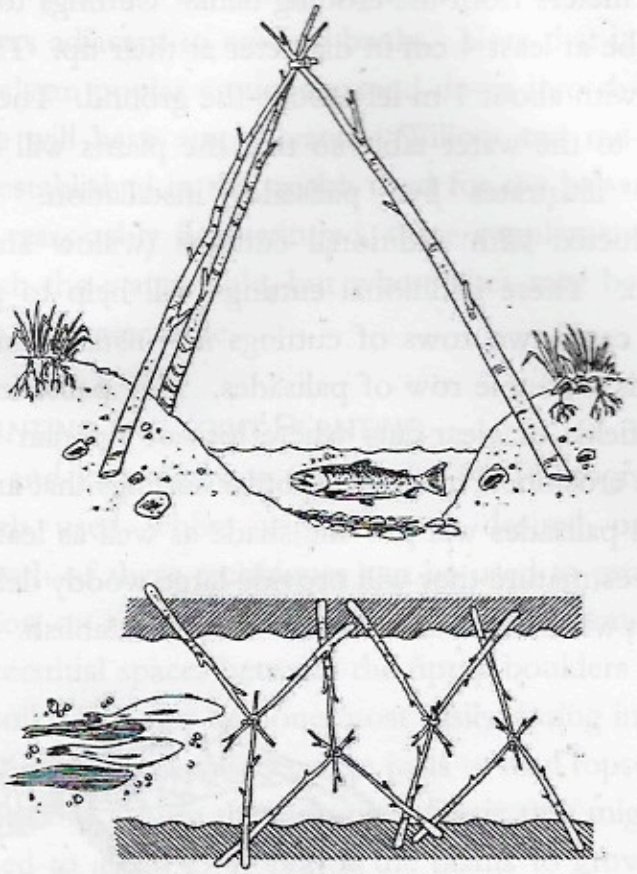


Figure 6.4-12. Live shade is designed to provide over-hanging riparian vegetation on newly constructed fish habitat. The structures send up numerous new shoots while the butt ends of the cuttings will root in the moist soils on the banks (see photo below). The basal ends of the cuttings used in live shade construction should be inserted well into the banks of the new channel. The key to avoiding a severe root to shoot imbalance is to ensure the basal ends are within the groundwater zone. The tips should be tied together with binder twine or other biodegradable material. The legs of the tripod forming the live shade should be adjusted so that the slope of the cuttings is at least 45°. Overlapping the basal ends of the tripods used for live shade can be used as a means of controlling how much cover is afforded by the structures. A dense lattice work of living willows will provide more complete canopy closure than an open structure. This can be used to regulate water temperatures.

6.4.13 Live Palisades

There are numerous sites where clearing to the banks of streams and rivers has eliminated the riparian vegetation and thus the bank holding root systems. Replacement of suitably sized trees can take many decades. Live palisades (Figure 6.4-13) are designed to provide a wall of stout balsam poplar trees along eroding stream banks. The trees will develop a dense root network and resist erosion of the bank. Live palisades consist of a row of large balsam poplar (cottonwood) cuttings established in a trench two or

more meters from the eroding bank. Cuttings to be used for live palisades must be at least 4 cm in diameter at their tip. They should be at least 3 m long, with about 1 m left above the ground. The cuttings must be inserted down to the water table so that the plants will have water. The drawing below illustrates live palisades installation. Live palisades can be constructed with additional cuttings (willow and red-osier dogwood) as shown. These additional cuttings will help to provide site diversity. In some cases two rows of cuttings are installed in the same trench so that there is a double row of palisades. Live palisades can be used on eroding farm fields or clear-cuts where loss of riparian vegetation has resulted in severe erosion. The balsam poplar cuttings that are used in the construction of live palisades will provide shade as well as leaf litter for the stream. As the trees mature they will provide large woody debris that can act as interim habitat while later successional conifers establish.

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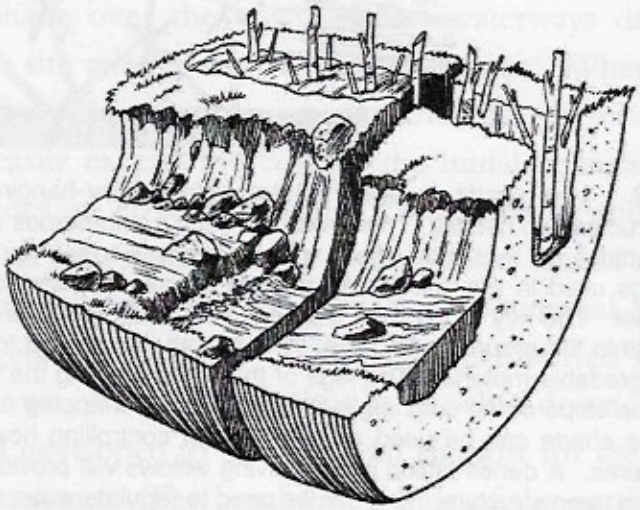

Figure 6.4-13. Live palisades can be used to provide a row of dense root systems to hold eroding banks in place. Note that the large posts must extend to the water level.

A trench should be excavated to the water table 2 or 3 metres from the crest of the eroding slope. The full depth need not be excavated as the balsam poplar posts can be inserted into slits in the bottom of the trench created by the excavator. Additional cuttings can be added to the open trench prior to backfilling. Watering may be needed if the depth to the water table is too great for reasonable excavation. Stout (up to 20 cm diameter) posts should be used as these will grow most rapidly (Photograph 6.4-17). Live palisades

are designed to provide a strong riparian cover of balsam poplar (cottonwood) trees adjacent to eroding banks. Note that it is important to have the large balsam poplar cuttings extend down into the water table so that these plants will have ample water. Willow and red-osier dogwood cuttings can be established in the trench used for the balsam poplar posts. Where soils are reasonably fine textured, these supplementary cuttings do not have to reach the water table, but where sites may be droughty, they should extend to the water table.

6.4.14 Pocket Planting and Joint Planting

Pocket planting and joint planting (Figure 6.4-14, Photographs 6.4-18 and 6.4-19) are both used where vegetation is desired on a rip-rapped streambanks. Both of these techniques can be used to provide pioneering riparian vegetation on rip-rapped streambanks. In pocket planting, soil is placed in the interstitial spaces between the riprap boulders and cuttings are planted in this soil. This can be done most easily during installation of the riprap but can also be done using 5 gallon pails to haul topsoil to the riprap. Care must be taken to ensure that any filter fabric that might be under the riprap is breached to allow the roots of the plants to grow down into the underlying substrate. Joint planting is simply the establishment of cuttings in the substrate below the riprap without additional soil. The cuttings are planted into the native soils under the riprap taking care to breach any filter fabric that may be present. Both joint planting and pocket planting will strengthen the riprap by slowing the flow of water across the rock surface and by "locking" the rock in place with the growth of the planted species. Willow, balsam poplar and red-osier dogwood can be used in pocket planting and joint planting. Pocket planting is used where large rip-rap blocks have replaced sites where riparian vegetation might grow or where there is a need for providing a riparian cover along the stream; and, mitigation for the installation of rip-rap is needed. Joint planting is used where a shallow layer of rip-rap covers the streambank and has replaced sites where riparian vegetation might grow. Joint planting can be used where there is a need for establishment of vegetation in the rip-rap; such as sites where mitigation is needed for loss of habitat.

Cuttings are most easily established in rip-rap during construction of the rip-rap slope. Soils can be placed among the boulders of the rip-rap during construction for subsequent planting if the timing is wrong for the use of cuttings at the time of construction. Other riparian species can be added to the "pockets" of soil. Cuttings must be buried by soil for at least 75% of their length. Holes for planting of cuttings in rip-rap can be created using a planting bar with a pointed tip. Large diameter cuttings will do better than smaller cuttings where sites are dry. Vegetated rip-rap can provide escape habitat for fish during periods of high flow. The vegetation can also add small organic debris as well as insects to the stream.

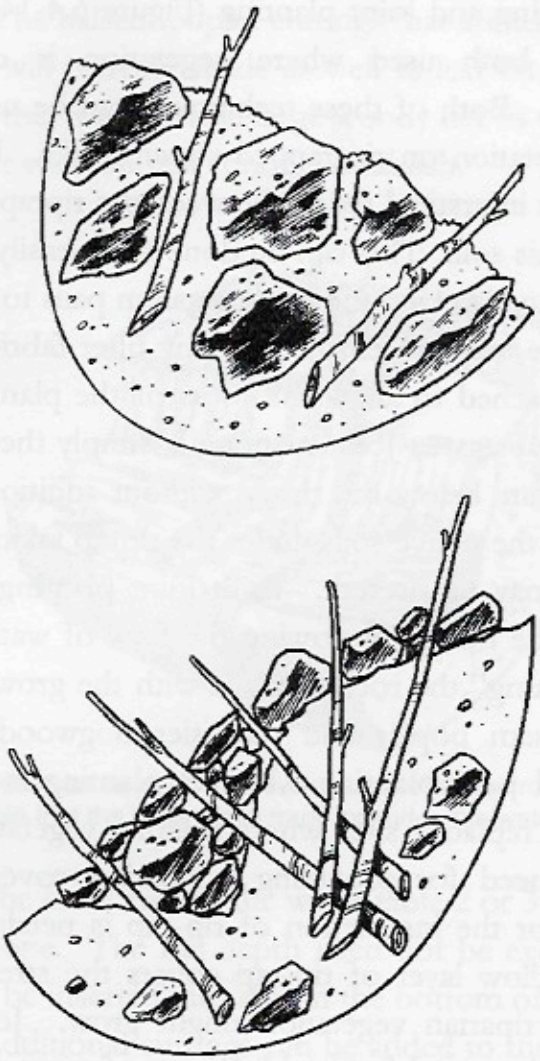

Figure 6.4-14. Pocket planting (top) recreates the natural process of vegetation establishment in coarse boulders by creating a pocket of soil in which the plants can grow. Joint planting (bottom) consists of planting cuttings through the spaces between the rocks of the rip-rap. .

6.5 HERBIVORY

Herbivory can be a major player in shaping the species composition of ecosystems (Hobbs and Suding 2009; Gonzales 2008). Where growth of woody species is constrained by intermittent moisture availability, the rate of plant growth and the level of herbivory may control forest development (Hobbs and Suding 2009). Control of herbivory can be the critical element in many restoration projects. Fencing may be the only effective way of reducing the impacts of herbivory (see Photograph 6.3-2 and 6.5-1) and should be considered at most restoration sites.

Planting unpalatable species may be an effective way of establishing vegetation on a site in the face of intense herbivory. However, this can result in an unbalanced species composition that may be as much a problem from a restoration perspective as the herbivory. Sometimes unpalatable species can be used to protect species that would otherwise be eaten before they could grow sufficiently to avoid damage. Some later successional species such as Western Redcedar (*Thuja plicata*) that are highly sought after by deer can find cover under Red Alder (*Alnus rubra*) and other pioneering species and can establish in the face of heavy pressure from the deer.

6.6 INVASIVE SPECIES

Dealing with invasive species is becoming an increasingly important part of ecosystem restoration activities. Understanding how to effectively deal with invasive species is critical to success of many restoration projects. Treatments that might have once been effective in agricultural fields will not provide solutions to the ever more complex situations where invasive species are becoming a problem. In fact, even the species of concern are changing. Native species are becoming invasive in the face of modified natural disturbance regimes (Friederici 2003). Effective restoration requires that new strategies for dealing with invasive species be adopted.

Societal expectations around invasive species management have also changed. Rachel Carson's '*Silent Spring*' was the gateway to a change in the way society views pest management. This is reflected in the laws and regulations dealing with pesticides and their use for invasive species management. Similarly, the view of earth from space; a tiny blue-green

sphere in a sea of blackness, has changed the way we view environmental matters. Gone are the days when environmental issues could be dealt with on a one by one basis. Disasters in Bhopal are linked in the public's mind to weed management on Vancouver Island. Changes in the traditional management strategies are being demanded from a wide variety of public sectors, including First Nations, environmental groups, organic farmers, mothers groups and in some cases, the traditional managers themselves. To be effective, invasive species management strategies must address in a meaningful way these new societal demands.

The requirements of invasive species management are also changing. Traditional weed management is being replaced by integrated vegetation management where values such as improved ecosystem health are replacing the single focus approach of traditional weed control. This requires that an understanding of ecosystem health be applied within the context of invasive species management. Treatment approaches that cause ecosystem degradation are not effective within the context of ecological restoration. Integrating invasive species management programs within wider ecological restoration projects provides an appropriate approach.

Knowledge of ecosystem processes is also being applied to effective invasive species management. Natural successional change in the vegetation can be a powerful tool in control of unwanted plants (termed successional advancement). Many invasive species are pioneers on disturbed sites and will not persist in the face of successional advancement. Similarly, maintaining early seral states in the vegetation can cause costly management problems. Understanding the ecological processes that are associated with the vegetation, both wanted and unwanted, allows effective management systems to be employed in a diversity of situations.

Development of this approach to vegetation management has been fostered by an increase in knowledge about the ecology of invasive species and how that understanding can be used to inform effective management systems. The ecological characteristics or autecology of individual invasive species provides a foundation for the design of systems to eliminate and or prevent

these species from establishing. Similarly, the manner in which invasives species as a group respond to environmental conditions or the synecology of these species can also provide a model for design of management systems. Understanding the ecology of invasive species allows management efforts to be much more effective than those developed without regard to the ecological consequences of the management action.

Invasive species pose a threat to natural ecosystems and ecosystem restoration projects by changing species composition, impacting biodiversity, modifying ecosystem structure and function and changing the trophic (energy flows) structure of the natural community. Knowing how a plant will naturally react in a given situation can help us apply stresses and management actions that will maneuver the plant and the plant community in the direction we find useful. For instance, repeated cutting of plants like willow (*Salix* spp.) and balsam poplar (*Populus balsamifera*) will cause the plant to send up multiple stems and to become denser than the single stem that was cut initially. Similarly, mowing an annual or biennial after it has gone to seed may provide little benefit in terms of control as the seeds will simply be spread further by the mowing. Table 6.6-1 provides a listing of some of the common characteristics that can be used to exert management pressures on the plants. The table also provides the rationale for considering this attribute of the plant.

The "invasiveness" of a species has a profound effect on the management of the species and the potential treatments that might be used in the context of an ecological restoration program. The Alien Plants Ranking System (ARPS) (ARPS Implementation Team 2000) provides biological, ecological and management criteria to determine the invasiveness of a species. These are centered on the biological as well as the ecological attributes of the species. The Invasive Species Council of British Columbia website provides a wealth of information on invasive species (http://bcinvasives.ca/). The Garry Oak Ecosystems Recovery Team website (http://www.goert.ca/) has information on invasive species that are common in Garry Oak and related ecosystems.

Table 6.6-1
Useful Characteristics of Plants

Plant Characteristic		Applications
Annual	Perennial	To break life cycle by cutting annuals
Tolerant of low nutrients	Requires nutrient rich conditions	To change site nutrient status for management
Shade tolerant	Shade intolerant	To change shading situation
Large plant	Small plant	To provide cover in ecosystem
High seed production	Low seed production	To know if seed numbers are potential problem
Seed banker	No seed banking	To design seed bank strategies
Rhizomatous	Non-rhizomatous	To understand spread potential
Re-grows from plant fragments	Does not re-grow from fragments	To design cutting and removal systems
Has toxic components	No toxic components	To design handling precautions

The reproductive abilities (biological attributes) of the species focus on:

- Mode of reproduction;
- Vegetative reproduction ability;
- Frequency of sexual reproduction;
- Number of seeds per plant;
- Dispersal ability;
- Germination requirements; and
- Seed banks.

In addition, the ecological attributes of invasive species include:

- Produces persistent litter or shade that affects germination or growth of native species;
- Affects availability of soil nutrients, e.g. a nitrogen fixer;
- Affects water availability to native plants; and
- Changes natural fire regime (e.g. downy brome, *Bromus tectorum*)

As well, the history of the plant in similar environments can also be used to indicate invasiveness. The ARPS ranking system also includes the ability to control the species. A species that is easy to control is ranked lower than a

species that is difficult to control. Similarly, a species that is found in an area that is susceptible to invasion would be ranked higher than one that is isolated from sites that it could invade. For instance, Scotch broom is far less of a problem in an area of undisturbed west coast forest (CWHvm1) than on disturbed sites on the east side of Vancouver Island (CDFmm).

"Weediness" is a collection of plant traits that are often used to describe a plant, but rarely defined. The following characteristics may be used to define "weediness" (modified from Frankton, 1963):

1. Most weeds are capable of growing under a wide variety of environmental conditions, so we may find the common dandelion grow well in a vacant lot in Vancouver, and equally well along an airstrip in Yellowknife.

2. A single weed species may occur in a variety of forms, allowing it to utilize different habitats. Again, the common dandelion is an excellent example. It can develop as a prostrate plant which escapes the blades of the lawn mower and frustrates the home gardener, or it may develop big broad upright leaves to successfully compete with the taller grasses and legumes in a hay field.

3. Most weeds produce many seeds, often with elaborate mechanisms to ensure dispersal. Again the common dandelion comes to mind.

4. Seeds of many weed species maintain viability for extended periods. Common Lambs Quarters (*Chenopodium album*) seed may be viable for 1,700 years while Scotch Broom (*Cytisus scoparius*) seed may be viable in the soil for up to 80 years.

5. Many perennial weeds may continue to grow after removal of the above ground parts of the plant. Toadflax has an extensive underground root system that has the ability to regenerate above ground shoots from the roots.

6. Weeds can survive in harsh conditions. The common dandelion growing in the sidewalk crack is an excellent example.

7. Many weeds can set viable seed even if the stem of the plant is cut before the seeds are mature.

8. Weeds will not perpetuate themselves in the absence of disturbance; they will eventually be out-competed by the next successional stage.

9. Most weed species are not native to the lands that they are problem weeds in. For example, two of the most problematic weeds in the Prairies, Kochia and Russian thistle are introduced species.

10. Many common weeds have developed a resistance/tolerance to the herbicides used to control them.

6.6.1 Ecology of Invasive Species

The ecology of weedy species can be used to inform management strategies. As a general rule, invasive species tend to require some form of disturbance for establishment and persistence, although exceptions occur. Similarly, weeds often occupy early successional stages in the vegetation, so changing the successional status of the site where the invasive species occur can be an effective treatment for the weeds. Of course there are situations where changing the successional status of a site is not desirable. Understanding the ecological conditions that foster weed growth as well as the autecological attributes of the invasive species themselves allows effective management systems to be developed.

Many weedy species are pioneers on disturbed sites. Their ability to grow in harsh sites such as the cracks in a sidewalk, allow them to exploit sites that are not already occupied by other plants. As the weed community matures and the harsh conditions of the site are ameliorated, other species can move in. By expediting the shift to the later successional plant community, the weedy stage can be avoided. By controlling the conditions such as disturbance that allow weeds to establish, many of the weeds can be controlled.

Many early pioneering species can produce large volumes of biomass, often early in the growing season so that they fully occupy the site and provide strong competition for other plants on the site (Walker et al 2007). Above and below ground growth of pioneering species can create situations where the vegetation becomes successionally stagnant (Kimmins 1987). Reed canary grass (*Phalaris arundinacea*) in some coastal situations can develop in stands that prelude the natural successional development of woody species. Dealing with the below

ground as well as the above ground portions of the plant are required to break the strangle hold this species sometimes develops on riparian ecosystems. The following sections provide some of the ecological and autecological attributes of woody species, herbaceous species and graminoids (grass-like) that can be applied to the management of these groups of species. Although many of these attributes apply to all three groups, there are enough differences so that framing the management around these three groups can provide insights. Site and species specific strategies are required to deal with invasive species, although understanding the ecology of these species can assist in the development of those strategies.

Many woody invasive species, Scotch broom (*Cytisus scoparius*), blackberry (*Rubus discolor*), English hawthorn (*Crataegus monogyna*), Russian olive (*Elaeagnus angustifolia*) and Cotoneaster (*Cotoneaster* spp.) are rapidly growing pioneers on sites where some form of disturbance has opened the native vegetation to invasion. In many cases, woody invasive species will re-sprout from cut stumps or even send up suckers from root systems when the main stem has been cut. In addition, cutting woody invasive species may involve significantly heavier equipment (chain saws, brush saws, etc.) than are needed for herbaceous species. Cutting woody invasive species can generate huge quantities of biomass that needs to be disposed of in some effective manner. Removal of cut Scotch broom, for instance can be as large a job as the actual cutting. If the broom is left in piles on the site, it can result in death of any plants it covers due to phytotoxins in the broom tissues.

Some woody invasive plants are shade intolerant and can be dealt with by establishing a shady later successional cover than the community occupied by the invasive species. However, many of the toughest woody invasives such as English ivy (*Hedera helix*) and holly (*Ilex aquifolium*) can persist under a dense canopy of later successional species. In addition, the seeds of these species are spread by birds so new plants can spring up significant distances from established populations. Understanding these attributes of woody invasives can provide clues to development of effective management solutions for these species.

Many of the most common invasive woody species are nitrogen fixers and can significantly change the nutrient regimes of the ecosystems they occupy (Von Holle et al 2006). Scotch broom has been implicated in enhancing the growth of non-native grasses (GOERT 2009). This makes the job of restoring the affected site doubly difficult as the woody species must be removed as well as the non-native grasses that now have enhanced growth due to the woody species. In addition to nitrogen fixation, Scotch broom also exudes a mild phytotoxin that limits competition and maintains the position of the broom in the ecosystem. Scotch Broom covered sites may remain covered by broom for many decades in a successionally stagnant condition. The ability of many woody invasive species to create monocultures which are difficult to break up provides an additional challenge for restoration.

Woody pioneers, including both native species and alien invasive species have adapted many characteristics that help them survive in otherwise hostile sites. Willows (*Salix* spp.) and poplars (*Populus* spp.) are able to re-grow from cut stems, either as root suckers (*Populus balsamifera*, *P. tremuloides*) or from cut segments of stem such as many willows or from cut stumps. Big leaf maple (*Acer macrophyllum*) a pioneering species in many coastal areas of British Columbia, can sucker abundantly from cut stumps, creating large bushy areas with dense foliage that prevent growth of conifers, block sight lines and hide wildlife along roadsides creating collision hazards. In many cases, efforts to manage native pioneering woody species create conditions that allow non-native herbaceous species to establish. Understanding the ecological attributes of these species can help in the development of systems to control them.

Most common weeds, Canada Thistle (*Cirsium arvense*), Knapweeds (*Centaurea* spp.) and Dalmatian Toadflax (*Linaria genistifolia* ssp *dalmatica*) are herbaceous, although some such as Japanese Knotweed (*Polygonum cuspidatum*) have woody stems that die back annually. With the exception of Gorse (*Ulex europaeus*) all of the plants listed on the BC Provincial Weeds list are non-woody, and with the exception of Yellow Nutsedge (*Carex esculentus*) all of the listed species can be considered herbaceous species. Herbaceous species can be broken into annuals, biennials and perennials, a distinction that influences treatment strategies.

Herbaceous weedy species share many of the attributes that woody invasives have that allow them to be invasive. Canada thistle (*Cirsium arvense*) produces large numbers of highly mobile seeds, (*'and away they all flew like the down of a thistle'*, Clement Moore, 1822, 'Twas the Night Before Christmas). Canada thistle will also re-grow readily from underground rhizomes when cut, sending up additional shoots that may well flower and set seed before the end of the season. Thistles can also occupy sites to the exclusion of more desirable species, usurping moisture and nutrients that would be used by the desirable species. In this way, thistles can prevent successional advancement and can lead to site degradation.

Herbaceous invasive species often require some form of disturbance to become established, although in some cases such as Knapweeds (*Centaurea* spp.), this disturbance may be minor and the plants may create their own disturbance by simply being there and distributing a phytotoxin (Müller-Schärer and Schroeder 1993). This can create species poor stands that are dominated by the knapweed, greatly decreasing range quality and changing the fire return interval in ecosystems where it has established (Zouhar 2001). Biocontrol using imported insects may prove to be the only way to deal with extensive infestations of some herbaceous species (Myers and Bazely 2003).

Graminoids, grasses (*Poaceae*). sedges (*Cyperaceae*), rushes (*Juncaceae*) and related species can be lumped together for the purposes of invasive plant management as graminoids. This group of invasive plants is perhaps the most vexing. Although only one species, Yellow Nutsedge (*Carex esculentus*), is listed on the BC Noxious Weeds list, many of these species constitute the most persistent problems for ecosystem restoration (GOERT 2009). Many invasive graminoids contribute substantially to ecological degradation. For instance, Downy Brome (*Bromus tectorum*) can drastically change fire return intervals. Where stands of Downy Brome have established in dry ecosystems, fires can occur almost annually, preventing growth of native species that may require several years of growth to become resistant to fire. Similarly, species such as Reed Canary Grass (*Phalaris arundinacea*) can choke waterways and create

oxygen depletion that leads to fish kills. Many invasive graminoids can create substantial damage, both economically and ecologically.

Graminoids can also be broken into annual and perennial groups with their own specific management problems. In addition, graminoids grow from the bottom up rather than the top up as in dicotyledonous plants. The intercalary meristem (growing tissues) (Esau 1960) on grasses and grass-like plants evolved with grazing animals and allows the plants to sustain repeated cutting with limited effect. Grassy golf courses are a testament to the ability of this group of plants to evade the harmful effects of the mower blades in terms of continued growth. Specific strategies must be employed for dealing with grassy weeds.

Understanding in a general way the population dynamics of invasive species is critical to development of effective management strategies. Population ecology is a broad field and well beyond the scope of this manual. However, a good understanding of the ecology of invasive species can be used to enhance management efforts.

Invasive species populations go through three distinct phases of growth as they develop on a site; establishment, explosive and biological potential. Figure 6.6-1 shows a graphic illustration of these phases.

By definition, alien invasive species establish from elsewhere. Unless the species is purposely brought in, as many of our invasive plants have been, populations start with only one or a few individuals. This group of plants is known as the founding population. Fortunately, in most cases, this population is small and establishes slowly, or may just die out after a few years. This establishment phase may last for only a few years in species that are well adapted to our climate or it may take many years for some invasive plants to become well established.

Once the population reaches a certain size, the invasion takes on explosive growth characteristics. This is when the plant starts to 'show up everywhere' and towards the end of this phase is when control actions are most commonly

implemented. However, as shown in Figure 6.6-1, the probability of success goes down and the costs go up during this phase. This phase of growth is interesting from a management perspective because this is when the small populations of the plants that have spread out across the landscape start to coalesce. The key to effective management is to mount a concerted attack before the plant populations enter this explosive phase.

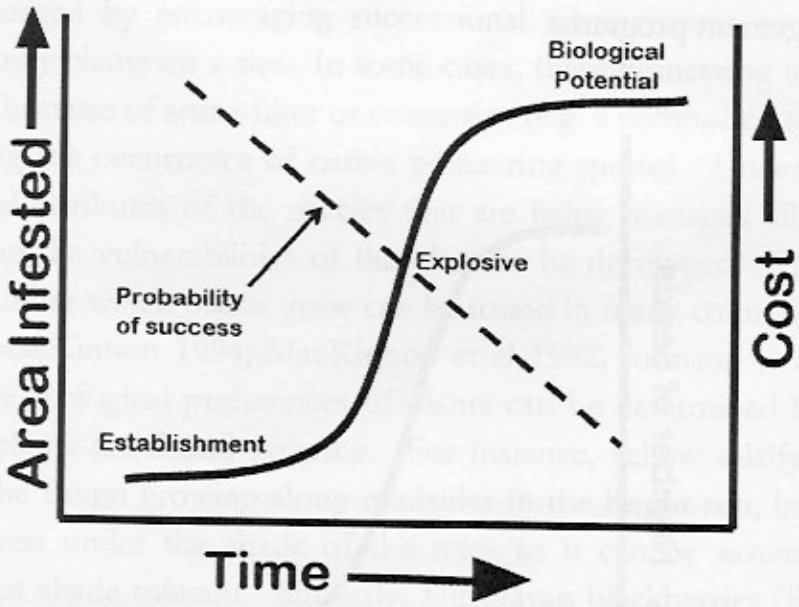

Figure 6.6-1. Dynamics of invasive species populations establishment and growth.

The final phase of invasive species population growth is when it reaches or nears its biological potential. It is clear that eventually populations of plants will occupy all suitable habitats in an area, much in the way Scotch broom has on Vancouver Island. When this occurs we consider that the species has reached its biological potential. At this point, management efforts should be directed towards removing it from specific habitats, but it is not effective to try and remove the plant from all areas. Understanding the phases invasive species populations go through allows management programs to be tailored to be most cost-effective.

Most plants spread their seeds within a few meters of the parent plant (Figure 6.6-2). This attribute of invasive plants is important in the design of management systems as control of seed spread is often one of the most effective tools in managing invasive species populations. The ability to spread

seeds long distances is a valuable attribute for the weeds as it allows them to become established in new habitats. However this comes at a cost in that light, wind-borne seeds may have a much lower percent viability than larger seeds. In some cases, such as Common Burdock (*Arctium minus*), plants have developed elaborate ways of spreading great distances and thus overcome the problems associated with seed spread. Knowledge about how the seeds of the specific species that are causing the problem are spread can assist in designing management programs.

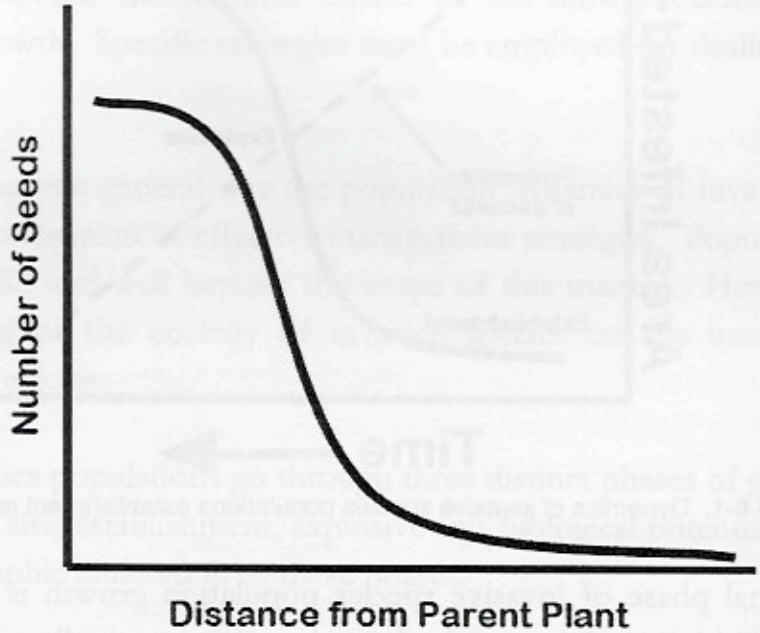

Figure 6.6-2. The seeds of most invasive species are spread near the parent plant.

6.6.2 Ecological Approach to Vegetation Management

The ecological approach to vegetation management combines traditional weed management, including integrated vegetation management with the science of plant ecology to provide a system of vegetation management that makes use of the natural properties and processes associated with vegetation to achieve effective vegetation management. By working with the natural processes of vegetation, significant economies can be achieved. The following sections provide details on how these natural processes can be harnessed to achieve the vegetation cover that provides us with the goods and services we require while reducing or preventing the establishment and spread of alien invasive species.

USE OF ECOLOGICAL CHARACTERISTICS TO MANAGE INVASIVE SPECIES

Each plant species has a set of ecological and biological characteristics that can be used to manage the species. Some species need to grow in full sun and will not tolerate shade. These species can be managed by providing shade. Similarly some species require sites with high fertility and can be managed by changing the fertility of the site. Some plants are pioneers and are adapted to being the first to establish in a new location. These early successional species can be managed by encouraging successional advancement so they are no longer the only plants on a site. In some cases, these pioneering weedy species are present because of some filter or constraint (e.g. a compacted old road) that is preventing the occurrence of native pioneering species. Understanding the autecological attributes of the species that are being managed allows systems that work on the vulnerabilities of the plant to be developed. The ecological conditions under which plants grow can be found in many common floras (e.g. Pojar and MacKinnon 1994; MacKinnon et al 1992; Johnson et al 1995). In addition, the ecological preferences of plants can be determined by observing where the plants are found growing. For instance, yellow salsify, (*Tragopogon dubius*) can be found growing along roadsides in the bright sun, but not in the adjacent forest under the shade of the trees so it can be assumed that this species is not shade tolerant. Similarly, Himalayan blackberries (*Rubus discolor*) perform poorly on dry rocky outcrops and are not found at all in shady forests. They will grow prolifically along creeks in the dark, rich organic soils associated with riparian areas where alder has been removed, but they are not found under the alder. From these observations it can be assumed that blackberries do not like sites that are nutrient poor or shady or too dry. By observing where problem species are found, deductions about their ecological preferences and/or tolerances can be made. The following paragraphs provide information on the common ecological characteristics of many invasive species and how these can be used in development of management systems.

The inability to tolerate shade is a common attribute of many invasive alien species. These plants have developed to exploit the full sun and, in some cases, cannot tolerate even partial shade. Creation of a shady cover can be used kill these species and to prevent these plants from re-establishing. In some cases, such as removal of Scotch broom (*Cytisus scoparius*) from an open Garry oak

ecosystem, creation of a shady cover that would prevent the broom is not desired as it would also result in the loss of the lovely spring flowers associated with the ecosystems. However, the broom can be tricked when it is cut by covering the cut stumps, cut as close to the ground as possible, with a bit of leaf litter or moss to provide a cover from direct sunlight as might occur in a shady area. This will prevent the cut stump from re-spouting.

Shade intolerance can be a very useful attribute when dealing with thorny species such as gorse (*Ulex europaeus*) and Himalayan blackberry (*Rubus discolor*) because shade can be achieved and the plants eradicated without actually having to deal with the prickly plant parts. In some cases, pioneering species such as Willows (*Salix* spp.) and Bigleaf Maples (*Acer macrophyllum*) that are common problems along roadsides and other rights-of-way can be dealt with by providing a shady cover.

Site fertility can sometimes be used as a character to separate desirable vegetation from species that are unwanted. For instance, many weedy species are tolerant of low nutrient sites because they are poor competitors on sites where more amenable nutrient conditions allow other more desirable species to grow. Orange hawkweed (*Hieracium auranticum*) is a perfect example of this. This species tends to take over on poor quality pastures where the grass cover has been degraded by grazing and the soils are gravelly and nutrient (and moisture) poor. If the pasture can be enhanced through nutrient additions or the establishment of a good cover of legumes, then the hawkweed can be eliminated. If however, it is uneconomic to enhance the fertility of the site sufficiently to prevent the hawkweed, it may not be reasonable to expect to have a pasture in this location and the site should be allowed to revert back to a forest. In either case, the hawkweed can be eliminated.

Many weedy plants are pioneers on disturbed sites. By encouraging successional advancement, the conditions that support these species can be eliminated. Oxeye daisy (*Leucanthemum vulgare*) provides an excellent example of a species that works with this approach. Daisies are not typically found in closed canopy forests or even in the understory of early successional deciduous forests, so establishment of any successional stage later than the pioneering

herbaceous stage (see Figure 6.6.2-1) would prevent these plants from occurring. There has been much discussion on the role of successional theory in vegetation ecology. For our purposes, we will use the successional terminology proposed in Figure 6.6.2-1 for convenience.

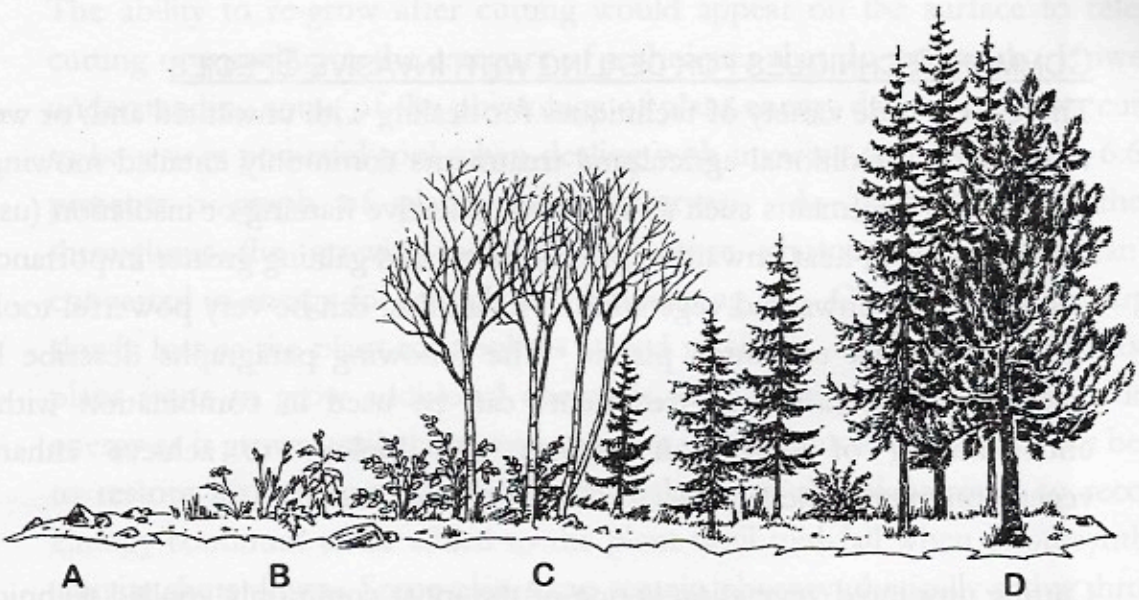

Figure 6.6.2.1. Theoretical successional sequence showing bare ground (A) through early successional herbaceous vegetation (B) to pioneering woody species (C) and finally to later successional woody species (D).

The moisture regime is probably the most common ecological attribute that is used to describe the arrangement of vegetation on the landscape. In some cases changes in the moisture regime can be used to create conditions that are not conducive to the growth of some species. Reed canary grass (*Phalaris arundinacea*) can be a problem in wetlands and along ditches. This species is not shade tolerant so establishment of a shady cover of pioneering woody species can be used to control this species. In addition, reed canary grass is not tolerant of prolonged flooding. Raising the water table half a meter can sometimes be effective in eliminating this species. Similarly, some aquatic weeds can be eliminated by draining the water. In some cases, establishing a cover of plants that have the ability to usurp moisture resources from competing species can result in the death of the competing species. Alfalfa (*Medicago sativa*) can be a very effective moisture competitor and a dense stand of alfalfa can prevent woody pioneers from establishing.

Knowledge of the ecological tolerances of invasive species can allow managers to create circumstances that the unwanted species cannot tolerate. Combining this knowledge with an understanding of the biological attributes of an unwanted plant can give vegetation managers powerful tools to deal with invasive species.

COMMON TECHNIQUES FOR DEALING WITH INVASIVE SPECIES

There are a wide variety of techniques for dealing with unwanted and/or weedy vegetation. Traditional agricultural treatments commonly entailed mowing or tilling while treatments such as steaming, selective flaming or insolation (use of sunlight to over-heat unwanted plants) have been gaining greater importance as treatments for unwanted vegetation. Herbicides, can be very powerful tools in the fight against unwanted plants. The following paragraphs describe how some of these traditional treatments can be used in combination with an understanding of vegetation ecology and biology to achieve enhanced vegetation management.

Cutting unwanted vegetation is one of the most commonly applied techniques for removing unwanted vegetation. However, unless the cutting is done properly, the treatment may only serve to create a greater problem. Cutting pioneering woody species (see Figure 6.6.2-1) such as willows (*Salix* spp.), poplars (*Populus* spp.), alder (*Alnus* spp.) and a wide variety of shrubby species can result in the re-growth of the plants at an increased density and vigor. These plants have evolved to establish under harsh conditions of flooding, or unstable ground, and/or browsing animals. Many plants that occupy the position of pioneering woody species will develop roots from cut stem pieces and can tolerate significant burial (Polster 2007). Willows, poplars (not Aspen, *Populus tremuloides*) and red-osier dogwood (*Cornus stolonifera*) re-grow readily from cut stem pieces. Aspen and balsam poplar (*Populus balsamifera*) will send up new shoots from their root systems if they are cut or burned severely. This causes an increase in density of pioneering woody species if these species are cut.

Many perennial herbaceous species also respond to cutting by sending up new shoots from the roots. Canada thistle (*Cirsium arvense*), Japanese knotweed

(*Polygonum cuspidatum*) and common toadflax (*Linaria vulgaris*) are good examples of plants that have this ability, although there are many more common weedy species that can re-grow after they have been cut. This response to mowing allows these plants to persist and even expand when they have been cut.

The ability to re-grow after cutting would appear on the surface to relegate cutting or mowing to the category of techniques that do not work. However, understanding some of the physiology of plant energy dynamics allows cutting to be a very powerful tool when dealing with invasive species. Figure 6.6.2-2 presents a graph of plant energy reserves. As plants photosynthesize throughout the growing season they store photosynthates that can be converted to energy for growth and maintaining life. Over the winter energy is slowly lost as the plant metabolizes stored reserves. In the early spring as the plant starts to grow additional energy is lost. The plant continues to loose energy as it grows until about mid-summer when photosynthetic activity begins to restore lost energy and the energy balance in the plant starts to recover. Energy continues to be added to the plant until mid-fall when photosynthetic activity shuts down. Some plants can remain photosynthetically active through most of the winter, as long as the temperature remains above about 4°C.

Cutting pioneering woody plants in the fall and winter allows all of the energy that has been stored in the roots to be converted into new growth. However, cutting plants in the mid-summer when the energy reserves are at their low point will result in significantly less re-growth. Repeated cutting every 2 or 3 weeks following the initial cut will cause the plant to expend all of the stored energy on trying to re-grow. As the cut plant will never get to the point where it is in a positive energy situation, it may die over the winter as it will have insufficient energy reserves to maintain basic metabolic functions. For some well-established plants that produce massive amounts of biomass from stored energy such as Japanese knotweed (*Polygonum cuspidatum*), repeated cutting over several years may be needed to deplete energy reserves to the point where the plant dies.

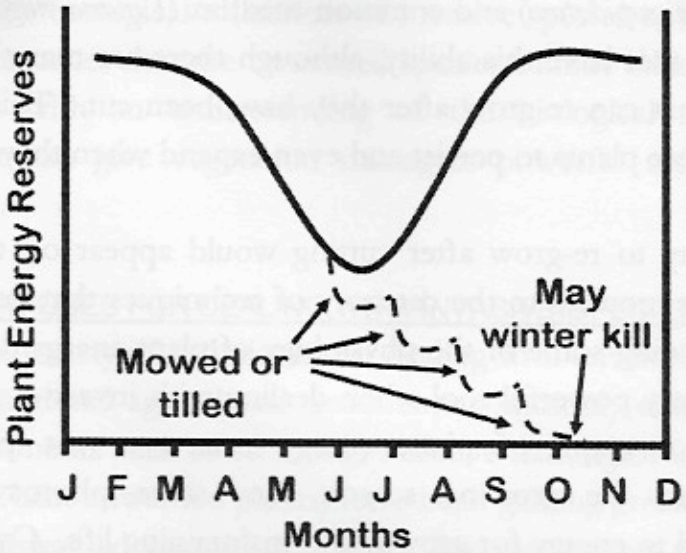

Figure 6.6.2-2. Plant energy reserves vary over the course of the year. By cutting the above ground portion of a plant repeatedly at the time of lowest energy reserves, the reserves can be depleted and the plant will eventually die.

Where pioneering woody vegetation such as willows (*Salix* spp.) and poplars (*Populus* spp.) are presenting a problem, such as along roadsides and under power lines, it may be best to retain at least one growing tip from each plant, trimming side branches and additional stems as needed to gain the utility required from the cutting. By maintaining the apical bud, hormonal control of the plant remains with the apical bud and there is a much reduced tendency (although not eliminated) for new shoots to arise. In addition, the canopy of pioneering woody species will prevent additional pioneering plants from establishing as would be the case if all the plants were cleared. In some cases it may be useful to plant later successional species underneath the pioneering plants so that the living space in the ecosystem (includes both physical space and moisture and nutrients needed for growth) is filled. As the plants mature, the pioneering species can be removed without fear that they will return because the later successional species will now occupy the ecosystem. These plants tend to be much slower growing and may prove to be an effective cover adjacent to roadsides and under power lines for many decades. Cutting the apical bud of these later successional plants will slow the growth rate even further. By understanding the growth patterns as well as the ecological positions occupied by the plants being managed, effective strategies can be developed.

Tilling and cultivation can be used where replacement of the weedy vegetation cover is considered to be the best option. In some cases, establishment of an effective, non-weedy cover can be cost-effective relative to continued vegetation management efforts. Pastures that are infested with weeds and weedy rights-of-way can be treated by tilling and replanting with a health cover of grasses and legumes. A rail yard in Montreal infested with ragweed (*Ambrosia artemisiifolia*) was treated by leveling, junk removal, cultivation and vegetation replacement with a 22.7 percent return on investment over the previous mowing costs. Cultivation on severely degraded sites can sometimes be used to change otherwise hostile sites that are prone to weed invasion into sites with productive vegetation covers.

Opportunities for improving the health and vigor of the vegetation can lead to improved weed control. Many weedy species exploit poorly maintained pastures and fields. Using standard agricultural treatments such as fertilizer applications, over-seeding and full cultivation and re-seeding can be an effective way of reducing crop losses due to weeds. Healthy vegetation tends to be less prone to weed invasions than vegetation that is in poor condition.

SUCCESSIONAL DISTANCING

Successional distancing (Polster 1994) is the term applied to the creation of successional or ecological distance between two physically adjacent vegetation types. For instance, a mature forest standing beside a hay field would be considered to be successionally distant from each other. Figure 6.6.2-1 shows a generalized theoretical successional sequence.

Successional distancing is particularly useful for right-of-way vegetation management. In many cases, bare ground areas are desired next to roadways and within the ballast section of railroads to allow for drainage and to provide unobstructed use of the road or railroad. However, traditional vegetation management activities often result in weedy areas adjacent to these bare areas with the result that the bare areas quickly become weedy. Creation of a later successional stage next to the bare area rather than the weedy stage that typically occurs can be a very powerful tool to eliminate the weeds.

Early successional vegetation, either weedy, in the early successional herbaceous stage, or composed of pioneering woody plants often dominate the rights-of-way of railroads, roads, pipelines, power lines and utility corridors. Traditional treatments of mowing, brush cutting, selective herbicide application (e.g. Picloram) or combinations of these perpetuate this early successional vegetation cover and entail significant resources to maintain. This is because this stage of vegetation growth is composed of species that are quick growing, produce abundant seeds and the other attributes that make these plants perfect invaders of bare ground.

Creation of later successional stages through successional distancing on the rights-of-way can avoid the problem of weedy or brushy rights-of-way. Because these later successional stages would be very slow to invade the bare ground that is desired on the travel portion of the road or railroad, vegetation management activities can be greatly reduced. There may be a need to trim branches and otherwise perform specific vegetation manipulations to obtain the utility of the later successional stages that is needed. In addition, a change in the vegetation management philosophy is needed as it may seem counter-productive to plant conifers along a right-of-way that has been mown or brush cut for the past decades to remove the trees. Photograph 6.6-1 shows a site where successional advancement and trimming has been used to open sightlines at a highway intersection.

7.0 Social Aspects of Ecological Restoration

There is an increasing recognition of the importance of engaging local people in the restoration of local areas (Clewell and Aronson 2013). In addition, the concept that people need a connection to the natural world is gaining credence (Louv 2005). The enthusiasm that local stewardship groups show in tackling local restoration issues is a demonstration that people want to be connected with the land (see Photograph 7.0-1). Clewell and Aronson (2006) state that people engage in ecological restoration for five basic reasons; technocratic, biotic, heuristic, idealistic, and pragmatic. In many cases, the reasons for conducting ecological restoration are combinations of these five so technocratic reasons may dominate government agencies that work to restore ecosystems to fulfill their mandate to protect rare species, but there may be biotic

reasons as well as idealistic reasons. The dedication that many engaged in ecological restoration show to the ecosystems they work on goes beyond the purely rational and can be summed up in what Clewell and Aronson (2006) call the idealistic reason. There is a spiritual connection that people get in their connection to the earth. Avid gardeners relate their feelings of peace as they work in their garden. Even hunters tell how they really don't care if they "get their moose" as they really hunt for the love of being out in the woods. Ecological restoration is no different. Engaging in restoration provides practitioners with a connection to earth and whether this is termed spiritual or not is up to each practitioner.

7.1 Four Quadrant Model of Ecological Restoration

Clewell and Aronson (2007) proposed a four quadrant model of holistic ecological restoration (Figure 7.1-1). This model suggests that in addition to the ecological and socio-economic values that are normally included in restoration projects our personal and cultural values need to be included to create sustainable restoration. Clewell and Aronson (2007) go on to suggest that the four quadrants are so inextricably overlapped that in a graphical representation looks more like a three dimensional sphere. This model recognizes that ecological restoration also restores people and their relationship to ecosystems. Work on forest landslides with displaced forest workers as well as with stewardship and community groups provides insights into this aspect of ecological restoration.

There are many benefits to working with others to restore ecosystems. Children can be particularly rewarding to work with. Ecological restoration is a hopeful activity. In most cases, the results of treatments applied now will not be seen for many years so hopefulness is needed to engage in these tasks. Bringing children into the project can have lasting benefits.

7.2 Building Heart into Ecosystems

Just as humans need functioning ecosystems to survive, ecosystems have little chance unless humans are operating in concert with nature. We have now reached a point in human history where we have significant influences on the ecosystems around us. In most cases, these influences have been negative, causing major ecological disruptions. Unless humans can learn to live within the ecological bounds the natural world sets there is little hope for humans and

many of the other organisms on earth. Ecological restoration offers an opportunity to change these destructive patterns. When people work to restore ecosystems they shift the way they approach the natural world so the very process of ecological restoration changes the way we deal with the natural world. By building this sense of 'love of nature' or 'heart' into ecological restoration projects, this shift in our approach to the natural world can be enhanced. Although this can be difficult when working on the restoration of a large open pit mine or industrial development, by keeping this idea in mind when working on such projects, the opportunities may arise to build 'heart' into the project.

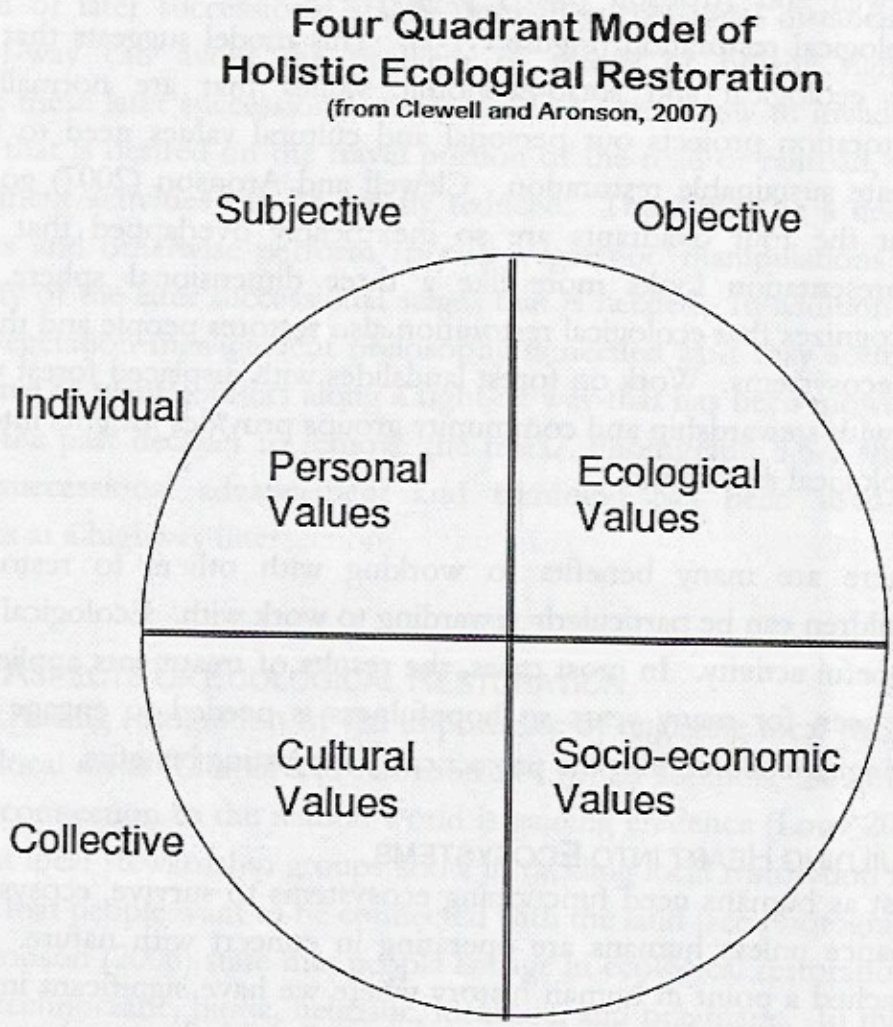

Figure 7.1-1. Four Quadrant Model of Holistic Ecological Restoration (modified from Clewell and Aronson 2007).

8.0 Some Common Operational Considerations

Restoration projects are often very complex and a wide variety of elements must be considered to ensure success. In addition, restoration work is conducted in the field and weather and other conditions can be uncertain. Detailed plans should be prepared prior to implementing any significant restoration program. The plans should include:

- The goals and objectives of the program including the desired ecosystem state at completion;
- An overview of the ecological conditions of the area where the work is to be conducted;
- Details of the specific site where the work is to be conducted (photographs and maps are often useful) including land ownership and/or land tenure. It is essential to have the owner/manager in agreement with the proposed treatments;
- Who will do the work (the owner, contractor, or by a stewardship group, etc.);
- The materials that will be needed and where these are to come from;
- Techniques/treatments that will be used;
- Supervision structure;
- Monitoring (during the work and following the work); and
- Opportunities for continued treatments.

The following sections provide some ideas about common operational considerations.

8.1 Procurement of Plant Materials

Plant materials for restoration projects are often difficult and costly to obtain. In addition, plant materials that come from the project area may not be readily available at local nurseries. Consideration should be given to looking into the supply of required plant materials early on in the project planning process. Local seed/propagule collection and subsequent growth of the required plants can be an important part of the restoration program for major projects. Several years advance notice may be required to conduct this work so that plants are available when they are needed for the treatments on the ground. Where live cuttings are required for soil bioengineering treatments, the locations of collection and permission from the land owner/manager must be determined prior to the start of the project.

8.2 Contracting Restoration Treatments

Some restoration projects are most effectively conducted using contracted crews. Soil bioengineering treatments are often conducted by contract crews.

The key to successful contracting is to avoid instructions that direct the contractor how the work is to be completed. Focus contract specifications on how the completed project is to be so that the contractor has the flexibility to determine the best way to achieve this end. Soil bioengineering treatments are often contracted by the linear meter of completed structure. So a meter of wattle fence would include all the work required for collection and handling of the cuttings as well as the labour required building the structure. Detail specifications of the materials that go into the structure would also be provided. Planting is often paid for by the number of plants planted. This may include all of the work required to collect the seed, grow the plants and plant them on the restoration site. There may also be a need to include some level of maintenance in the price so that the newly planted plants can be watered or otherwise tended early in the process.

9.0 MONITORING

Monitoring is an essential part of any restoration project. Gaboury and Wong (1999) provide an excellent account of monitoring systems for restoration projects. Where the objective of the restoration program is the re-integration of the disturbed site into the natural successional trajectories that operate in the region, then the monitoring work should focus on whether the project has reached a sustainable condition. Monitoring to determine if restoration work is sustainable is far different than monitoring that might be conducted to ascertain if the restoration treatments were conducted in accordance with the plans. The following points must be considered when looking at sustainability of restoration:

- Is the vegetation on a sustainable successional trajectory?
- Are ecosystem functions being re-established?
- Is soil being developed?
- Is the ecosystem structure being re-established?
- Can the established ecosystem withstand perturbations (is it resilient)?

These components of the monitoring systems are discussed below.

9.1 Measuring Successional Trajectories

Successional trajectories are measured by documenting the changes in species composition and cover that occur in the ecosystem. For instance, in the

example given in Photographs 5.1-1 and 5.1-2, the initial cover of Sitka Alder has been replaced by a cover of conifers. There are still some alder plants on the site, but a diversity of conifer species has established. Unfortunately this site is on a very steep rock cut and detailed assessments are not possible. However, visual monitoring of this location can reveal a lot about how ecosystems recover. Assessments are conducted by photographically monitoring the treated areas. The graph shown in Figure 9.1-1 is from the Island Copper Mine, a large reclaimed mine on the northwest coast of Vancouver Island, British Columbia. Here the area was seeded with grasses and legumes and planted with Red Alder. Assessment methods consist of transects with plots spaced along the transects. Each transect is about 300 m long (depends on if a plot is located at the start or not) with plots established every 30 m for 10 plots/transect. Seven transects have been established, with the fifth transect established in 2004 and the sixth and seventh established in 2011. The other four transects were established in 1997, one year after the major reclamation work was completed at the mine.

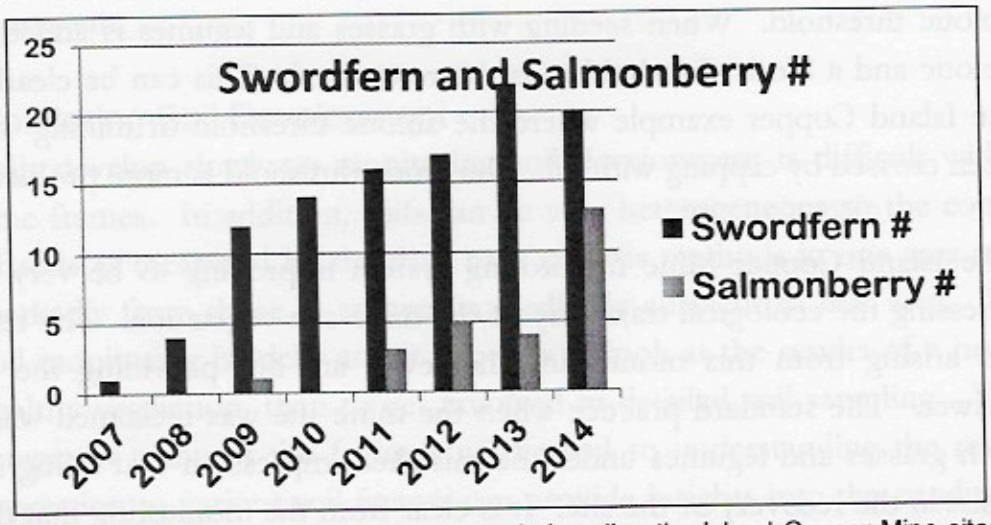

Figure 9.1-1. Swordferns and Salmonberry are slowly invading the Island Copper Mine sites that were reclaimed in 1996. This graph show the number of plots where these plants were found plants out of a total number of 50 plots. Transects 6 and 7 are not included in this graph as these sites were selected to document the change from the early seral alder forests to later successional conifers. Salmonberry and Swordferns occurred in most of the plots on transects 6 and 7.

Each plot along the Island Copper transects consists of a circle 5.62 m in radius, giving a plot area of 100 m^2. In the early years data recorded in the plots consisted solely of the number of planted trees (alder or pine) that were surviving, the percent cover of legumes and the total vegetation cover. More

recently in addition to the number, size and cover provided by the woody species and a listing of all of the species that occur in the plots along with an estimate of their combined cover and abundance is collected. Data are analysed using simple parametric statistics (means and variance). Monitoring at the Island Copper Mine is providing increasingly interesting information on the recovery of disturbed ecosystems.

The question of sustainability at many older reclaimed sites including the Island Copper Mine is complicated by the fact that the area was seeded with grasses and legumes. This creates a filter or barrier to recovery that may be difficult for the natural successional forces to overcome. Without the seeded grasses and legumes, it is probable that the recovery would have been faster and could be guaranteed at this point. Figure 3.1 shows a model of how ecosystem degradation occurs. This model suggests there are thresholds across which it is difficult to move an ecosystem. When restoration occurs some effort must be made to re-cross the threshold(s). Mining sites have crossed a substantial abiotic threshold. When seeding with grasses and legumes is added, both an abiotic and a biotic threshold must be re-crossed. This can be clearly seen in the Island Copper example where the abiotic threshold of mining wastes has been crossed by capping with till. The biotic threshold is more problematic.

The Island Copper Mine monitoring system is proving to be very useful in assessing the ecological trajectory of the mine site vegetation. The results that are arising from this monitoring, however, are not providing the expected answer. The standard practice when the mine site was reclaimed was to seed with grasses and legumes under the mistaken impression that doing so would assist in the recovery of the site. It is clear from the monitoring that this is not the case and that rather than helping the recovery of the site; the seeded species are actually hindering recovery by forming a biotic threshold that the restored ecosystem must now break through.

9.2 Monitoring Ecosystem Functions

Ecosystem functions are difficult to measure so surrogates are used. Nutrient cycling can be particularly difficult to follow directly. However, vegetation is a very good indicator of how effectively nutrient cycling systems are operating.

Photographs 5.1-1 and 5.1-2 show a 0.8:1 rock cut in the Roger's Pass where vegetation was established directly on the rock by seeding in the pioneering species Sitka Alder (too steep to plant seedlings). The alder provided the initial pioneering cover that fixed nitrogen and added leaf litter (nutrient rich organic matter). This facilitated invasion by conifers and now, 23 years later, a healthy stand of conifers has established. The conifers have good colour and are growing well. No fertilizer or other management treatments have been applied since the alder seeding in 1986 so the assumption is that nutrient cycling processes are operating effectively.

Monitoring ecosystem function can be based on visual assessments of plant health. Established plants will show how well ecosystem processes are functioning. If the plants look poorly, then the ecosystem is functioning poorly. However if the plants look healthy and detritus is being decomposed and recycled then it can be assumed that ecosystem functions are doing well. Care should be taken to avoid mistaking a fertilizer response for a healthy ecosystem.

9.3 Monitoring Soil Development

Soils develop slowly so monitoring soil development is difficult within short time frames. In addition, soils can be very heterogeneous so the composition of soils as measured by standard soils analysis methods in one area may differ markedly from those in an area immediately adjacent to that area. Therefore soil monitoring is tricky and it is better to look at the results of a healthy soil, healthy vegetation, than to get involved in detailed soil sampling. Vegetation integrates many of the features of the soil so understanding the response of vegetation to various soil factors can provide insights into the condition of the soils without soil tests.

9.4 Monitoring Ecosystem Structure

Ecosystem structure can play an important role in the ecology of recovering ecosystems. At the Island Copper Mine, Swordferns did not start showing up until the Red Alder trees were big enough to catch the wind-borne spores 10 years after planting. Similarly, species such as Salmonberry show up when trees get large enough to provide perches for birds carrying seeds. Monitoring the

development of structure in the restored ecosystem can be conducted by simply noting the height of the species that are encountered during the monitoring of successional trajectories (discussed above). In addition monitoring the results of structural additions such as rock piles (see Photograph 5.2-2) can provide information on whether these structural elements are providing a benefit.

9.5 Resiliency

Resiliency is another ecosystem attribute that is hard to measure. Consideration should be given to the natural disturbance regimes that are anticipated at the site and the ability of the established ecosystems to recover from these disturbances. There may be relatively few natural disturbances associated with some areas, although it is relatively rare that ecosystems will not experience some form of disturbance. The study of resiliency in restored ecosystems is in its infancy so detailed procedures for such studies have not been developed (Hobbs and Suding 2009). Further consideration of this topic can be developed within the context of the successional trajectory monitoring.

10.0 Conclusions

Ecological restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed (SERI 2004). Natural processes have been doing this for millions of years. By observing how these natural processes operate to restore disturbed sites, effective restoration strategies can be developed (Polster 2013). The first step in this process is to identify how the natural systems operate in the region where the restoration project is to occur. What are the successional patterns? Are there specific pioneering species that occur on the substrates that are similar to the substrates being restored? Are there specific processes that occur in the wet areas or on the dry knolls? Are there structures that are important to the growth of specific species? Once this understanding has been gained, the next step in the recovery process is to identify the filters that are preventing these processes from naturally restoring the site. Physical (abiotic) filters such as compaction, excess erosion, steep slopes (lack of surface stability), adverse texture, lack of micro-sites, soil temperature extremes, lack of nutrients and adverse chemical properties can prevent or limit recovery of sites. Similarly the biological (biotic) filters of herbivory, competition, allelopathic (phytotoxic exudates), lack of propagules, facilitation of one species over

others and adverse interactions between species can also prevent recovery. Knowing what it is that is preventing recovery is half of the process of finding solutions.

Combining the knowledge of how natural systems operate and how filters impede recovery allow solutions to be developed to assist natural recovery. In many cases simple steps such as making sites rough and loose to control erosion and create micro-sites for seeds to lodge in, germinate and grow may be all that is needed to allow the site to recover (Polster 2015). In other cases such as the situation where acid generating mine wastes are preventing plant growth (as well as polluting local water courses) more elaborate treatments to isolate the offending materials might be needed. In these cases, care must be taken in the development of the isolating capping to ensure this capping does not create other filters to plant growth (compaction, lack of rooting depth, lack of micro-sites, etc.).

Starting with pioneering species is often an effective way of restoring drastically disturbed sites. Seeding or planting pioneering species can be used to re-establish natural successional trajectories that will lead to the recovery of the site. Other species will move into the restoration site when conditions are appropriate. In some cases the use of these species in soil bioengineering structures can provide a very effective solution to drastically disturbed sites. Management of invasive species may be an important part of the restoration processes. Many invasive species create competitive conditions that prevent recovery of the site and may hold the site in a successionally stagnant condition. As with the development of restoration treatments, understanding the ecology of the invasive species of concern can allow treatments that serve to foster recovery rather than perpetuating the problems.

The inclusion of social and cultural aspects in the restoration of ecosystems is critical to the success of the restoration project. In many cases, having local people involved in the restoration activities provides a connection between the restored ecosystem and the community which fosters a sense of land stewardship. Ecosystem restoration can help to build community as well as healthy ecosystems that are essential for healthy populations.

There are many elements to a successful restoration project and monitoring is one of the ways of ensuring success. In addition to documenting the progress of the restored

site, monitoring programs can provide insights into the recovery processes and allow refinements in the treatments to be employed in future projects. Even simple photograph documentation of recovery progress extended over long periods can be useful in gaining insights into the ecology of recovery.

Restoration is a young science and many of the intricacies have yet to be elucidated. By trying new treatments and looking to natural processes for solutions, many new restoration strategies will be found for drastically disturbed sites.

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PHOTOGRAPHS

Photograph 3.2-1. Changes in natural disturbance regimes (e.g. control of fires) can result in significant ecological changes such as the growth of forest species on former grasslands as shown here.

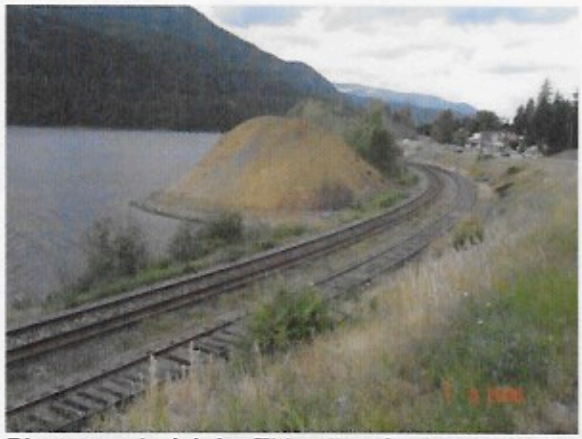
Photograph 4.1-3. High metals levels and acidic conditions prevent the growth of most species except species such as Tufted Hair-grass (*Deschampsia cespitosa*).

Photograph 4.1-1. Erosion associated with the over-steepened portion of this partially re-sloped waste rock dump is preventing recovery.

Photograph 4.1-4. Compaction of this road surface has prevented establishment of the alder and swordferns that line the road margins where there is little or no compaction.

Photograph 4.1-2. Compaction of this waste rock dump platform is preventing effective growth of the planted trees and fostering invasion by non-native (weedy) species (*Verbascum thapsus*).

Photograph 4.1-5. Compacted basal tills create slide surfaces when forest cover is removed and the less than 2 mm roots systems that hold the slope together decompose. Revegetation of these sites is difficult.



Photograph 4.1-6. This pile of acid generating waste rock has been sitting on the shore of Moyie Lake for about 100 years. The steep slopes and acidic conditions are preventing vegetation growth.

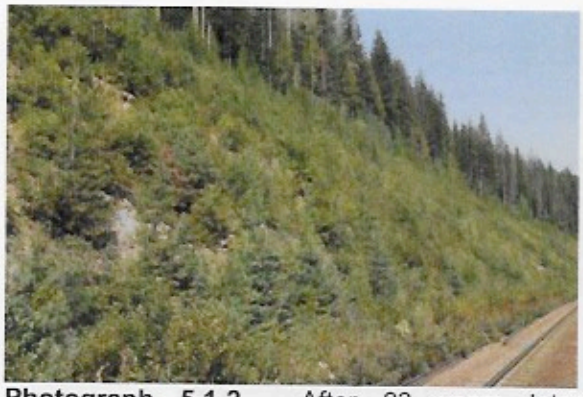
Photograph 4.1-7. Chlorotic leaves can indicate metal toxicity. In this case, high levels of zinc are replacing the iron molecules in the chlorophyll of this Balsam Poplar growing near a large smelter.

Photograph 4.2-1. Insects (*Leucoma salicis*) can shift the species composition in ecosystems. Seed weevils and other insects that target susceptible life stages can change ecosystem dynamics.

Photograph 4.2-2. A distinct browse line and a lack of understory species has been created by Fallow Deer on Sidney Island.

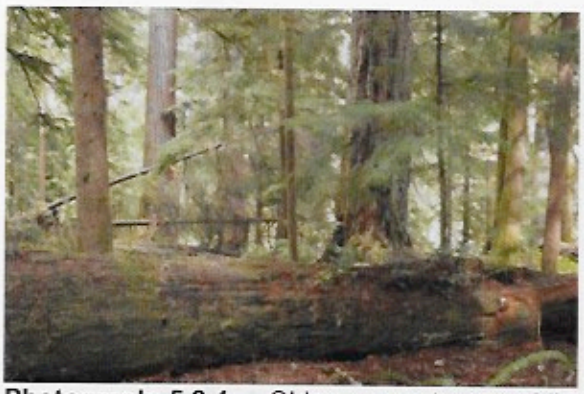
Photograph 4.2-3. Competition from the grasses and legumes that were seeded on this exploration trench in 1977 have prevented invasion by woody species for over 32 years.

Photograph 5.1-1. Seeding alder (a pioneering species) on this 0.8:1 rock cut initiated the successional processes that re-establish the forest species (see Photograph 5.1-2). Photograph taken on October 30, 1986.



Photograph 5.1-2. After 23 years later successional conifers are well established on this rock cut that was seeded with alder (see Photograph 5.1-1). Photograph taken on August 1, 2009.

Photograph 5.1-3. Pioneering species, in this case as live stakes, can be used for the establishment of the initial cover on drastically disturbed sites. Note the rough and loose surface shape on this site to control erosion.

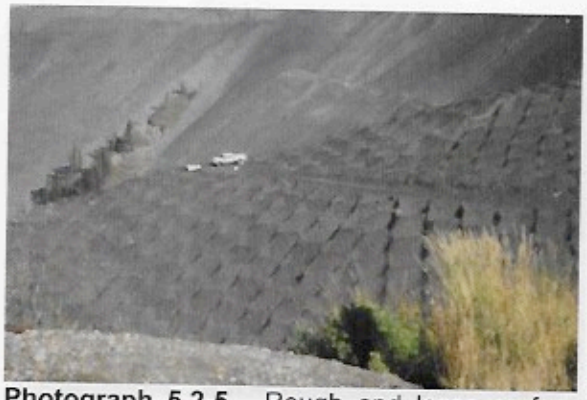


Photograph 5.2-1. Older ecosystems exhibit greater structure than young ecosystems.

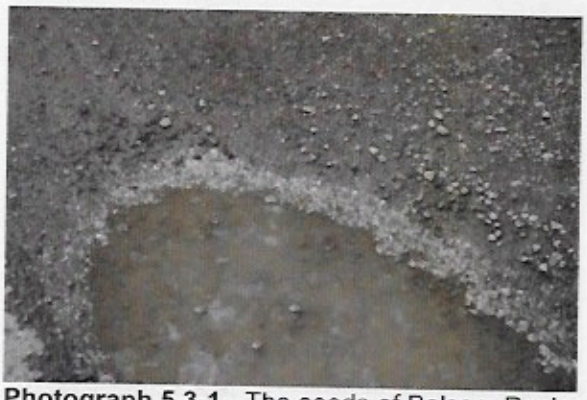
Photograph 5.2-2. Piles of large rocks can create structure at sites such as this mine tailings pond where structure is lacking. Such rock piles can provide habitat for small mammals as well as perching sites for birds. Bird carried seed was instrumental in the establishment of the Elderberry bush growing among the rocks.

Photograph 5.2-3. Woody debris piles can add structure to tailings pond sites, enhancing biodiversity.

Photograph 5.2-4. Upturned trees can be used to provide platforms for Osprey nesting. Combinations of rock and wood can enhance structure creation.



Photograph 5.2-5. Rough and loose surface treatments such as at this coal mine create ecosystem structures that allow different species to establish in the different habitats that are created.



Photograph 5.3-1. The seeds of Balsam Poplar (*Populus balsamifera*) are trapped on the margins of this puddle where the moist mud provides an ideal site for germination and growth.

Photograph 5.3-2. The narrow crevices on this cliff face are suitable safe sites for the establishment of Broad-leaved Stonecrop. Other species are precluded by the harsh conditions of limited summer moisture. The Stonecrop is a poor competitor on less severe sites.

Photograph 5.5-1. The initial establishment of Red Alder facilitates the establishment and growth of later successional conifers.

Photograph 6.1-1. Removal of the natural riparian vegetation during clearing for agriculture has left the streambanks in a very vulnerable condition.

Photograph 6.2-1. Upturned trees create a rough and loose surface condition, bringing non-mobile nutrients to the surface and exposing mineral soil where pioneering species can establish.

Photograph 6.2.2. Rough and loose surface treatments at this mine site can solve erosion and compaction issues and provide safe sites for species establishment and growth.

Photograph 6.2-3. Traditional smooth surface treatments lack the many ecological advantages of a rough and loose surface treatment and are prone to erosion.

Photograph 6.3-1. Planting rooted grass plugs on restoration sites can be an effective way of establishing these species.

Photograph 6.3-2. Direct planting of dormant stem cuttings can be an effective way of establishing some species on restoration sites.

Photograph 6.4-1. Wattle fences can be used to treat very steep (70° average slope) slopes. Note the untreated slope in the background (red arrow).

Photograph 6.4-2. Growth of the cuttings used in the wattle fences provides a vegetation cover on this 70° slope. Note the untreated area in the background (red arrow).

Photograph 6.4-3. The wattle fences do not change the actual slope (see background), but change the characteristics of the slope surface relative to plant growth. By preventing soil movement on the slope, the wattle fences allow vegetation to be established.

Photograph 6.4-4. Wattle fences constructed starting with the butt ends of the cuttings at one end of the fence and alternating create a zigzag pattern on the slope.

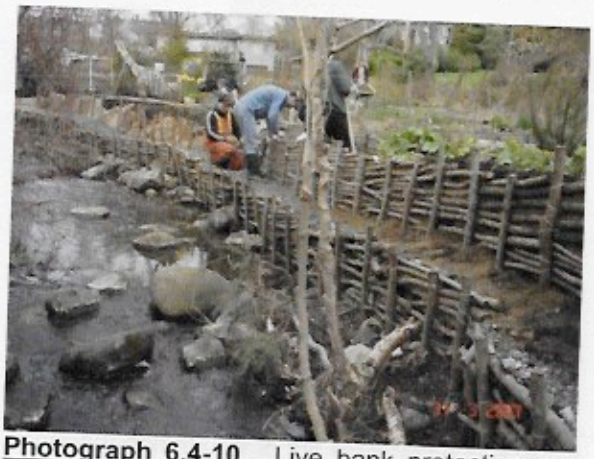
Photograph 6.4-5. Live pole drains can be used to drain saturated soils and thereby enhance slope stability.

Photograph 6.4-6. Live pole drains were installed in the scarp to control movement of the large block of soil (on left). The soil was so wet rocks were needed to hold down the drain. Note the moisture draining from the ends of the drains (red arrows).

Photograph 6.4-7. A dense copse of willows has established after 22 years. The hard engineering solution, to extend the tied back shotcrete wall (right) would have cost several orders of magnitude more than the soil bioengineering treatment.

Photograph 6.4-8. Modified brush layers can be used to stabilize large raveling slopes. The small terraces created by the modified brush layers catches rolling rocks initiating the successional processes on the slope.

Photograph 6.4-9. Brush layers can be used strengthen the backfill used to treat slumps.



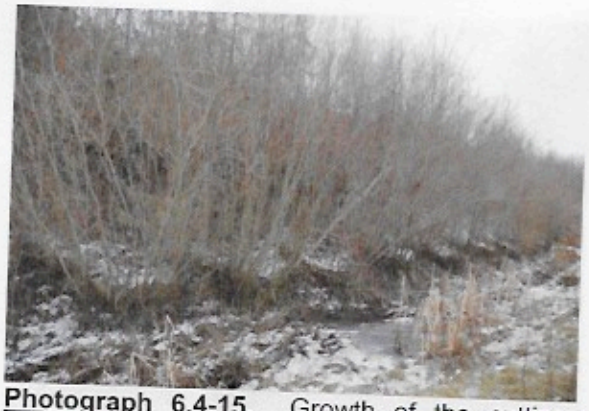
Photograph 6.4-10. Live bank protection can be used to treat eroding streambanks. Growth of the cuttings further strengthens the protection.

Photograph 6.4-11. Live silt fences control sediment and prevent ditch erosion by slowing water flows.

Photograph 6.4-12. Live gravel bar staking (March 12, 1998) can be used to initiate successional processes on bare gravel bars, trapping sediment and building up the gravel bar while deepening the thalwag (Red arrow indicates tree shown in Photograph 6.4-13).

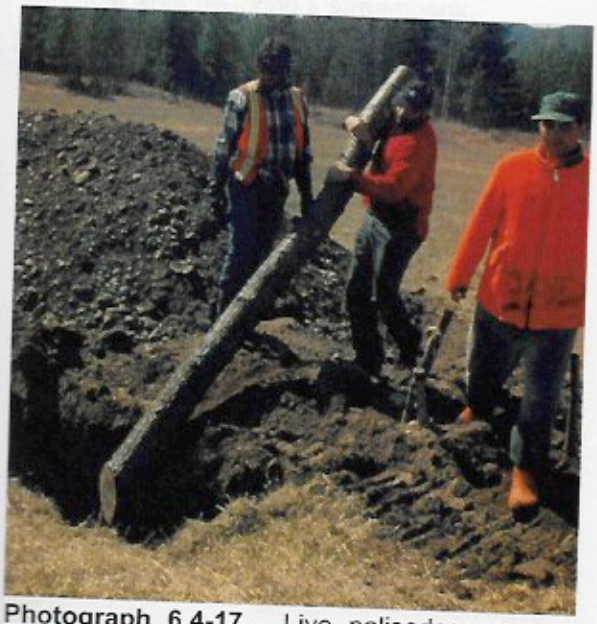
Photograph 6.4-13. Growth of the cuttings used in live gravel bar staking starts the successional processes that "terrestrialize" the gravel bar and deepen the stream channel (San Juan River site June 19, 2011).

Photograph 6.4-14. Live smiles can be used to treat very wet muddy slopes.



Photograph 6.4-15. Growth of the cuttings used in the live smiles initiates the natural successional processes that will maintain vegetation on the slope forever.

Photograph 6.4-16. Live shade can be an important contributor to the restoration of riparian areas on newly constructed fish channels. This site is 3 years old.



Photograph 6.4-17. Live palisades can use large balsam poplar logs to create a dense wall of roots that will slow river bank erosion.

Photograph 6.4-18. Pocket planting was used to establish riparian vegetation in the riprap along the Seaton River in Lillooet, B.C.

Photograph 6.4-19. Joint planting was used to establish vegetation in the culvert headwall.

Photograph 6.5-1. Stout fences are used to keep elk away from newly planted areas. Note the use of a rough and loose surface treatment at this coal mine site.

Photograph 6.6-1. Successional advancement and trimming has been used to open sightlines at this highway intersection.

Photograph 7.0-1. A local steam stewardship group is all smiles after completing a day of hard physical work restoring a streambank.