Chapter 7

ECOTECHNOLOGICAL SOLUTIONS FOR UNSTABLE SLOPES: GROUND BIO- AND ECO-ENGINEERING TECHNIQUES AND STRATEGIES

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Abstract: *For centuries vegetation has been used to prevent and control the effects of erosion and mass wasting processes. Techniques have developed continuously until now, when the increased environmental awareness of society has resulted in them being used as key tools in landscape conservation. The need for environmentally friendly techniques to mitigate the problems generated by soil instability (mass movements, rockfall, landslides, etc.) and the incidence of erosion have provoked the appearance in recent years of two different ecotechnological concepts: ground bio-engineering and eco-engineering. Both concepts are complementary, sometimes controversial, and have in common the use of biological materials (live and inert plant materials) as main and essential tools. In this Chapter, an updated and complete review of the different ground bio- and eco-engineering techniques in use is presented. The possible advantages and drawbacks of their application with regard to different degradation factors and processes are presented and future perspectives discussed. From the simplest methods such as seeding, mulching or planting, to the most complex ones that integrate different engineering techniques using very different materials (live cribwalls, vegetated gabions, etc.), we describe the uses of vegetation for increasing slope stability and restoring and preserving degraded land. The use of eco-engineering techniques against rockfall and windthrow, relevant problems in many European mountainous areas have also been considered. Finally, the possibilities of combining both eco- and bio-engineering techniques are described.*

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Key words: management strategies, slope stabilization, rockfall, windthrow, erosion control, restoration techniques, plant species, environmental conservation, forest fires

1. INTRODUCTION

Live vegetation and inert plant materials have been used for erosion control and also to stabilize and restore degraded slopes and river banks for several centuries, but generally using local knowledge and lacking specific scientific criteria. The first reference to this kind of engineering work was in 28BC in China (Redfield 2000). In ancient Greece, Sophocles warned against the intensive farming of olive trees. Although olive trees possess deep taproots, few surface roots exist to hold the topsoil in place (Stokes et al. 2004). The Roman writer Pliny stressed the importance of ditching and terracing slopes to control erosion, as early as the 1st century AD. In the 16th century, some cases of the use of willow plantings to control and stabilize slopes to prevent mass movements and erosion have also been reported (Lewis 2000).

In the last few decades, due to the increasing interest in environmental restoration and conservation, together with the implementation of ecotechnological solutions, the development of ground bio- and eco-engineering techniques has increased enormously. It must be remembered that vegetation slope interactions are very complex, difficult to quantify and to model, therefore any study must be tackled from an interdisciplinary approach, involving forest scientists, ecologists, geomorphologists, pedologists, geologists and engineers.

Both ground bio- and eco-engineering techniques have in common the use of biological materials, mainly plants and vegetation, as essential tools. Therefore, in many cases they can be used complementarily but this approach requires a careful appraisal, and the selection of species should be made carefully by considering the criteria given in Chapter 6.

This chapter highlights the advantages and disadvantages of the established ground bio-engineering techniques, introduces new strategies for protecting forests from substantial erosion damage, windthrow and rockfall, and finally reports on how both ground bio- and eco-engineering techniques can be used in combination to promote soil stability and land regeneration.

2. GROUND BIO-ENGINEERING TECHNIQUES

Slopes that are potentially suitable for ground bio-engineering require a careful choice of the particular ground bio-engineering technique. New slopes (e.g. embankments or cuttings) or slopes that have undergone land use change (e.g. terraces) may require planting, reforestation or seeding with appropriate species. The advantages and disadvantages and methods of application are described in Tables 7-1 and 7-2. Table 7-3 lists the most used ground bio-engineering techniques and their possible application in mitigation of some instability phenomena (see Coppin and Richards 1990; Gray and Sotir 1996; Schiechtl and Stern 1996 for further information). Existing slopes that are either unstable from soil erosion or from shallow slope failure may be suitable for the ground bio-engineering techniques that are described in Tables 7-4 to 7-35.

Some important considerations when establishing vegetation on slopes are:

- Loss of vegetation leaves the slope vulnerable to runoff, erosion and sedimentation. Furthermore it enhances weed growth, degrades habitats and decreases forest regeneration. In order to combat the consequences of loss of vegetation on slopes, revegetation strategies can be adopted, in which seeding and planting will be major treatments.
- The choice of the best applicable treatment depends on the nature of vegetation loss (forest fire and its intensity, sylvicultural operations e.g. clearcuts, etc), slope type and inclination, proximity to drainage, possibility for weed spread and the management objectives.
- In semi-arid conditions, like those characteristics of Mediterranean environments, the plantation technique to use, the place and the hole design (for runoff collecting) should be selected very carefully. In the same way, the season for planting must be chosen, being preferably in autumn, but not in the period of hydrological deficit (spring or summer).
- The vegetation along the edge of the top of the slope serves as a protective buffer for the slope face. If possible, a greenbelt which would provide a buffer between the slope face and residential constructions should be maintained or re-established.
- Vegetation should be established on patchy and barren slope faces or terraces to reduce erosion (see Chapter 6). Various species and mixtures of them can be planted on slope faces and expected to succeed in this rather severe environment. These include seed mixtures of grasses and legumes and a range of shrubs and minor trees.
- Large trees should be used on the face of slopes sparingly and with caution. These trees could collapse because of undermining of the root system by erosion or by windthrow, large volumes of earth can be disturbed by the tree roots when they are pulled away from the slope. The resulting large, bare areas are opened to further erosion, which may endanger adjacent land and vegetation. If the trees become unstable, they should be cut or coppiced before they fall. Root systems should be left intact to bind the soil for a short period of time while new live, well-rooted vegetation is established. Planting new vegetation prior to felling a tree would be advantageous to the slope protection program.
- In those situations where the bottom of a slope is susceptible to frequent or periodic water erosion, e.g., at the coast, vegetation alone will not be

adequate as an erosion control tool. In such cases a form of structural toe protection may also be required. If the toe is not subject to coastal marine erosive forces, trees and woody shrubs can be useful in resisting upland landsliding and tolerating the dynamic changes in the coastal shore system. Vegetation at the slope toe can sometimes help reduce marine erosion to manageable levels.

Table 7-1. Planting and reforestation techniques

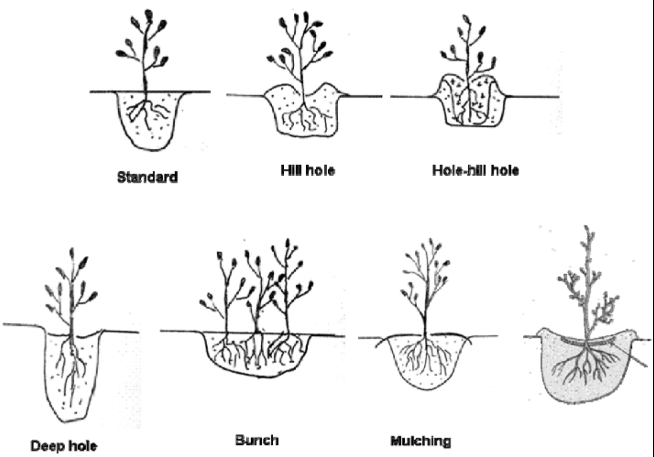
Application	**Advantages**	**Disadvantages**	**Effectiveness**
On slopes with maximum inclination of 1:1.5 (V:H) On low banks and marine estuaries	Fast action program for specific slope areas Higher plant survival Minimum slope disturbance when using planting in holes	Does not solve some erosion problems (gully erosion) Container grown plants might be expensive Hard to install in some mulching systems Has to be performed in dormant season (late autumn or early spring) and requires watering	Plant root systems penetrate into the lower soil horizons and stabilize the soil Plant roots can subsequently drain the slope by using underground water for survival
Material	**Diagram**		
Plants installed in groups or at specific distances and then pruned Plant selection is dependent on site conditions and erosion problems Structural diversity in plant selection (trees/shrubs with ground cover) is effective Planting should be done during dormancy and when water is available			

Table 7-2. Seeding techniques

Application	Advantages	Disadvantages	Effectiveness
On mild slopes, in small-scale areas affected by erosion processes Usually applied in combination with other planting techniques	Quick application Low cost of materials Compatible with many slope situations	Does not readily self-repair eroded slope areas, and should not be applied alone in highly eroded areas or for shallow seated landslide stabilization Seed needs to be mulched immediately to avoid it washing/blowing away, or the action of any fauna, mainly rodents Soil needs to be kept moist	Creates a shallow fibrous rooting zone in the uppermost 0.30 m of the soil which binds the surface soil particles and protects soil surface from runoff, wind and freeze-thaw erosive processes

Material	Observations
Grass, forb and woody plant seed mixes are sown directly or hydro-seeded Perennial grasses and forbs (for long term cover but slower to establish) for severely and moderately disturbed sites which are less than 15 m to a drainage channel Annual ryegrass and small grains should be seeded on moderately disturbed slopes of 15% and more inclination Seeding should be done in late autumn or early spring, or in the case of wildfires, immediately after the fire when the soil surface has lost to some degree its vegetation cover	Loss of vegetation leaves the slopes vulnerable to increased runoff, erosion, and sedimentation. Furthermore, it enhances weed growth, degrades habitats and decreases forest regeneration. In order to combat the consequences of vegetation on slopes, a revegetation strategy can be adopted in which seeding and planting will be major treatments. The choice of best applicable treatment depends on the nature of vegetation loss (forest fire and its intensity, silvicultural operations like clearcuts, etc), slope type and inclination, proximity to drainages, possibility for weed spread, climate conditions and the management objectives. In Mediterranean conditions, the use of this technique is closely dependent on the soil water regime. Slopes that suffered severe or moderate vegetation loss e.g. after a fire, in some cases, should be reseeded to minimise the likelihood of erosion and sediment movement downslope. For slopes suffering from light vegetation loss, reseeding is not necessary since they can recover quickly. Native species should be used where the re-establishment of the native plant community is the primary objective. Introduced species should be used when stabilization and resource protection are main objectives. A mixture of native and introduced species is not recommended since the introduced species might hinder the establishment of the natural species.

Table 7-3. Ground bio-engineering techniques and their possible application in mitigation of some instability phenomena on slopes

Bio-engineering technique	Shallow slides	Moderate mass movement	Mud slides	Debris creep/flow	Soil creep	Seepage erosion	Overland flow erosion	Splash erosion	Rill erosion	Gully erosion	Pipe erosion	Streamflow erosion	Flood inundation	Avalanche
Branch layering in gullies			Y	Y						Y				
Branchpacking	Y					Y	Y	Y	Y	Y				
Brush mattress construction						Y	Y	Y				Y		
Brush wattles	Y*					Y	Y	Y	Y			Y		
Brushlayer construction	Y	Y	Y	P	Y	Y	Y					Y		
Contour log terraces	Y		Y	Y		Y			Y	Y	Y	Y		
Contouring, sloping, regrading			Y					Y						
Cordon construction	Y		Y	Y	Y									
Crib-wall construction with branchlayering	Y		P	P	P									
Earth berm water bars						Y	Y		Y	Y		Y		
Furrowing, contour scarification					Y	Y		Y				Y		
Grassed waterways							Y	Y					Y	
Gravel drains							Y		Y	Y		Y	Y	
Groove construction						Y	Y	Y	Y				Y	
Hedge brushlayer construction	Y		Y		Y								Y	
Hedge layer construction	Y		Y		Y								Y	
Live crib walls (concrete and prefabricated elements)	Y		Y	Y	Y									
Live fascine drains							Y		Y	Y			Y	
Live pole drains							Y		Y	Y			Y	
Live shoring of open water canals							Y		Y	Y			Y	
Live slope gratings						Y	Y	Y	Y	Y				
Live staking/live fascine	Y		Y		Y		Y	Y				Y		
Matchsticks							Y	Y	Y	Y				
Mulching	P						Y	Y					Y	
Placing of cuttings and wall-joint planting	Y			P			Y							Y
Silt fences	Y		Y	Y										
Slope drainage using phreatophytes	Y													
Sodding or turfing	Y*					Y		Y	Y	Y				
Straw bale check dams	Y		Y	Y										
Vegetated gabions	Y			P					Y	Y		Y		
Vegetated geogrids		Y	Y			Y						Y		
Vegetated palisade and pole construction	Y				P					Y		Y		
Vegetated stone walls and rock piles	Y				P									
Wattle fences	Y		Y				Y	Y	Y		Y			

* subject to successful rooting; Y successful bio-engineering technique; P not a proven successful technique.

Table 7-4. Branch layering in gullies

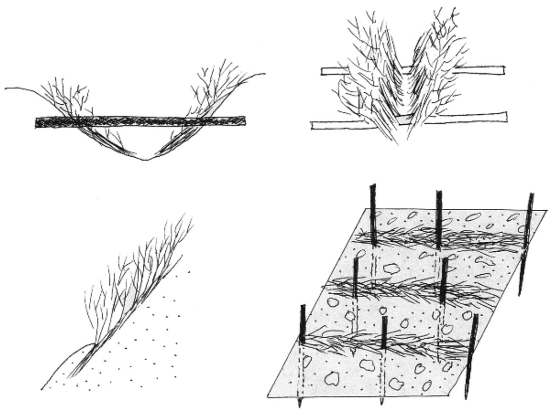
Application	**Advantages**	**Disadvantages**	**Effectiveness**
For repairing of shallow gullies (no deeper than 3 m and no wider than 8 m)	Provides continued effectiveness through the use of live plant material	Slightly more expensive than dead branch layering of gullies Cannot cope with continuous flow Cannot be applied if severe bed load and shoulder movement with significant deposition is expected	Live branches root and secure the gully bed. Well rooted branches can withstand temporary flooding Silt should not cover more than a third of the annual growth of the branch
Material	**Diagram**		
Long and strong live branches of rooting plants (for gullies deeper than 1.5 m, very bushy branches can be used) Cross beams placed at a distance of 2 m, with length and thickness depending on the gully			

Table 7-5. Branchpacking

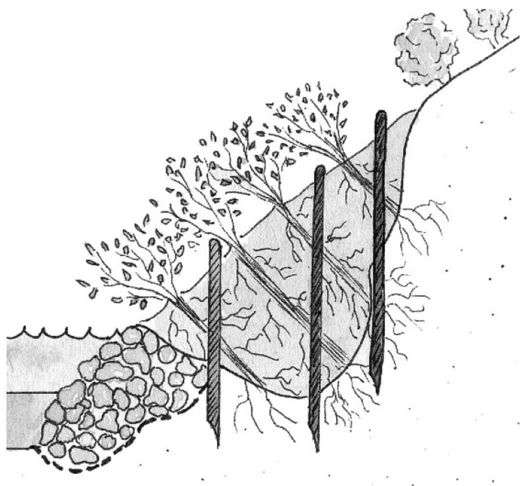
Application	**Advantages**	**Disadvantages**	**Effectiveness**
For repairing of small localized slumps and holes (0.005 to 0.01 m in width and depth) in stream banks	Effective Inexpensive Provides immediate soil reinforcement Rapidly establishes a vegetated stream bank	Not effective for slumps and holes wider and deeper than 1.0 m	Produces a filter barrier that prevents erosion and scouring from stream bank or over bank flow Live branches serve as tensile inclusions for reinforcement once installed As plants begin to grow, the system becomes more effective in retarding runoff and reducing surface erosion Trapped sediment refills the localized slumps or hole, while roots spread throughout the backfill and surrounding earth to form a unified mass
Material	**Diagram**		
Wooden stakes 1.5 to 2.0 m long, 0.05 x 0.10 m in cross section driven to 1.0 to 1.2 m into the undisturbed soil Live branches 1.5 to 5 cm in diameter inserted between compacted backfill Toe bank protection of large stones and geotextiles may be required at the toe of the slope in stream banks			

Table 7-6. Brush mattress construction

Application	**Advantages**	**Disadvantages**	**Effectiveness**
Surface protection Water/wind/wave erosion protection Protection of water channel banks against flowing water Repairing damaged areas	Immediate effectiveness even before the plants root Dense root and thicket development	Much material and labor is needed The effect of soil stabilization is lower than the one of brush layers Thinning may be required	Immediate cover and protection Roots can penetrate deeply if the soil is dry and permeable Permanent effect with live materials Possibility for the climax vegetation to establish itself quickly

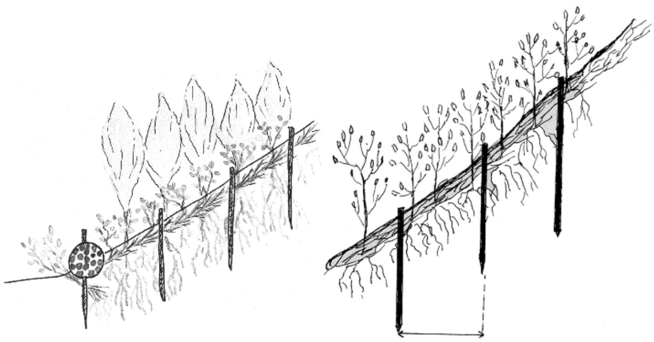
Material	**Diagram**
Long (>1.5 m), straight branches which root easily Smooth branches (5 kg/m^2) Bushy branches (5 to 10 kg/m^2) Live and dead material can be mixed 20-50 branches per meter length of the construction	

Table 7-7. Brush wattles (slope fascines)

Application	Advantages	Disadvantages	Effectiveness
For cut slopes in deep and soft sand In low altitudes with good growth conditions Areas where live branches are available and where fast growth can be expected	Very fast construction Simple Little soil disturbance	Lateral spreading branches cannot be used The system is susceptible to rockfall	Slope stabilization is provided by shading the soil and penetration of the roots

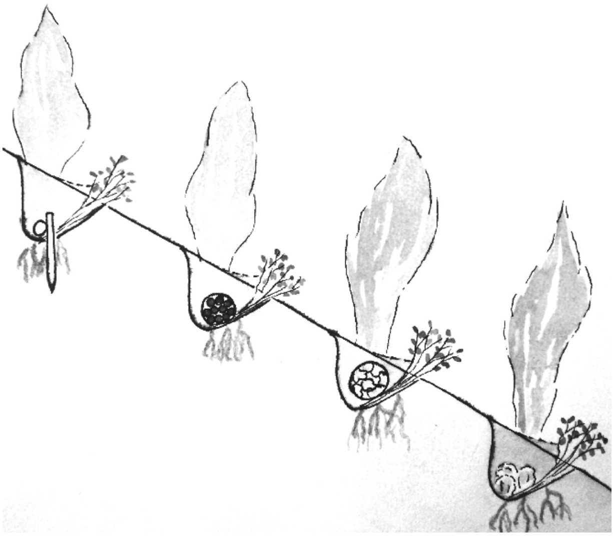
Material	Diagram
Long and straight branches of live woody plants Each fascine contains 5 branches with diameter of around 0.01 m, and pegs (>0.60 m/m) and are held in place by either wooden stakes, live fascines, gabion nets or large stone blocks (as illustrated from left to right)	

Table 7-8. Contour log terraces/barriers

Application	**Advantages**	**Disadvantages**	**Effectiveness**
Post-fire treatment providing obstacle to runoff from heavy rainstorms On slopes with an angle that varies from 31-50° On burned slopes where there are a number of dead trees that have little or no economic value	Local materials used Inexpensive Development of soil barriers with time Allows the establishment of vegetation	Cannot be used on steep slopes and heavy machinery must be avoided Enough trees must be felled to create a barrier that interrupts the movement of water and sediment downslope Little or no effect achieved if the logs are not in contact with the soil	Logs are placed in an alternating scheme so the runoff no longer has a straight down slope path to follow, reducing its kinetic energy. The water is forced to meander back and forth between logs, reducing the velocity and energy of the runoff, and giving water time to infiltrate into the soil.

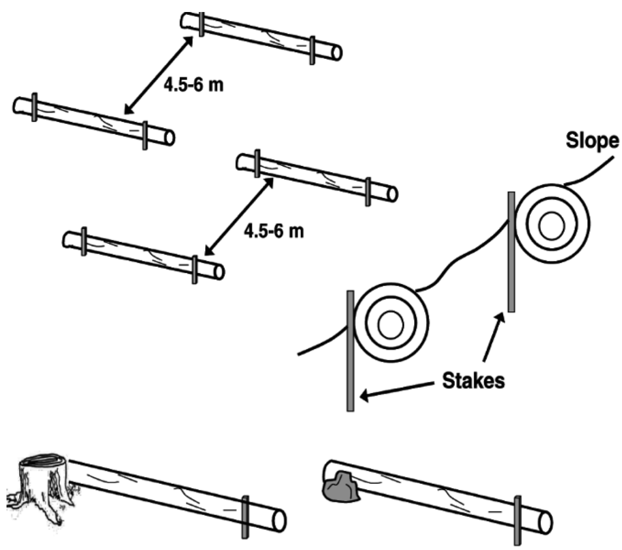
Material	**Diagram**
Dead trees are felled, limbed, and placed on the contour perpendicular to the direction of the slope. The logs should be bedded into the soil for its entire length and backfilled with soil so water cannot run underneath; backfill should be trampled down. Logs should be secured from rolling by driving stakes on the downhill side.	

Table 7-9. Contouring, sloping, regrading

<table>
<tr><th>Application</th><th>Advantages</th><th>Disadvantages</th><th>Effectiveness</th></tr>
<tr><td>Low slopes with enough space at the top to allow access</td><td>Slopes can be left steeper than their natural angle of inclination</td><td>Neither economically feasible nor technically desirable for an individual property owner</td><td>Produces an ideal form of a slope without sharp edges, especially at the top and the toe</td></tr>
<tr><th colspan="2">Materials</th><th colspan="2">Description</th></tr>
<tr><td colspan="2">Most commonly used method is regrading with effective earth moving machines, but only on sites where there is no problem with deposition of the excess material

Water pressure (underwashing or inducing artificial slides) applied from the toe to the crest is a more viable option if local conditions allow it</td><td colspan="2">Proper rounding off will cover every difference between the cut and the natural landscape

Grading the slopes to an inclination of 1:3 (V:H) or flatter is ideal because these slopes can be prepared and planted with wheeled vehicles

Blasting, drilling and jackhammering usually are expensive and they do not produce desired results</td></tr>
</table>

Table 7-10. Cordon construction

Application	**Advantages**	**Disadvantages**	**Effectiveness**
Moist slopes with clayey soils, heavy clay soils, limestone soils, mica slate soils, soil containing schistose material Dry slopes Couturier method is particularly effective for reafforestation of dry slopes.	**Couturier method** Excellent for water retention in dry climatic zones **Praxl method** Stabilizes suitable slopes Offers high resistance to slides and slippages Improves the aeration of the plant roots	**Couturier method** Should not be used on slopes prone to slipping Offers high risk of water impoundment **Praxl method** Has high labor and material costs Might cause damage in the surrounding shrub or forest areas More economical and effective methods exist (hedge brush layer, brush layer)	**Couturier method** Improves slope stability by retaining water and levelling out the planting beds **Praxl method** Strong branch overlay provides very good stabilisation of suitable slope sections Provides good root penetration

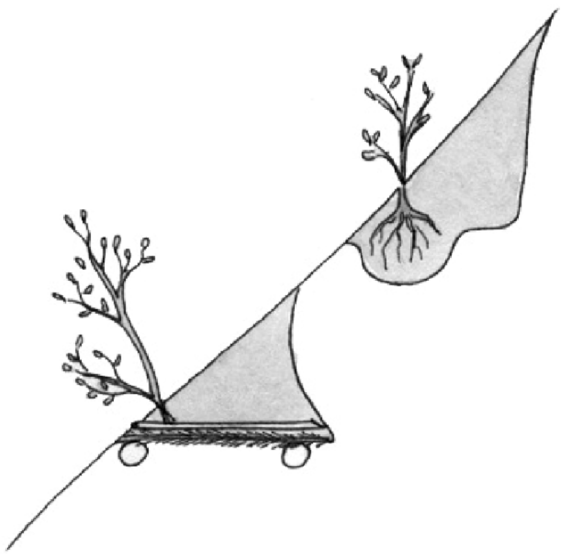
Materials	**Diagram**
Couturier method the (right hand drawing) three rooted seedlings of trees or shrubs for every running meter, 2 to 5 cuttings at 0.10 m from the sloping ground surface **Praxl method** (left hand drawing) two posts 0.06 to 0.12 m in diameter 10 to 25 cuttings with a minimum length of 0.50 m between the two posts	

Table 7-11. Earth-berm water bars

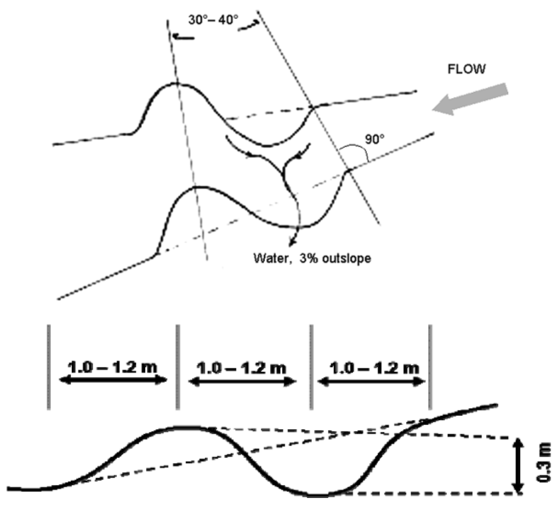
Application	Advantages	Disadvantages	Effectiveness
On slopes after a high/very high intensity fire The local soils and the road/trial grade will dictate the spacing between the berms	Properly built earth-berm water bars are very effective in diverting water off roads, trails, and landings. They also limit undesirable traffic following closure.	Hard to drive over and may be difficult to maintain They do not work well for active traffic surfaces during most operations. Frozen soils and rock may limit their use. They require caution when blading to maintain the road	Channel water off roads and trails to avoid the creation of gullies Water bars are angled down slope to the outlet side and can divert water to a vegetated slope below or redirect it into a channel that will take it to a culvert
Material	**Diagram**		
Berms of soil or embedded logs			

Table 7-12. Furrowing, contour scarification

Application	Advantages	Disadvantages	Effectiveness
In moderately to severely disturbed (burned) areas Burned upland areas with hydrophobic soil properties On slopes 0-30° to facilitate safe operation by machinery	Effective as a preparatory measure before vegetation seeding Multiple gains for reducing soil loss	Not to be used in swales, drainage ways, gullies or other areas of concentrated flow Requires usage of machinery	To break up the hydrophobic soil layer To aid in the establishment of vegetative cover from seed To reduce runoff velocity To increase infiltration To reduce erosion
Material	**Diagram**		
Small tractors, bull dozers or all-terrain vehicles equipped with a tool bar with tines, rippers or other scarification devices capable of loosening and mixing the soil to a depth of 0.05-0.10 m Can be done in strips 2-3 m wide spaced uniformly over the slope. The spacing between strips can be between 10 m for slopes with 20-30° inclination up to 50 m for slope inclinations less than 5°			

Table 7-13. Grassed waterways

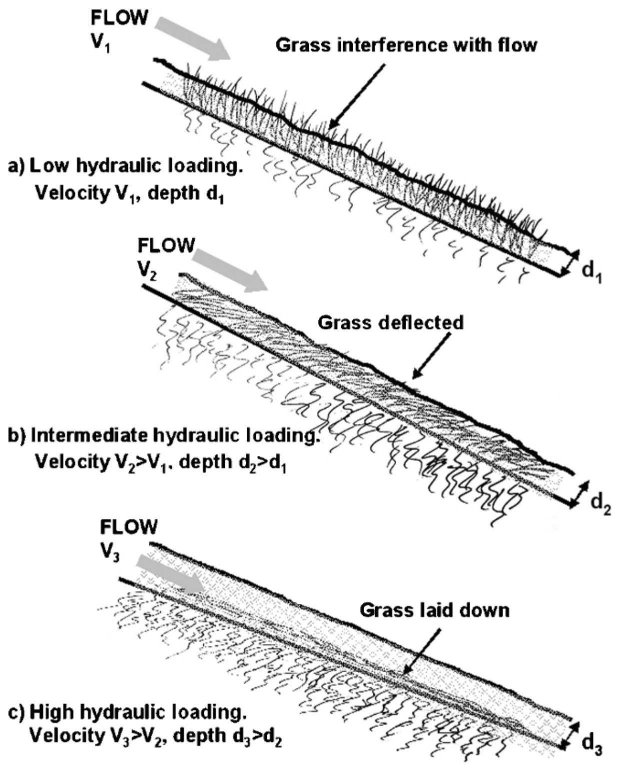
Application	**Advantages**	**Disadvantages**	**Effectiveness**
For slope drainage For surface water drainage around the toe of a slope Road construction Regulation of the water drainage on ski runs Artificial fill slopes or earthworks	Effective immediately if sods are used Easy to check its functioning because it can be viewed from above Blends well into the landscape	Very difficult to establish on rocky slopes Cannot be used for gullies with a steady water flow	Effective for the channeling of surface water Sods act as a water pump in draining the slope, especially in waterlogged soils
Material	**Description**		
Sods, reed sods, seed mats, hydro seeding material, pegs, hay, straw, wire or plastic netting, bitumen	 after Hewlett et al. 1987.		

Table 7-14. Gravel drains

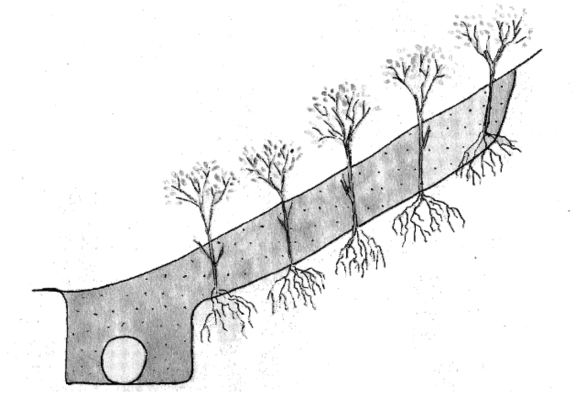
Application	Advantages	Disadvantages	Effectiveness
Instantaneous repair of slides Catching water layers at the toe of the slope Protection from frost damage	Simple system with permanent effectiveness More attractive than conventional engineering construction No maintenance required if far enough from roots	Only possible where machines are available and rocks or gravel are on hand Height is limited by vehicular access	Acts immediately as a support and a drain
Material	**Diagram**		
Rocks or gravel Branches of live woody plants (several meters long)			

Table 7-15. Hedge brush layer construction

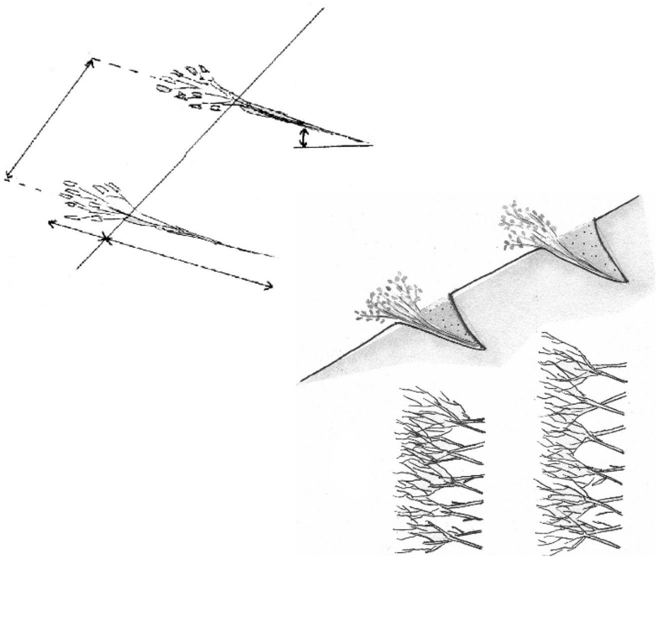
Application	**Advantages**	**Disadvantages**	**Effectiveness**
Fill slopes (where danger of erosion, slides, rock fall exists) Dry slopes Riverbanks Water channel protection Steep slopes protection Slopes of rocky and loose material Cut slopes	Simple Heavily branched twigs can be used Less expensive Little loss of plants Low material demand In one operation two stages of vegetation community plant succession are established	Unsuitable for retaining topsoil	Best penetration effect of all stabilizing constructions. It starts immediately and increases with rooting. The microclimate improvement on the slope surface is effective. Gully erosion can be stopped if the brush layers are constructed on longitudinal strips of dead material. The inclusion of nitrogen-fixing plants will reduce soil nitrogen deficiency and will improve soil condition rapidly
Material	**Diagram**		
Fill slope 1 or 2 rooted healthy plants (fast growing pioneer plants, several years old); 1.5-5.0 m spacing, inserted 2.0-5.0 m into the slope at a minimum gradient of 10% (left diagram) **Cut slope** 10 branches of live woody plants with all their side branches; 1.5-5.0 m spacing, inserted 0.5-2.0 m into the slope at a minimum gradient of 10% (right diagram)			

Table 7-16. Hedge layer construction

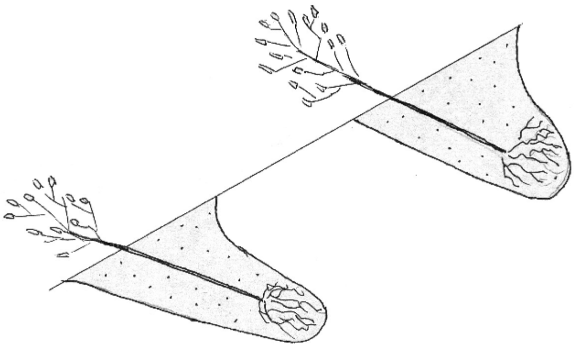
Application	Advantages	Disadvantages	Effectiveness
Good soils Fertile loess and gravel soils Sandy and clayey soils Areas where there is no material available	Enables creation of a forest plant community with closed canopy without planting pioneer species	Large quantity of plants required Very high cost	Soil stabilization begins immediately after construction, but hedge layers are most effective in long term Soil penetration is good among with soil improvement, soil activation, and shading Woody plants that will create the climax community should be used
Material	**Diagram**		
Rooted woody plants (2 to 4 year-old) that are fast growing and very resistant 5 to 20 plants per running meter upslope spacing between 1.0 m and 3.0 m apart, inserted at a minimum gradient of 10%			

Table 7-17. Live cribwalls (concrete and prefabricated elements)

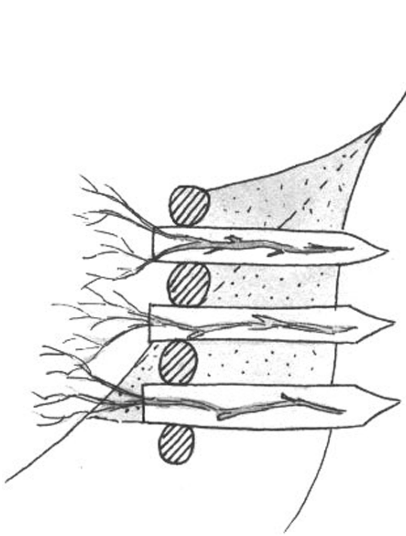
Application	Advantages	Disadvantages	Effectiveness
Urgent repair of disaster stricken areas Repair of slides Shore or steam channel bank protection (instead of solid concrete walls) Stabilization of slopes, slope sections, toes of slopes, water channel beds	Provide excellent stability Fast and simple construction Suitable for urgent repair work after a disaster	Not very good for the landscape Construction has relatively high costs Very heavy materials are used	The rotting timber is replaced by the growing plants The established plants drain the slope effectively through transpiration
Material	**Diagram**		
Branches of plants that will root from cuttings (10 branches per running meter of construction) A single live cribwall is illustrated			

Table 7-18. Live cribwalls

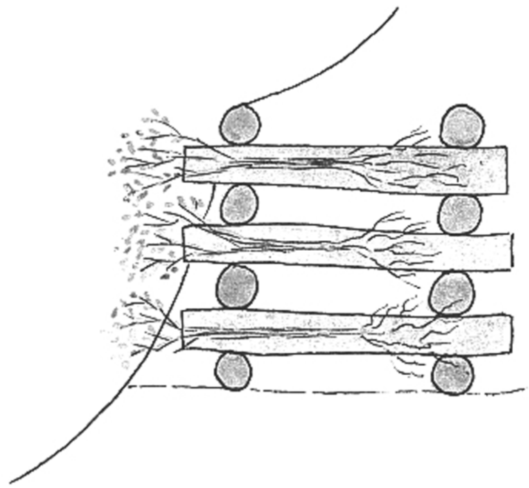
Application	Advantages	Disadvantages	Effectiveness
Areas where a catastrophe (soil instability) has already occurred For stabilization of parts of slopes, water channels, and toes of slopes Reinforcement constructions for linear and/or spatial slope stabilization	Fast stabilization Short building period Can be constructed in a horizontal line Provide active drainage and the increase of the root systems' armouring effects	The lumber can lack durability	Plants drain the slopes very effectively through transpiration Single or double crib walls consisting of timber, concrete, metal or synthetic materials represent technical stabilization elements, whilst the simultaneous use of live plant material and branch inlays initialize the establishment of the vegetation
Material		**Diagram**	
Round or square timber (0.10-0.25 m in diameter, at 1.0-1.5 m spacing). Strong 1 m long branches from species that root easily (10 branches per running meter of construction) such as larch, silver fir, pine, oak, European chestnut or black locust A double live cribwall is illustrated			

Table 7-19. Live fascine drains

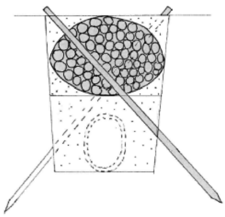
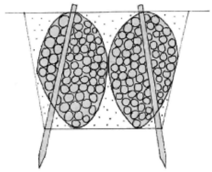
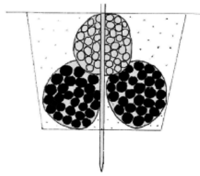
Application	**Advantages**	**Disadvantages**	**Effectiveness**
Slope drainage where the water is not too deep-seated Suitable for extensive surface area drainage	Simple Fast Less expensive and more attractive than conventional engineering construction	Construction only possible during the dormant season	The channeling effect of the longitudinal branches enables effective fascine drainage immediately after the placement Desiccates the area further by transpiration after the development of the roots
Material	**Diagram**		
Very long live branches tied together in bundles and staked in to the ground	 fascine bundle overlies gravel fill, staked with a live plug	 fascine bundles placed next to each other in a hole and staked with a live plug	 a live fascine bundle sits on top of two dead bundles and staked

Table 7-20. Live pole drains

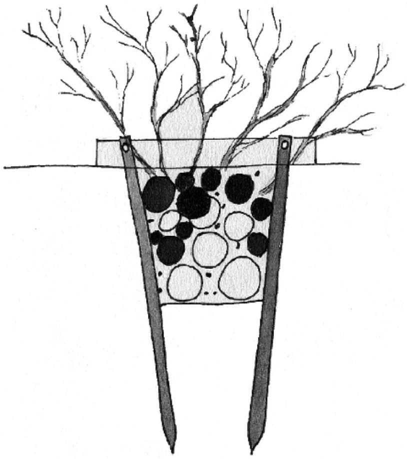
Application	**Advantages**	**Disadvantages**	**Effectiveness**
Slope drainage where the water is not too deep-seated Suitable for extensive surface area drainage	Usually better growth is obtained than with fascine drains Cheaper than hard engineering construction	Higher cost (higher consumption of material that is difficult to obtain)	Only difference from fascine drains is the use of sturdy live branches (instead of slender ones) either loosely arranged in the ditch and secured with crossbeams or tied with pegs and secured with timber and covered with gravel
Material	**Diagram**		
Live poles (heavy and rigid branches or small trees) of 3-14 cm in diameter Dead material for the bottom of the ditch Live pegs or timber 0.8 m long which form the sides of the drain			

Table 7-21. Live shoring of open water canals

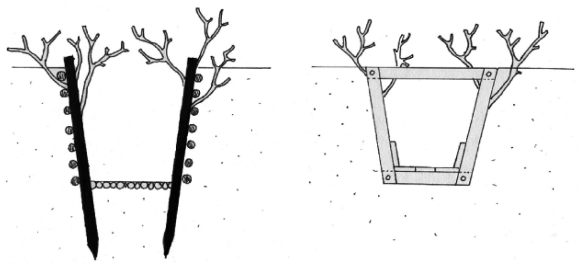
Application	**Advantages**	**Disadvantages**	**Effectiveness**
Slope drainage Surface water drainage around the toe of a slope Road construction Water drainage regulation on ski runs Useful for temporary or continuous low water flow Where open drainage is required	Cheap to construct	Costs can be much higher if boards or plants are used for securing the walls or the bottom	The channeling effect of the longitudinal branches enables effective fascine drainage immediately after the placement Desiccates the area further by transpiration after root system development
Material	**Diagram**		
Live branches or poles Live pegs 1 m long (left diagram) Boards can be used to secure bottom of potentially steady stoke flow channel (right diagram)			

Table 7-22. Live slope gratings

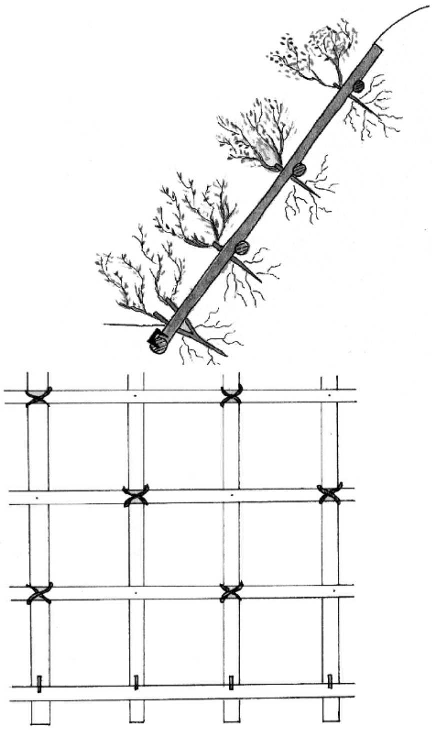
Application	Advantages	Disadvantages	Effectiveness
Very steep slopes where angle cannot be reduced, with height of the gratings between 10 and 15 m Infrequently used method (sloping is preferred)	Immediate effectiveness Combinations and variations are possible	High labour costs	The live building material for the grating denotes that the entire protection system is alive and rooted in the slope at the same time, thus stabilizing and draining it
Material	**Diagram**		
Round or square timber, corresponding to the dimensions and the type of construction either nailed together or tied with wire, and clamped at the base			

Table 7-23. Live staking

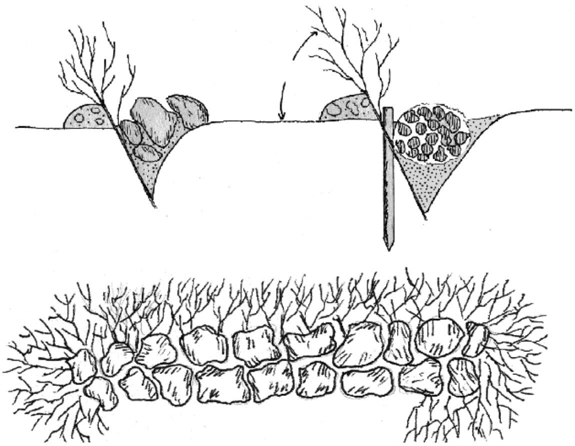
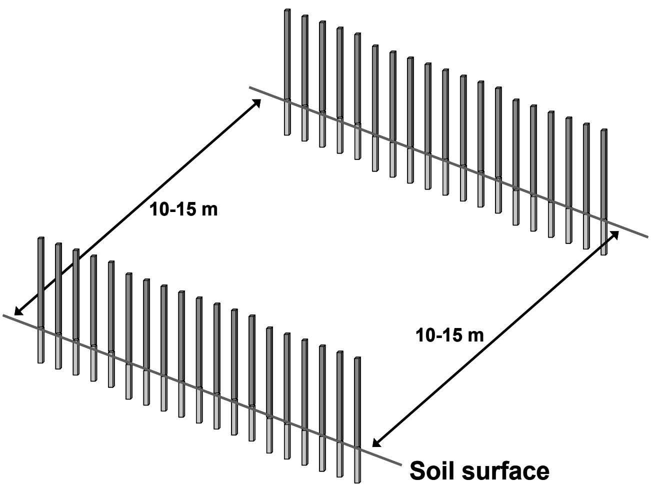
Application	Advantages	Disadvantages	Effectiveness
Where single stem plantings will provide adequate plant cover, slope stability and fish habitat Can be applied on stable, irregular slope surfaces	Plentiful and inexpensive material Can be applied with minimum slope disturbance Helps in reducing slope soil moisture It may be combined with other revegetation techniques to anchor bundles, brush mats and erosion control fabric	Not a short term solution to slope instability problems Does not solve existing erosion problems Live stakes require moist soils, but watering is not required (although it can increase survival and promote plant growth)	Simple technique that installs a dormant cutting directly into the ground Occasional deep watering is more effective and encourages deeper rooting than frequent light watering
Material	**Diagram**		
Several live stakes (0.25 to 0.65 m long, 0.005 to 0.015 m in diameter) from a dormant cutting should be buried upwards on a distance of 0.30 m to 1 m with only one or two buds left exposed out of the soil Water during the first 6 weeks after planting if the soil is dry			

Table 7-24. Matchsticks, vertical mulching

Application	**Advantages**	**Disadvantages**	**Effectiveness**
On slopes with an angle between 0-30° after a medium or high intensity fire Large sandy areas	Perform very well in dry climates Cheap Does not leave permanent patterns on the landscape after removal Increases soil moisture storage >20%	Not effective on steep slopes Not applicable on slopes with rock face	Slowing water movement Provides open channels for water penetration into the deep soil Collecting the sediment, sand and stones moving downwards from the slopes Stopping soil erosion during heavy rainfall Provides both wind breaks to trap seeds and dust and shade and cover for seedlings
Material	**Diagram**		
Branches, branchlets, thin boles, and the remnants of clear felling, stacked on the ground in horizontal lines, (on the uphill side of the stumps) should be arranged in rows The distance between these rows has been calculated to be 10-15 m depending on relief			

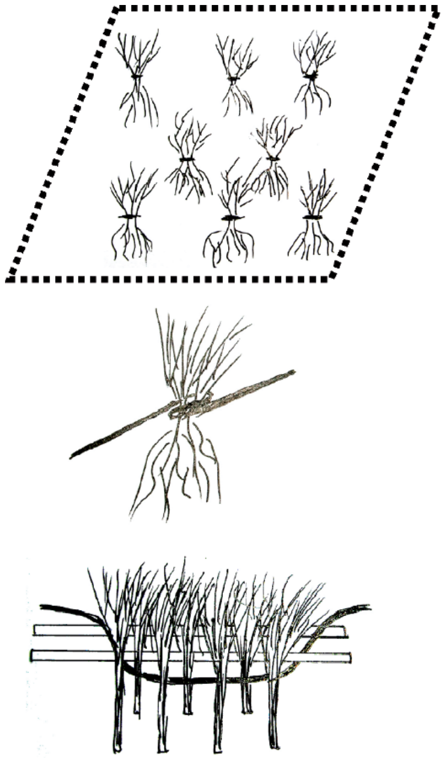
Material	Diagram
Their dimensions are, height 0.50-0.75 m, width 1.0-1.5 m and length from 1 to a thousand and more meters Several materials can be used for vertical mulch, including: broom corn, straw, brush and reeds. The best choice for a given site will depend on availability and cost of materials, project demand for aesthetics, integration of seeding and container planting, and severity of erosion and land stability problems.	

Table 7-25. Mulching

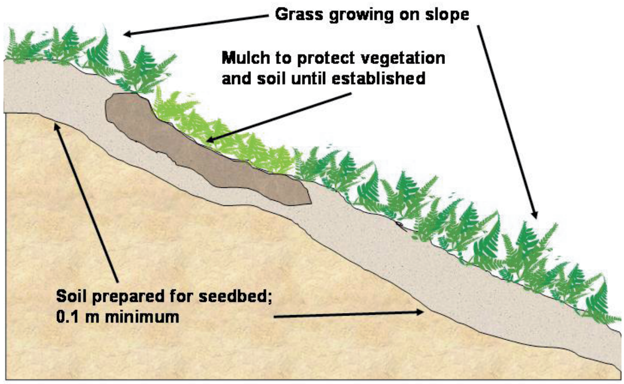
Application	**Advantages**	**Disadvantages**	**Effectiveness**
For protection of slope plantings On slopes with high erosion potential On slopes affected by forest fires On coastal slopes a mulch cover is necessary if vegetation is to be established from seed	Can be done quickly and at low cost even using mechanization It can be applied even on long and flat slopes Maintain soil moisture	Restricted to sites where there is an access for mechanization Limited to slopes with inclination less than 1:1 (V:H) (45°)	Protects against rain and wind while seeds are germinating Reduces loss of soil moisture during extended dry periods Reduces heaving (plant roots forced upward out of soil) of small plants as a result of alternate freezing and thawing
Material	**Diagram**		
Hay or straw (250-500 g/m^2), bamboo, reed, jute netting, plastic netting (not recommended), manure or compost (not recommended), wood fiber or fiber matting Anchoring of the mulch can be provided with hand, roller or crimper punching, or alternatively with erosion control netting Must be punched into the soil or covered with erosion control netting			

Table 7-26. Placing of cuttings and wall joint planting

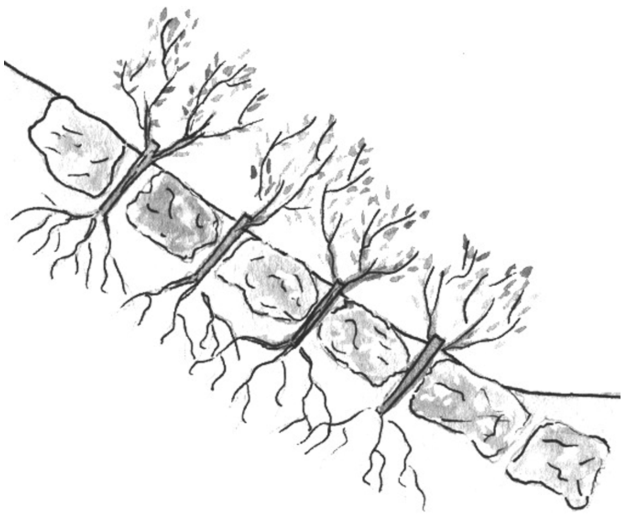
Application	Advantages	Disadvantages	Effectiveness
Planting on moist slopes for controlling wind, water, and avalanche erosion Reinforces rock paving in earthworks and in avalanche protection constructions Available for vegetation on stone piles	Inexpensive Quick building Excellent effect along an entire area Rock paving enables the use of smaller otherwise unsuitable rocks	Stabilization does not start before the plants are rooted The operation is only possible during the period of dormancy	Soil stabilization and drainage strengthening achieved with plant roots Strengthens avalanche brake constructions, avalanche diversions, channel protection walls, or channeling walls Improves the microclimate The falling leaves protect the rock wall effectively
Material	**Diagram**		
1 to 2 year-old cuttings without branches (diameter 0.02-0.04 m, length 0.20-0.40 m) If the water supply or retention is poor the cutting should be 0.40-0.60 m long			

Table 7-27. Silt fences

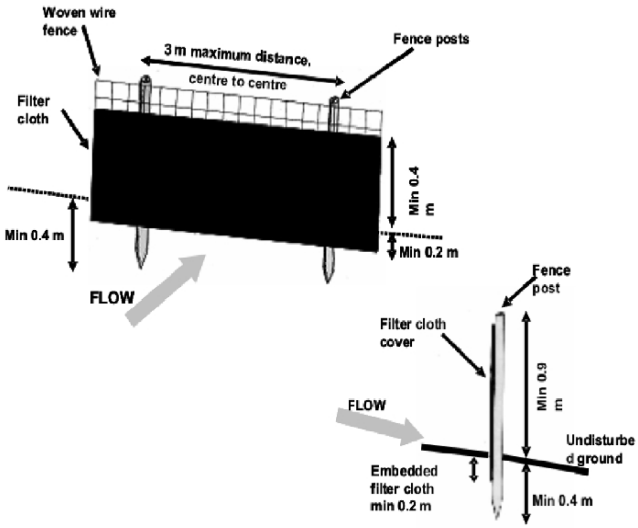
Application	**Advantages**	**Disadvantages**	**Effectiveness**
On disturbed soils such as following a wildfire	Can be used across a wide range of slope inclinations, covering different slope lengths: For slope inclination 1:2, the max slope length covered is 15 m, while slopes gentler than 1:5 can be up to 60 m long when covered by a silt fence	Not effective across drainage ways, gullies, ditches or other areas of concentrated water flow	Temporary measure that provides barrier to catch the sediment and the runoff from small areas
Material	**Diagram**		
Fence posts (at least 0.90 m long, of hardwood with minimum diameter of 0.08 m if wooden, or a standard T profile if metallic), wire, geotextile fabric Should be installed on the contour of the slope			

Table 7-28. Slope drainage using phreatophytes

<table>
<tr><th>Application</th><th>Advantages</th><th>Disadvantages</th><th>Effectiveness</th></tr>
<tr><td>Wet areas

Suitable in areas of high summer rainfall

In combination with other bioengineering systems</td><td>Simple and economical method in large wet areas

Pumping plants can be used to drain deeper layers in the ground</td><td>Effective only after the plants have rooted</td><td>The plants draw most of the water they need for survival out of the ground

The individual roots work as pumps</td></tr>
<tr><th>Material</th><th colspan="3">Diagram</th></tr>
<tr><td>Plant species with high water consumption - phreatophytes (deep-rooting plants)

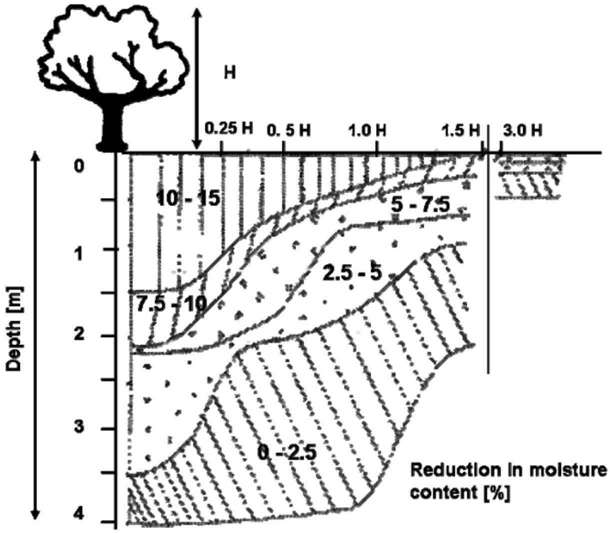
An example of water consumption of a poplar tree is given here to illustrate the reduction in moisture content with the distance from the tree (Greenway 1987)</td><td colspan="3">
</td></tr>
</table>

Table 7-29. Sodding or turfing

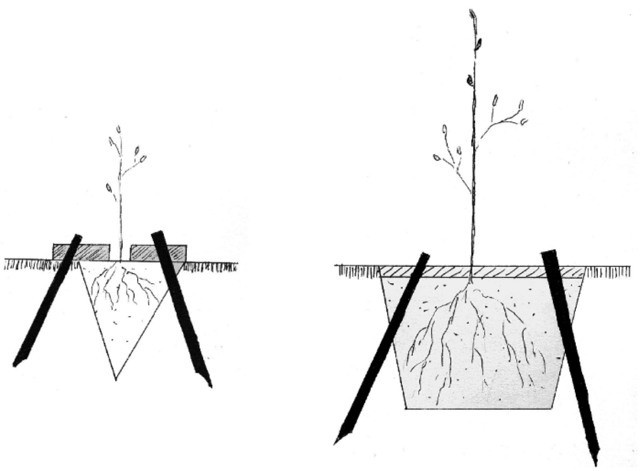
Application	**Advantages**	**Disadvantages**	**Effectiveness**
On slopes with an angle between 0-30° after a medium or high intensity fire Large sandy areas	Perform very well in dry climate Cheap Does not leave permanent patterns on the landscape after removal Increases soil moisture storage >20%	Not effective on steep slopes Not applicable on slopes with rock face	Slowing water movement Provides open channels for water penetration into the deep soil Collecting the sediment, sand and stones moving downwards from the slopes Stopping soil erosion during heavy rainfall Provides both wind breaks to trap seeds and dust and shade and cover for seedlings
Material	**Diagram**		
Hand dug sod slabs: square pieces of 0.40 by 0.40 m are cut out of meadows with more soil (0.08 m thick) **Commercial sod**: the sods are available in strips of 0.3 to 0.4 by 1.5 to 2 m, 0.02 to 0.04 m thick			

Table 7-30. Straw bale or wattle check dams

Application	**Advantages**	**Disadvantages**	**Effectiveness**
On gentle slopes after a high or very high intensity fire	Relatively low cost On a slope 0-15° the max drainage between check dams can be up to 4000 m^2 and the maximum slope length up to 60 m. On a slope 15-20° the max drain area between check dams can be up to 2000 m^2 and the maximum slope length up to 30 m.	Not suitable for protection from large storm events or for controlling debris flow in water bodies such as creeks, streams and rivers Not recommended for usage on slopes with inclination greater than 20° Should be very carefully applied avoiding any kind of aggressive treatments	Straw bales are placed in small drainages acting as a dam, collecting upslope sediments and slowing the velocity of water down slope

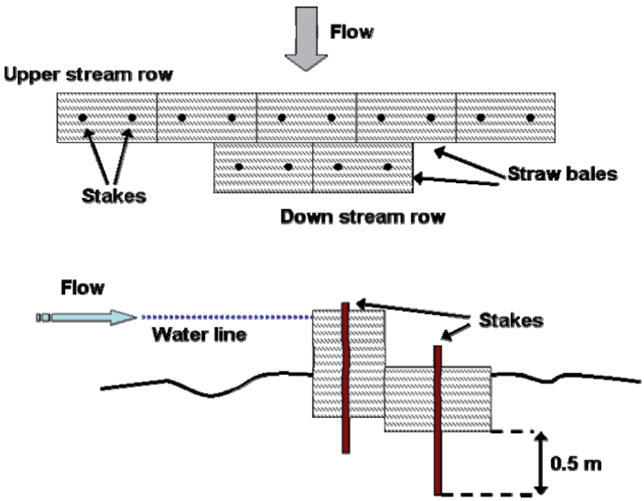
Material	**Diagram**
Straw bales or wattles placed in rows with overlapping joints (like a brick wall) Some excavation is necessary to ensure bales butt up tightly against one another forming a good seal Two rows (or walls) of bales are necessary and should be embedded below the ground line at least 0.30 m. The bales and the stakes should be removed once the permanent drainage and stabilization is re-established	

Table 7-31. Vegetated gabions

Application	**Advantages**	**Disadvantages**	**Effectiveness**
To secure unstable slopes (erosion gullies, banks) To provide drainage through water absorption and transpiration Used in wet areas of fine-grained soil (schistose, clayey, silty substrates)	Fast Simple construction Elastic Can be erected along horizontal lines on wet slopes or along stream channels	Only applicable where gravel and small rocks are available	Gabions form solid protection points There is no danger of water impoundment The plants improve drainage through water absorption and transpiration

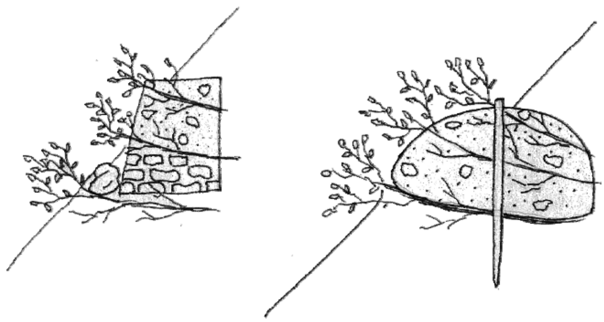
Material	**Diagram**
Wire mesh (0.05m) (right diagram) Steel mesh (left diagram) Coarse gravel Wire for tying Steel pegs Live branches Rooted plants	

Table 7-32. Vegetated geogrid

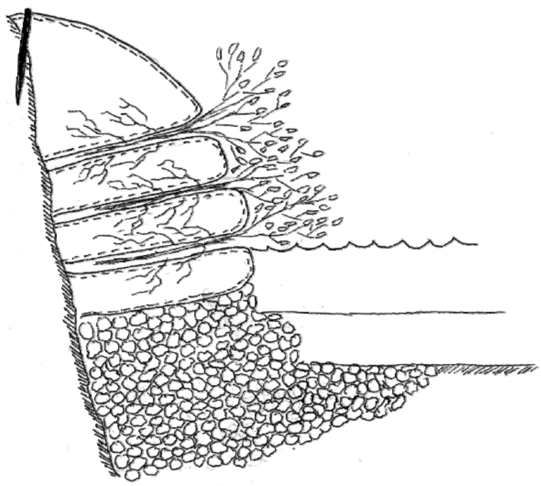
Application	Advantages	Disadvantages	Effectiveness
Similar to branchpacking except that natural or synthetic geotextile materials are wrapped around each soil lift and live branch cuttings are placed between them. For rebuilding very steep eroded streambanks or configuring new banks in stream realignment projects with slopes too steep for normal brushlayering Particularly useful where land has been previously lost and needs to be restored	Efficient minimization of bank erosion Higher initial tolerance of velocity than traditional brushlayering techniques	Systems over 2 m in height and 6 m in length should be subjected to engineering slope stability analysis This technique requires both heavy equipment and intensive manual labour to install	Provide immediate soil reinforcement produce rapid growth, offering overhanging material for aquatic habitat Once the live cuttings become established, their root systems penetrate the grids and the entire system becomes a cohesive mass Improve habitat for aquatic plants and animals Contribute to food web dynamics Enhance aesthetics through the establishment of vegetation
Material	**Diagram**		
Dormant branches from 0.015 to 0.05 m in diameter, long enough to reach the back of the trench to be filled and to extend slightly beyond the surface of the completed slope Geotextile, live stakes and dead stakes, and plants to be installed on top of slope are also necessary			

Table 7-33. Vegetated palisade and pole construction

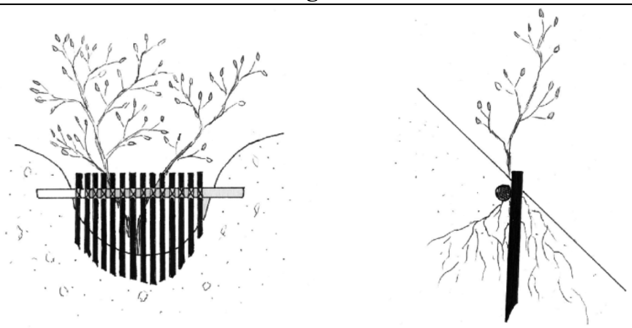
Application	**Advantages**	**Disadvantages**	**Effectiveness**
In areas of abundant growth (river terraces, forests) Effective method to wall deep and steep V-gullies stair wise with live material Repair of erosion damage in soft fine soils (clay, loess, sand)	Quickly and easily built Immediately effective Exhibits excellent growth	Limited width (6 m) and height (2 to 4 m) Can only be constructed in areas of favorable plant growth	Stabilizes the gully or water channel and causes silting Has an immediate effect as a barrier even before rooting The poles root and pump up water for their growth
Material	**Diagram**		
Pegs or poles from live plants with a diameter of 0.05 m min. (5 to 20 pieces per running meter of construction)			

Table 7-34. Vegetated stone walls and rock piles

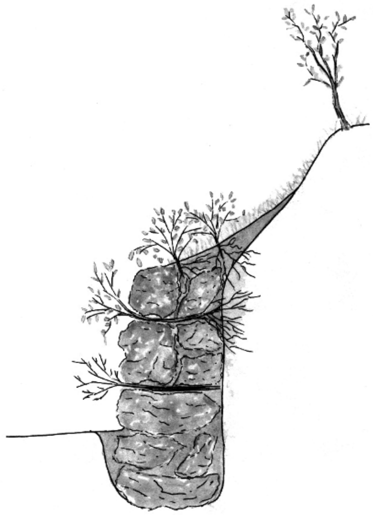
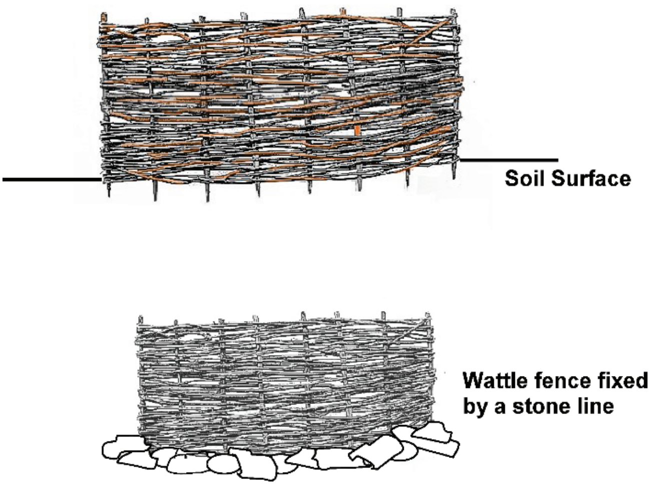
Application	**Advantages**	**Disadvantages**	**Effectiveness**
Stabilization of slope parts (toe of the slope) Stabilization of gullies and banks	Possibility of using rubble of mediocre quality and of any size Low cost This construction has flexibility, permeability, and durability Better than non-vegetated stone walls and piles	Possible only during the dormant season of vegetation Wall height is limited	The stone walls and piles with branch layering remain not only permeable, but the plant roots also absorb and transpire a large quantity of water, ensuring drainage, plus the vegetation stabilizes the construction
Material	**Diagram**		
Rocks Slender live branches (2 to 5 per square m) Rooted shrubs (not trees!)			

Table 7-35. Wattle fences

Application	**Advantages**	**Disadvantages**	**Effectiveness**
For the retention of topsoil in minor soil slippages Good in combination with other bio-engineering methods (drainage methods, bank stabilization)	Can be used for mild gully erosion control Can serve as slope drain when wattle fences are arranged with an angle Provide a possible way of stopping the moving materials on slope With the interwoven branches, solid steps can be built into the slope	Unable to stop deep soil movement Large quantity of plant materials Only long flexible branches can be used The branches lie partially on the surface and do not root at all Water can easily penetrate into the soil and cause slippage. The pegs easily broken by a rockfall. High labour and material costs More readily available measures exist for slope stabilisation	Continuously laid packed bundles of plant material intercept surface water runoff and divert it laterally before it creates erosion problems The wattles help trapping sediment to protect downslope areas from material falls or erosion
Material		**Diagram**	
Flexible branches with few side branches (1.20 m) preferably (shrubby willows) Wooden or steel pegs 1 m long. Combination of live and dead pegs less than 1 m long Plants that root easily from cuttings should be used	 		

3. ECO-ENGINEERING TECHNIQUES

3.1 Management strategies for limiting erosion

Techniques have been developed to maintain or to minimize erosion rates to levels below the soil generation rates. Their objectives are mainly to avoid or to compensate erosion losses and the maintenance of sustainable soil productivity and soil ecological functions. It is a theme in which the use of ground bio- and eco-engineering techniques is very concomitant and difficult to differentiate. Generally, management practices are focused on these main tasks (Schiechtl 1980, Coppin and Richards 1990, Gray and Sotir 1996):

- Increasing or maintenance of the vegetation cover
- Improving the soil hydrology
- Increasing the soil structural stability
- Increasing the surface roughness
- Physically slowing down of erosion dynamics
- Compatibility with traditional management systems

The role of vegetation in erosion control can be summarized as:

Protective role of vegetation	• Interception of the rainfall • Restraint • Retardation of runoff • Infiltration
Most effective vegetation for erosion control	• Herbaceous plants • Grasses and shrubs, possibly with dense near surface root mat and good surface cover and foliage

The principles, when designing a prevention and control system, are based on the basic knowledge of the biophysical characteristics of the intervention area, and the common sense and their application in combination with one or more particular erosion control measures. In many cases, ground bio- and eco-engineering methods can be complementarily applied to increase the effectiveness of the actions realized.

General principles are:

- Extensive grading and earthwork in erosion prone areas or slopes should be avoided
- Increased runoff should be handled with installed hydraulic conveyance facilities

- Runoff velocities should be kept as low as possible
- Soil moisture should be maintained as much as possible
- Interceptor drains and berms should be constructed to divert the runoff away from steep and bare slopes
- Native vegetation on the site should be saved and protected where possible
- If the vegetation needs to be cleared, this should be done in small workable increments, keeping the duration of exposure as short as possible
- Cleared areas should be protected with mulches and temporary fast growing herbaceous covers
- Sediment basins should be constructed in order to prevent eroded soil or sediment from leaving the site
- Erosion control measures should be applied as soon as possible
- The erosion control measures should be surveyed and maintained regularly

In this sense, the most used management practices to prevent or reduce erosion are:

Crop Management

- Crop rotation, choosing a crop sequence that maintains the residue cover (e.g. double-cropping or use of winter cover crops)
- High density planting to create a thick cover for soil protection
- Multiple cropping, by combination of crops with different morphological structures and heights
- Mulching, by addition of crop residues, straw, "green amendments", etc. to the soil surface
- Using conservation tillage, which basically is the tillage/planting system that leaves at least 30% of the field surface covered with crop residue after planting, has been completed.
- Using contour tillage, contour ploughing and wind breaks
- Avoiding overgrazing and the over-use of crop lands
- Selecting crops that produce large amounts of residue (corn grain/*Zea mays* L., sorghum/*Sorghum vulgare* (L.) etc) and/or a high degree of soil cover per kilogram of residue (e.g. wheat/*Triticum aestivum* L.)

Vegetation Management

- Revegetation by planting adequate native species of shrubs and grasses
- Reforestation

- Using agro-forestry techniques
- Planting shrubs or native vegetation to grow along the river banks instead of ploughing and planting crops right up to the water's edge
- Applying bioengineering techniques (Tables 7-1–7-35)
- Leaving unploughed grass strips between ploughed lands
- Planting appropriate vegetation in areas where erosion is most concentrated (see Chapter 6)

Soil management

- Application of organic amendments
- Using soil stabilizers
- Preventing soil compaction
- Preparing adequately the soil-hole for planting (Table 7-1)
- Applying minimum or no tillage practices
- Using crops that provide long-lasting residues (i.e. crops with a high carbon-to-nitrogen ratio, e.g. wheat).
- Surface soil mulching (Table 7-25)

Mechanical methods

- Contouring structures (Tables 7-8 and 7-9)
- Terracing (bench terraces, mini-terraces, etc; wattle fences, logs, etc) (Table 7-35)
- Stabilisation structures (e.g. retaining walls) (Table 7-34)
- Ditches, berms (Table 7-11)

3.2 Eco-engineering techniques against rockfall

An excellent alternative for technical protective constructions against rockfall can be provided by different types of forest stands, given the urgency of the protection needed and the site conditions that determine forest stand development. The management of protection forests is to a large degree a trade-off between optimizing the protective effect and assuring forest stand stability at present and over the long-term (Motta and Haudemand 2000). Since stand stability is mostly at risk in over-mature stands that lack sufficient regeneration, management interventions in rockfall protection forests often aim at thinning or creating gaps to allow more light into the forest stand. To increase terrain roughness, a common recommendation in rockfall protection forest management is to leave the trunks of cut trees lying on the slope, preferably diagonally to the slope direction, to create obstacles (Mössmer et al. 1994, Dorren et al. 2005, Frehner et al. 2005). These diagonally positioned logs prevent the development of rock accumulations and allow continued rock transport in a controlled manner. Experience in Austria is that larger *Picea abies* trees (DBH > 50 cm) can act as effective rockfall barriers for approximately 10 years (Dorren et al. 2005). Additionally, high tree stumps (e.g. > 1.3 m) have been noted to further reduce residual rockfall hazard on a site (cf. Dorren et al. 2005; Frehner et al. 2005).

To give a guideline for the different options for using eco-engineering techniques against rockfall, the optimal forest cover type for each characteristic rockfall zone is discussed. These are 1) the rockfall source area, 2) the transport zone and 3) the rockfall accumulation or deposit area (Figure 7.1). The optimal forest cover type will be discussed in terms of structure and tree species.

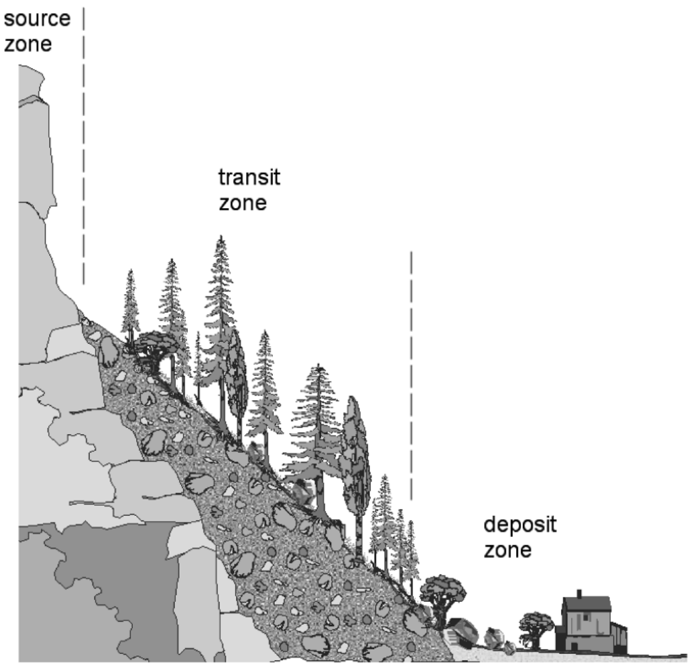


Figure 7-1. Characteristic zones on an active rockfall slope.

Source area

Rockfall source areas are generally characterized by steep cliff faces that show unfavorable combinations of the exposition of the slope face with the dip and strike of the bedding planes and the most prominent joint sets. Root actions of large trees can increase the production of individual falling rocks.

Therefore, large trees growing on top or in vertical cliff faces should be removed. In case of a stepped terrain, where vertical cliff faces and more horizontal areas occur on top of each other, trees do not necessarily promote rockfall activity by their roots. Moreover, they can reduce the initial velocity and jump height of falling rocks. In such cases they should be examined to ascertain whether they do have a rockfall promoting effect, before removing them. We do not recommend any specific forest management actions other than the removal of trees if necessary. If cut tree stems can be put in a stable position, diagonal to the slope direction, additional rockfall barriers can be created.

Transport zone

The rockfall transport zone lies in between the rockfall source area and the deposition area. In this zone the rockfall velocities as well as the jump heights are maximal. Consequently, the objective of rockfall protection in this zone is to reduce both of them or, in an optimal case, to stop the falling rock. The first guidelines for achieving the latter using a forest stand were published by Wasser and Frehner (1996). They recommended a forest stand consisting of more than 400 trees per ha with diameters larger than 40 cm. In the European Alps, such a forest, however, consists mostly only in stands with a regular structure. Such stand structures are not stable in the long-term and therefore cannot provide sustainable mitigation. Irregular forest stands consisting of trees of various ages and diameters and preferably mixed species are much more stable and provide better protection in the long-term. The question is then, what type of stand structure (density of trees, species, spatial distribution of diameter) is needed? The answer to this question depends on the average size of the falling rocks and the slope angle. These two factors determine the energy that has to be dissipated.

Rockfall experiments on forested slopes showed that the number of impacts against trees is more important than the efficacy of the impact expressed in the amount of dissipated energy (e.g. Berger et al. 2002; Dorren et al. 2005). Therefore, a large number of trees is more important than having only thick tree stems. Again, diagonally positioned tree stems can have the same effect as standing trees and reduce the energy of falling rocks. The larger the tree the more energy can be dissipated. This resulted from a large number of real size rockfall experiments on both non-forested slopes and forested slopes with different forest types. Experimental slopes had a slope angle between 38° and 42°, which is typical for forest covered rockfall talus slopes and rockfall transport zones. The guidelines given here are certainly valid for less steeper slopes. For steeper slopes, a greater number of trees is needed, but this is often difficult as site conditions do not allow that. The rock size used in the experiments varied between diameters of 25 cm to

125 cm. Tables 7-36 and 7-37 are presented to assist in the design of optimal protection forests against rockfall. The initial data needed to design the protection forest is the average energy of the falling rock, as shown in Table 7-36; this can be calculated from the average diameter of the falling rock. This allows calculation of the mass (assuming a rock density of 2800 kg/m^3) and the energy, given a certain velocity related to the initial fall height. Subsequently, Table 7-37 provides information about the amount of energy that can be dissipated during a single frontal impact on different types of trees as derived from Dorren and Berger (2006). Frontal impacts on trees are the most effective and scratch impacts (impacts on the side of the tree stem) are least or almost not effective in terms of energy dissipation).

Scratch impacts, however, do cause lateral deviations in the rockfall trajectory, as seen from the slope direction, causing the rock to travel a longer distance in the forest. As a result the chance of the rock impacting a tree increases. On our study sites, the forest cover reduced the rockfall velocity by 20% and the jump heights by 60%. However, it also results in lateral deviation and therefore a wider runout zone. For safety reasons, we take into account a runout zone as shown in Figure 7.2, which means a lateral deviation of 10º from the straight downslope direction to both sides.

Analysis of the results of the real size rockfall experiments in a mixed forest covering a slope with a mean slope gradient of 38º showed that the average distance between two tree impacts was 31.7 m. This is the first important condition to assess the required structure of a rockfall protection forest stand.

Next a procedure is needed that translates the spatial distribution of the tree diameters and the number of trees per hectare into the probable distance between two subsequent impacts against trees. We developed a simple method, adapted from the Mean Tree Free Distance concept of Gsteiger (1993), which assumes that a certain forest structure can be expressed in a virtual sequence of rockfall protective tree nets (curtains) consisting of a row of trees perpendicular to the direction of the slope, as shown in Figure 7.3. The distance between two trees in one virtual row is 90% of the diameter of the average falling rock (represented by a sphere with the equivalent volume). By using the average tree diameter, the existing forest structure can be expressed in a number of virtual tree nets, which is equal to the number of probable impacts.

By knowing the minimal distance between rock impacts and the number of impacts needed to stop a falling rock, the total number of trees and their average diameter can be calculated using the above principle. If, in addition, the slope length is known, the number of trees in the transport area can be calculated, using the 20º angle area shown in Figure 7.2. This number of

Table 7-36. Average size of the falling rock and its energies (in grey: values that are not realistic)

Diameter (cm) Volume (m^3) Mass (kg)	25 0.008 23			50 0.065 183			100 0.524 1466			125 1.023 2863		
Energy (kJ)	**Velocity ($m s^{-1}$)**	**Velocity ($km h^{-1}$)**	**Fall height (m)**	**Velocity ($m s^{-1}$)**	**Velocity ($km h^{-1}$)**	**Fall height (m)**	**Velocity ($m s^{-1}$)**	**Velocity ($km h^{-1}$)**	**Fall height (m)**	**Velocity ($m s^{-1}$)**	**Velocity ($km h^{-1}$)**	**Fall height (m)**
10	30	106	44	10	38	6	4	13	1	3	10	0.4
100	93	336	445	33	119	56	12	42	7	8	30	4
500	209	752	2225	74	266	278	26	94	35	19	67	18
1000	295	1064	4450	104	376	556	37	133	70	26	95	36
1500	362	1303	6675	128	461	834	45	163	104	32	117	53

Table 7-37. The effective tree diameter [cm] for a total energy dissipation in a single impact

Energy (kJ)	***Picea abies***	***Abies alba***	***Acer pseudoplatanus***	***Fagus sylvatica***
10	12	11	11	9
100	31	30	29	24
500	63	60	57	48
1000	85	81	77	65
1500	101	97	92	78

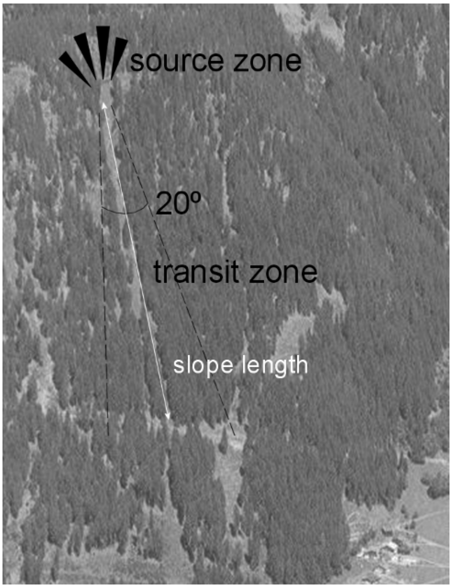


Figure 7-2. Lateral deviation of the falling rock on forested slopes results in wide runout zones. An angle of 20º has to be taken into account as shown in the figure.

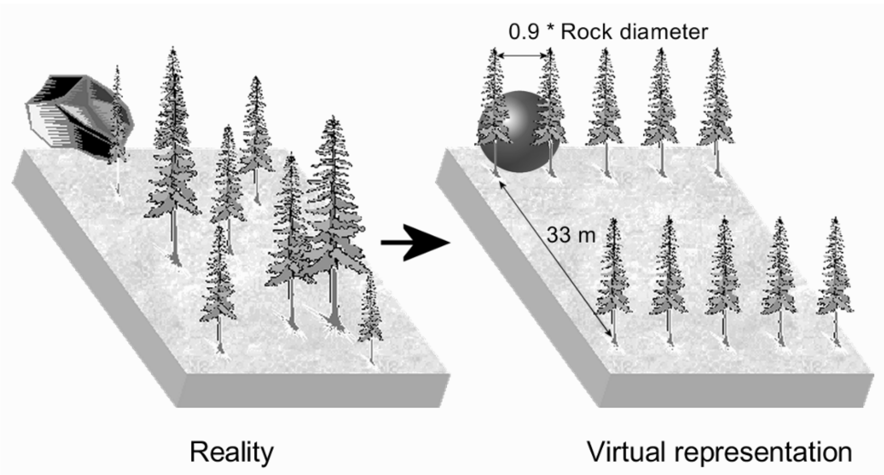


Figure 7-3. Explanation of the principle for expressing a real forest structure in a sequence of virtual rockfall protective tree nets (curtains).

trees can then be expressed in the number of trees per hectare in the transport area. Combining this number with the average diameter provides the volume. This above described method forms the basis for Tables 7-38 and 7-39. These tables provide guidelines for the number of trees per hectare and their minimal average effective diameter for a given slope length and for a given rock diameter. These data are given both for spruce and for beech on a slope of 40° or less. The minimal slope length in the tables is 100 m as the data analysis showed that for a slope length of 50 m the required forest structure (expressed in stem density and diameters) to stop a falling rock with a diameter of 1 m and an energy between 500-1000 kJ is not realistic. This is shown in Figure 7.4. Similar analyses can be performed online, using the free and publicly available tool at www.rockfor.net.

Deposition area

In the rockfall deposition area, the same guidelines can be used as in the transport zone, but the diameters can be smaller. It is more important that a lot of trees occupy this zone, e.g. coppice stands, and that the surface is as rough as possible (e.g. deposited rocks, cut tree stems). Therefore, regeneration has to be promoted, preferably fast growing species combined with strong rockfall resisting trees such as beech and sycamore. A dense forest stand with tree diameters of 10 cm could already be effective here.

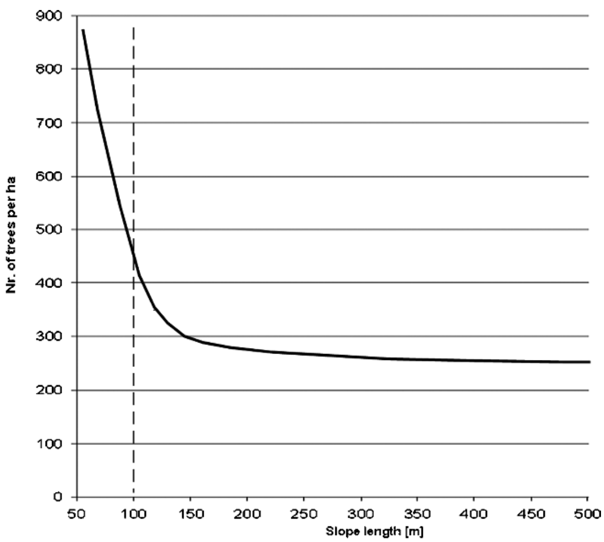


Figure 7-4. Slope length versus the number of trees per hectare (average diameter of 35 cm) needed to stop a falling rock with a diameter of 1 m and an energy between 500-1000 kJ. The figure shows that a minimum slope length of approximately 100 m is required for a realistic, sustainable protection provided by forests.

Table 7-38. Proposed parameters for a protection forest consisting of spruce trees (in grey: values that are not realistic)

Spruce 100m slope length	Rock diameter [cm]	25			50			100			125		
Energy [kJ]	Energy to be dissipated by impact[kJ]	Min Average tree Diameter [cm]	Min Stem density [stem/ha]	Min Basal area [m^2/ha]	Min Average tree Diameter [cm]	Min Stem density [stem/ha]	Min Basal area [m^2/ha]	Min Average tree Diameter [cm]	Min Stem density [stem/ha]	Min Basal area [m^2/ha]	Min Average tree Diameter [cm]	Min Stem density [stem/ha]	Min Basal area [m^2/ha]
10	3	10	1846	14	10	1091	9	10	600	5	10	490	4
100	30	15	1600	28	15	1000	18	15	571	10	15	471	8
500	150	35	1043	100	35	750	72	35	480	46	35	407	39
1000	300	50	828	162	50	632	124	50	429	84	50	369	72
1500	450	60	727	206	60	571	162	60	400	113	60	348	98
Spruce 250m slope length	**Rock diameter [cm]**	**25**			**50**			**100**			**125**		
Energy [kJ]	**Energy to be dissipated by impact[kJ]**	**Min Average tree Diameter [cm]**	**Min Stem density [stem/ha]**	**Min Basal area [m^2/ha]**	**Min Average tree Diameter [cm]**	**Min Stem density [stem/ha]**	**Min Basal area [m^2/ha]**	**Min Average tree Diameter [cm]**	**Min Stem density [stem/ha]**	**Min Basal area [m^2/ha]**	**Min Average tree Diameter [cm]**	**Min Stem density [stem/ha]**	**Min Basal area [m^2/ha]**
10	3	10	1063	8	10	628	5	10	346	3	10	282	2
100	30	15	922	16	15	576	10	15	329	6	15	271	5
500	150	35	601	58	35	432	42	35	276	27	35	234	23
1000	300	50	477	94	50	364	71	50	247	48	50	213	42
1500	450	60	419	118	60	329	93	60	230	65	60	200	57

Table 7-38. (Continued)

Spruce 500-1000m slope length	Rock diameter [cm]	25			50			100			125		
Energy [kJ]	Energy to be dissipated by impact[kJ]	Min Average tree Diameter [cm]`	Min Stem density [stem/ha]	Min Basal area [m²/ha]	Min Average tree Diameter [cm]	Min Stem density [stem/ha]	Min Basal area [m²/ha]	Min Average tree Diameter [cm]	Min Stem density [stem/ha]	Min Basal area [m²/ha]	Min Average tree Diameter [cm]	Min Stem density [stem/ha]	Min Basal area [m²/ha]
10	3	10	1004	8	10	593	5	10	326	3	10	266	2
100	30	15	870	15	15	544	10	15	311	5	15	256	5
500	150	35	568	55	35	408	39	35	261	25	35	221	21
1000	300	50	450	88	50	344	67	50	233	46	50	201	39
1500	450	60	396	112	60	311	88	60	218	62	60	189	53

Table 7-39. Proposed parameters for a protection forest consisting of beech trees (in grey: values that are not realistic)

Beech 100m slope length	**Rock diameter [cm]**	**25**			**50**			**100**			**125**	
Energy [kJ]	**Energy to be dissipated by impact[kJ]**	**Min Average tree Diameter [cm]**	**Min Stem density [stem/ha]**	**Min Basal area [m²/ha]**	**Min Average tree Diameter [cm]**	**Min Stem density [stem/ha]**	**Min Basal area [m²/ha]**	**Min Average tree Diameter [cm]**	**Min Stem density [stem/ha]**	**Min Basal area [m²/ha]**	**Min Average tree Diameter [cm]**	**Min Stem density [stem/ha]**
10	3	5	2182	4	5	1200	2	5	632	1	5	511
100	30	15	1600	28	15	1000	18	15	571	10	15	471
500	150	25	1263	62	25	857	42	25	522	26	25	436
1000	300	35	1043	100	35	750	72	35	480	46	35	407
1500	450	45	889	141	45	667	106	45	444	71	45	381

Beech 250m slope length	**Rock diameter [cm]**	**25**			**50**			**100**			**125**		
Energy [kJ]	**Energy to be dissipated by impact[kJ]**	**Min Average tree Diameter [cm]**	**Min Stem density [stem/ha]**	**Min Basal area [m²/ha]**	**Min Average tree Diameter [cm]**	**Min Stem density [stem/ha]**	**Min Basal area [m²/ha]**	**Min Average tree Diameter [cm]**	**Min Stem density [stem/ha]**	**Min Basal area [m²/ha]**	**Min Average tree Diameter [cm]**	**Min Stem density [stem/ha]**	**Min Basal area [m²/ha]**
10	3	5	1257	2	5	691	1	5	364	1	5	294	1
100	30	15	922	16	15	576	10	15	329	6	15	271	5
500	150	25	728	36	25	494	24	25	301	15	25	251	12
1000	300	35	601	58	35	432	42	35	276	27	35	234	23
1500	450	45	512	81	45	384	61	45	256	41	45	219	35

Table 7-39. (Continued)

Beech 500-1000m slope length	Rock diameter [cm]	25			50			100			125		
Energy [kJ]	Energy to be dissipated by impact[kJ]	Min Average tree Diameter [cm]	Min Stem density [stem/ha]	Min Basal area [m^2/ha]	Min Average tree Diameter [cm]	Min Stem density [stem/ha]	Min Basal area [m^2/ha]	Min Average tree Diameter [cm]	Min Stem density [stem/ha]	Min Basal area [m^2/ha]	Min Average tree Diameter [cm]	Min Stem density [stem/ha]	Min Basal area [m^2/ha]
10	3	5	1187	2	5	653	1	5	344	1	5	278	
100	30	15	870	15	15	544	10	15	311	5	15	256	5
500	150	25	687	34	25	466	23	25	284	14	25	237	12
1000	300	35	568	55	35	408	39	35	261	25	35	221	21
1500	450	45	484	77	45	363	58	45	242	38	45	207	33

3.3 Management strategies to protect against windthrow

The contribution of a forest stand to the reduction of erosion, rockfall and landslide risks on a slope will change over time. It is the role of forest managers to understand how and why these changes take place, and to devise silvicultural scenarios accordingly. These scenarios should describe the methodology by which a forest stand will be tended, harvested and replaced; a process often categorized into 'silvicultural systems', according to the chosen reproduction method (Daniel et al. 1979).

Forest managers have to ensure that the silvicultural system they choose meets their management objectives but remains within given environmental and operational constraints. Silvicultural textbooks (e.g. Daniel et al. 1979; Smith et al. 1997; Nyland 2002) provide detailed explanations on how different silvicultural systems can be applied to different situations. In the following sections we highlight how this choice will affect the distribution of the risk of significant wind damage over time. As part of these silvicultural systems, several forest operations are used to maintain, harvest and regenerate stands. We therefore describe operational strategies that may be used to minimise risk to forest stands in wind exposed situations.

3.3.1 Silvicultural systems and wind risk

High forest

1. Even-aged stands

Even-aged stands are those which are regenerated at once or, in the case of naturally regenerated stands, during a short period corresponding to less than 1/5th of the full rotation period.

2. Clear-felling system

This system is characterized by the harvesting of all trees in the stand at the end of the rotation period. As risk increases with tree height and age (see Chapter 5), the risk of wind damage to an old even-aged stand is likely to be high (Figure 7.5). The increase of risk with time is a factor to take into consideration when afforesting an unstable slope with young trees. Under such a system, the role of the forest manager is to choose a suitable rotation age for regenerating the stand. One important drawback of this system is that there is a period between the clear felling and the reforestation when the site has completely lost its tree cover. The risk this creates for slope stability may be mitigated by using variants of the same system, i.e. by designing the spatial distribution of felling coupes so that the slope keeps some tree cover. For example, the forest manager may choose to harvest the trees in alternate strips.

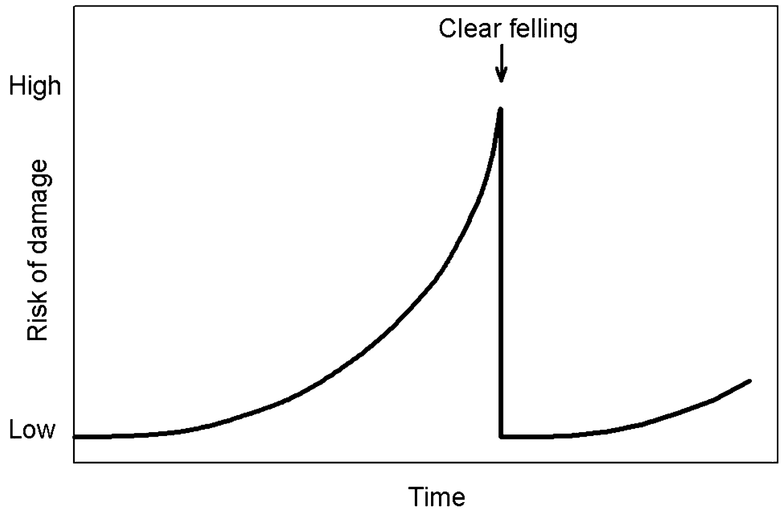


Figure 7-5. Changing risk of wind damage to a stand managed with the Clear-felling System.

3. Seed-tree system

This system is similar to the clear-felling system, except that a small number of trees are left standing in order to provide a seed source that will help regenerate the site naturally. This will result in increased wind loading to the seed trees and, as they are not adapted to the new conditions, wind damage will be common in the first few years after the harvest (Figure 7.6).

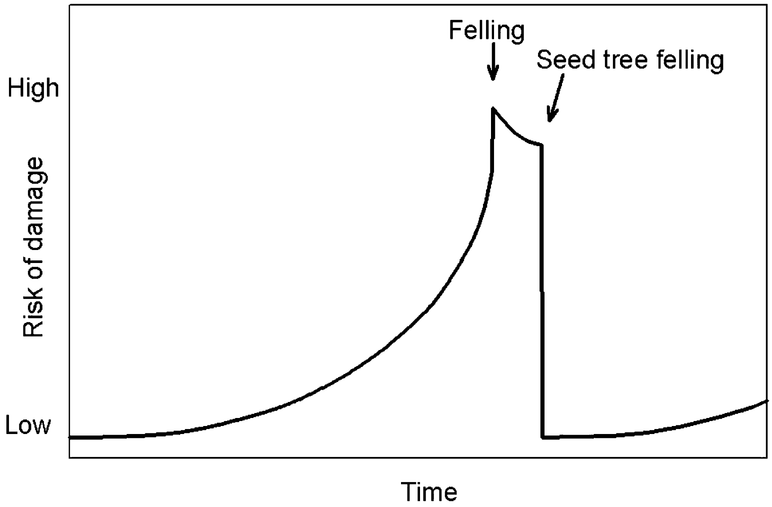


Figure 7-6. Changing risk of wind damage to a stand managed using the Seed-tree System.

However, if no or limited damage occurs, a site managed under this system will always contain some trees – although the amount of slope protection provided by the seed trees is likely to be limited.

4. Shelterwood system

Under this system, the site is naturally regenerated through a series of (generally two or three) partial cuts which aim to provide a seed source and the right conditions in the understory for natural regeneration to be established. The final harvest is conducted only when there is sufficient natural regeneration under the mature crop and therefore the site will always maintain a tree cover. The risk of wind damage (Figure 7.7) after the partial cuts will increase, but the gradual opening of the stand will reduce the likelihood of a catastrophic event (Gardiner et al. 2005). As for other systems, the manager may decide to distribute the coupes into different spatial patterns. Commonly used methods include uniform, group and strip shelterwood. In the first case individual stems are harvested across the site, in the second case stems are harvested in small groups, and in the last case they are harvested in strips. The latter may be applied to slopes where the risk of wind damage is considered high. A good strategy is to work in successive strips going towards the main wind direction but the applicability of this on a slope will depend on its orientation. Care must be taken when performing the harvesting operations in order to avoid damaging the regeneration.

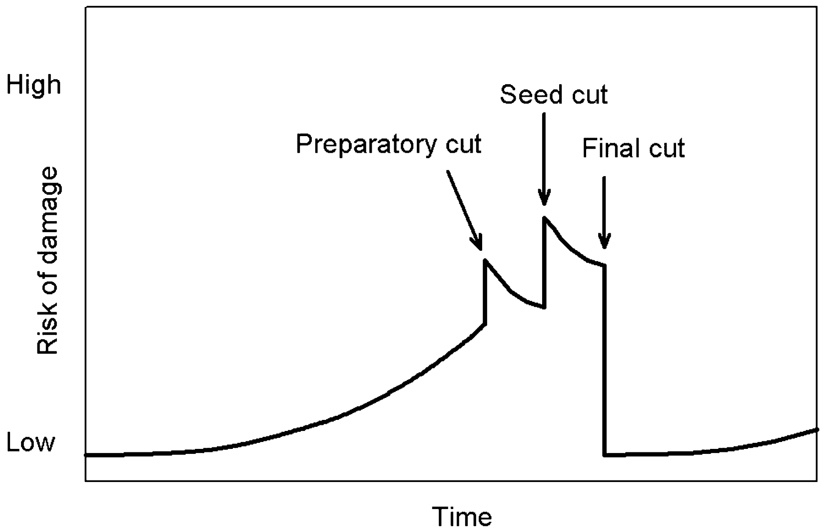


Figure 7-7. Changing risk of wind damage to a stand managed using the Shelterwood System.

Uneven-aged stands

An uneven-aged stand is an area containing trees at different stages of development. Silviculturists often perpetuate a stand structure where the distribution of trees in different age classes leads to a distribution in a 'reverse-j', i.e. the number of stems decreases with increasing age class. This is the 'selection system'.

5. Selection system

The main characteristics of this system are that 1) it perpetuates the uneven-aged structure of the stand and 2) the regeneration is always protected by the presence of older trees. It will therefore maintain a good tree cover through time which is an advantage for the protection of very sensitive slopes. Generally, a cycle of three or four harvesting operations will be planned during a full rotation. There are several variants that exist within this system, depending on how these operations are conducted. For example, these can involve the removal of individual stems (single-tree selection) or groups of stems (group-selection). The risk of wind damage to trees will be heightened after each intervention in the forest, but because of the continuous presence of young trees in the stand the risk of an event completely destroying the tree cover is relatively low (Figure 7.8).

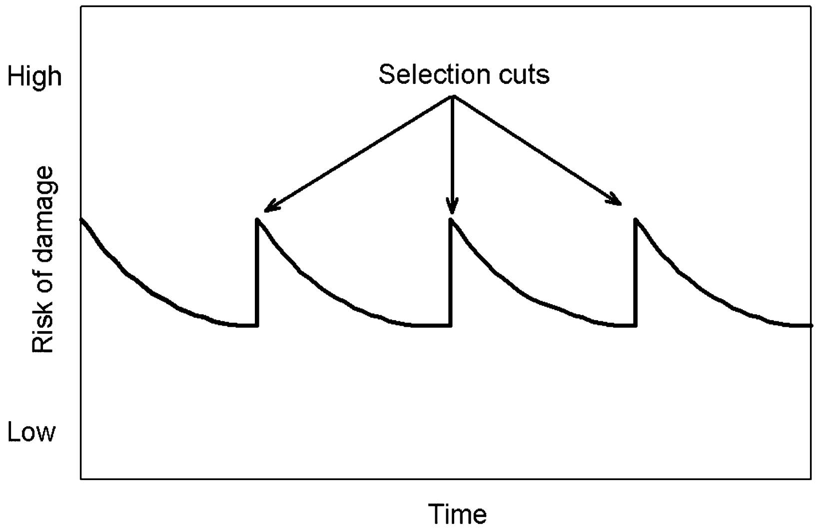


Figure 7-8. Changing risk over time of significant wind damage in a stand managed using the Selection System.

6. Coppice forest

Coppice forests are those which are regenerated through the vegetative sprouting of buds following the harvesting of the stem. Sprouts can originate from the stump or the root system of the tree. They are particularly vigorous in some species so that the coppice regeneration method is often used when the site is dedicated to the production of biomass. The harvesting of the trees is normally conducted using a clear-felling reproduction method. The system is interesting from the point of view of slope stabilisation because even though the aerial parts of the trees are removed periodically the site will benefit from the continuous presence of a well-developed rooting network. The rotation period is usually short (it can be as little as two to five years). It therefore involves frequent operations which might not be suitable for very sensitive or steep slopes.

3.3.2 Operational strategies

1. Thinning

Forest stands on steep slopes that have high topographical exposure and a high risk of wind damage should be managed carefully to avoid any increase in risk. In particular, stand thinning immediately increases the risk of tree overturning and stem breakage and should be practiced with care in wind exposed stands. The magnitude of this increase in windthrow risk depends on how and when the stand is thinned (Hibberd 1991). The larger the gaps that are created, the greater the increase in risk, so heavy thinning should be avoided on vulnerable sites. Thinning at an early age, i.e. ‘precommercial thinning’ leads to only slightly increased risk, while thinning more mature stands with a high canopy will make the trees immediately vulnerable to wind damage. However, stands that survive this increased risk will restabilise themselves over subsequent years, with risk commonly returning to pre-thinning levels within five to ten years of thinning, depending on species, yield class and age. An option that avoids a sudden increase in wind risk, is to plant ‘self-thinning’ mixtures of fast and slower growing tree species. Over time, the faster growing trees shade out the slower growing trees which eventually die out. For example, in the UK, plantations of self thinning mixtures of Scots pine and Sitka spruce have been successful in producing a final crop of well spaced Sitka spruce.

2. Felling

When felling vulnerable stands of trees on slopes, losses to windthrow may be minimised by felling stands with the highest windthrow risk before more stable or more sheltered stands. In addition, it is possible to plan felling operations to avoid or minimise exposing other vulnerable stands, by commencing felling at the downwind end relative to the prevailing wind. If selecting stands of older trees to be retained past their expected felling age, it is advisable to avoid stands on exposed sites, wet soils, and those that are immediately downwind of planned fellings (Quine et al. 1995).

Trees are particularly vulnerable to windthrow where the roots have restricted downward development. Roots compensate to some extent with adaptive growth and production of wider root plates, but shallow rooted trees remain less stable than deep rooted trees (Ray and Nicoll 1998). Early felling of stands may be necessary on soils where rooting depth is limited by a high water-table, induration, strong iron pan or shallow bedrock.

3. Stand edges

The wind loading is higher on trees close to the forest edge than on trees inside the forest. If trees have grown up at a forest edge, they will have adapted to their wind environment and be no more vulnerable than interior trees. The existence of windfirm edges is crucial to successful coupe design in moderate to high wind risk locations, such as on exposed slopes. Edges become windfirm because trees exposed to wind develop buttresses, stronger roots, wider root systems, and greater stem taper (Nicoll and Ray 1996; Cucchi et al. 2004). These stable edges also reduce the penetration of strong winds into the stand. Problems occur when a new edge is created, for example through clear felling or road construction. The newly exposed trees are much more vulnerable to being windthrown, even with relatively low wind speeds, because they are not adapted to their new wind environment (Quine and Gardiner 1992).

Topping (removing up to a third of the top of the crown) or high pruning (removing a third of the lower crown) the edge trees can significantly reduce the risk of wind damage (Hunt and Gardiner 2002). Alternatively, severance cuts can be made a few years ahead of clear felling or road building to precondition the remaining trees to their environments.

Evidence suggests that trees about 4-5 tree heights back from the forest edge are the most vulnerable. This appears to be due to flow distortion of wind at the forest edge and the time it takes for damaging gusts to develop. Modifying the shape of the forest edge at establishment or during management operations in order to create tapered edges (by planting or favouring slower growing species at the edge) or having graduated tree density at the edge can have stability benefits (Figure 7.9). This is because the flow distortion at the edge is minimised.

Tapered edges should be at least ½ tree heights wide and any manipulation to the edge of the stand should bear in mind that remaining trees will take time to adjust to their new environment (Gardiner and Stacey 1996). The shape of the edge also influences the risk of damage, and it is important when designing forests in exposed situations to avoid creating concave stand edges that accentuate the topographic funnelling of the wind.

Although wind loading on edge trees is greater than trees within the stand, growth of the stem and root system more than compensates for this. Severance cuts are designed to prepare and condition the forest for a future harvesting operation (Quine et al. 1995). These can be used to create a wind-firm edge in an exposed upland forest by exposing young trees to increased wind loading so that they adapt their growth in subsequent years.

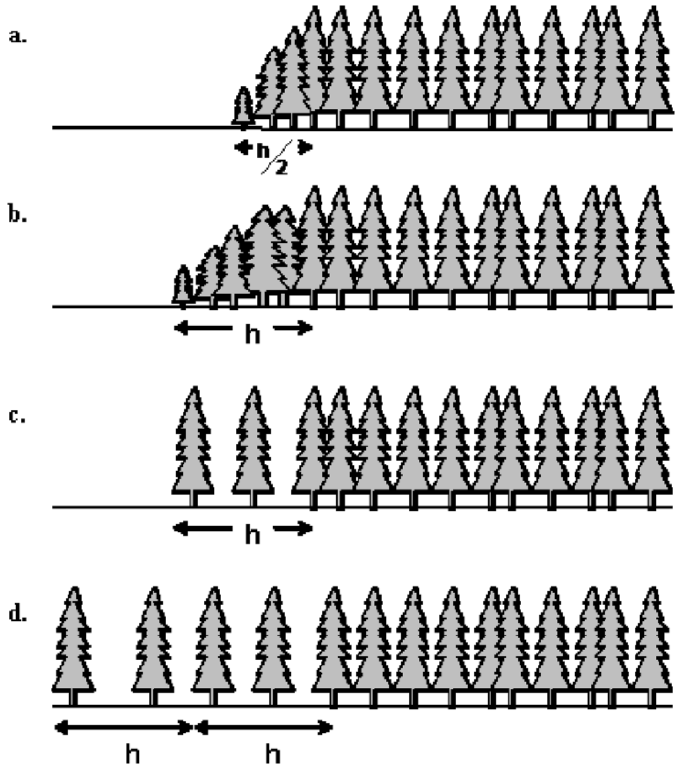


Figure 7-9. Recommended alternative designs of forest edges to improve stand stability by reducing air-flow distortion (adapted from Gardiner and Stacey 1996). a. and b. tapered edges that are ½ and 1 tree heights (h) wide, c. and d. graduated tree density for 1 and 2 tree heights.

Severance cuts should be made during a period when the trees are at low risk, and they should be as wide as the height the trees will be when they are expected to form a new edge. Severance cuts may be combined with respacing to create a graduated density edge.

4. COMBINING GROUND BIO- AND ECO- ENGINEERING TECHNIQUES

Ground bio- and eco-engineering techniques can be combined depending on the particular problem and type of vegetated slope. An example may be the restoration of degraded woodlands due to forest fires, intensive farming or forestry activities and over-grazing. Three groups of restoration activities are required: 1) erosion control works, 2) waterflow control works and 3) vegetation recovery by artificial reforestations and by natural regeneration.

4.1 Erosion control works

These are usually built up on a temporary basis over 5-10 years to stop sheet erosion caused by heavy rain. The ground bioengineering techniques suitable for erosion control works are:

- *Matchsticks* - made of branches, bracelets, thin boles, and the remnants of clear fellings, stacked on the ground in horizontal lines, (on the uphill side of the stumps), in areas of moderate slopes (10-30°). The distance between these rows is usually 8-15 m depending on relief. Dimensions are, height 0.50-0.75 m, width 1.0-1.5 m and length from 1 to >1000 m (see Table 7-24). These structures collect the sediment, sand and stones stones from moving downslope and stop soil erosion during heavy rainfall.
- *Log erosion barriers* - these structures constitute logs of dead trees, stacked on the ground by poles or tied to tree stumps in horizontal lines, in places where slopes are steep (31-50°). A small trench is built upwards to stop soil moving downwards after rainfall. The distance between each log is varied (8-10 m), height and width equals log diameter (about 0.20 m), and length from 1 to >1000 m (see Table 7-8).

These methods can be combined with eco-engineering techniques such as:

- *Clear felling* - in areas with very steep slopes (more than 50°), the dead (burnt) trees should be cut in to pieces of about 1 m in length and distributed across the slope to form log erosion barriers (see Table 7-8).

- *Ploughing and furrowing* - a heavy machine e.g. a Caterpillar with two ploughs at the rear (nails 1.0 m long at a distance of 2.0 m from each other), ploughs the area once horizontally across the slope at a depth of 0.70-1.0 m between the wood stacks where the slope is moderate 0-30°, leaving a furrow. This technique should be applied only in certain circumstances and aims at preventing further soil erosion and also at improving the soil condition. First, by furrowing the ground, water, soil, and sediment are collected into furrows. Secondly by loosening the soil at the ground surface, rainwater is absorbed and penetrates more easily to deeper layers without eroding the surface. Thirdly, the soil is prepared for plantations. In sleep shallow-rocky soils individual holes for tree/bush planting should be considered.

4.2 Waterflow control works

These works are aimed at controlling waterflow by keeping in place the water and sediments that have escaped the erosion control works. The ground bio-engineering constructions that can be put in place are:

- *Small timbered dams* - these are temporary structures used for 7-10 years. They are wooden structures made with logs from dead trees on 2^{nd} and 3^{rd} degree currents. They are usually constructed in certain places along current beds. They are usually 1 m tall and specially stacked in place.
- *Check dams* - these are permanent constructions made of concrete with heights up to 5.0 m, placed at the lower places of the 1^{st} degree current beds.

4.3 Vegetation recovery by reforestation and natural regeneration

A new management perspective that emphasizes a variety of amenities and commodities is needed for woodlands. Today throughout Europe there is an increasing awareness of the necessity to apply and implement management practices that consider the multiple values in the woodlands on the long-term sustainable basis. The new forest ecosystem should be stable, upgraded, adapted to the climatic and soil conditions, more resistant to fire and insect pests, with a normal potential of fauna and flora. For the re-establishment of a future forest the multiple and social uses of woodlands (e.g., watershed management, wildlife, recreation, hunting, aesthetics, education, etc.), as well as the long-term protection from many dangers (e.g., wildfires, soil erosion, storms, etc.) should be considered.

There are two approaches to this aim: 1) artificial reforestation and 2) to protect the natural regeneration.

1. Artificial reforestation

Artificial reforestation is aimed at initially filling the gaps left from natural regeneration, secondly to re-establish species which have disappeared because of human activity, and thirdly to renew and improve vegetation. Species should be indigenous, whenever possible, and be well adapted to the soil and climatic conditions present. Some exotic species may be used in certain circumstances.

Artificial restoration may use conifer and broadleaved species, evergreen and deciduous species depending on the original woodland or forest. Soil and climatic conditions, space, altitude, exposure, and topography must also be taken into consideration (see Chapter 6).

Conifers can be planted on poorer soils. Some typical species are: *Pinus brutia* (Ten.), *Pinus halepensis* Mill., *Pinus pinea* L., *Pinus nigra* L., *Cupressus sempervirens* L., *Cupressus arizonica* Greene, *Cedrus deodara* (D. Don) G. Don, *Cedrus libani* A.Rich, *Cedrus atlantica* (Endl.) Carrière, *Thuja* sp. L.. Broadleaved species are recommended for planting where better environmental and soil conditions exist. Some typical species are:

- *Quercus aegilops* L., *Quercus pubescens* Willd., *Morus alba* L. on southern exposures with low elevation (where soil moisture is low during the summer in particular).
- *Acer negundo* L., *Acer pseudoplatanus* L., *Quercus ilex* L. on northern exposures (where soil moisture is high during the summer in particular)
- *Quercus frainetto* Ten., *Quercus cerris* L. in higher latitudes
- *Celtis australis* L., *Cercis siliquastrum* L., *Fraxinus ornus* L., *Fraxinus excelsior* L., *Acer campestre* L., *Acer negundo* L., *Robinia pseudacacia* L., *Tillia tomentosa* Moench., *Carpinus orientalis* Mill., *Ulmus* sp. L., in certain places and all over the planted area.

Secondary species such as *Laurus nobilis* L., *Spartium junceum* L., *Rosmarinus officinalis* L., *Nerium oleander* L., *Ligustrum vulgare* L., *Cotoneaster horizontalis* Dcne., *Pyracantha coccinea* M.Roem., *Pyrus malus* L., *Prunus insisititia* L., should be established around recreation sites, fire lanes and forest roads.

2. Natural regeneration

Many species are well adapted to regenerate after wildfire, for example the following conifers; *Pinus brutia* Ten., *Pinus halepensis* Mill., *Pinus pinea* L., *Pinus pinaster* Ait., *Pinus radiata* D.Don, *Cupressus sempervirens* L., *Cupressus arizonica* Greene. Although, in many cases, natural regeneration maybe at risk, because of the possibility that a high percentage of seedlings weaken from drought and pests.

The main understory sprouted shrubs, that adapt to regeneration after wildfires are: *Quercus coccifera* L., *Phillyrea latifolia* L., *Pistacia lentiscus* L., *Pistacia terebinthus* L., *Arbutus unedo* L., *Arbutus andrachne* L., *Paliurus spina-christi* Mill. and *Anthyllis hermanniae* L., (Spanos et al. 2000).

5. CONCLUSION

In this Chapter, we have presented many different ecotechnological solutions including the traditional ground bio-engineering techniques for combating mass movements especially soil erosion, shallow slope instability, rockfall and windthrow. The success of these ecotechnological solutions is very much dependent on local conditions and site-specific factors, therefore it cannot be assumed that each technique will work for you. It is important to assess the success or failure of an ecotechnological solution on a particular site, before deciding on an appropriate solution, for example, Stangl (2007) investigated the performance of 60 year old hedge brush layers and live crib walls in torrent catchment areas in Italy and Austria. Stangl's (2007) results showed that with increasing age, tree species diversity had decreased, yet there was no loss in soil reinforcement and both methods were found to have excellent soil armouring and anchoring effects.

Traditionally, ground bio-engineering techniques have not been preferentially selected for use in large infrastructure projects, but this does not need to be the case as they can be widely used and applied in large construction projects, as experienced by the Egnatia Odos AE (EOAE) company. The EOAE was set up specifically to manage the design, construction, maintenance, and use of the Egnatia Motorway in Southern Europe. One of their aims was to ensure the environmental protection and land restoration of disturbed land due to construction works. The success of the ecotechnological solutions employed were quantified by Katridzidakis et al. (2007a,b) and Koukoura et al. (2007), and the methodologies employed by Egnatia Odos AE of sourcing locally produced seeds and growing them in their own nursery added to the project's success (Katridzidakis et al. 2007a).

With regard to eco-engineering techniques, careful thought must be given to the instability problem on the slope, how that problem will change over time, and whether the species selected for planting on the site in question will themselves be subject to temporal changes. In the case of e.g. rockfall or windthrow problems on slopes, the forester must also take into account planting density and thinning practices and how the management of a stand with regard to such spatial factors might affect slope mass movement. The combination of ground bio- and eco-engineering techniques should also allow for greater slope stability to be achieved with minimal cost. Nevertheless, it is recommended that professional advice be sought before carrying out any of the applications described in this chapter, as detailed information on installation methods and planting guidelines are not given.

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