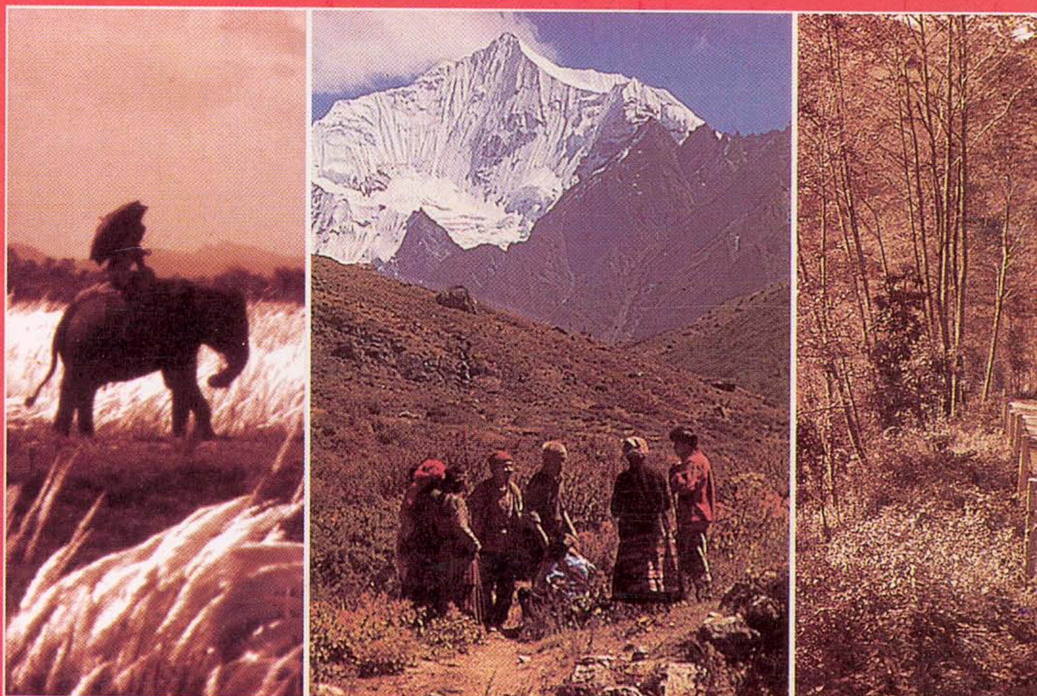
ROADSIDE
Bio-engineering



REFERENCE MANUAL

Department of Roads
His Majesty's Government of Nepal

ROADSIDE
Bio-engineering

REFERENCE MANUAL

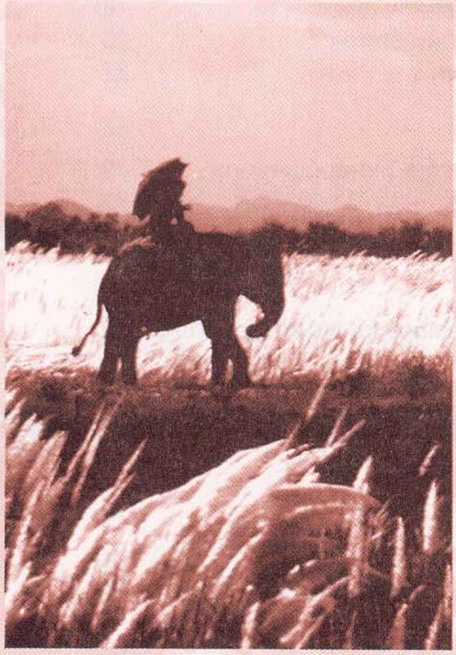
First Edition : 1999
Re-print : 2002

ISBN 1 86192 170 5

This document is an output of the Nepal-UK Road Maintenance Project, which was undertaken jointly by His Majesty's Government of Nepal and the Department for International Development of the United Kingdom. The views expressed are not necessarily those of either government.

Editor :	Omar Sattaur
Design :	Chris Jones, Design for Science
Photography :	Jane Clark, John Howell, Shankar Rai and Ishwar Sunwar
Graphics :	Mark Fletcher, Smith Ward Design
Original Typesetting :	Paul Samat
Re-typesetting :	Jesus Nyachhyon
Printed in Nepal at :	Spectrum Offset Press Ganabahal, Kathmandu

ROADSIDE Bio-engineering



REFERENCE MANUAL

John Howell

Published by
His Majesty's Government of Nepal
Department of Roads
Babar Mahal, Kathmandu, Nepal

Funded by
DFID Department for International Development
94 Victoria Street, London, SW1E 5JL, UK

CONTENTS

CONTENTS

ACKNOWLEDGEMENTS

This manual of Roadside Bio-engineering has been developed from an enormous amount of experience, gained throughout the road network of Nepal between 1984 and 1998. It is written for the exceptional conditions found in Nepal (characterised mainly by very active geomorphology, steep slopes, intense rainfall and a restricted economy) and the techniques have been tested under those conditions.

So many people have been involved that it is quite impossible to acknowledge them all. Nothing could have been achieved without the full support of the Department of Roads, the financial support of the Department for International Development of the United Kingdom and the administrative support of Roughton International. In writing this manual I have drawn on material and comments from a large number of people. In particular, parts of chapter 2 and Annex A were originally written by Cliff Lawrance of the Transport Research Laboratory and Samjwal Ratna Bajracharya of the Mountain Risk Engineering Unit, Tribhuvan University. Narendra Paudyal drew the botanical illustrations. Some other illustrations are based on the work of Jaquelien Chapman, formerly of FRR Limited, and also of Sue Wickison. The other main personal contributions and support are listed below.

Department of Roads: Varun Prasad Shrestha, Niranjan Prasad Chalise, Mohan Bahadur Karki, Bharati Sharma, Suresh Kumar Regmi, Shyam Prasad Adhikari, Medini Prasad Rijal, Madan Gopal Maleku, Basu Dev Jha, Keshav Pokhrel, Ananda Kumar Batajoo, Indu Sharma Dhakal, Biplabh Karki, Jamuna Bahadur Shrestha, Vishnu Prasad Shrestha, Yogendra Kumar Rai, Deepak Raj Maskey, Ajay Kumar Mull, Bijay Chapagain, Shankar Prasad Rajbhandari, Buddhi Prasad Neupane, Sudarsan Lal Shrestha, Deepak KC, Raj Kumar Maharjan.

Department for International Development, United Kingdom: Jane Clark, Peter Roberts, Martin Sergeant, Ed Farrand, Janet Seeley, Bettina Demby.

Eastern Region Road Maintenance: Ishwar Sunwar, Indra Kafle, Shankar Rai.

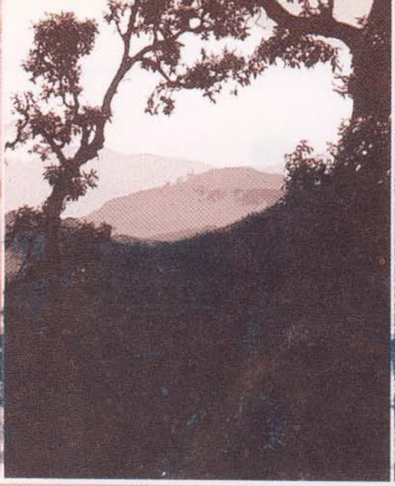
Mountain Risk Engineering Unit, Tribhuvan University: Megh Raj Dhital, Narendra Man Shakya, Siddhi Bir Karmacharya, Padma Bahadur Khadka.

Others: Bob George (Wolverhampton University) Hare Ram Shrestha and Govinda Mallick (Sustainable Infrastructure Development Foundation), Mohan Dhoj Joshi and Kalyan Thapa (Third Road Improvement Project), Werner Paul Meyer (Helvetas), Simon Howarth (Sir Mott MacDonald and Partners), Stephen Eagle (Forestry and Bio-engineering Consultant), Dev Bir Basnyet (Alliance Nepal), John Millband (WSP International), the staff of Roughton International and Scott Wilson Kirkpatrick, Keshar Man Sthapit (Ministry of Forests and Soil Conservation), Ramesh Bikram Karky (Karky Law Chambers), Pushpa Lal Moktan (New Era), Peter Branney (Forestry and Rural Development Consultant), Paul Balogun (Natural Resources Economics Consultant), and Keshar Man Bajracharya (Royal Nepal Academy of Science and Technology).

John Howell (Living Resources Limited).
July 1999.

USING THE *REFERENCE MANUAL*

This provides a theoretical background for the use of vegetation in engineering. In addition to covering the principles underlying techniques of slope stabilisation, the manual outlines those aspects of the ecology, geology, geography and law of Nepal that would be of relevance to practising bio-engineers. The manual is intended for office use and provides standard specifications for bio-engineering works, profiles of the main bio-engineering species and rate analysis norms for bio-engineering approved by His Majesty's Government, Ministry of works and Transport.
(The companion *site handbook* provides the information needed to design, plan, implement and maintain roadside bio-engineering works and is intended for use on site.)


Vegetation in engineering

This chapter

- Defines bio-engineering and summarises its practical application,as given in the *Site Handbook* (1.1).
- Assesses the role of vegetation in engineering: the benefits and disadvantages (1.2).
- Describes the main bio-engineering systems and their effects (1.3).
- Discusses the integration of civil and bio-engineering (1.4).
- Describes the process for determining which species to use for each bio-engineering technique (1.5).
- Provides a brief introduction to general plant ecology in Nepal (1.6).
- Defines the site suitability of the main species used for bio-engineering (1.7).
- Discusses the importance of other aspects of plant ecology, including water and nutrient availability for plants (1.8), progression and regression (1,9), competition between plants (1.10) and common natural plant communities (1.11).
- summarises the implications of plant ecology for bio-engineering (1.12).

Downslope planting lines allow rapid surface drainage of this impermeable Siwalik mudstone, while still armouring the surface against erosion

1.1 INTRODUCTION TO BIO-ENGINEERING

What is bio-engineering?

Bio-engineering is the use of living plants for engineering purposes. Vegetation is carefully selected for the functions it can serve in stabilising roadside slopes and for its suitability to the site. It is usually used in combination with civil engineering structures. Bio-engineering offers the engineer a new set of tools, but does not normally replace the use of civil engineering structures. Incorporating bio-engineering techniques usually offers a more effective solution to the problem. The materials and skills are all available in rural areas, however remote.

What does bio-engineering do?

- Bio-engineering can be used to protect almost all slopes against erosion[1].
- Bio-engineering reduces the instances of shallow planar sliding[2].
- Bio-engineering can be used to improve surface drainage and reduce slumping[3].

Bio-engineering systems work in the same way as civil engineering systems and have the same functions. They are effective at depths of up to 500 mm below the surface. They are not effective for deep-seated slope failures.

Where the best quality engineering solution is being sought, designs that incorporate bio-engineering are usually the most effective and the most economic solutions for the shallow-seated problems listed above. Obviously the use of bio-engineering techniques costs more in the short term than the 'do nothing' approach. But in the long term, there should be additional benefits from reduced maintenance costs

How does bio-engineering work?

Bio-engineering systems work by fulfilling the engineering functions required for the protection and stabilisation of slopes. The difference between revegetation and bio-engineering is that plants must provide one or more of the roles of catching debris, armouring the surface, reinforcing the soil, anchoring the surface layer, supporting the slope or draining the material. This means serving an engineering function. This is examined in more detail in 1.2 below.

Potential uses of bio-engineering techniques

On small sites, where erosion or shallow planar failure are the only likely problems, bio-engineering techniques alone may be adequate. However, bio-engineering is more often closely integrated with civil engineering structures.

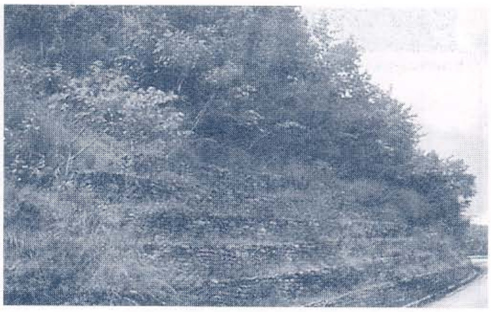
[1] Erosion is the gradual wearing away of soil (or other material) and its loss, particle by particle.

[2] Planar sliding is a mass slope failure on a slip plane parallel to the surface (*i.e.* not rotational). It is the most common type of landslide and is usually shallow (less than 1.5 metres deep). It is also called a debris slide or a translational landslide.

[3] Slumping is a form of saturated flow of soil or debris. It occurs mostly in weak, poorly drained materials, when a point of liquefaction is reached following heavy rain. It is usually shallow (less than 500 mm deep).

Large grasses planted at random provide complete surface armouring

Bamboos provide support to aid stability above this gabion retaining wall (right)



Examples are as follows:

- Prevention of scour around drain and culvert discharge points.
- Prevention of scour around civil engineering structures, particularly at the soil/structure interface.
- Protection against debris blocking side drains.
- Protection against debris coming on to the carriageway.
- Protection of uncompacted spoil.
- Protection of embankments and fill areas.
- Protection of bare cut slopes.
- Protection of bare surfaces on rehabilitated landslides.
- Protection of slope toes from erosion, where undercutting and over-steepening may arise.
- Stabilisation of gullies.
- Rehabilitation of quarries and borrow pits.
- Prevention of shallow planar failures (less than 0.5 m deep).
- Prevention of shallow slumps (less than 0.5 m deep).
- Reduction of minor rock falls in weak, shattered rock.
- Reduction of debris creep on steep, unconsolidated colluvial slopes.

Bio-engineering is mostly used for relatively small scale works, such as armouring bare cut and fill slopes against erosion, catching debris to reduce drain blockages and so on. In Nepal, bio-engineering is used more widely, on account of the extreme terrain conditions and the need for extensive low-cost techniques for protecting slopes and stabilising shallow-seated failures.

The many cuttings that make up these brush layers have dense, fibrous roots that reinforce the soil

Figure 1.1: Engineering functions of vegetation

Engineering function	Requirements	Examples in Nepal	Civil engineering equivalent	Combination of both
Catch eroding material moving down the slope, as a result of gravity alone or with the aid of water. The stems of the vegetation perform this function.	Strong, numerous and flexible stems. Ability to recover from damage.	Micro scale: clumping grasses in contour grass lines. Larger scales: shrubs with many stems; large bamboos.	Catch walls.	Catch wall with bamboos above.
Armour the slope against surface erosion from both runoff and rain splash. To be effective, this requires a continuous cover of low vegetation. Plants with high canopies alone do not armour the slope (the terminal velocity of a rain drop is reached after a fall of only 2 metres, and some canopies generate larger rain drops).	Dense surface cover of vegetation. Low canopy. Small leaves.	Grass lines or a complete grass carpet of clumping or spreading grasses.	Revetments.	Vegetated stone pitching.
Reinforce the soil by providing a network of roots that increases the soil's resistance to shear. The degree of effective reinforcement depends on the form of the roots and the nature of the soil.	Plants with extensive roots with many bifurcations. Many strong, fibrous roots.	Densely rooting clumping grasses planted in lines; some shrubs and trees.	Reinforced earth.	Jute netting with planted grass.
Anchor the surface material by extending roots through potential failure planes into firmer strata below. If the potential failure is deeper than about 0.5 metre, this is achieved only by large woody plants with big vertical roots (tap roots).	Plants with deep roots. Strong, long, vertically oriented roots.	Shrubs and trees which are deeply rooting.	Soil anchors.	Combination of anchors and trees.
Support the soil mass by buttressing and arching. Large heavy vegetation, such as trees, at the base of a slope can provide such support in the form of buttresses; or on a micro scale, clumps of grass can buttress small amounts of the soil above them. Across the slope, a lateral effect is created in the form of arching: this is where the soil between buttresses is supported from the sides by compression. The buttresses and arches of a building have the same engineering functions.	Extensive, deep and wide-spreading root systems. Many strong, fibrous roots.	Large clumping bamboos; most trees.	Retaining walls.	Retaining wall with bamboos above.
Drain excess water from the slope. The planting configuration of the vegetation can enhance drainage, avoiding saturation and slumping of material. Vegetation can also help to reduce pore-water pressure within the slope, by extracting water from the roots and transpiring it out through the leaves.	Plants small enough to be planted in closely-packed lines. Ability to resist scour. High leaf area to enhance transpiration.	Downslope and diagonal vegetation lines, particularly those using clumping grasses. Most shrubs and trees.	Surface or sub-surface drains.	French drains and angled grass lines.

After Clark and Hellin (1996).

Many plants provide root reinforcement without affecting the structure of a slope. These utis trees grow on a gabion without distorting it

Figure 1.2: Relative strengths of various plant categories in serving the main engineering functions (general case)

	Woody			Non-woody		
Engineering function	Trees	Shrubs	Bamboos	Clumping grasses	Matting grasses	Other herbs †
Catch	*	***	***	**	*	-
Armour	*	*	*	***	***	*
Reinforce	**	***	*	**	*	-
Anchor	***	**	-	-	-	-
Support	***	**	***	-	-	-
Drain	-	-	-	***	*	-

Certain functions require the plants to be in closely spaced lines.At the micro scale, small plants can provide functions of anchoring and supporting.

† Herbs are small plants without wood in the stems or roots.

Key:
- *** Excellent
- ** Good
- * Moderately useful
- - Not useful at all

1.2 ENGINEERING FUNCTIONS AND HYDROLOGICAL EFFECTS OF VEGETATION

Both bio-engineering and civil engineering systems perform engineering functions. Figure 1.1 shows the six main engineering functions of bioengineering systems; obviously plants cannot emulate all of the functions of civil engineering systems, particularly those having effects deeper than about 0.5 metre.

Plant types vary in their ability to serve the various engineering functions. Figure 1.2 compares the performance of the main categories of plants. Selecting the category best suited to fulfil the required engineering function is an important step in applying bio-engineering techniques.

Difference of rooting patterns

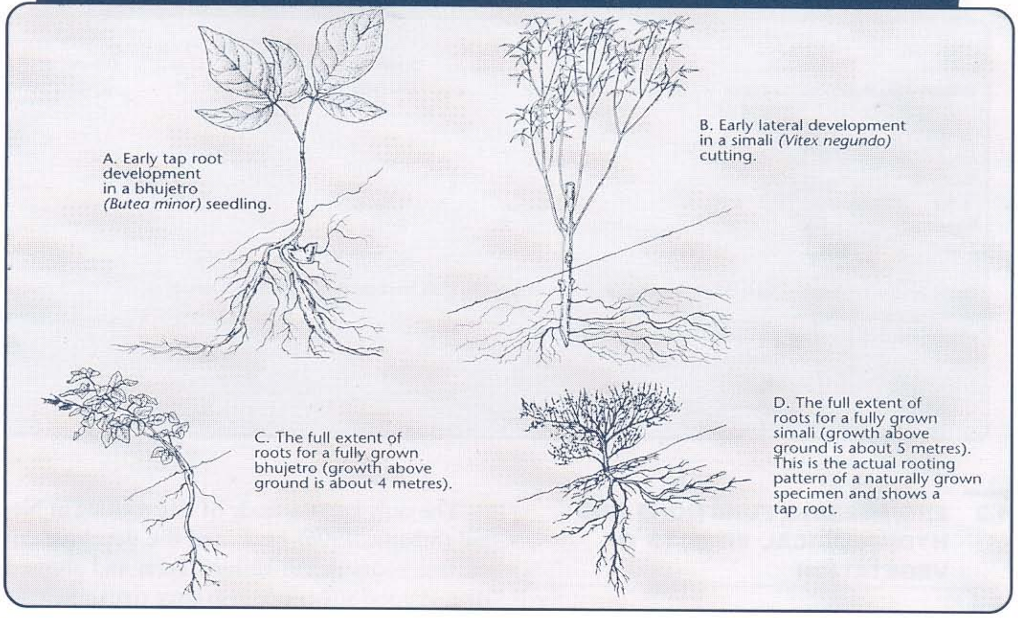
In assessing the engineering functions of plants, the pattern of plant rooting, and therefore the way in which they serve functions, is very important. The development of plant roots is highly variable and depends greatly on the characteristics of individual plants, on the conditions under which they are growing and often on the method of propagation. In woody plants (shrubs and trees) there are two main root types: tap roots, which grow predominantly downwards; and lateral roots, which grow predominantly sideways. The drawings in Figure 1.3 show the early development of these roots for two widely used bio-engineering species.

The only known study of tree rooting in Nepal (Sthapit, 1996) examined the development of tree roots in the eastern Terai and showed that, in good soil conditions large trees generally have a complex network of horizontal and vertical roots. These trees were mostly naturally sown *in situ*, and so the effects of planting technique were not apparent. Many trees developed 'sinker' roots, which branched vertically downwards from the laterals. It is not known whether the pruning of roots in polypot seedlings inhibits the later growth of tap roots or not. Cuttings tend to develop fibrous lateral roots and it is generally thought that plants propagated by this means rarely develop tap roots.

In practice, it appears that woody plants propagated from cuttings may well produce the best shallow rooting systems for reinforcement, whereas those grown from seed may produce the best roots for anchorage. Many bio-engineering techniques depend on a certain method of plant propagation: for example, brush layering, palisades and fascines are all constructed using hardwood cuttings. As a result, the propagation method can be an important consideration in the determination of the engineering effects of the different methods.

Grasses appear to be simpler in the development of their rooting patterns. Whether they are grown from seed or from slip or rhizome cuttings, they seem to develop a similar full root pattern which is determined by the species rather than by the method of propagation. This is shown in Figure 1.4. This demonstrates the significant dif-

Figure 1.3. Differences of root development in two shrubs used for bio-engineering



ferences between shallow-rooting grasses such as musekharuki, and the sizeable clump grasses like khar, which are favoured for bio-engineering: the roots of musekharuki penetrate to only about 50 mm, whereas the main root network of khar penetrates to at least 500 mm; and khar is one of the smaller clumping grasses.

The maximum effective depth of rooting of plants, and therefore the depth to which they can reinforce or anchor the soil, is also a subject for debate in the world-wide bio-engineering literature. In exceptional cases, it is clear that certain plants can have extremely long roots. Grass clumps can sometimes send roots to four or five metres below the surface, and trees can send roots even deeper. But on roadside slopes, where materials tend to be stony and rooting conditions are poor, far shallower rooting is normal. Figure 1.5 gives the maximum rooting depths for the classes of plants used for bio-engineering in Nepal: these can be used for design purposes and may be exceeded in many cases.

Other benefits from vegetation

Vegetation provides two further benefits that cannot be given by civil engineering. These are:

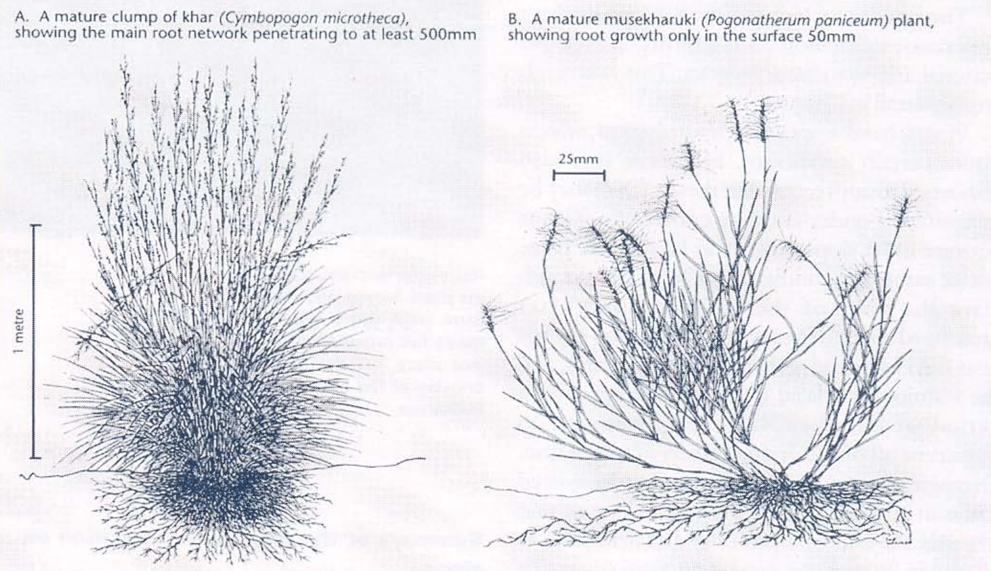
- environmental improvement: vegetation cover encourages other plants and animals to live on the slope, and gradually enables a better soil to form;
- limiting the lateral extent of instability: the rooting system of larger plants can interrupt a shear plane and stop it spreading further in the current phase of active instability.

Hydrological effects of vegetation

Plants affect the hydrological condition in and around a slope in a variety of ways:

- interception: rain strikes the leaves before striking the ground;
- evaporation: water may evaporate from the leaf surfaces;
- storage: leaves and stems hold water for some time before it eventually reaches the ground;
- leaf drip: accumulated water can drip off the leaves and fall to the ground;
- pool formation: stems may trap water running over the ground surface to form

Figure 1.4. Differences of rooting in two grass species. Note the significantly different scales



pools, preventing run-off;

- infiltration: stems and shoots roughen and loosen the ground, enabling water to infiltrate more easily;
- water uptake: plants take up water through their roots and return it to the atmosphere through transpiration, the release of water through the leaves. Plants that transpire relatively large volumes of water are sometimes referred to as phraetophytes.

Many of these effects serve to reduce the amount of moisture in the soil. During heavy rainfall, vegetation can significantly increase infiltration . All colluvial soils have very high infiltration rates; most *in situ* weathered soils are also very porous and so permit high rates of infiltration. Only the deeply weathered clay loams, usually known as rato mato, retain low infiltration

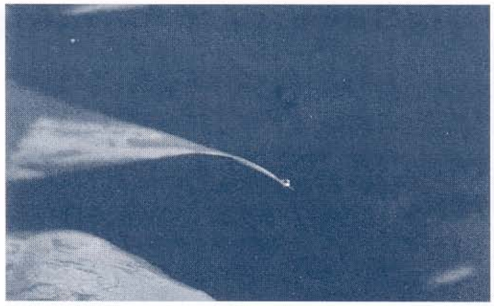
Figure 1.5. The main plant classes and their anticipated effective depths of rooting

Plant type	Example		Maximum effective rooting depth
Small grass	Dubo	*Cynodon dactylon*	100 mm
	Kikiyu	*Pennisetum clandestinum*	
Large grass	Kans	*Saccharum spontaneum*	0.5 to 1 metre
	Amliso	*Thysanolaena maxima*	
	Khar	*Cymbopogon microtheca*	
Large bamboo	Mal bans	*Bambusa nutans*	1 metre
Shrubs	Dhanyero	*Woodfordia fruticosa*	1.5 metres
	Bhujetro	*Butea minor*	
Trees	Khayer	*Acacia catechu*	2 metres
	Utis	*Alnus nepalensis*	
	Bakaino	*Melia azedarach*	

rates even with dense vegetation cover and are therefore prone to high rates of runoff.

The extent to which it is desirable to increase or decrease infiltration on a slope depends on the material and site characteristics. This is considered in detail in Chapter 2.

Plants have important hydrological effects under certain conditions. However, it is also important to appreciate that these effects may be insignificant under extreme conditions. This is because most slope failures in Nepal take place under saturated conditions at least one month after the start of the monsoon and after prolonged spells of heavy rain. The soil is already near field capacity[1] before the storm starts, and the addition of at least 100 mm more rain over a period of less than 48 hours is enough to overcome all of the drying effects of vegetation. Damaging monsoon storms frequently exceed 250 mm in 24 hours, while a heavy burst of rain towards the end of a prolonged storm, such as 50 mm in 30 minutes, can be the final triggering factor. Thus the phraetophytic effect mentioned in text books, which may be significant in areas with lower rainfall intensities, may not be a relevant consideration under the monsoonal climate of Nepal.



Rainwater accumulates on plant leaves and can form large drips. When these fall repeatedly in one place, the risk of erosion at the micro level increases

Summary of the effects of vegetation on slopes

The beneficial and adverse effects of vegetation on slopes are summarised in Figure 1.6. Bio-engineering techniques must be selected so that the benefits outweigh potential disadvantages.

[1] Field capacity describes the degree of saturation that a soil has reached once water has been allowed to drain freely from soil pores and drainage ceases.

Figure 1.6: Summary of the beneficial and adverse effects of vegetation on slopes

	Mechanical mechanisms	Effect
1	Stems and trunks trap materials that are moving down the slope.	Good
2	Roots bind soil particles to the ground surface and reduce their susceptibility to erosion.	Good
3	Roots penetrating through the soil cause it to resist deformation.	Good
4	Woody roots bind fragmented rocks together.*	Good
5	Woody roots may open the rock joints due to thickening as they grow. *	Bad
6	The root cylinder of trees holds up the slope above through buttressing and arching.	Good
7	Tap roots or near vertical roots penetrate into the firmer stratum below and pin down the overlying materials.	Good
8	Vegetation exposed to wind transmits dynamic forces into the slope.	Bad
	Hydrological mechanisms	**Effect**
1	Leaves intercept raindrops before they hit the ground.	Good
2	Water evaporates from the leaf surface.	Good
3	Water is stored in the canopy and stems.	Good
4	Large or localised water droplets fall from the leaves.	Bad
5	Surface run-off is slowed by stems and grass leaves.	Good
6	Stems and roots increase the roughness of the ground surface and the permeability of the soil.	Site dependent
7	Roots extract moisture from the soil, which is then released to the atmosphere through transpiration.	Weather dependent

* The effects of root wedging vary from site to site. In many locations, roots help to bind fragmented rocks together while, in others, they tend to break them apart. It may be a function of the species more than of the rock condition: for example, utis (*Alnus nepalensis*) is usually observed as binding rocks together, whereas pipal (*Ficus religiosa*) is notorious for wedging masonry walls apart.

Figure 1.7. The main bio-engineering techniques used in the Nepal road sector, and their engineering functions

System	Design and function
Planted grass lines: contour/horizontal	Grass slips (rooted cuttings), rooted stem cuttings or clumps grown from seed are planted in lines across the slope. They provide a surface cover, which reduces the speed of runoff and catches debris, thereby armouring the slopes.
Planted grass lines: downslope/vertical	Grass slips (rooted cuttings), rooted stem cuttings or seedlings are planted in lines running down the slope. They armour the slope and help to drain surface water. They do not catch debris. Using this technique, a slope is allowed to develop a semi-natural drainage system, gullying in a controlled way.
Planted grass lines: diagonal	Grass slips (rooted cuttings), rooted stem cuttings or seedlings are planted in lines running diagonally across the slope. They armour the slope and have limited functions of catching debris and draining surface water. This technique offers the best compromise of the grass line planting systems in many situations.
Planted grasses: random planting	Grass slips (rooted cuttings), rooted stem cuttings or seedlings are planted at random on a slope, to an approximate specified density. They armour and reinforce the slope with their roots and by providing a surface cover. They also have a limited function of catching debris. This technique is most commonly used in conjunction with standard mesh jute netting, where complete surface protection is needed on very steep, harsh slopes. In most other cases, however, the advantages of one of the grass line planting systems (*i.e.* contour, downslope or diagonal) offer better protection to the slope.
Grass seeding	Grass is sown direct on to the site. It allows easy vegetation coverage of large areas. This technique is often used in conjunction with mulching and jute netting to aid establishment.
Turfing	Turf, consisting of a shallow rooting grass and the soil it is growing in, is placed on the slope. A technique commonly used on gentle embankment slopes. Its only function is armouring.
Shrub and tree planting	Shrubs or trees are planted at regular intervals on the slope. As they grow, they create a dense network of roots in the soil. The main engineering functions are to reinforce and, later, to anchor. In the long term, large trees can also be used for slope support.
Shrub and tree seeding	Shrub (or tree) seeds are applied directly to the site. This technique allows very steep, rocky and unstable slopes to be revegetated where cuttings and seedlings cannot be planted. There are two methods: direct sowing and broadcasting. In the first, seeds are placed individually, whereas the second involves throwing the seed all over the site. The main engineering functions are to reinforce and, later, to anchor.
Large bamboo	Large bamboos can reduce movement of material and stabilise slopes. They are usually raised by the traditional method or by rooted culm cuttings from a nursery. Large clumps of the larger stature bamboos are one of the most substantial vegetation structures available to reinforce and support a slope. However, they do not have deeply penetrating roots and so do not serve an anchoring function; also, they can surcharge upper slope areas.
Brush layering	Woody (or hardwood) cuttings are laid in lines across the slope, usually following the contour. These form a strong barrier, preventing the development of rills, and trap material moving down the slope. In the long term, a small terrace will develop. The main engineering functions are to catch debris, and to armour and reinforce the slope. In certain locations, brush layers can be angled to provide drainage.
Palisades	Woody (or hardwood) cuttings are planted in lines across the slope, usually following the contour. These form a strong barrier and trap material moving down the slope. In the long term, a small terrace will develop. The main engineering functions are to catch debris, and to armour and reinforce the slope. In certain locations, palisades can be angled to provide drainage.
Live check dams	Large woody (or hardwood) cuttings are planted across a gully, usually following the contour. These form a strong barrier and trap material moving downwards. In the longer term, a small step will develop in the floor of the gully. The main engineering functions are to catch debris, and to armour and reinforce the gully floor.
Fascines	The word "fascine" means a bundle of sticks. In this technique, bundles of live branches are laid in shallow trenches. After burial in the trenches, they put out roots and shoots, forming a strong line of vegetation. It is sometimes called live contour wattling. The main engineering functions are to catch debris, and to armour and reinforce the slope. In certain locations, fascines can be angled to provide drainage. Where time is at a premium, brush layers may be more appropriate as these are quicker to establish than fascines.
Vegetated stone pitching	Slopes are strengthened by a combination of dry stone walling or cobbling, and vegetation planted in the gaps between the stones. There are two distinct uses: reinforced toe walls; and protected gully beds. This technique provides a very strong form of armouring. Because it specifically uses vegetation to strengthen a simple civil engineering technique, it represents a stronger form of normal stone pitching.

Figure 1.7. The main bio-engineering techniques used in the Nepal road sector, and their engineering functions. *continued*

SYSTEM	DESIGN AND FUNCTION
Jute netting (standard mesh)*	A locally made geotextile of woven jute netting is placed on the slope. Standard mesh jute netting (mesh size about 40× 40 mm) has four main functions: (a) Protection of the surface, armouring against erosion and catching small debris; (b) Allowing seeds to hold and germinate; (c) Improvement of the microclimate on the slope surface by holding moisture and increasing infiltration; (d) As it decays, it acts as a mulch for the vegetation established.
Jute netting (wide mesh)*	A locally made geotextile of woven jute netting (mesh size about 150 × 450 mm) is placed on the slope. It is used to hold mulch on slopes that have been seeded and serves no engineering function itself.

* Any use of jute netting is a temporary measure designed to enhance vegetation establishment. It does not protect a surface in itself for more than one or two seasons of monsoon rains.

1.3 BIO-ENGINEERING SYSTEMS AND THEIR EFFECTS

Using vegetation for engineering purposes in practice differs somewhat from the theory. On gentle slopes (*i.e.* those < 30°), a simple planting pattern is often enough. On steep and often intrinsically unstable roadside slopes, however, experience has shown that only a relatively small number of robust techniques serve the range of engineering functions required.

The slopes addressed by the techniques in this manual are extreme in their length and steepness, the disturbance and weakness of the materials of which they are composed, and the intensity of periodic monsoon rainfall. All of these are considered in detail in Chapter 2. At this stage, it is necessary to consider only the engineering functions required to stabilise them.

So far in this Chapter, the principles of vegetation in engineering have been considered, and the contribution made by individual plants. Plants used in combination can provide much greater effects than can single plants. For example, a single grass plant can catch a small amount of debris and reinforce a small volume of soil with its roots. But grasses can be planted across a slope, to form a continuous line to catch debris, and so provide a line rather than a point of reinforcement. In the process of serving these functions, however, the contour line of grass will also increase the infiltration capacity of the soil. If this is likely to lead to a critical condition, then another function, that of drainage, will be required. This can be achieved using grass lines by angling the lines down rather than across the slope. The more the line is angled, the less it will catch debris and the more it will help to drain the slope. The approximate limits for the use of different techniques is given in practical detail in Section 1 of the *Site Handbook*.

The range of techniques adopted for use in the road sector of Nepal is described in Figure 1.7. This is based on experience gained over many years of trials and applications throughout Nepal. Each of these has identifiable engineering functions. Most techniques fulfil more than one function, and so can be used for more than one purpose.

Despite the versatility of the bio-engineering techniques, the complexity of most sites means that a range of techniques are usually required, just as civil engineering works usually require a range of different structures serving separate but complementary functions. It is not possible to tabulate this information, since the numerous factors contributing to slope instability (see Chapter 2) means that there is effectively infinite variability in site characteristics and require-

Shrubs planted above a toe wall catch loose debris moving down the slope

Figure 1.8. Techniques required to fulfil the engineering functions of slope stabilisation at different scales of seriousness

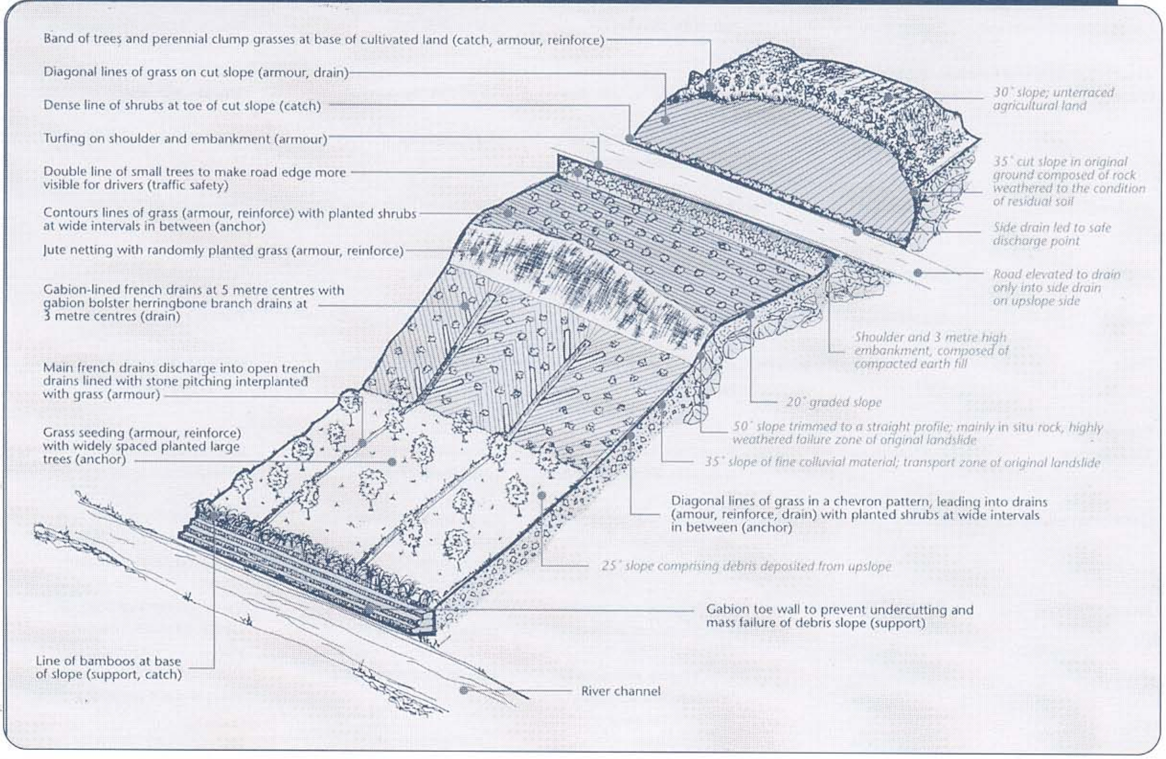
Engineering function	Small scale	Medium scale	Larger scale	Major scale
Simple (*i.e.* only one function required)				
Catch	Contour grass lines	Brush layers or palisades	Large bamboo clumps	Gabion catch wall
Armour	Grass lines	Standard jute netting and random grass planting	Not applicable	Vegetated stone pitching
Reinforce	Grass lines	Brush layers, palisades or fascines	Planted shrubs or trees	Reinforced earth or cement slurry
Anchor	Not applicable	Planted shrubs or trees	Planted trees	Soil or rock anchors
Support	Not applicable	Not applicable	Large bamboos or trees	Retaining wall
Drain	Diagonal or downslope grass lines	Angled brush layers, palisades or fascines	Vegetated stone pitching	Masonry or gabion drain
Composite *				
Catch/armour	Contour grass lines	Brush layers or palisades with grass lines in between	Large bamboo clumps with grass lines in between	Gabion catch wall with vegetated stone pitching
Catch/armour/reinforce	Contour grass lines	Brush layers or palisades with grass lines in between	Large bamboo clumps with grass lines and planted shrubs or trees in between	Gabion catch wall with vegetated stone pitching and reinforced earth or cement slurry
Armour/reinforce	Contour grass lines	Brush layers or palisades with grass lines in between	Planted shrubs or trees with grass lines in between	Vegetated stone pitching and reinforced earth or cement slurry
Reinforce/anchor	Not applicable	Brush layers, palisades or fascines with planted shrubs or trees in between	Planted shrubs and trees	Reinforced earth or cement slurry and soil or rock anchors
Anchor/support	Not applicable	Not applicable	Large bamboos and trees	Soil or rock anchors and retaining wall
Catch/armour/drain	Diagonal grass lines	Angled brush layers or palisades with grass lines in between	Large bamboo clumps with vegetated stone pitching	Gabion catch wall with vegetated stone pitching and possibly other masonry drains
Armour/reinforce/drain	Diagonal grass lines	Angled brush layers or palisades with grass lines in between	Planted shrubs or trees with vegetated stone pitching	Vegetated stone pitching and reinforced earth or cement slurry and masonry or gabion drains

* A few examples only are given: in theory 720 permutations are possible.

ments. This is why an engineer is required to assess every site individually to determine the optimum stabilisation procedure. Nevertheless, Figure 1.8 shows the techniques which can be used to fulfil the engineering functions in the simplest situations, as well as in some of the common combinations.

Figure 1.8 also demonstrates that, the larger the scale of problem, and the more functions that are required of the stabilisation measures, the more complex the solutions become. The smaller-scale problems can be resolved by straightforward and inexpensive measures; and it should be stressed that, even in the vast and dynamic terrain of the Himalayas, the majority of slope problems can be resolved using relatively small measures. The versatility of planted grass lines, and particularly of diagonal grass lines, has been shown on numerous sites where catching, armouring, reinforcing and draining, or some combination of these, are the main requirements to achieve stabilisation: these are the needs most commonly found.

Figure 1.9: A hypothetical scheme for stabilising a large slope, showing the ways in which civil and bio-engineering measures are commonly combined



1.4 INTEGRATION OF CIVIL AND BIO-ENGINEERING STRUCTURES

The engineer may choose to stabilise a slope by using

- civil engineering on its own;
- vegetative engineering alone;
- a combination of the two.

This manual is written with the underlying assumption that a combination of both normally offers the most complete solution to the variety of instability problems affecting a site. Road engineers need to understand the principles governing the relationship between vegetative engineering systems and civil engineering systems.

The previous sections have shown how slope stabilisation requires a number of engineering functions to be fulfilled. In most cases the complexities of the site mean that a range of different techniques, whether of civil or bio-engineering or both, are required to serve the purposes. Figure 1.9 shows how it is possible (and quite normal) to combine the range of measures to good effect.

Relative strength of structures over time

The strength of a structure at various stages of its life can be related to its maximum strength. Figure 1.10 shows how this is different for bio-engineering and civil engineering structures: vegetation takes a few years to reach maximum strength.

Figure 1.10: Life span of small civil engineering and vegetative structures (general case, assuming good maintenance)

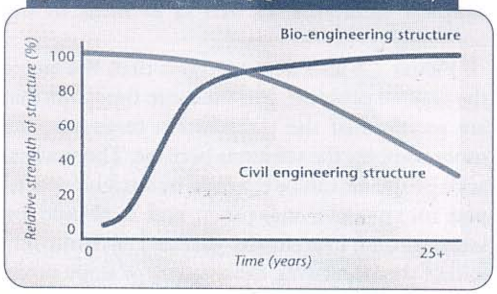


Figure 1.12: Hypothetical site requiring civil and bio-engineering works serving different functions

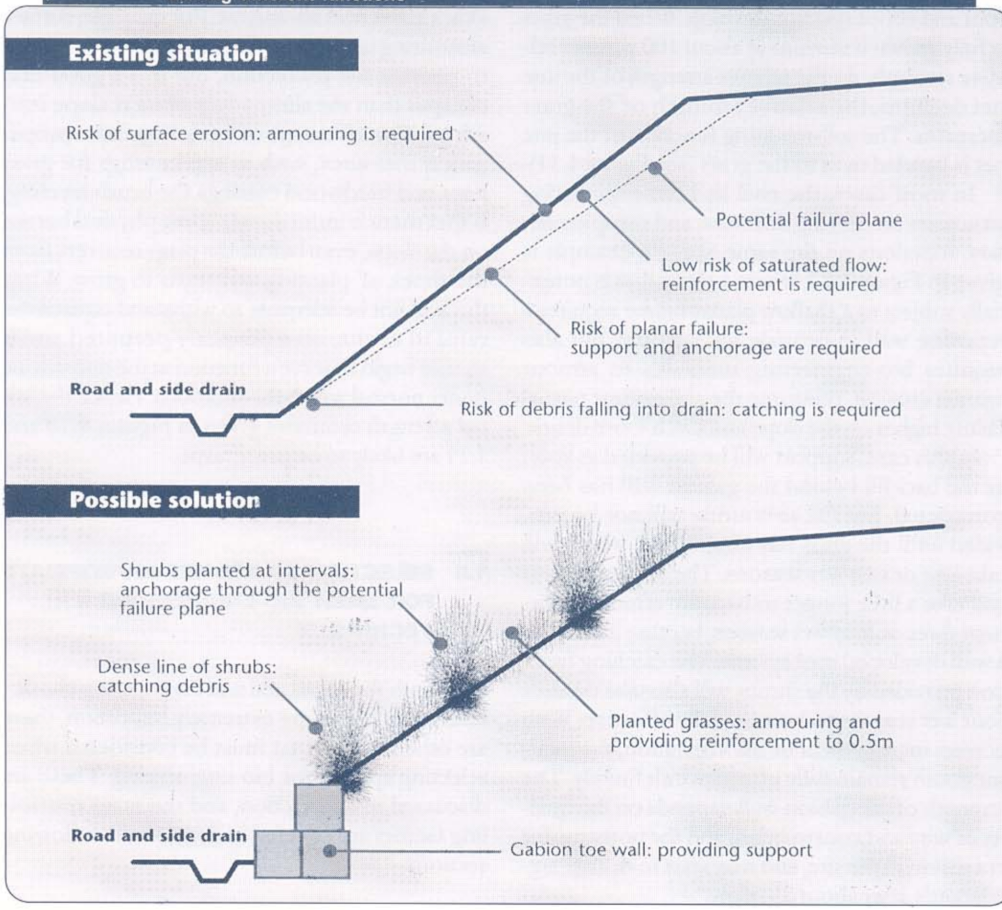
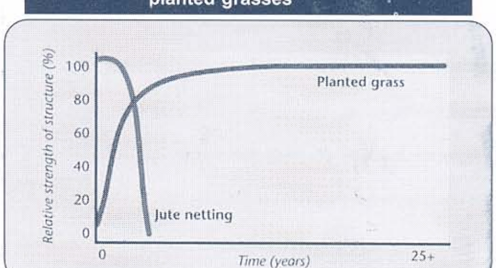


Figure 1.11: Life span of jute netting and planted grasses



Combined life spans: civil and bio-engineering structures serving the same function

As the relative strength of engineering structures decrease, the relative strength of plant structures increases. Note that these graphs compare the performance of each type of structure and not their actual strength.

An example on a micro scale is as follows. Jute net and grass can be used in combination to perform a catching function. The capacity of the jute net to retain soil is very high at first; each small square behaves as a mini check dam. With time the jute decays, which weakens the net and consequently its soil-retaining capacity decreases. Eventually the net will fail to carry out any retaining function at all. In contrast, grass slips are not immediately very effective, but their capacity to retain soil increases as the plants grow and their root and shoot systems develop. When the grass is fully grown it remains at about 100 percent relative strength. As the relative strength of the jute net declines, the relative strength of the grass increases. The soil-retaining function of the jute net is handed over to the grass (see Figure 1.11).

In most cases, the civil and bio-engineering structures are serving different, and complementary, functions on the same site. An example is given in Figure 1.12, where a slope that is potentially subject to a shallow planar failure requires a retaining wall to provide toe support, but also requires bio-engineering measures to armour against erosion, reinforce the soil against partial failure higher on the slope and catch loose debris.

In this case, support will be provided as soon as the backfill behind the gabion wall has been compacted, but the armouring will not be provided until the grass has established, which will take one or two wet seasons. The reinforcement will take a little longer to become effective, perhaps three or four wet seasons, because it relies on a well developed root system. The catching function provided by the shrubs will also take three or four wet seasons to become fully effective. With correct management of the vegetation, the treatment can remain fully effective indefinitely. The strength of the gabion wall depends on the quality of wire and construction, and the potential for corrosion in the site, and may start to decline significantly after about 25 years.

The bio-engineering techniques do not provide instantly strong solutions, but they do provide a lower cost alternative. For example, surface armouring using grass lines may take a few years to provide full protection, but it is a good deal cheaper than the alternatives of inert slope coverings. The advantage of using vegetative propagation measures, such as slip cuttings for grass lines and hardwood cuttings for brush layering, is that there is immediately some physical barrier on the slope, even before the plant recovers from the shock of planting and starts to grow. While this will not be adequate to withstand an extreme rainfall event, on a properly prepared site it should begin to serve a function at the micro scale under normal weather conditions. Hence the initial strength estimates given in Figures 1.10 and 1.11 are likely to be pessimistic.

1.5 SELECTION OF SPECIES APPROPRIATE FOR EACH BIO-ENGINEERING TECHNIQUE

Although the structural and engineering characteristics of plants are extremely important, there are other factors that must be considered when selecting species for bio-engineering. These are discussed in this section, and the main controlling factors are covered in detail in the following sections.

Figure 1.13. Methods of propagation for plants used in each bio-engineering technique

Techniques	Plant class to use
Planted grass lines (all configurations) and vegetated stone pitching gully beds	Grasses grown from slip/rhizome cuttings
Brush layers, palisades, live check dams, fascines and vegetated stone pitching walls	Shrubs/small trees grown from hardwood cuttings
Large bamboo planting	Large bamboos
Site seeding with grass	Grasses grown from seed
Turfing	Small sward grasses
Site seeding with shrubs/small trees	Robust shrubs/small trees grown from seeds
Shrub/small tree planting	Shrubs/small trees (grown from seeds/polypots)
Large tree planting	Large trees (grown from seeds/polypots)

Method of propagation

Bio-engineering works require a large amount of planting material, especially grasses, as they are often planted densely over large areas. Plants that are propagated vegetatively (from cuttings) usually grow faster and larger than those they raised from seed. Planted lines of clumping grasses are often propagated from slips in order to provide a physical effect on the slope surface within a short period of time, and to develop rapidly into a strong plant (a slip is a piece separated from a clump of grass so that it has shoots with buds and as much root as possible). Therefore, if the bio-engineering technique to be used requires the use of grass slips, the species used must be easily propagated by this method. Figure 1.13 shows the relationship between bio-engineering techniques and methods of propagation.

Biological and social considerations

Once this point has been reached, it is clear as to what type of plant (*i.e.* grass, shrub, tree or bamboo) for each part of the bio-engineering measures; it is also known how the plants should be propagated (*i.e.* from seed directly, from slip or hardwood cuttings, from seed via polypots, or by some other method). The situation is summarised in Figure 1.13.

For each type of plant, there is a range of options which can be adopted as regards the actual species. But first it is necessary to satisfy four other criteria:

- what species will be robust enough to fulfil the bio-engineering function?
- what will grow on the site?
- are there possible species that can be put to additional uses by local farmers?
  and, if all those are satisfied,
- can it be made available in adequate quantities?

The paragraphs below address these issues briefly. As in the box on the right, these will lead to the final choice of species.

Establishment, vigour and persistence

In bio-engineering, plants should become well-established in the season of planting so that they are able to survive the dry months until the next monsoon. Many bio-engineering sites have extremely poor and stony soils, which drain rapidly. This makes good establishment very important.

Vigorous growth in a plant means that the plant establishes quickly and continues to grow well. Examples of plants which display vigorous growth and are commonly used for bio-engineering are: khar, saruwa, kans, amliso, simali, areri, assuro, sito.

Many plants are annuals. This means they complete their life cycle in less than a year and then die. If they were used for bio-engineering, they would have to be replaced every year and the root systems would never become strongly established. Bio-engineering requires perennial plants: those that grow and reproduce for many years.

The ability of a plant to live for many years and survive in harsh conditions is of fundamental importance in bio-engineering species. This is called persistence.

In exceptional conditions, annual grasses can be sown or planted to give surface protection through a single monsoon. This might be where major engineering works have had to be post-

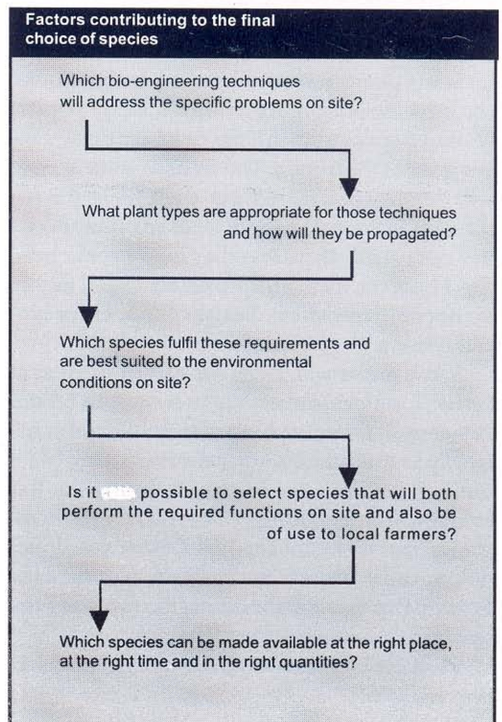


Figure 1.14: The main factors determining plant growth

Factor	Determined by
Temperature	Altitude mostly; to some extent also by aspect; there is also a variation of average temperatures from the east of Nepal to the west.
Moisture	The rainfall patterns on the site, which are in turn determined by the regional rainfall (more in the east than the west), the topography (uplift of rain-bearing winds is caused by large ridges), rain shadow effects (mostly in the lee of large ridges), aspect (northern aspects are shady and generally damper), altitude (there is less drying in cooler, higher locations) and soil characteristics (coarse textures hold less water).
Nutrients	The soil type (in general, fine textures and well developed topsoil or kalo mato hold more nutrients) and the local climate (generally, more nutrients become available to plants under warm, damp conditions).
Exposure to sunlight	Aspect; the presence of other large plants nearby.

poned due to budget constraints. An example might be where kodo (millet) is sown on a bare surface.

Site suitability

All plants are naturally adapted to grow under particular ecological conditions. The ability of a particular plant to grow in a certain site is determined by the suitability of the species to that site. The main factors determining growth are given in Figure 1.14.

Some plants require a long day length during the growing season: for example, many poplars (*Populus* species or varieties of lahare pipal) cannot grow in the tropics. The seeds of some species will not germinate unless they have passed through a very cold period; seeds of other species will not germinate unless they have experienced fire. However, these exceptional ecological factors do not normally affect the use of species for bio-engineering.

Some plants will thrive for part of the year in certain locations, only to die later on. Utis (*Alnus nepalensis*), for example, can be established at relatively low altitudes during the monsoon; but it can be killed by hot, dry winds during the following summer. Cuttings of bihaya (*Ipomoea fistulosa*) can be established on Churia cut slopes during the monsoon and will show good early growth. But they will die during the following dry season.

Plant ecology is covered in more detail in section 1.6 below.

Potential value to local farmers

Many roadside bio-engineering sites are in inhabited areas. In many cases, local farmers may be able to make use of the plants grown on the sites. The engineering functions must always be given priority and, on critical sites, utilisation may not be permissible. However, wherever possible, the choice of species should be made with the consideration that products are of potential use to local people. An example might be where babiyo (*Eulaliopsis binata*) is used instead of kans (*Saccharum spontaneum*), or amliso (*Thysanolaena maxima*) is used instead of sito (*Neyraudia arundinacea*). Wherever possible, it is best to discuss the choice with local people and make a tentative agreement on how they might use the products when the plants are big enough.

Availability

Availability means that the planting material must be obtainable at the right location, at an affordable price, at the right time and in the quantities needed.

Species that are local to the site are generally better suited to conditions there than species from another area. This means that the first choice should normally be a species found in the area where the bio-engineering is being implemented. Nurseries are established in order to provide the planting material that is required, at the right time and in the right place. If the availability requirement is to be met they must be well managed.

Plant species for bio-engineering

The species for bio-engineering are listed in Annex B of the *Site Handbook*. In addition, the main bio-engineering species are described in detail in Annex B of this *Reference Manual*. If the main species are used, they all have the correct attributes of establishment, vigour and persistence; between them they are suitable for practically any site beside a road in Nepal and can be propagated by the correct methods; and some of them are of value to farmers for a range of purposes.

The plants should be propagated in nurseries as described in Section 4 of the *Site Handbook*. Material for the species used as hardwood cuttings can usually be collected from forests and farms in local areas.

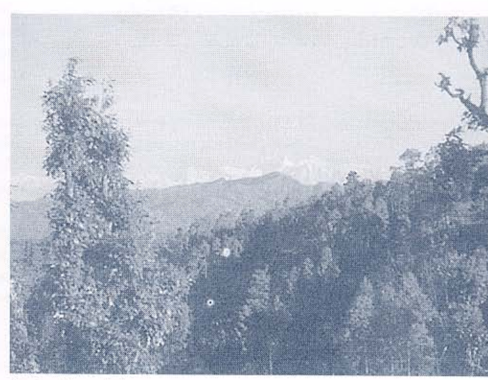
The rest of this chapter gives information on the ecology of plants in Nepal, why they grow where they do and in what combinations, and the ways in which this can be used to advantage in bio-engineering works.

Sal *(Shorea robusta)* in the western Terai

1.6 PLANT ECOLOGY OF NEPAL

Plant ecology is the study of plants in relation to the environment in which they grow. It was mentioned briefly in 1.5 in relation to the suitability of plants to grow in particular sites. This section examines in more detail the ways in which plants grow in different locations. It is a very complex subject about which much has been written; this section does not go into great detail. More thorough coverage is given in the books by the botanist Stainton (1972), the ecologist Dobremez (1976) and the forester Jackson (1994). However, there is still no complete and fully definitive account of the many rich vegetation communities found through the Nepal Himalayas.

A knowledge of plant ecology is necessary for understanding not only why particular plants grow in certain areas, but also how plants should be managed to obtain the maximum results for bio-engineering. In the *Site Handbook*, as in Annex B of this *Reference Manual*, recommended species are given for bio-engineering in Nepal. In drawing up these lists, consideration was given to the ecology of the plants. The main purpose behind this section, therefore, is to equip the reader with the knowledge required to add to those lists of potential bio-engineering species; this is often required when working in new or remote locations.



A dry forest type containing both oaks *(Quercus species)*, and pines *(Pinus species)*, in Far Western Nepal, (above)

Khote salla *(Pinus roxburghii)* forest on a south-facing slope at 1600 m, in central Nepal, (far left)

Chilaune-katus *(Schima-Castanopsis)* forest at 1800 m above the Kathmandu Valley. The area in the foreground has been cleared to allow the trees to coppice, (left)

Factors governing the distribution of vegetation in Nepal

The main factors that govern the distribution of vegetation are:

- the availability of moisture;
- temperature and the amount of sunlight; and
- the availability of nutrients.

These are in turn determined in Nepal by:

- altitude;
- aspect;
- other factors controlling the distribution of rainfall and site moisture;
- geology, geomorphology and soils.

Figure 1.6 (Page 28) gives more details.

In the mountains, altitude is the most important factor influencing the distribution of vegetation, with the effects of aspect on moisture and temperature being the next most dominant factor. The zonation of vegetation is therefore usually based on altitude, although it is stressed that this provides only an approximation and not a set of precise rules.

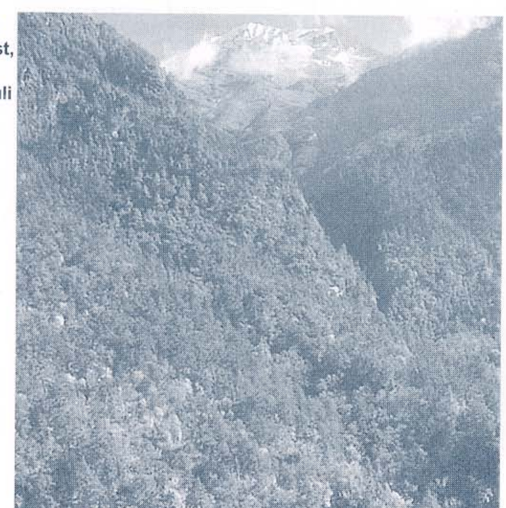
Figure 1.15: Eco-climatic zones, altitude and forest types

Zone	Altitudinal ranges	Main forest types (depending on site)
Alpine zone	Between the tree line and the line of perpetual snow.	Scrubby gurans species (*Rhododendron* species), armalito (seabuckthorn, *Hippophae rhamnoides*) etc.
Sub-alpine zone	3000 – 4500 m in the west 2800 – 4200 m in the east.	Talis patra (*Abies spectabilis*) forest; saur (*Betula utilis*) forest; high altitude gurans (*Rhododendron* species) forest; dhupi (*Juniperus indica*) steppe.
Upper temperate zone	2700 - 3100 m in the west; 2400 - 2800 m in the east.	Banjh (*Quercus semecarpifolia*) forest; upper temperate mixed broadleaved forest; lali gurans (*Rhododendron arboreum*) forest; upper gobre salla (*Pinus wallichiana*) forest.
Lower temperate zone	2000 - 2700 m in the west; 1700 - 2400 m in the east.	Banjh (oak) forest, three main types: *Quercus leucotrichophora/ Q. lanata*, *Q. floribunda* and *Q. lamellosa*, in differing sites; lower temperate mixed broadleaved forest; lower gobre salla (*Pinus wallichiana*) forest.
Sub-tropical zone	1200 - 2000 m in the west; 1000 - 1700 m in the east.	Khote salla (*Pinus roxburghii*) forest; chilaune-katus (*Schima-Castanopsis*) forest; utis (*Alnus nepalensis*) forest; riverain forest with tuni and siris (*Toona* and *Albizia* species).
Tropical zone	Upper boundary at about 1200 m in the west; 1000 m in the east.	Sal (*Shorea robusta*) forest with mixed tropical hardwoods; khayer-sisau (*Acacia catechu-Dalbergia sissoo*) forest; other riverain forest (mixed species); grassland of kans (*Saccharum spontaneum*), narkat (*Phragmites karka* and *Arundo clonax*) or babiyo (*Eulaliopsis binata*); saaj-banghi (*Terminalia-Anogeissus*) forest.

Abies spectobilis forest near the tree line at approximately 3500m, in Central Nepal

The effects of altitude are well known and clearly visible throughout the country. Sal (*Shorea robusta*) forest is dominant in the Terai, Bhabar and lower valleys: this seems to be closely related to temperature. In central Nepal the hill sal forest disappears at almost exactly 1000 metres altitude. Lali gurans (*Rhododendron arboreum*) and banjh (*Quercus* species, or oaks) are other examples: they are common on ridges above 1500 metres, with variations depending on the actual species. For instance, khasru (*Quercus semecarpifolia*) grows from 1700 metres almost to the tree line at 3800 metres, mostly in western Nepal, whereas phalant (*Quercus lamellosa*) grows in central and eastern Nepal from 1600 to only 2800 metres altitude. Many middle mountain valley sides between 1000 and 1900 metres have khote salla (*Pinus roxburghii*) on the south-facing side and katus-chilaune (*Castanopsis-Schima*) forest on the north-facing side, demonstrating the effects of aspect. Khayer (*Acacia catechu*) forest grows below 1000 metres in many areas which are exceptionally dry, such as south-facing slopes in rain shadow areas. Utis (*Alnus nepalensis*) grows only in damp, shady areas or zones of higher rainfall, and is rarely found below 900 metres. Vegetation type can be an excellent initial indicator for the engineer, providing immediate information about the dryness of a site and the likelihood of water-related slope problems.

Mixed pine and hardwood forest, 2000-3000m, in the Upper Trisuli Valley, Central Nepal



From east to west in Nepal there is a general change in climate. The western part has warmer summers and colder winters, hence the higher summer temperature at Nepalgunj compared with Biratnagar. The lowest winter snowline is at about 2400 metres in the Mechi hills, 2200 metres on the ridges around Kathmandu and 1800 metres in the Far Western hills near the Mahakali valley. The effect is apparently due to distance from the maritime influence of the Bay of Bengal, and the increasingly continental climate towards the north-west. Although the change is gradual across the country, the line made by the Kali Gandaki and Tinau valleys, which cut across the geographical centre of Nepal (*i.e.* from Mustang to Bhairahawa) form the general line of change.

These broad variations in climate are reflected by differences in the forest types. West of the Kali

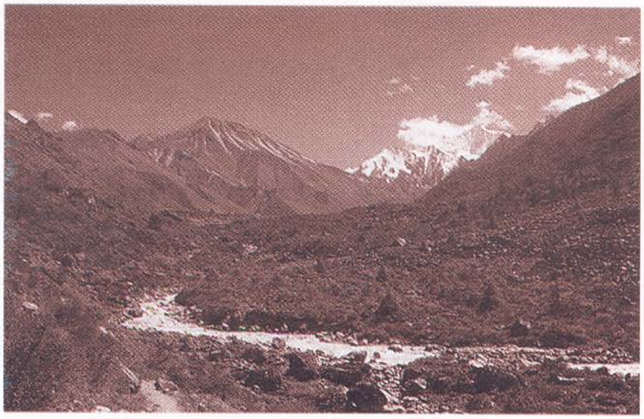
Gandaki-Tinau line, the lower forest in the Churia, inner Terai and valleys is drier and is commonly a sal-khote salla (*Shorea robusta-Pinus roxburghii*) mixture. Khote salla (*Pinus roxburghii*) and gobre salla (*Pinus wallichiana*) forests are much more common. The species of banjh (*Quercus* species, or oaks) are different, with a range more tolerant of dry sites; and chilaune-katus (*Schima-Castanopsis*) forest is not found.

Most roads in Nepal are between 80 and 2500 metres above sea level, and so fall only into the lower and warmer eco-climatic zones. The major exception to this is the Trisuli-Somdang road, which rises as high as 3650 metres at one point. That is the only area where the road network enters the high-altitude forest types dominated by talis patra (*Abies spectabilis*) and a mixture of yarla (*Acer* species) and seto gurans (white *Rhododendron* species).

Vegetation zones and forest types

In simplification, Nepal can be divided into five main landscape or physiographic zones, based on the geological origin. They are:

- Trans-Himalaya
- Higher Himalaya



Low scrubby vegetation above the tree line, in the alpine zone of Cenral Nepal

- Lesser Himalaya (middle mountain)
  Midlands (middle hills)
  Mahabharat Range
- Sub-Himalaya (Siwaliks)
  Churia
  Inner Terai
- Terai and Bhabar

However, there is no accurate relationship between these and the eco-climatic zones used to describe vegetation. The reason for this is that the mountain geological zones have extensive altitude

Figure 1.16: The relationship between altitude, longitude, and eco-climatic and geological zones

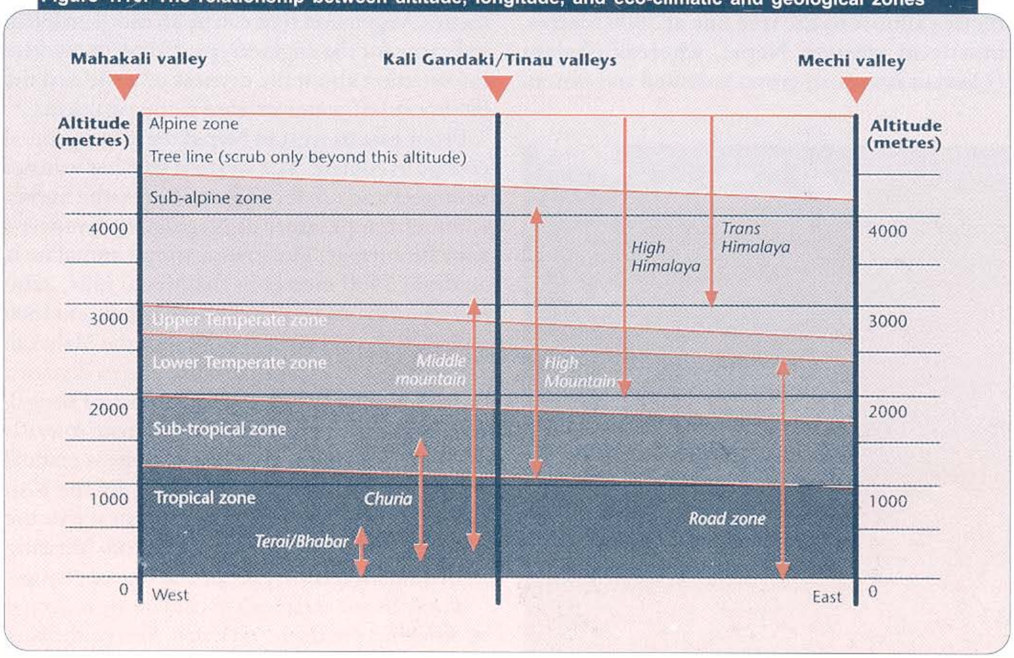
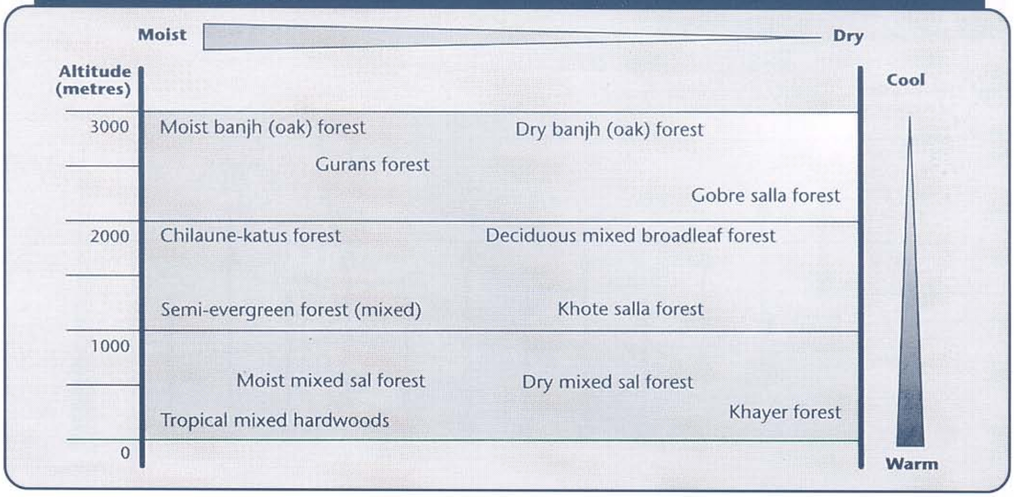


Figure 1.17: Major forest types expressed in relation to site moisture and temperature for central Nepal



ranges, from the bottom of the deep valleys (often less than 1000 metres above sea level and therefore sub-tropical) to the top of the high ridges (often 2500 metres high or more, making the climate cool temperate), and so cut across the climatic zones dominated by altitude-determined temperature patterns. The big valleys cutting right through the Himalayas, such as the Karnali, Kali Gandaki, Sun Koshi and Arun are the most spectacular examples. In places, valley side transects show a succession of different vegetation types and villages with different agricultural systems.

The simplified general zones used by both Dobremez and Jackson (modified slightly) and the main forest types which occur in them are shown in Figure 1.15, page 26. Note that the use of the term 'tropical' is based on the fact that the forest types extend south into the tropics although, technically, Nepal is in the sub-tropics.

Both the eco-climatic and geological zones are related to altitude and longitude (Figure 1.16). Within the broad eco-climatic zones of Nepal, there are various forest types, which have already been referred to. These occur in different areas depending on the temperature and moisture characteristics of each locality. Figure 1.17 shows how the main forest types are distributed in central Nepal.

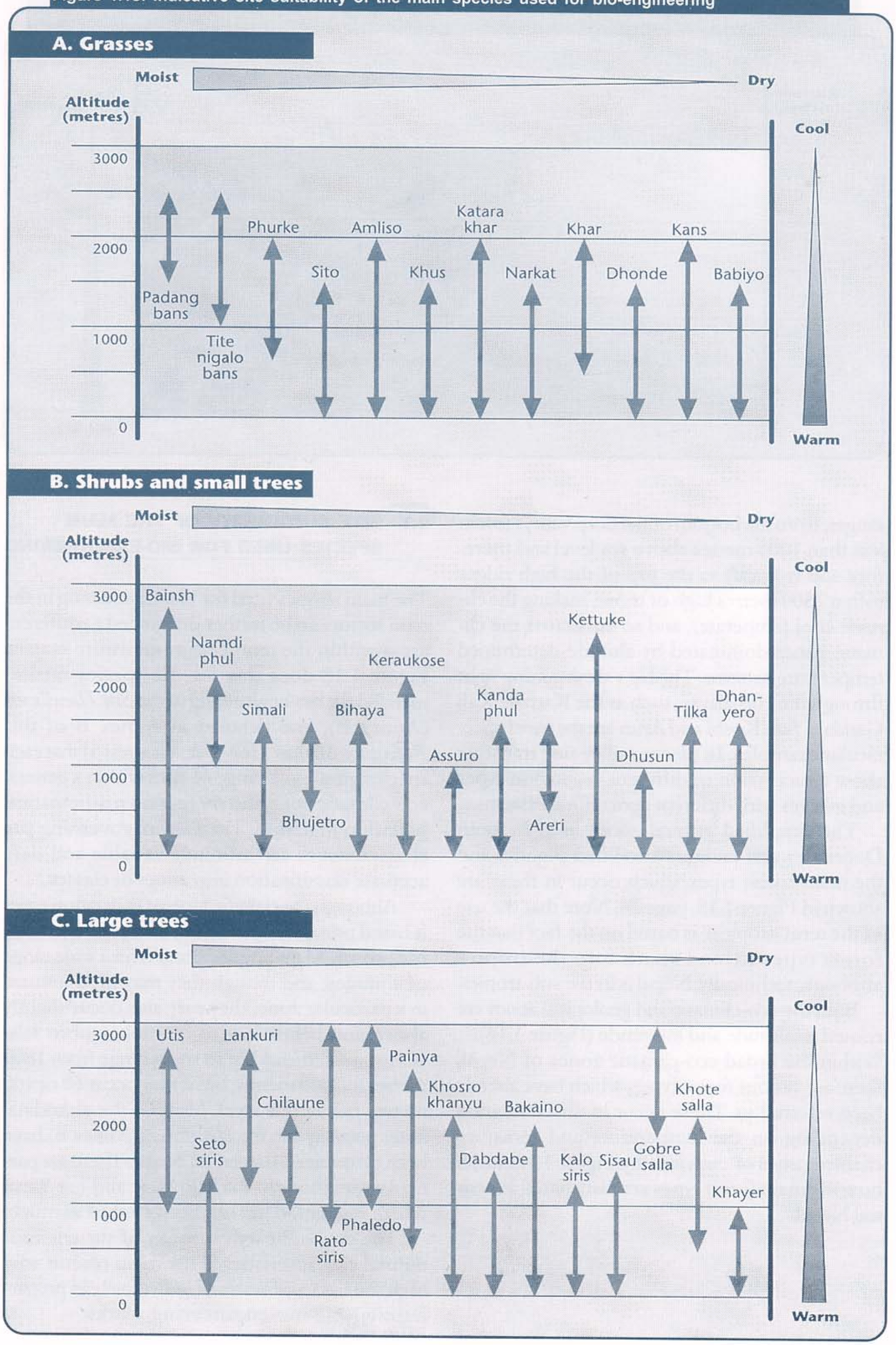
1.7 SITE SUITABILITY OF THE MAIN SPECIES USED FOR BIO-ENGINEERING

The main species used for bio-engineering in the road sector can be further designated to different areas within the temperature-moisture matrix. Figure 1.18 does this for the species recommended for bio-engineering in the *Site Handbook* (Annex B), and detailed in Annex B of this *Reference Manual*. However, it is stressed that each species grows in a range of sites within a general eco-climatic zone and there is no mathematical precision in nature. The factors governing site characteristics are infinitely variable and defy accurate classification into zones or classes.

Although the classification of vegetation types is based primarily on altitude, the stated limits are not precise. Many species occur over a wide range of altitudes, and though they may predominate in a particular zone, they may also occur slightly above and below it. For example, gobre salla (*Pinus wallichiana*) has its main range from 1800 metres to 3000 metres, but it may occur 80 or 100 metres below this level. Most of the altitudinal limits given in the *Site Handbook* (Annex B) have been determined for central Nepal. There are particular variations in the Mid West and Far West, where vegetation has not been studied as much.

The extraordinary variability of site environmental characteristics is the main reason why each site has to be assessed individually in preparing civil and bio-engineering works.

Figure 1.18: Indicative site suitability of the main species used for bio-engineering



This north facing slope in Eastern Nepal (right) is well shaded and therefore retains moisture, making it excellent for agriculture. In contrast, the south-facing slope across the valley (far right) is much drier and the land is consequently less productive

1.8 WATER AND NUTRIENT AVAILABILITY FOR PLANTS

Once a plant is environmentally adapted to a particular site, its growth depends on the availability of water and nutrients in the soil. An understanding of this topic helps the engineer to explain variations of plant growth between different sites.

Water in the soil

In the soil, either air or water occupies the spaces or voids between the soil particles. Unless the soil is fully saturated, water is held as a thin film on the soil particles; or if the particles are close enough, as bridges between the particles (see Figure 1.19).

There are three types of soil pore, described below.

- The largest pores are *macropores* and are >100 μm (> 0.1 mm). Water drains freely through a network of spaces and air is pulled in and roots proliferate. These are the main sites of air and roots.
- The *mesopores* are 30 - 100 μ m (0.03 - 0.01 mm). These larger pores are the right size for rapid capillary flow - the movement of water through the soil in any direction. This is the main source of water for plants.
- The *micropores* are <30 μ m (< 0.03 mm). They hold the water tightly, partly by chemical attraction. This means they retain the water and do not release it easily.

Water drains through clay soils at a fairly steady rate, but with sandy soils there is initially a rapid loss of water, and then the rate of drainage tails off. Most soils in Nepal, outside the lower Terai, have a relatively coarse texture and therefore drain quickly; the main exceptions are rato mato (red clay loam, semi-lateritic soils).

Saturated soils, such as khet (paddy) soils, give conditions which are suitable for particular plants like rice; but the majority of plants require oxygen in the rooting zone. As a result, plant growth is best when there is a good balance of the two: a moist, porous soil.

In the nursery, considerable efforts are made to ensure that these conditions are met. Loamy soil is brought in and is kept moist but not saturated. Bio-engineering site planting is carried out once the monsoon rains have broken, so that there is adequate moisture for the young plants. In some cases it is also necessary to add water by hand.

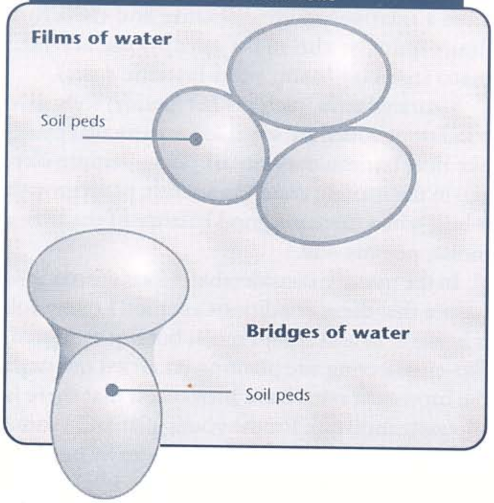
Availability of water to plants

Water drains freely from soil pores until it reaches a constant point called field capacity. Some water, however, remains in the soil as films or bridges that cling to the surfaces of soil particles (Figure 1.19). Field capacity, then, is a measurable limit that describes the amount of water that will be held in a freely drained soil.

Plants extract water most readily from the soil particle surfaces and larger voids. The main source of water for plants is the mesopores. As water is pulled out of the smaller voids it becomes progressively harder to extract. If the plant roots are not in the mesopores they obtain water by capillary attraction from the micropores, but this is much harder for the plants.

In practice, there is a moisture range within which soil must be kept. On site it is difficult to control, since it is determined by weather. Hot sun can dry the surface soil rapidly, and it is often not practical to add water. Heavy rain can saturate the soil, although it is usually only those with a high clay content, or with other impeded drainage, which remain waterlogged for more than a few hours. In the nursery, much depends on the naike's skill in keeping the soil in the beds within the critical limits. In planning nurseries, particularly in the Terai, drainage is an important consideration, to minimise the risks of the soil remaining saturated. Site implementation schedules must always be flexible to avoid planting works being done if the soil is too dry or too wet.

Figure 1.19: Films and bridges of water in unsaturated soils



Effect of stoniness in reducing available water in soil

Stoniness is the main factor affecting the amount of available water in the soil. As stoniness increases, the size of the pores also increases. This means that the water bridges form less easily and the water is held only in a thin film on the soil particles.

This effect is made worse in many Nepal hill slope soils because the colluvium is constantly moving down the steep slopes, and this keeps the soil very loose and open. The angular rock fragments result in larger voids with less contact between the particles to hold bridges of water. This seriously reduces the amount of available water in the soil.

Many materials found in Nepal have high proportions of stones. This is particularly the case with landslides in areas of harder rocks, such as the Mahabharat ranges, and certain river borne deposits and debris fans. Even in relatively moist sites, these materials can give rise to dry rooting conditions if rain is not regular. In stony sites, therefore, the choice of species for bio-engineering must take the greater risk of drought into consideration.

Plant nutrient requirements

The three main plant nutrients are:

- nitrate, which helps leaf growth and if available in adequate quantities results in generally increased growth;
- phosphate, which is important for root growth, helps plants to become established (and is particularly important for leguminous plants) and
- potassium, which is needed to keep plants healthy, is involved in the production and storage of sugar and starch, and helps drought resistance.

Plants need a balance of these nutrients and also require other nutrients in smaller quantities.

The low nutrient status of Nepalese soils

In general, most soils in Nepal are relatively low in nutrients. This is a natural occurrence in most cases and is mainly due to:

- hill slope soils containing many fragments of weathered rock, which has not been weathered adequately to release the nutrients;
- most hillslope and Bhabar soils being newly formed and highly dynamic, so there has not been long enough for nutrients to be released from rock material;
- high intensity monsoon rainfall leaching out a high proportion of the soluble nutrients;
- the high permeability of many soils allowing the maximum leaching effect;
- erosion, either now or at some stage in the past, removing topsoil, which contains organic matter and nutrients;
- high temperatures speeding up the breakdown of organic matter;
- on cultivated soils, heavy and repeated cropping with inadequate inputs of nutrients through compost or fertiliser;
- on forest soils, continuous removal of leaves and tree litter for fodder and compost;
- other human activities resulting in minimum vegetation cover.

Natural colonisation of utis *(Alnus nepalensis)* on bare landslide debris

The result is that even in forest and agricultural soils, the conditions for plant growth are far from ideal. Roadside slopes usually have skeletal soils and so are often extremely poor in nutrition.

Despite the inherent infertility of most soils, especially in the hills, the plants that have adapted to the Nepal Himalaya are capable of short bursts of rapid growth. During the dry season, a reasonable amount of nitrogen can be mineralised in the soil, so that as soon as the rains make the soil moist, it is mobilised and available to plants. The summer monsoon rains give rise to a warm, wet period, which is ideal for the weathering of rock and the release of nutrients. Plants are able to take up adequate nutrients in this period, despite the leaching of a large proportion of the most soluble elements. Nitrogen is particularly soluble and, if plants are not in the ground by early in the monsoon, they often suffer a deficiency of this major nutrient. Many plants improve noticeably in the early rains during the year after planting, when they benefit from the next season's flush of nitrogen.

Many of the recommended bio-engineering plants are pioneer species, which means that they are naturally adapted to grow and survive on poor sites with extremes of sunlight, heat, drought and low nutrition levels. This avoids the cost and difficulty of having to apply topsoil to steep and unstable slopes in order to allow plants to grow. The dynamic mountain geomorphology that has led to such poor soils and harsh sites, has also given rise to a range of plants well-adjusted for these conditions.

Use of leguminous plants to improve soil fertility

The legumes (Leguminosae) are a large family of plants whose seeds are formed in pods. They include a range of important crop plants (*e.g.* peas, beans, lentils) as well as a number of trees such as sisau (*Dalbergia sissoo*) and khayer (*Acacia catechu*). Most leguminous plants have special bacteria living in nodules on their roots called *Rhizobia*. These are able to take nitrogen from air in the soil and convert it to a form that is available to the plant. Because of this feature, legumes are often planted to enrich the soil. In general they do help to improve the soil because nitrogen is such an important nutrient, but it is still important to appreciate that heavy cropping of leguminous plants can deplete the soil of other vital nutrients.

1.9 PROGRESSION AND REGRESSION

Plants become established in any place that meets their basic requirements. In nature, there is a progressive development of vegetation on a fresh site. Some plants become established, then others come in and they interact with each other resulting in changes in the vegetation. Finally, stable vegetation becomes established. In Nepal, if it is left undisturbed, most bare ground will soon become covered with small plants and will gradually return to full forest cover. This can be seen with sand banks in river beds and landslides in many mountain areas.

A similar pattern of change and development is seen when bio-engineering plants are established on a site. In some cases, if the plants are left alone, an unsuitable balance of species may develop after a few years or the species planted may be killed off by weeds. By understanding the changes which occur in nature it is possible to plan the right balance of different species and manage maintenance so that a suitable balance is kept. The main rules governing this are as follows.

1. On a bare, inhospitable site, revegetation must start with pioneer species.
2. Once pioneer species have established, other plants will begin to colonise naturally. Many of these will not have the desired properties for bio-engineering and, if left undisturbed, they might kill the planted species.

3. Pioneer species cannot survive together in the long term (beyond about 10 years), because they compete with each other too much. They must give way to a community of climax species.
4. To establish a climax community, a different range of species must be planted to replace the first lot.
5. If the sequence is managed, it can be achieved much more quickly and effectively than if it is left to nature.

These are explained in more detail below.

Progression

This is the natural development of vegetation on a site over a period of time.

A fresh landslide will have a bare slope that consists of raw minerals, weathering products and fragments of rock. Within a couple of years it will probably be covered with vegetation such as tite pati (*Artemisia vulgaris*), kans (*Saccharum spontaneum*) and simali (*Vitex negundo*). These first plants on a bare site are called pioneers because they establish themselves easily in difficult conditions such as bare, infertile slopes. They grow from seeds, which may be blown, or be carried in by animals or birds.

Pioneer plants have special adaptations, which enable them to survive on harsh sites. These include:

- low nutrient requirement;
- drought resistance;
- ability to recover after disturbance caused by moving soil;
- produce large quantities of seeds to overcome poor germination conditions.

Their colonisation and development lead to better conditions, which other species then take advantage of. For example:

- vegetation cover increases the permeability of the soil, reducing soil capping and letting water in;
- leaves shade the surface so it is cooler and evaporation is reduced;
- leaves intercept rainfall, reducing raindrop impact and therefore lessening erosion;
- plants create a micro-environment below ground in which micro-organisms and small animals live and improve the quality of the soil;
- plants add humus to the soil, which helps to retain moisture.

The first plants to become established will be smaller grasses and herbs, but within two years large herbs will tend to dominate the site. Ban mara (*Eupatorium adenophorum*) is the most prevalent of these. This development continues and the grasses and herbs are gradually replaced by larger woody shrubs and trees. Examples of these plants are kunelo (*Trema orientalis*), utis (*Alnus nepalensis*) and bhujetro (*Butea minor*), and takal palm (*Phoenix humilis*) on the edge of forests. These species tend to be short-lived for woody plants, generally lasting only 10 to 15 years. As they develop, they tend to shade almost everything else out. Utis is a well-known example of this type of plant.

The following qualities make these plants successful:

- rapid growth: they may grow 1 metre in height and 20 mm in diameter each year, e.g. bakaino (*Melia azedarach*);
- efficient arrangement of leaves: they trap light well and the canopy closes quickly, shading out any competitors;
- produce many seeds which are efficiently dispersed, *e.g.* tilka (*Wendlandia puberula*);
- seed has long life and can lie dormant in the soil for many years until ideal germination conditions arise: this is seen when a tree falls, causing a gap in the canopy, and many seedlings suddenly develop in the light; the dormant seeds lying in the soil are called a 'seed bank'.

These short-lived trees are gradually replaced by trees that have a longer life-span. For example, painyu (*Prunus cerasoides*) and chilaune (*Schima wallichii*) often start to grow under utis (*Alnus nepalensis*) forest.

Development of organic top soil

At first the soil on a bare site is formed almost entirely from weathered rock. This bare soil can easily be eroded by rain water. When a vegetation cover has established, erosion is reduced and a better soil can develop.

The original mineral matter of the soil is supplemented by organic matter, which comes mainly from leaf litter. As well as providing organic matter, the leaf litter armours the surface,

Mixed hardwood forest on a south-facing slope at 1000 m in the Trisuli Valley. At this point, sal (Shorea robusta) is being replaced by a range of other species

further reducing erosion. As the process continues, a darker top soil develops. This has a greater content of organic matter and is more cohesive. It usually starts to have a higher proportion of sand, silt and clay, because the finer particles cease to be washed out. Its fertility increases. Below the soil surface an interdependent community of animals, micro-organisms and fungi becomes established. Decaying plant and animal remains are converted into nutrients that can be used by plants, and soil minerals are broken down to release the nutrients they contain.

Despite this process starting relatively rapidly, the formation of a good topsoil takes many decades to become significant. In the mountains of Nepal, even in good quality natural forest, the slopes are often too steep, and the geomorphological processes too dynamic for good topsoil ever to establish.

Establishment of stable vegetation

Established forests are seen in many areas. In some cases, such as sal (*Shorea robusta*) forest, there are tall trees with broad canopies. They reach an apparently stable mixture with a range of different species. They provide homes for larger animals such as monkeys, which in turn support the trees by contributing to seed dispersal. Dead trees become homes to insects and fungi, and as they gradually decay they return to the soil and feed other trees. The gap in the canopy produced by their death allows replacement trees of the same species to develop from the seed bank. If there is no major disturbance the forest may remain unchanged.

In the past this was described as climax forest. It was seen as the end product of progression. No further development was imagined and it was seen as the goal of environmental protection. Now we see this as a stage of stable development. The vegetation may stay in this state for a considerable time. But in its natural development gradual changes may occur which are acceptable.

Regression

Progression does not lead to a permanent state. However, changes may occur which disrupt the normal development towards stability. This is called regression.

Regression may be caused by several factors, including fire, grazing, cutting and landslides.

Fire can be very damaging, as it can destroy all seedlings and replacement growth. A less severe fire can still scorch and check the growth of larger trees and kill young trees.

Grazing by cows and goats destroys all the young, palatable growth within their reach. Goats also disturb the soil as they climb slopes and may lead to the reduction of vegetation cover and to small landslips.

Over-cutting by people may destroy mature trees and leave large openings in the canopy which allow other species to invade. Alternatively, cutting smaller trees for firewood may remove all the potential replacement trees.

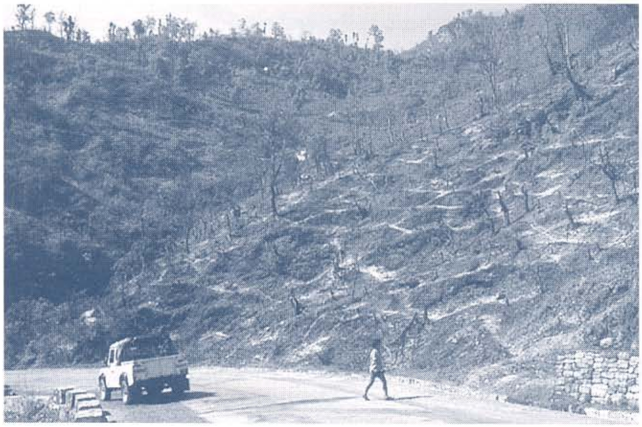
Landslides have a major, localised effect in destroying mature, stable vegetation.

In each case, one of the main effects is the destruction of young plants. This means that when the older plants reach maturity and die, they are not replaced.

Implications for bio-engineering

Pioneer plant species are important for bio-engineering because their adaptations are well-suited to the dry, infertile conditions characteristic of landslide sites, and bare cut slopes. In bio-engineering it is necessary to select species showing these characteristics.

The ability to cope with moving soil is less important because bio-engineering is only used for stabilising shallow failures up to about 500 mm. Deeper failures are managed by civil engineering structures, which should be constructed first. Nevertheless, bamboos are very sensitive to soil movement and should not be planted if there



Cutting and burning vegetation has reduced the stability of this slope and left it highly susceptible to erosion

is a risk of movement around their roots. The recommended bio-engineering grasses, shrubs and small trees are all tolerant of movement.

Large numbers of plants are required in bio-engineering. The ability to produce many seeds is not necessarily important because many species are propagated vegetatively. However, the ability to produce a large quantity of planting material, either by seed or from vegetative cuttings, is important.

In the absence of large quantities of natural leaf litter on bare sites, mulch can be used when establishing plants. Later the sites should develop their own leaf litter.

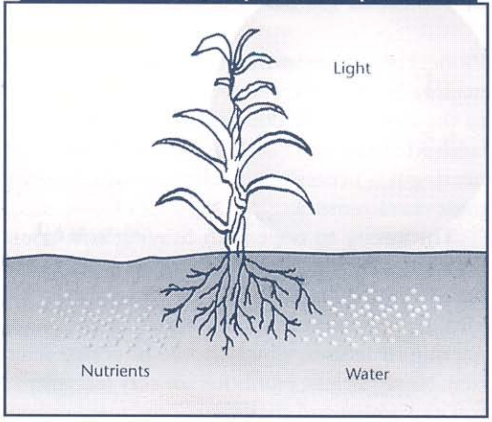
The main points related to the establishment of stable natural vegetation are:

- the use of fast-growing species for rapid establishment;
- the establishment of a stable, easily maintained plant community;
- the development of a vegetation cover that will reduce erosion;
- the development of a canopy, which shades the soil and improves rooting conditions.

Since it is usually necessary to establish a balanced plant community with a variety of plants carrying out different bio-engineering functions, one feature to avoid is an unbroken higher plant canopy, which shades out all shorter species such as grasses.

It is important to try to avoid all of the regression factors. Fire, grazing and cutting are tackled through protection of the site, and liaison with local people wherever possible. Landslide damage is avoided by careful stabilisation measures, using both civil and bio-engineering structures.

Figure 1.20: The main resources for which plants compete



Good management ensures that trees are well spaced and are lopped to keep them small, as in this roadside slope. Here, highly productive fodder grasses have been planted between the trees to provide complete surface cover

This plantation is well managed for soil conservation as it has been thinned to allow sufficient light to penetrate the canopy and for grasses to flourish. The result is a complete surface cover of grasses

1.10 COMPETITION BETWEEN PLANTS

Plants grow singly, in groups of the same species or with other species as a community. Each plant has a tendency to use as much of the available resources as possible. The resources for plants are water, nutrients and light, located both above and below ground (Figure 1.20). This usually leads to a problem between any plant and its neighbours. Obtaining any resource at the expense of another plant is termed competition. Competition takes place in two areas:

- above the ground, competition is mainly for light;
- below the ground, competition is mainly for nutrients and moisture (water). The manner in which root systems interact and compete is not completely understood.

Light

Plants will start to compete for light as soon as they form a continuous canopy. This starts when they are very small if the plants are growing close together. In trees the main problem is seen from four to five years onwards. If there is a higher canopy with an understorey below it, the shading of the understorey plants is a particular problem.

There are three main options for overcoming the problem:

- remove or space out the tall plants;
- reduce the volume of the canopy;
- introduce plants that are shade-tolerant into the understorey.

Since they have been put there to fulfil a bio-engineering function, it is not usually desirable to remove all the tall plants. However, once the vegetation has become established, it can be thinned to provide space for light to penetrate between the plants. This is generally necessary at intervals as tree plantations develop.

The volume of the canopy can be reduced in a number of ways. Pruning is the selective removal of branches. On most shrubs and trees it is safe to remove all the branches from the lower half or two thirds of the plant. This alone can improve light penetration when branching is heavy.

Complete thinning is the most common and effective way of increasing the light penetrating a closed canopy of larger plants. This is where a shrub or tree is cut off at the ground and not expected to re-grow from the stump. Where a complete canopy has formed, it is usually necessary to remove between half and two-thirds of the canopy. Full details of pruning and thinning are given in Section 5 of the *Site Handbook*, and are discussed comprehensively in Chapter 3 of this *Reference Manual*.

Some trees can also be pollarded or coppiced. In pollarding, the whole of the top of the tree is removed, typically at about 2 to 4 metres above the ground. After pollarding, new branches develop at the top of the trunk. Coppicing is a similar process, but the tree is cut off just above ground level. New branches then grow in the same way that they develop after pollarding. The advantage of these techniques is that a canopy can be completely thinned while still retaining the extensive network of roots from the larger plants. The lists of bio-engineering species in Annex B of the *Site Handbook* give details on the tolerance of different trees to coppicing and pollarding.

Shade-tolerant species can be used in the understorey, but there are not many species that provide the 100 percent ground cover that is required in bio-engineering. Almost all the grasses require full light in which to grow, and can tolerate only very limited amounts of shading. Therefore if a ground cover of grasses is required, the canopy must be kept very light.

Water

When there is not enough water to go round, plants compete for water and this can become a problem. Generally, this happens in Nepal from February to May. It varies from place to place and can be different from year to year. Some areas have extremely high rainfall but may still face problems for part of the year. (Lumle, with an average of over 5000 mm per year, suffers from a soil water shortage for nearly one month in May.)

Possible solutions involve providing more water, reducing the level of demand for water and using drought-resistant species.

It is possible to provide additional water in the nursery, and sometimes also on site when it is being planted. After that it is not a realistic solution. If conditions are dry, water may not be available within a reasonable distance. Even if it is available, watering is not a good solution. Plants that are regularly watered in dry seasons tend to develop shallower rooting systems and as a result they become more dependent on being watered and do not fulfil the engineering functions so well. Watering is also very labour demanding and labourers can be more usefully employed on other work.

Weeding can reduce the demand for water. This is important during establishment, so that the desirable species have the best opportunity for development. Pruning reduces water demand, and is often used on bamboos. Mulching can also reduce the loss of water from the soil. That involves placing a layer of cut vegetation on the surface of the soil. This should be close to the plant but not touching it. Mulching is described in Section 3.17 of the *Site Handbook*.

Finally, drought-resistant species can be selected. This is the best and most common approach in roadside bio-engineering. In an environmentally dry area, it is best to plan to use drought-resistant species from the beginning. Examples are all of those tolerant of dry sites in Figure 1.18 (see p30), such as khayer (*Acacia catechu*) and babiyo (*Eulaliopsis binata*).

Nutrients

The problem of competition for nutrients is similar to the problem of competition for water, except that it can occur during the warmer and damper part of the year since plants use nutrients whenever they are growing. If there are not enough nutrients in the soil, plants will compete for them. This can begin as soon as a seedling has put out roots and can no longer grow on its own food reserves.

Just as the problems of competition for water and nutrients are similar, the solutions are similar. More nutrients can be supplied through putting compost near the plant, or from the mulches that have been used to reduce water loss. Nitrates can be provided through using leguminous plants, which have bacteria on their roots that are able to use nitrogen from the air. These nitrates can then become available for other plants.

Experiments on roadside slopes have shown that adding chemical fertilisers does not give a response of improved growth in grasses. This means that either nutrition is not the factor limiting growth; or if it is, that it cannot be overcome using chemical fertilisers.

Weeding reduces the competition for nutrients on a site that is becoming established.

Plants that are able to tolerate low nutrient levels, such as kans (*Saccharum spontaneum*), can be used.

1.11 PLANT COMMUNITIES

A plant community is an established group of plants living more-or-less in balance with each other and their environment. The group can be natural or managed. The community is usually dominated by the main species of trees, but also contains lower plants, such as shrubs, grasses and herbs. Some trees tolerate large numbers of climbers and other parasitic plants, such as orchids. Figure 1.21 gives some examples of vegetation communities.

Most natural vegetation communities in Nepal are characterised by a large number of species. By comparison, planted communities have relatively few species. An ideal plant community for bio-engineering contains a carefully planned variety of different plants which together meet the

Figure 1.21: Examples of vegetation communities, based on forest types

DOMINANT SPECIES	MAIN ASSOCIATED SPECIES	PERIOD OF COMMUNITY SURVIVAL	COMMENTS
Banjh(*Quercus leucotrichophora* and *Q. lanata*)	Variable, depending on location; lali gurans (*Rhododendron arboreum*), angeri (*Lyonia ovalifolia*), bhalayo (*Rhus wallichii*), tite nigalo bans (*Drepanostachyum intermedium*) and lokta (*Daphne* species)are common in some areas;	Indefinitely	There are many types of banjh (oak) forest community across the length of Nepal. There are wet and dry types. *Quercus leucotrichophora* is more dominant in the west and *Q. lanata* more dominant in the east.
Utis (*Alnus nepalensis*)	Almost pure; some angeri (*Lyonia ovalifolia*) and often a dense understorey of ban mara (*Eupatorium adenophorum*)	Temporary: utis appears able to regenerate only on open ground; other species start to appear, such as chilaune (*Schima wallichii*) and katus (*Castanopsis* species)	
Chilaune-katus (*Schima wallichii*-*Castanopsis* species)	Variable, depending on location; often almost pure stands of these two species.	Indefinitely	A wide range of species is seen under chilaune forest, but in small quantities. Because this forest type occurs in the populated middle hills, it has often been seriously disturbed.
Khote salla (*Pinus roxburghii*)	Dhanyero (*Woodfordia fruticosa*), sal (*Shorea robusta*), chilaune (*Schima wallichii*), katus (*Castanopsis* species), khar (*Cymbopogon microtheca*) etc.	Salla acts as a pioneer species; after five to ten years, the associated species will start to establish and will last indefinitely	Salla can be planted as a pioneer species, as in Kavrepalanchok district, and gradually moved to a mixed forest as other species come in and are favoured in forest management operations.
Khayer (*Acacia catechu*)	Bel (*Aegle marmelos*), kadam (*Anthocephalus chinensis*), dhonde (*Neyraudia reynaudiana*) etc.	Indefinitely	In some cases the khayer becomes dominant, with a poor understorey which allows erosion to take place under the established forest.
Sal (*Shorea robusta*)	Saaj (*Terminalia* species); karma (*Adina cordifolia*); banjhi (*Anogeissus latifolia*); jamun (*Syzygium cumini*) etc.	Indefinitely	This community is found mostly in Terai sal forests; hill sal forests (on the lower slopes of deep valleys) are often almost pure sal.

engineering needs of the site. Examples of this might be:

- an open canopy of khayer (*Acacia catechu*) with a dense ground cover of babiyo (*Eulaliopsis binata*);
- an open canopy of mixed dhanyero (*Woodfordia fruticosa*) and areri (*Acacia pennata*), with a ground cover of kans (*Saccharum spontaneum*);
- an open canopy of mixed utis (*Alnus nepalensis*) and painyu (*Prunus cerasoides*), a middle storey of mixed bhujetro (*Butea minor*) and areri (*Acacia pennata*), and a ground cover of sito (*Neyraudia arundinacea*);

However, the exact community which is developed under bio-engineering depends on the engineering requirements of the site and the environmental conditions of the locality.

The general principles for managing plant communities in bio-engineering are as follows.

- Where possible, use a mixture of plants in the initial planting. If you rely on one species and this fails, there may be a complete loss of the planted material.
- Start with pioneer species. For example, with a damp and north facing slope you might introduce utis and some understorey grasses.
- Plan a balance of plant species in the community. Generally include grasses, shrubs and trees (but the exact balance is determined by the engineering requirements of the site).
- Remember that dominant plants such as utis must be replaced or thinned out within five to 10 years. Otherwise the understorey plants

will be overshadowed and eradicated completely, allowing erosion to start under the tree canopy.

- Thin the plants out properly to maintain a balance.
- Clear weeds to reduce competition.
- Re-plant gaps.

These are given in more detail in Section 5 of the *Site Handbook* and elaborated in Chapter 3 of this *Reference Manual*.

1.12 SUMMARY OF THE IMPLICATIONS OF PLANT ECOLOGY FOR BIO-ENGINEERING

- Vegetation in Nepal grows in zones determined mainly by the temperature and moisture conditions for which each species is adapted.
- The zones are recognisable and definable within certain limits. They do not coincide with the terrain zones.
- Each of the species used for bio-engineering has a tolerance for site conditions that is reasonably well defined. As a result, species can be found to grow on almost any site, depending on its characteristics.
- Water is the main factor limiting plant growth in the warmer months.
- Soil nutrition seems rarely to be a limiting factor; in any case, the species used for bio-engineering are tolerant of very low fertility.
- The use of pioneer species for bio-engineering on bare roadside slopes helps to allow a vegetation community to establish, through the development of shade and better soil.
- A number of factors can cause regression if the plants are not well protected.
- Plants compete with each other for resources.
- In bio-engineering, the competition for light is the most critical aspect. If not managed, the canopy of higher plants can shade out the ground cover.
- As a result, regular maintenance is required to ensure that bio-engineering systems develop as required.
- There is a range of natural plant communities. These do not hold all the engineering attributes required of bio-engineering vegetation systems. For this reason as well, regular maintenance of the vegetation is needed to ensure that the optimum mixture of plants is both attained and sustained.

The use of vegetation in engineering involves manipulating nature for specific purposes. It is not simply a matter of establishing a vegetation cover to become part of a long term natural plant community. Management of the plants to fulfil specific engineering functions can make vegetation play a much larger role in stabilising and protecting a slope than it would do otherwise.

Because of the harsh nature of bare landslide or other disturbed roadside slopes, it is rarely possible to establish the final plants straight away. Instead it is necessary to start with pioneers that are adapted to these conditions and then change the mixture of plants gradually to a community which is more-or-less stable. However, it is usually important to ensure that the slope is armoured against erosion. Grasses are by far the best plants to achieve this. But grasses mostly require full sunlight in which to grow; so to sustain a good cover of grasses it is necessary to keep the shrub or tree canopy as thin as possible. On the other hand, without the shrubs and trees, the deeper reinforcing and armouring functions required on many sites would not be provided.