# NATURE-BASED LANDSLIDE RISK MANAGEMENT PROJECT IN SRI LANKA

## PLANT MANUAL

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# Summary

This report presents information about a framework that selects plant species for bioengineering applications, such as cost-effective and ecologically sustainable slope stabilization and landslide risk reduction techniques, with a focus on shallow or near-surface slope stabilization.

The first chapter gives a general overview of bioengineering concepts with a particular focus on plant characteristics and their engineering, socio-ecological, and economic importance. Chapter One also presents the framework for plant selection and the criteria to be considered in the process. The information presented in Chapter One was obtained through an extensive literature review and from survey and interview responses from experts. Information gained from the literature review and the interview responses was incorporated into this report as the body of the text and as additional resources, references, slope stabilization techniques and tools, current and effective management practices, useful points, photographs, and knowledge and research gaps.

The historical evaluation of nature based solutions for bioengineering applications is presented in Chapter two. This chapter also present the scientific approaches which have been adapted in different bioengineering applications. Furthermore, the Chapter describes the bioengineering research and development activities that have been reported in Sri Lanka.

Chapter three briefly describes the methodology and experimentation procedure resulting from ongoing collaborative research between the University of Peradeniya, the Asian Disaster Preparedness Center (ADPC) and the National Building Research Organization (NBRO) into plant root traits. A detailed account of the root traits of 120 plants found in landslide prone areas are presented in order to demonstrate the potential of different vegetation types as bioengineering tools. A comprehensive index was developed and presented with a sample analysis of 32 selected plants that are considered to be useful species for bioengineering.

The criteria for plant selection are discussed in Chapter four. This Chapter presents the use of different plant traits in selection process and its significance. A simple plant selection framework is presented at the later sections of the Chapter four.

The plant manual, the core content of this report, is presented in Chapter Five. The plant manual presents a detailed account of plant characteristics, recommended agro-climate regions, propagation methods, and engineering significance. The list includes six grass species, six minor export crops, two multipurpose tree species, five agroforestry species, six natural and native vegetations, and two neutralized species.

Chapter six discusses the outcomes of field and laboratory experiments on plant root strength testing. The chapter discusses the limitations of the bioengineering solutions in general and the constraints and limits of the plant manual. Recommended future developments and actions are also discussed in this final chapter.

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# 1 Introduction

## 1.1 Purpose and importance of a nature-based landslide risk management strategy

The application of appropriate technologies in the sustainable management, conservation, and restoration of ecosystem to reduce disaster risk is an important aspect of natural resource management. A landslide (or landslip) is a natural phenomenon that can trigger a disaster if it occurs at an unexpected time or space. A landslide is described as a movement of soil, rock, and organic debris under gravity. Management of landslides, and, particularly, *protection* against landslides, is conventionally treated as a resource-intensive activity. However, historical development of vegetation and nature-based techniques in erosion control have evolved to a broader context of bioengineering.

It is well known that vegetation plays an important role in protecting natural and artificial earth systems against shallow-seated landslides, surface erosion, and shallow mass-wasting in projects such as cut and fill slope stabilization, earth embankment protection, and small gully repair treatment.

Soil bioengineering is the use of plant material, living or dead, to alleviate environmental problems, such as shallow rapid landslides or eroding slopes and streambanks (Lewis et al., 2001). In bioengineering systems, plants are important structural components, rather than just aesthetic features. The bioengineering approach to slope stabilization requires a true partnership between engineering geologists, maintenance personnel, civil engineers, and landscape architects.

The application of bioengineering for slope stabilization and protection is now used world-wide as a nature-based, economical, and eco-friendly approach. In recent years, bioengineering solutions have effectively been implemented in many Asian countries, such as Nepal (Dhital et al., 2013), Pakistan (Faiz et al., 2015), India (Singh, 2010), and Sri Lanka (Bandara & Jayasingha, 2018; Balasuriya et al., 2018). However, nature-based bioengineering solutions are often unique to particular ecosystems, thereby limiting their repeatability. Moreover, the selection and use of appropriate plants and vegetation for bioengineering applications have been overlooked due to the unavailability of proper selection criteria.

However, it should be noted that not all types of landslide can be mitigated through bio-engineering techniques alone. In deep-seated landslides, for example, factors such as the level of ground water table, the requirement of toe supports, and the direction of surface water outflow should be determined with care to minimize the landslide risk. Hence, it is better to plan a solution using both geo-technical and bio-engineering inputs, which can be defined as *hybrid approaches*.

## 1.2 The need for a plant manual

Ideally, the selection of a plant for bioengineering applications should combine easily measurable plant traits with a sound geotechnical basis (Stokes et al., 2009; Mickovski et al., 2006). Meanwhile, the environmental variability of the plant, soil, and climate should also be considered. Geotechnical engineers and practitioners, landscape architects, land planners and restoration ecologists would all benefit from effective plant selection criteria once ecological evaluation of the candidate plants has been carried out (Evette et al., 2012; Jones, 2013). Such a tool would permit these professionals to foresee the long-term effects of different plant covers on slopes, the results of combining plant functional groups in restoration actions, or the responses under different soil and climate scenarios.

The objective of this plant manual is to assist professionals and practitioners concerned with planning and implementing soil bio-engineering techniques by providing practical information on plant selection and use in a wide variety of situations.

## 1.3 The socio-economic, ecological, and engineering significance of a plant manual

Sri Lanka's diverse and hilly landscapes once were covered by natural vegetation but have recently suffered from rapid land use changes, which have caused widespread soil erosion and landslides. Sri Lanka is an island with a unique geomorphological setting. Hills and mountains are concentrated within the central region, known as the *Central Highlands*. The highlands cover approximately 20% of the land area and the elevation of the highlands ranges from 300 to 2500 m. Due to the Central Highlands' unique features, most of Sri Lanka's major rivers' main tributaries originate in the highlands and have a radial flow pattern. The highlands are generally covered by evergreen, tropical, and mountain forests. Until the British period, there was no evidence of human habitation in the hill country (above 1066 m) since the disappearance of Stone Age peoples from these elevations (Deraniyagala, 1972). However, the land use of the hill country changed from natural forest to plantation crops over a period of approximately one hundred years (1830s to 1930s) under British colonial rule (Wickramagamage, 1998). This historical development has changed not only the environment setup but also the socioeconomic status of the country. From the start of plantation cropping, the hill country underwent rapid land use change: from lands predominantly under natural vegetation cover to lands predominantly under agricultural crops. The change of land use brought up issues such as accelerated soil erosion, slope failures and landslides. The issues were aggravated due to further transitions in recent history, where plantation agricultural lands were rapidly converted to other urban uses, such as home gardening, minor agriculture cropping, housing, roads, and community infrastructures. Consequently, the environmental, economic and social problems caused by slope failures and landslides are increasingly recognized as major issues in recent Sri Lankan history.

Effective landslide mitigation strategies must include not only physical interventions but also socio-economic changes, including more integrated land use of vulnerable areas. Commercial tea plantations cover a vast area of the hill country land in Sri Lanka. Rubber plantations are often found in mid and low country regions of the island. Moreover, the recent changes in the socioeconomics of the country has transformed most of the medium and small-scale plantation crop lands to either agricultural uses, such as intensive vegetable cultivation and minor export crops, or to home gardens. The changes interact with the biophysical environment in numerous diminutions: ecological, economic, social, and agricultural. In a recent study by Perera et al. (2018) agriculture and the plantation-based socioeconomic system were indicated as factors in landslide causation, especially in the paleo-landslide environment. Moreover, they found that agriculture-related activities account for a major share of rural livelihoods in many landslide-affected areas of Sri Lanka. Therefore, landslide hazards mitigation strategies should consider not only the physical and ecological features of vulnerable areas but also their socioeconomics.

The contribution of certain plants to the stability of a slope have been described by many researchers (Pallewattha et al., 2019; Leung et al., 2015). Greenwood et al., (2004) lists the main stabilizing effects of vegetation on a slope: additional effective cohesion, an increase in weight, tensile reinforcement by the roots present on the base of tree, and possible changes in undrained soil strength due to moisture removal derived from the evapotranspiration cycle processes. These natural phenomena increase the shear strength of soils and thereby contribute positively to slope stability.

Hence, the development of bioengineering solutions, and, particularly, recommendation of effective plant species for slope stabilization, will create a win-win situation where the bioengineering solutions will safeguard the rural livelihood while adequately contributing to landslide mitigation strategies.

# 2 Evolution from landscape cultivation to bioengineering

## 2.1 Past and present status of nature-based landslide risk management strategies

The use of vegetation to control erosion has been practiced in many parts of the world for centuries; however, the application of bioengineering techniques as an accepted method for landslide prevention and slope protection is comparatively new and is continuously evolving. Faiz et al., (2015) states that soil bioengineering is a technique that has been used for decades in countries such as Nepal and, in other cases (e.g., in Pakistan), has recently been adopted as a viable soil stabilization method.

### 2.1.1 Bioengineering and biotechnical stabilization techniques

The terms *soil bioengineering* and *soil biotechnical techniques* are used in concurrence. Soil bioengineering is a technique that uses plants and plant material alone, whereas biotechnical techniques use plants in conjunction with more traditional engineering measures and structures to stabilize slopes (Gray & Sotir, 1996; Schiechtl & Stern, 1996) and are currently employed to alleviate shallow, rapid landslides and eroding stream banks (Lewis et al., 2001). In addition to engineering, ecological, and economic benefits, both bioengineering and biotechnical techniques contribute to sustainable development practices as they enhance the aesthetics of the environment and reduce the ecological impacts of construction, maintenance, and operations (Fay et al., 2012). In soil bioengineering systems, plants (grasses and shrubs, especially deep-rooted species) are an important structural component in reducing the risk of slope erosion (Jiang, 2004). Soil bioengineering measures are designed to aid or enhance the reestablishment of vegetation (United States Department of Agriculture [USDA], 1992). The general perspective is that properly designed and installed vegetative portions of systems should become self-repairing, with only minor maintenance to maintain healthy and vigorous vegetation. Soil bioengineering frequently mimics nature by using locally available materials and minimal heavy equipment, and is an inexpensive way to treat slope stabilization (Lewis et al., 2001).

The following basic concepts aid in the selection of soil bioengineering and biotechnical treatments (USDA 1992; Lewis et al., 2001; Fay et al., 2012):

- ✓ Fit the system to the site. Consider topography, geology, soils, vegetation, and hydrology. Avoid extensive grading and earthwork in critical areas.
- ✓ Test soils to determine if amendments are necessary.
- ✓ Use on-site vegetation whenever possible.
- ✓ Limit the amount of disturbed area at each site. Any displaced materials are to be kept on site and reused if possible.
- ✓ Clear sites during times of low precipitation.
- ✓ Stockpile or protect the topsoil and reuse during planting.
- ✓ Utilize temporary erosion and sediment control measures.
- ✓ Divert, drain, and/or store excess water.

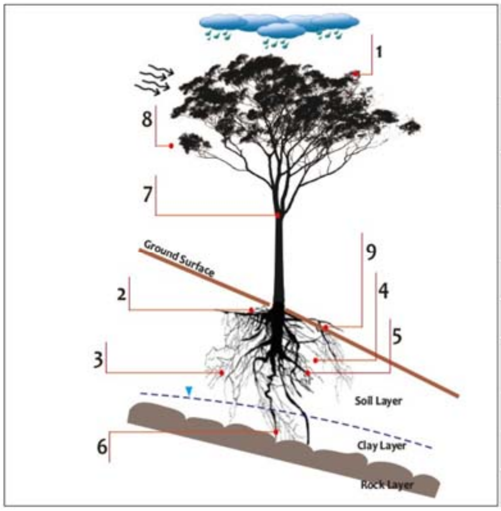
The selection of plants or vegetation for bioengineering applications should consider the views of several disciplines and is often a collaborative exercise between soil scientists, hydrologists, botanists, engineering geologists, maintenance personnel, civil engineers, and landscape architects (Lewis et al., 2001). The role of vegetation in protecting the soil from erosion has long been recognized (Morgan, 2005). The effectiveness of plants for erosion control, slope protection, and landslide prevention depends on the plant architecture and mechanical properties. Some plants will be more suitable than others for erosion control, but may be less effective against slope failures and landslides. Thus, the selection of suitable plant species to achieve the desired objective requires a careful balance of considerations. For each field site and each set of objectives, different factors should be considered.

Fay et al. (2012) explains that soil bioengineering has six main functions:

i. To catch eroded materials with physical barriers (e.g., walls, vegetation);
ii. To armor the slope from erosion caused by runoff or rain splash using vegetative cover / to create partial armoring using lines of vegetation;
iii. To reinforce soil physically with plant roots;
iv. To anchor surface material to deeper layers using rock bolts or large vegetation with deep roots;
v. To support soil by buttressing with retaining walls or large vegetation; and
vi. To drain excess water from the slope through the use of drains and vegetation.

### 2.1.2 The role of vegetation in bioengineering

The role of vegetation is to stabilize the slope with mechanical reinforcement of soils through roots as mechanical aspects and through the hydrological impact of the reduction of soil water content through transpiration and interception of precipitation (Ziemer, 1981; Greenway, 1987; Mulyono et al., 2018). The hydrological and mechanical aspects of the vegetative contribution are shown in **Figure 2-1**.



| Number | Hydrological Mechanism | |
|---|---|---|
| 1 | Foliage intercepts rainfall, causing adsorptive and evaporative losses that reduce precipitation to infiltrate. | (+) |
| 2 | Roots and stems increase the roughness of the ground surface and soil permeability, thereby expanding the infiltration capacity. | (-) |
| 3 | The roots absorb water from the soil, which is released in to the atmosphere through transpiration mechanism that cause the pore water to decrease. | (+) |
| 4 | Depletion of soil moisture by the root adsorption may encourage the soil to crack, thus increasing the infiltration capacity. | (-) |
| | **Mechanical Mechanism** | |
| 5 | Roots reinforce the soil, increasing soil shear strength. | (+) |
| 6 | Vegetation roots anchor to the deep soil layer, providing support to the upslope soil mantle through buttering and arching. | (+) |
| 7 | The weight of vegetation increases the normal and downhill force components. | (+) |
| 8 | Plants exposed to the wind transmit dynamic forces to the hill. | (-) |
| 9 | Roots bind soil particles and reduce their susceptibility to erosion. | (+) |

**Figure 2-1** Hydromechanical effects of vegetation on slope stability (adapted from Mulyono et al., 2018)

Plant evapotranspiration mechanisms serve as rainfall holders by maintaining the negative pore water pressure on the ground (Greenway, 1987). The higher the density of the canopy and leaf area, the greater the ability to catch rainfall (water interception) and interception reduces and delays rainfall to the soil surface (Mulyono et al., 2018).

Shear stress, transferred in the ground into tensile resistance in the roots, carries out the mechanical soil reinforcement by the roots. Root condition also has a role in holding the soil layer. Fibrous roots help the plant hold the soil more strongly (Danjon et al., 2008). In addition to plant root characteristics (Collison and Pollen, 2005), the magnitude of overall soil shear strength is also influenced by general soil conditions (moisture, clay fraction, porosity). A tree's roots will increase the soil shear strength via the tensile strength of its own roots and provide slope-shearing resistance during or after heavy rainfall on shallow landslides (Fan and Su, 2008).

The interaction between vegetation and soil does not always benefit the system because some interactions adversely affect stability. For instance, an increase in ground surface roughness by vegetation reduces the overland flow velocity, thus increasing infiltration. The infiltration process results in the presence of perched water on the boundaries of two differently permeable materials, which can increase the soil pore-water pressure and provide additional forces to soil mass movement (Danjon et al., 2008). Increased infiltration of water into the soil through the scar created by an uprooted or decayed tree can then lower the resistance of the whole soil. The wind pressure on a tree could also produce a destabilizing effect if the tree is not well anchored and can eventually cause slope failure (Li and Eddleman, 2002). Roots provide a better connection between soil particles in the soil body (tensile force on the surface), which results in cementation forces in the mass of the soil (Ibid.).

The growth habits of native plant species can greatly influence slope stability because each species has a unique rooting pattern and tensile strength. For instance, grass roots are very fibrous and abundant in the surface horizon, adding surface stability when grass cover is high. Grass and forb roots, however, add very little soil strength at deeper depths because their roots are not as strong and do not penetrate as deeply as tree roots (Gray and Leiser, 1982). Alternatively, the roots of shrub and tree species are long and deep, with relatively high tensile strength (Ibid.). The main advantage of tree and shrub species is their long vertical roots (taproots) that can cross failure planes and bind the soil strata together.

The sole purpose of plant establishment is not to limit the roles played by live plants. For example, biotechnical slope stabilization techniques use vegetative cuttings from easy-to-root species (e.g., *Gliricidia sepium*) to structurally reinforce the soil. As these materials root, they add further stabilization to slopes through interconnecting root systems and soil moisture withdrawal. Biotechnical slope stabilization practices include stake planting, pole planting, joint planting, brush layers, and branch packing.

### 2.1.3 Root traits

A plant trait is defined as a distinct and quantitative feature of a species in terms of plant morphology, physiology, or biomechanics (Stokes et al., 2009). In addition to the general and specific qualitative features of plants, there has been an increasing focus on using plant traits as screening criteria to assist engineers in identifying suitable species for slope stabilization (Ibid.). Geotechnical engineers who wish to apply soil bioengineering techniques need to identify relevant plant traits for plant screening and selection in relation to the mechanical strength the system gains through bioengineering. Soil mechanical properties are generally most influenced by (i) the density of roots crossing the shear plane, (ii) the branching density throughout the soil profile, (iii) the total length of coarse roots above the shear plane, and (iv) the total volume of coarse root and fine root density below the shear plane (Mattia et al., 2005; De Baets et al., 2008; De Baets et al., 2009; Stokes et al., 2009; Ghestem et al., 2014a). During failure, fine, short, and branched roots slip through the soil rather than breaking. Moreover, a plant's hydrologic reinforcement also influences a plant's traits (Ghestem et al., 2014a). Simplified screening criteria can be drawn based on the available information on root traits (**Figure 2-2**).

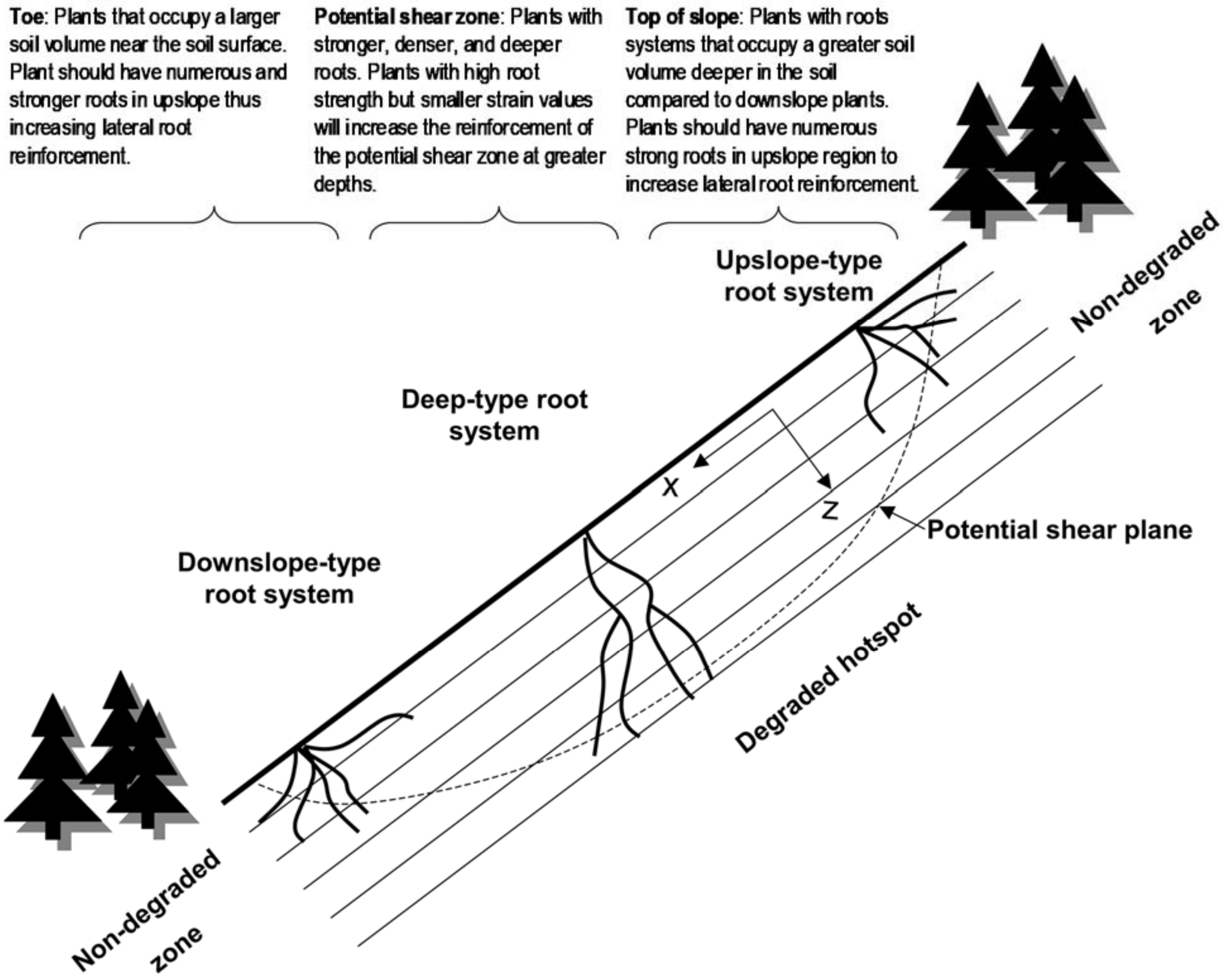


**Figure 2-2** Simplified scheme for root trait-based plant species selection for bioengineering (modified after Ghestem et al., 2014a, 2014b)

### 2.1.4 Selection of plant species

Plants form the nucleus of bioengineering techniques; thus, the selection of appropriate plants is the first move towards success. Plant trait-based selection is the best approach. First, the architectural features or structure of plant root systems play a significant role in shallow slope stabilization and erosion control (Reubens et al., 2007). Second, the ecological significance, and particularly the compatibility with the surrounding environment, is important. It is well established that native plant species are preferred because they tend to tolerate drought and need little irrigation, fertilizer, pest and disease control, and demand less trimming (Dollhopf et al., 2008). Low plant maintenance creates significant savings in labor, fuel, chemical use, and maintenance equipment costs. Finally, a mixture of compatible plant species is preferred over a single species as plant succession determines long-term ecological sustainability (Fay et al., 2012).

Aboveground plant structure is as important as the belowground root system. The structure of aboveground vegetation plays an important role in stabilizing slopes by intercepting and absorbing water, retaining soil, retarding runoff velocity (by providing a break in the water's path), and by increasing surface roughness, rainwater interception and evapotranspiration (Schor and Gray, 2007). Each type of vegetation serves a critical function. Grasses, or herbaceous cover, protects sloped surfaces from rain and wind erosion. Shrubs, trees, and other vegetation with deeper roots are more effective at preventing shallow soil failures, as their roots and stems provide mechanical reinforcement and restraint and their root uptake and foliage interception modify slope hydrology (Ibid.). Where the main function of structural elements is to allow vegetation to become established and take over the role of slope stabilization, the eventual deterioration of the structures is not a cause for concern (USDA, 1992).

## 2.2 Landslides and bioengineering solutions: a Sri Lankan perspective

Recent history has seen an increase in the incidence and frequency of landslides in Sri Lanka. Landslide density is reported to increase in regions where slope degradation processes are at an advanced stage (Rathnaweera et al., 2012; Bandara & Jayasingha, 2018). It is believed that rapid change of land use, such as inappropriate land use or cropping practices, settlements in unstable areas, changes to natural drainage paths resulting in blockages, and non-engineered development and expansion have caused a phenomenal increase in the incidence of landslides in the hilly areas of Sri Lanka (Seneviratne et al., 2005).

Though bioengineering solutions for slope stabilization and landslide mitigation has not been widely studied in Sri Lanka, the effect of geology, land use and other triggering factors on slope stability and landslide occurrence *have* widely been studied (Cooray, 1994 Seneviratne et al., 2005; Bandara, 2010; Bandara & Weerasinghe, 2013; Silva & Sakalasooriya, 2018). The first systematic study that evaluated the contribution of vegetation on slope stability and landslide risk reduction was conducted very recently by Balasuriya et al. (2018). The study revealed the potential of native and natural vegetation as bioengineering solutions, especially in the Badulla district. The study further identified several herb, shrub and tree species as potential vegetation for bioengineering applications.

Bandara & Jayasingha (2018) reported that the landslide risk reduction process has been strategized in a number of ways which follow basic guidelines of disaster management. In view of developing cost-effective and ecological strategies, the National Building Research Organization (NBRO) has identified that bioengineering techniques are appropriate (2015).

## 2.3 Limitations of bioengineering strategies

Bioengineering strategies do have limitations in terms of their effectiveness and applications. The first is that only a limited available number of plants from a given habitat have the necessary technical characteristics, constraining the potential use of the aimed technical solutions. Secondly, plants, as living organisms, do not behave in a standardized way, limiting the ability to precisely calculate the technical effectiveness of the interventions. Finally, plants have limited root growth, hindering their capacity to stabilize soils at depths lower than 1.5-2 m, depending on the species. It is also important to note that there is a lack of systematized knowledge on the physical behavior of plants and, particularly, of their roots and root systems when exposed to external forces, despite the promising results of ever-growing research efforts.

These limitations imply the need for the use of complementary structures to help overcome, temporarily or permanently, the local adverse conditions. This situation determines the development of a particular segment of the industry related to complementary materials (e.g., organic geotextiles) aimed at reducing the impact of water and soil erosion in the initial development phases of construction and intervention and to the conception of construction techniques using classical civil engineering approaches and materials in combination with the advantages brought by vegetation.

# 3 A technical approach to plant selection

This chapter briefly describes the purposes of plant manual development and then aims to achieve them.

## 3.1 Rationale

Many types of plant and vegetation can be used to stabilize slopes and landslides, yet the best selection should be site-specific. The plant manual provides a basic framework for plant selection for bioengineering solutions; however, the practitioners should be able to critically assess the worksite before making conclusions. Every worksite is unique, and it is critical to understand the site water, soil, and topography, as well as its socio-economic needs, before selecting an appropriate plant type for slope stabilization. To accomplish this, a full site assessment should be completed, one that provides information on the soil types and characteristics and surface and subsurface water conditions, and also takes into consideration short-term and long-term land use planning. Developers should consider using a multidisciplinary team with a diverse knowledge and experience base.

## 3.2 Scientific approach

The plant manual is principally a review of existing knowledge in the form of literature, expert interviews, field visits, and preliminary laboratory studies.

Information gained from the literature review was further developed by additional information from practitioners, scientists, and engineers on the current practices, effective practices, and emerging solutions being used nationally and internationally. Information gained from the literature review and additional sources was incorporated into this report as the body of the text, additional resources, references, current and effective management practices, useful points, photographs, and knowledge and research gaps.

## 3.3 Natural vegetation types in landslide-prone areas of Sri Lanka

The landslide-prone areas of Sri Lanka are generally overlapped with wet and intermediate zones. In the wet zone, the dominant vegetation of the lowlands is tropical evergreen forest, with tall trees, broad foliage, and a dense undergrowth of vines and creepers. Subtropical evergreen forests resembling those of temperate climates flourish in the higher altitudes. Montane vegetation at the highest altitudes tends to be stunted and windswept.

At one time, forests covered almost the entire island but, by the late twentieth century, lands classified as ‘forests’ or ‘forest reserves’ covered only one-fifth of the land. The southwestern interior contains the only large remnants of the original forests of the wet zone.

## 3.4 Root-soil matrix

Roots are strong in tension, whereas soils are strong in compression but weak in tension; thus, the combined effect of soil and roots results in a reinforced soil. When shearing the soil, roots mobilize their tensile strength whereby shear stresses that develop in the soil matrix are transferred to the root fibers via interface friction along the root length (Gray and Barker, 2004) or via the tensile resistance of the roots (Ennos, 1990). There are several ways to assess the increase in soil shear strength: laboratory tensile tests, in-situ shear tests on root-reinforced soils, laboratory testing of root-soil composites, and modelling the root-soil interaction. In this experiment, we adapted the simple laboratory tensile strength measurement as the first step of an experimental series aiming to define parameters incorporating root traits in model simulations.

### 3.4.1 Strength of plant roots in landslide prone areas

The root strengths of eleven plant species collected from areas close to the Badulusirigama pilot site, a landslide prone area in Badulla, were measured through laboratory experiments.

Eleven plant species were selected for the first trial experiment. For each selected plant species, approximately 10 undamaged roots with an average diameter of 2 to 50 mm, and a minimum root length of 0.15 m were selected. To collect the roots, a few individual, medium-size plants, growing in the same microenvironment (same habitat, similar landscape position), were dug out using the dry excavation method. The roots were manually collected by careful excavation, and also by cutting the roots on exposed profiles (**Figure 4-1**). After excavation, the roots were individually stored in a plastic bag to preserve their moisture content. The collected root samples were immediately transported to the laboratory; however, the tested roots probably had slightly different moisture contents.

**Figure 3-1** Root sample collection for laboratory tests

Root tensile strength tests were conducted in the laboratory using Dynamometer universal tensile and compression test machine (Model LW 6527, WC DILLON & Co Inc, USA) (**Figure 4-1**). This device combines three functions: (1) traction force generation, (2) measuring load and displacement, and (3) data acquisition. Clamping is the most critical issue when measuring root strength. Roots with fleshy root epithelia could not be tested due to clamping problems, as the samples slipped without breaking. Also, direct mounting of roots causes grip damage to the roots. In this experiment, we wrapped cotton textile bandage around the griping ends of the roots to increase the grip and to minimize the damage to the roots.

**Figure 3-2** Root tensile strength testing using Dynamometer

The initial root length was set to 150 mm. The root diameter was measured at both ends and the middle was measured using Vernier calipers or a micrometer. The elongation at the breaking point, load, and time taken for the test were recorded.

The following formula was used to calculate the tensile strength:

$$T_r = \frac{F_{max}}{\pi\left(\frac{D^2}{4}\right)}$$

where $F_{max}$ is the maximum force (N) needed to break the root and D is the mean root diameter (mm) before the break.

# 4 General guide for plant selection

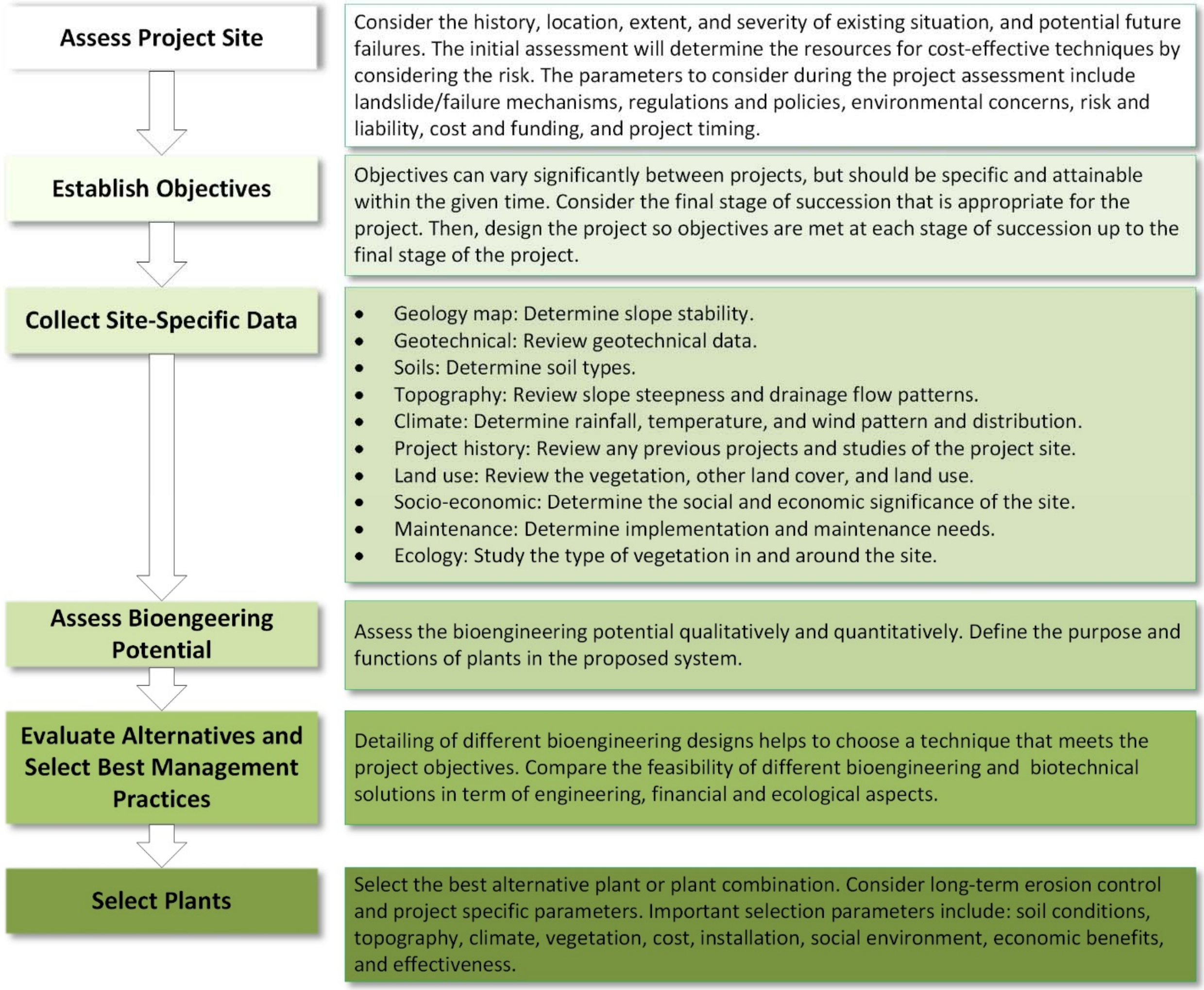
## 4.1 Planning process

Soil bioengineering, in the context of landslide and slope protection, is an integrated approach combining geological, physical, mechanical, biological, and ecological concepts to arrest and prevent shallow landslides and slope failures. It should not be a difficult process; however, given the complexity of plant-soil interactions and other external factors, any selection or recommendation may have its own shortcomings.

Plant species selection should be considered early in the process of planning the bioengineering solution. The tropical ecosystems host a diverse range of vegetation and plant species due to its variation in both soils and climate. Thus, not only the natural vegetation but also introduced plant species thrive well in tropical environments. However, for practical use, socio-economic stabilization and, long-term ecosystem sustainability of the sites and their surrounding environment, species selection should be made with care. Many widely occurring plants are inappropriate for soil stabilization because they do not protect the soil effectively, are not economical to establish or maintain, or because they are not quickly and easily established. Some plant types grow well in many soil types and climates, but others may require specific soil and/or climatic conditions. Plants that are preferred for some sites may be poor choices for others; some can become troublesome weeds.

In a broader context, the approaches to bioengineering solutions can be classified into two general categories: living and nonliving. The living approach uses live plant materials, while the nonliving approach uses geological, physical, and mechanical means. However, living and nonliving measures are often combined to form a complete system. Unlike many mechanical and physical structural designs, selection of proper plant species to integrate with the system requires numerous studies that are often costly and time-consuming. The need of a proper vegetation and plant selection criteria arises at the planning stage; thus, a comprehensive plant manual will assist planners with practical use.

This section provides a step-by-step description of plant selection for a given situation (**Figure 4-1**). The approach used in developing the plant manual is a six-step decision-making process and guides users to select appropriate plants for a worksite.



**Assess Project Site**

Consider the history, location, extent, and severity of existing situation, and potential future failures. The initial assessment will determine the resources for cost-effective techniques by considering the risk. The parameters to consider during the project assessment include landslide/failure mechanisms, regulations and policies, environmental concerns, risk and liability, cost and funding, and project timing.

**Establish Objectives**

Objectives can vary significantly between projects, but should be specific and attainable within the given time. Consider the final stage of succession that is appropriate for the project. Then, design the project so objectives are met at each stage of succession up to the final stage of the project.

**Collect Site-Specific Data**

- Geology map: Determine slope stability.
- Geotechnical: Review geotechnical data.
- Soils: Determine soil types.
- Topography: Review slope steepness and drainage flow patterns.
- Climate: Determine rainfall, temperature, and wind pattern and distribution.
- Project history: Review any previous projects and studies of the project site.
- Land use: Review the vegetation, other land cover, and land use.
- Socio-economic: Determine the social and economic significance of the site.
- Maintenance: Determine implementation and maintenance needs.
- Ecology: Study the type of vegetation in and around the site.

**Assess Bioengeering Potential**

Assess the bioengineering potential qualitatively and quantitatively. Define the purpose and functions of plants in the proposed system.

**Evaluate Alternatives and Select Best Management Practices**

Detailing of different bioengineering designs helps to choose a technique that meets the project objectives. Compare the feasibility of different bioengineering and biotechnical solutions in term of engineering, financial and ecological aspects.

**Select Plants**

Select the best alternative plant or plant combination. Consider long-term erosion control and project specific parameters. Important selection parameters include: soil conditions, topography, climate, vegetation, cost, installation, social environment, economic benefits, and effectiveness.

**Figure 4-1** The six steps of the plant selection process

## 4.2 Aspects of concern

The foremost concern is to consider the plant community succession; in cases where planners wish to regenerate natural vegetation over a long period of time, planting early seral species at the beginning may work. In other cases, where the objective is to limit the number of vegetation to one or few species, it may be necessary to intervene immediately after seeding or planting in order to meet the revegetation objectives of the project. For example, short-term revegetation planning may require site preparation works, enabling particular vegetation to thrive while other species are suppressed. In the meantime, any move against natural succession may require regular intervention, such as the removal of any invasive species before they produce seeds or regenerative parts, gap filling and replanting, and even fertilizer application and pest control. If the plan is to use vegetation or plants that generate income through crop, fodder, wood, or timber harvest, the site could be managed as an agricultural field.

Controlling weeds and competitive vegetation increases the chances of target plant survival and rapid growth. However, decrease of vegetative cover by weeding reduces the rate at which water is withdrawn from the root zone. For example, grasses have a very fibrous root system in the upper soil horizon that allows them to withdraw moisture very quickly and efficiently, lowering the available water in the upper soil horizons. On the other hand, perennial forbs (herbaceous, broad-leafed plants) are generally less competitive than grasses because their root systems are deeper and less concentrated in the surface where the seedlings are withdrawing moisture. Therefore, the establishment of a combination of different plant species may create advantages for site stability and plant succession.

As discussed in previous chapters, the biological components of increased soil strength are the matrix of roots that reinforce the surface horizon, roots that anchor an unstable soil mantle to stable subsoils or rock, and stems that add support to the soil. However, desirable physical soil factors do not always support plant growth. Engineers and geologists regard high soil porosity as an undesirable characteristic, as high porosity soils have lower soil strength because soil particles are not packed closely together and interlock less. However, high porosity soils are of particular interest to the agronomist because of the role porosity plays in root growth. Therefore, balancing the needs of creating a healthy soil for optimum vegetation while still maintaining slope stability until established vegetation adds root strength to the soil is a challenge to engineers and revegetation specialists.

## 4.3 Types of plant

Soil bioengineering uses particular characteristics of plant components and integrates the specific characteristics of the soil and geomorphology of the site. The resulting soil-plant system and its components have benefits and limitations that need to be considered prior to selecting the appropriate plants for use. The following sections describe typical plant types and specific characteristics that need to be considered when selecting a plant species or several plant species in combination.

### 4.3.1 Herbaceous species

Herbaceous vegetation, especially grasses and forbs, offers long-term protection against surface erosion on slopes. Herbaceous vegetation has been used extensively as an erosion control measure as it exhibits excellent surface coverage, shallow soil reinforcement, rapid regeneration, and high evapotranspiration. These positive characteristics are due to several factors: they bind and restrain soil particles in place by their dense fibrous root structure, they reduce sediment transport by physical entrapment by aboveground stems and leaves, they intercept raindrops by thick foliage cover, they retard the velocity of runoff by increased drag from stems and leaves, and they enhance infiltration capacity by slowing overland flow velocity. Herbaceous species are almost always used in conjunction with soil bioengineering projects to add protection against surface erosion. Grass and forb species can become quickly established on drier sites, but soil strength is limited to the surface of the soil profile where the roots are most abundant. For this reason, grasses and forbs do not provide much stability. Consequently, herbaceous vegetation provides only a minor protection against shallow mass movement.

### 4.3.2 Woody tree species

More deeply rooted woody vegetation provides greater protection against shallow mass movement by mechanically reinforcing the soil with roots, depleting soil water through transpiration and interception, and buttressing and soil arching from embedded stems. Deeper-rooted woody perennials improve the mechanical reinforcement of soil at depth. While these species are slower growing, they usually have deeper root systems and persist longer once they are established. Ecologically appropriate plant materials are those that exhibit ecological fitness for their intended site, display compatibility with other members of the plant community, mediate succession, and demonstrate no invasive tendencies. If sites are to be restored to the natural landscape, individual species can be used to provide a significant contribution to mitigating hillslope instability during the early stages of stabilization. However, allowing succession to occur, and the replacement of pioneer plants by later successional communities, is highly desirable. Pioneer shrub and tree species are often short-lived and unable to reproduce in their own shade and may only enhance stability for a limited period. Nevertheless, trees may fall due to winds and localized instabilities. Therefore, if trees grow too tall for a fragile slope, they may need to be pruned or felled to ensure that the integrity of the slope (or engineering structure) is not compromised.

## 4.4 Plant materials and planting

Typically, there is no such thing as an "ideal" all-purpose planting approach that will always work in any situation. After compiling a list of species to use for establishment, the next steps are to determine the optimal propagation methods for each species and to identify the most appropriate plant material sources for a particular site. This step is an integrated, sequential process for evaluating plant material requirements within the context of project objectives and site characteristics that may influence the suitability of planting materials, as well as the timing and optimal method of planting. The fitness of the plant material should be determined by its appropriateness to the site.

Once plant species have been selected and potential sources have been identified, the next step is to determine the most appropriate plant materials for the project. In areas with relatively good soil stability that are bordered by healthy populations of plant species, the existing vegetation may provide the necessary plant materials for the new site. However, if vegetation in and around the site is not sufficient for propagation, additional plant materials will need to be obtained and established. Plant materials may include seeds, cuttings, and/or plants.

Determining which plant materials to select for establishment depends on the type of plant species. For example, many tree and shrubs species have been shown to establish better and faster from plants rather than from seeds or cuttings. Alternatively, grasses can be established from plants (turf), but growing grass plants and planting them is very expensive compared to using seeds. Some species, however, do not produce reliable crops of seeds and, therefore, other plant materials, such as cuttings, will have to be used.

### 4.4.1 Seeds

Seeds can be collected from stands of grasses, forbs, shrubs, and trees. If large amounts of grass or forb seeds are required for a project, seeds can be purchased from seed suppliers. Seeds of grass and forb species are best used for direct sowing, whereas seeds of shrubs and tree species are best used to grow nursery plants. One of the advantages of direct seeding is that it can be an inexpensive method of establishing plants for a large area.

### 4.4.2 Cuttings

Cuttings are taken from stems, roots, or other plant parts and directly planted on the project site or grown into rooted cuttings at a nursery for later planting. In the Sri Lankan context, information on vegetative propagation of wild plant species is scarce. However, substantial information is available on vegetative propagation of commercially grown plant species. Propagating plants from cuttings of most large native tree species is not possible under most conditions. If large quantities of cuttings are required, they can be propagated by growing in a nursery or other growing facility. However, in contrast to the deep taproot structure of naturally propagated large tree species, the root system developed from vegetative propagation (e.g., stem cuttings) often develop a root structure that spreads horizontally. If the purpose of tree species is to develop a deep and vertical root system, it is important to opt for seedlings.

### 4.4.3 Plants

Trees and shrubs are typically established using nursery stocks, rather than by direct seeding, for several reasons. First, obtaining seeds from most tree and shrub species is difficult. Second, shrub and tree seeds germinate and grow into seedlings at a slower rate than grass and forb species, giving them a disadvantage on sites where grasses and forbs are present. Therefore, starting shrubs and conifers from large plants instead of seeds gives them a competitive advantage over grasses and forbs because their roots are often longer and better developed, allowing access to deeper soil moisture. Grass and forb species are seldom established from nursery-grown plants because of the high cost of nursery management. Exceptions are when grass or forb seeds are rare or difficult to collect, if species are difficult to establish from seeds on disturbed sites, or when the project requires quick establishment.

## 4.5 Ecological, management, and economic criteria

The root traits and plant-specific characteristics alone will not make the best selection. The practitioners will have to consider ecological, management, and economic criteria before making the final decision on plant selection. The following table details some criteria that may assist plant selection from the list of plants shown in Annex 1.

**Table 4-1** Plant species selection based on objective criteria

| Criteria | Description |
|---|---|
| Nativity | If the revegetation objective is to establish native plants, then species on the comprehensive species list (Annex 1) are first sorted by whether it is native or not. |
| Workhorse species | *Workhorse species* is a term used to describe locally adapted native plants that: (1) have broad ecological amplitude, (2) have high abundance, and (3) are relatively easy to propagate. The species listed in Annex 1 may need to be evaluated for their potential as a workhorse species based on the project objectives and needs. |
| Availability of starter plant materials | Seeds, plants, and cuttings often have to be collected from the surroundings and supplied to the nursery or seed producer for plant production. Species that are difficult to obtain or collect are not good candidates. |
| Nursery and seed production | Species that are difficult to propagate in the nursery, stooling beds, or seed production fields do not make good workhorse species. Techniques to propagate native species are rarely available, but this is slowly improving. Therefore, refer to documented plant production protocols available in the literature and consult experts. |
| Field establishment | Some species do not perform well because breaking seed dormancy and obtaining good germination may be difficult. Other species, planted as seedlings, experience unusually high transplant shock that significantly reduces plant survival. |

| Criteria | Description |
|---|---|
| Expense | The total cost to establish the plants on the project site is the easiest measure of whether a species is a good candidate for bioengineering. |
| Monoculture or mixture of species | A mix of species is often developed for a specific ecological function or management objective. One of the best ways to develop a compatible mixture of species is to sort the comprehensive species list by ecological setting and succession. This will assemble species into groups that naturally occur together. From these groups, mixtures are developed based on project objectives, such as root traits, weed control, visual enhancement, conservation management, and erosion control. |
| Specialist species | Projects that involve special microclimates or soils may require a unique mix of specialist species, while other projects may require a specific species to meet a project objective. |
| Value/ productivity | If the objective is to establish economically viable and productive plants, selection should be based on ecological and socio-economic feasibility assessments. |
| Maintenance | Some species require regular maintenance even after the initial phases of establishment. This may include logging, trimming, and replanting. The availability of a mechanism for maintenance should be considered. |

## 4.6 A simplified plant species selection framework

One of the main objectives of this plant manual is to develop simple, yet useful, plant selection criteria for application both in slope stability and landslide mitigation works. However, it is unlikely that a simple guideline can consider all factors controlling the plant-soil interactions; therefore, this manual proposes some key plant characteristics to use.

The effectiveness of plants for bioengineering depends on the plant architecture and mechanical properties, particularly its root system (Morgan, 2005). Some plants are more suitable for slope stabilization than others, but the same species may have low ecological and economic significance. Thus, the selection of suitable plant species to stabilize slopes and, more importantly, a complementary mixture of species requires a careful balance of considerations. For each field site and for each set of objectives, the factors to be taken into account may be different.

The following architectural and mechanical plant properties will influence the interaction between vegetation and soil hydro-mechanical forces:

i. The structural characteristics of the individual plants, such as the size and shape of its stems and roots, the spatial distribution of its plant stems and roots within a plant stand, and the spatial pattern of plants along or at a site;
ii. The hydrological significance of the plants;
iii. The behavior of the plant during soil shearing, expressed by the tensile strength of its roots and the flexibility of both individual plant stems and the whole plant stand (Styczen & Morgan, 1995).

Additionally, the practitioners may be interested in the ecological and socio-economic significance of the plant species. Therefore, the framework considers the ecological and socio-economic significance of vegetation.

A representation of the multi-criteria framework used to select suitable species is presented below. The following five main criteria were selected to provide the appropriate information for plant selection:

1) Plant type and structural characteristics
2) Hydrological significance
3) Root strength characteristics
4) Ecological significance
5) Economic value

### 4.6.1 Plant type and structural characteristics

Plant architectural traits allow for the description of stem and root system morphology and topology, each of which influence slope stability. There is a wide range of plant types from millimeters-high small creepers to giant trees that that stand up to 50 meters. The height and mass of the plant influences the stability of the plant itself and also influences the interaction with the soil system. Generally, smaller plants, such as grasses, sedges, and creepers, produce lower biomass, and thus impose lower forces on soil systems. Massive trees put a great weight on the soil system that may confer additional stress on the soil system if the root system does not adequately support the aboveground biomass.

A plant's root system architecture and its individual soil volume is known at the root system's *overall envelope*, which is calculated by its maximum radius (horizontal extension) multiplied by its maximum depth (vertical extension), and thus quantifies the root spread of an individual on a slope.

Trees have deeper-seated effects and can enhance soil strength to depths of three meters or more, depending upon the root morphology of the species. Yen (1972) characterized the patterns of root growth in trees into five groups (Table 4-2).

**Table 4-2** Patterns of root growth in trees (after Yen, 1972).

| | |
|---|---|
| **a) H-type:** maximum root development occurs at moderate depth, with more than 80% of the root matrix found in the top 60 cm; most of the roots extend horizontally and their lateral extent is wide. | |
| **(b) R-type:** maximum root development is deep, with only 20% of the root matrix found in the top 60 cm; most of the main roots extend obliquely or at right angles to the slope and their lateral extent is wide. | |

| | |
|---|---|
| **(c) VH-type**: maximum root development is moderate-to-deep but 80% of the root matrix occurs within the top 60 cm; there is a strong taproot but the lateral roots grow horizontally and profusely, and their lateral extent is wide. | |
| **(d) V-type**: maximum root development is moderate to deep; there is a strong taproot but the lateral roots are sparse and narrow in extent. | |
| **(e) M-type**: maximum root development is deep but 80% of the root matrix occurs within the top 30 cm; the main roots grow profusely and massively under the stump and have a narrow lateral extent. | |

### 4.6.2 Hydrological significance

Evapotranspiration and interception are the key phenomena that contribute to lower the development of excessive soil moisture during heavy precipitation events. Evapotranspiration is the combined process of the removal of moisture from the earth's surface by evaporation and transpiration from the vegetation cover. Evapotranspiration from plant surfaces is compared to the equivalent evaporation from an open water body. The two rates are not the same because the energy balances of the surfaces are markedly different.

The interception of the canopy of a vegetation cover is the rainfall which directly strikes the vegetation cover during a rainfall and other precipitation events. If it is assumed that some of the intercepted rainfall is stored on the leaves and stems and is later returned to the atmosphere by evaporation. The remainder of the intercepted rainfall reaches the ground either as stem-flow or leaf drainage.

In addition, prevention of soil detachment by rain drop is an important aspect of the tree canopy. Vegetation affects these properties by altering the mass of rainfall reaching the ground, its drop-size distribution, and its local intensity.

A recent study by Fan et al., (2017) revealed strong sensitivities of rooting depth to local soil water profiles determined by precipitation infiltration depth from the top (reflecting climate and soil), and groundwater table depth from below (reflecting topography-driven land drainage). In well-drained uplands, rooting depth follows infiltration depth; in waterlogged lowlands, roots stay shallow, avoiding oxygen stress below the water table; in between, high productivity and drought can send roots many meters down to the groundwater capillary fringe. This framework explains the contrasting rooting depths observed under the same climate for the same species but at distinct topographic positions.

### 4.6.3 Root strength characteristics

Numerous studies show that root reinforcement can make significant contributions to soil strength, even at low root densities and low shear strengths. Generally, soil apparent cohesion increases rapidly with increasing root density at low root densities but increasing root density above 0.5 Mg/m$^3$ on clay soils and above 0.7 Mg/m$^3$ on sandy clay loam soils has little additional effect (Styczen & Morgan, 1995). This implies that vegetation can have its greatest effect close to the soil surface, where the root density is generally high and the soil is weakest. Since shear strength affects the resistance of the soil to detachment by rain drop impact, and the susceptibility of the soil to rill erosion, as well as the likelihood of mass soil failure, root systems can have a considerable influence on all these processes. The maximum effect on resistance to soil failure occurs when the tensile strength of the roots is fully mobilized and when, under strain, the behavior of the roots and the soil are compatible. This requires roots of high stiffness or tensile modulus to mobilize sufficient strength and leads to the 8-10% failure strains of most soils. The tensile effect is limited with shallow-rooted vegetation, where the roots fail by pullout, i.e., slipping due to loss of bonding between the root and the soil, before peak tensile strength is reached. Tree roots penetrate several meters into the soil and their tortuous paths around stones and other roots provide good anchorage. Root failure may still occur, however, by rupture, i.e., breaking of the roots when their tensile strength is exceeded. The strengthening effect of the roots will also be minimized in situations where the soil is held in compression instead of tension, e.g., at the bottom of hillslopes.

### 4.6.4 Ecological significance

Vegetation types and their ecology vary considerably across climatic zones, soil types, and land use patterns. The intention of this manual is to take a specific approach to select vegetation for the establishment and maintenance of hillslopes, with the aim of slope stabilization and landslide risk reduction. To do this in detail would require an immense amount of space, hence the emphasis is on principles which local specialists can apply using local knowledge.

Establishment involves the process of obtaining a vegetation cover using seeding and planting techniques, including a period of aftercare until the vegetation is fully established. In some situations, the aftercare period has to be quite long (2-5 years). Maintenance requires periodic input and management in order to maintain the required vegetation in the required form, and to prevent unwanted effects.

In order to be able to assess whether biological construction techniques are likely to be feasible in any particular area, it is important to have a broad understanding of the natural vegetation cover and the way in which it closely reflects the interaction of natural conditions prevailing at any given location. Whatever the climatic zone, a combination of factors affects the choice of approach to the establishment and management of vegetation. Phytosociological (ecological) and environmental factors and constraints have to be reconciled with biotechnical (functional) requirements. Before selecting vegetation, a basic choice has to be made between two approaches:

1. Modifying the site or environmental conditions to suit the desired vegetation. (This is most appropriate when the situation requires a specific type of vegetation or when resources are not limited.)
2. Selecting appropriate species to suit the prevailing site and environmental conditions.

The first principle is that of succession: a sequence of developing plant communities from the first colonizers of bare ground, through a series of stages, until a stable natural vegetation or climax is reached. The direction and rate of succession depends mainly on environmental factors, particularly climate, but is also greatly influenced by the availability of plant propagules. Natural succession, therefore, involves a large element of chance, though most vegetation is affected by human activity to some extent. Establishment of pioneer communities, which have the required biotechnical properties and will develop to a suitable climax or sub-climax by natural succession, is a desirable means of natural vegetation development. Less management is required, sufficient only to ensure succession in the desired direction. It may be appropriate to introduce further species at a later time in order to encourage the required succession. The concept is more applicable to the situation where a practitioner wishes to establish natural vegetation over a long period of time.

Secondly, the role and success of an individual species within a community will depend on its strategy for establishment and growth, based on basic strategies for dealing with varying intensities of environmental stress (brought about by the availability of light, water, nutrients, temperature, etc.) and disturbance (arising from the activities of humans, herbivores, pathogens, damage, erosion, and fire). This concept is more applicable to a situation where a practitioner wishes to establish selected plant species with the aim of extensive interferences such as cropping and plantation.

In addition, the introduction of plant species that are not commonly found in the site location or the introduction of non-native species may interfere with the site as well as its surrounding vegetation. For instance, a plant may have excellent characteristics in terms of bioengineering properties, yet may be an invasive plant for a particular region or country. The socio-ecological limitations may hinder the selection of such plant species.

### 4.6.5 Economic value

Areas that have already been disturbed by landslides or have been identified as risk areas are not always non-productive lands. One might need to continue the land for production, particularly for agriculture, if the land supports livelihoods through agricultural production. Therefore, the selection criteria should have an economic criterion that can recognize the value of the plant to be established. Plants and vegetation generate direct and indirect economic benefits. The harvest of fruits, fodder, timber, or many other vegetative produce directly earn an income. The soil stability improvement, erosion control, aesthetics, and environmental benefits are key indirect considerations.

## 4.7 Simplified scale for plant species characterization

In order to compare species, the specific characteristics of each plant were scored. The scores ranged from 0 to 5, as illustrated in **Table 4-3**. The transition from one score to another was fixed when there was an uncertainty due to lack of information/data. A higher score for a given characteristic (e.g. hydrological significance) indicates that the considered plant has preferable features with respect to characteristics. The procedure of scoring is discussed in **Table 5-1**.

**Table 4-3** Scaling the desired plant characteristics

| Score | Plant type and structural characteristics | Hydrological significance | Root strength characteristics | Ecological significance | Economic value |
|---|---|---|---|---|---|
| **0** | Herbs | Insignificant | Shallow, low strength | Invasive | Unimportant |
| **1** | Creepers | Low | Shallow, medium strength | Introduced, non-invasive | Indirect only |
| **2** | Shrubs | Moderate | Moderate depth, medium strength | Introduced, non-pioneer, agricultural | Indirect and low direct benefits |
| **3** | Small trees | High | Moderate depth, high strength | Native, pioneer, agricultural | High indirect and direct benefits |
| **4** | Large trees | Very high | Deep, high strength | Native/endemic, pioneer, agricultural | Very high indirect and direct benefits |

# 5 The plant manual

## 5.1 General description

This section is organized into three parts. First, a general description of native, introduced, and commercially grown (economical) vegetation types in landslide-prone climatic/agro-ecological zones of Sri Lanka is presented. A summary of plant species that have been fully or partly studied for their bioengineering characteristics are presented in Annex 1. The plants' characteristics are described with brief details of vegetation type, growing climate and ecological zones, soil types, establishment methods on ground, key soil bioengineering properties, and method of propagation. Where the details are available, the general morphological features, such as plant family, growth type, branching pattern, and economically valuable parts, are described. The list includes 120 selected species.

The second part presents an index of selected plants that are recommended for bioengineering applications. This section gives an overview of the criteria-based assessment scheme.

The third section gives comprehensive details of indexed plants, thus allowing practitioners to identify specific features and characteristics related to bioengineering.

The plants shown in **Table 6-1** were assessed by allowing a score based on the scale shown in **Table 5-1**. The cumulative score is the mean average score of five root traits, thus a higher cumulative score indicates that a particular plant has more desirable characteristics for bioengineering solutions.

The detail field guide mentioned in Table 6-1 can be used to identify, characterize, and manage plant species and is presented in Annex 2.

**Table 5-1** An index of selected plants that are recommended for bioengineering applications.

| # | Type | Scientific name | Common name | Plant type and structural characteristics | Score | Hydrological significance (evapotranspiration rate) | Score | Root strength characteristics | Score | Ecological significance | Score | Economic value | Score | Cumulative score |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Grass | *Cymbopogon citratus* | Lemongrass | Medium-sized perennial grass | 2 | Low to moderate | 2 | Dense fibrous roots penetrate to moderate depth | 3 | Introduced grass for erosion control and soil improvement | 3 | Vegetable, spice, and essential oil | 3 | 2.6 |
| 2 | Grass | *Chrysopogon zizanioides* | Vetiver grass | Medium-sized perennial grass | 2 | Moderate | 3 | Dense fibrous roots penetrate to large depth | 4 | Native grass for erosion control and soil improvement | 4 | Spice and essential oil | 2 | 3.0 |
| 3 | Grass | *Chrysopogon nardus* | Citronella | Medium-sized perennial grass | 2 | Low to moderate | 2 | Dense fibrous roots penetrate to moderate depth | 3 | Native grass for erosion control and soil improvement | 4 | Spice and essential oil | 3 | 2.8 |
| 4 | Grass | *Bambusa vulgaris* | Common bamboo | Densely tufted culms | 4 | Medium to high | 3 | Dense fibrous roots penetrate to moderate depth | 3 | Native, naturally occurs in river banks | 4 | Multipurpose (fodder, firewood, shade, fencing) | 4 | 3.6 |
| 5 | Grass | *Imperata cylindrica* | Cogongrass | Medium-sized grass | 2 | Low to moderate | 2 | Dense underground rhizomes and deep fibrous roots | 4 | Native weed grass, invasive | 0 | Low economical value | 1 | 1.8 |
| 6 | Grass | *Arundo donax* | Wild cane | Tall, clumping grass | 4 | High | 4 | Dense fibrous roots penetrate to moderate depth | 4 | Introduced fodder and use for soil conservation | 3 | Stems used as poles, used in handicrafts | 3 | 3.6 |
| 7 | Shrub | *Hibiscus tiliaceus* | Belipatta | Medium to large shrub | 3 | High | 4 | Taproot system up to 2 m; VH-type roots | 4 | Native tree, not a pioneer species | 2 | Low-value timber | 1 | 2.8 |
| 8 | Shrub | *Murraya paniculata* | Etteria | Small to medium shrub | 3 | Low to moderate | 2 | Taproot system up to 1 m; H-type roots | 3 | Native tree, not a pioneer species | 3 | Low-value timber | 2 | 2.6 |
| 9 | Shrub | *Jatropha curcas* | Physic nut | Small to medium shrub | 4 | High | 4 | Taproot system up to 2 m; R-type roots | 4 | Native and agricultural crop | 3 | Seeds used for bio-oil | 3 | 3.6 |
| 10 | Shrub | *Vitex negundo* | Chaste tree | Small to medium shrub | 4 | Low to moderate | 3 | Taproot system up to 2 m; H-type roots | 4 | Native forest tree species | 4 | Medicinal use and fodder | 3 | 3.6 |
| 11 | Shrub | *Melastoma malabathricum* | Biwitiya | Small shrub | 4 | Low to moderate | 3 | Taproot system up to 2 m; M-type roots | 4 | Native forest shrub species | 4 | Medicinal use and ornamental | 3 | 3.6 |
| 12 | Shrub | *Coffea arabica* | Arabian coffee | Medium-sized shrub | 3 | Moderate | 3 | Taproot system up to 1 m; H-type roots | 3 | Introduced and neutralized as an agricultural crop | 3 | Food crop | 4 | 3.2 |
| 13 | Tree | *Acacia catechu* | Katu andara | Small to medium tree | 4 | Low to moderate | 2 | Taproot system up to 4 m; VH-type roots | 4 | Native forest tree | 3 | Low-value timber or fuelwood | 2 | 3.0 |
| 14 | Tree | *Michelia champaca* | Ginisapu | Large tree | 4 | High | 4 | Taproot system up to 2 m; VH-type roots | 4 | Introduced as a timber and shade tree, neutralized | 3 | High-value timber | 4 | 3.8 |
| 15 | Tree | *Bauhinia racemosa* | Maila | Medium to large tree | 4 | Medium to high | 3 | Taproot system up to 4 m; VH-type roots | 4 | Native pioneer tree species | 4 | Low-value timber or fuelwood | 2 | 3.4 |
| 16 | Tree | *Bauhinia purpurea* | Bauhinia | Medium to large tree | 4 | Medium to high | 3 | Taproot system up to 2 m; H-type roots | 4 | Native pioneer tree species | 4 | Ornamental tree or fuelwood | 2 | 3.4 |
| 17 | Tree | *Azadirachta indica* | Kohomba | Large tree | 4 | Medium to high | 3 | Taproot system up to 4 m; VH-type roots | 4 | Native pioneer tree species | 4 | High-value timber, pesticide, oil | 3 | 3.6 |
| 18 | Tree | *Leucaena leucocephala* | Ipil Ipil | Medium to large tree | 4 | Medium to high | 3 | Taproot system up to 4 m; VH-type roots | 4 | Introduced multipurpose tree, invasive but neutralized | 3 | Multipurpose (fodder, firewood, shade, fencing) | 4 | 3.6 |
| 19 | Tree | *Peltophorum pterocarpum* | Wal ehela | Medium to large tree | 4 | Medium to high | 3 | Taproot system up to 2 m; R-type roots | 4 | Introduced multipurpose tree, but neutralized | 4 | Ornamental tree or fuelwood | 2 | 3.4 |
| 20 | Tree | *Pterocarpus indicus* | Wal ehela | Large tree | 4 | Medium to high | 3 | Taproot system up to 4 m; VH-type roots | 4 | Native forest tree | 3 | High-value timber | 3 | 3.4 |
| 21 | Tree | *Wendlandia bicuspidate* | Rawan Idala | Small tree | 3 | Low to moderate | 3 | Taproot system up to 2 m; R-type roots | 4 | Native forest species in secondary forest, pioneer | 4 | Forest species | 2 | 3.2 |
| 22 | Tree | *Eurya accuminata* |  | Small tree | 3 | Low to moderate | 3 | Taproot system up to 2 m; R-type roots | 4 | Native forest species in secondary forest, pioneer | 4 | Forest species, fuelwood | 3 | 3.4 |
| 23 | Tree | *Macaranga peltata* | Kenda | Medium to large tree | 4 | High | 4 | Taproot system up to 2 m; VH-type roots | 4 | Native forest species in secondary forest, pioneer | 4 | Low-value timber or fuelwood | 3 | 3.8 |
| 24 | Tree | *Trema orientalis* | Gadumba | Medium to large tree | 4 | High | 4 | Taproot system up to 2 m; VH-type roots | 4 | Native forest species in secondary forest, pioneer | 4 | Low-value timber or fuelwood | 3 | 3.8 |
| 25 | Tree | *Glochidion moonii* |  | Medium to large tree | 4 | High | 4 | Taproot system up to 2 m; M-type roots | 4 | Native forest species in secondary forest, pioneer | 4 | Forest species | 2 | 3.6 |
| 26 | Tree | *Myristica fragrans* | Nutmeg | Medium-sized tree | 3 | Moderate | 3 | Taproot system up to 2 m; R-type roots | 4 | Introduced and neutralized as an agricultural crop | 4 | Food and spice crop | 4 | 3.6 |
| 27 | Tree | *Eugenia caryophyllus* | Clove | Medium-sized tree | 3 | Moderate | 3 | Taproot system up to 2 m; R-type roots | 4 | Introduced and neutralized as an agricultural crop | 4 | Food and spice crop | 4 | 3.6 |
| 28 | Tree | *Theobroma cacao* | Cacoa | Medium-sized tree | 3 | High | 4 | Taproot system up to 1 m; VH-type roots | 4 | Introduced and neutralized as an agricultural crop | 4 | Food crop | 4 | 3.8 |
| 29 | Tree | *Gliricidia sepium* | Gliricidia | Medium-sized tree | 3 | High | 4 | Taproot system up to 2 m; VH-type roots | 4 | Introduced and neutralized as an agricultural crop | 3 | Multipurpose (fodder, firewood, shade, fencing) | 4 | 3.6 |
| 30 | Tree | *Areca catechu* | Areca | Large, tall monocot tree | 1 | Low to moderate | 2 | Dense fibrous roots penetrate to moderate depth | 3 | Native tree use as fence and for river bank protection | 2 | Spice and export crop | 3 | 2.2 |

| # | Type | Scientific name | Common name | Plant type and structural characteristics | Score | Hydrological significance (evapotranspiration rate) | Score | Root strength characteristics | Score | Ecological significance | Score | Economic value | Score | Cumulative score |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 31 | Tree | *Cinnamomum verum* | Cinnamomum | Medium-sized tree | 3 | Moderate | 3 | Taproot system up to 2 m; VH-type roots | 4 | Native, indigenous, and agricultural crop | 4 | Spice and export crop | 4 | 3.6 |
| 32 | Tree | *Dillenia indica* | Hondapara | Medium to large tree | 3 | High | 4 | Taproot system up to 2 m; VH-type roots | 4 | Native tree, not a pioneer species | 2 | Low value timber | 1 | 2.8 |
| 33 | Tree | *Dillenia retusa* | Godapara | Medium to large tree | 3 | High | 4 | Taproot system up to 1 m; H-type roots | 3 | Native tree, not a pioneer species | 2 | Low value timber | 1 | 2.6 |

# 6 Research and development for bio-engineering solutions

## 6.1 Preliminary results of root tensile strength testing

**Table 6-1** shows the test data recorded during the preliminary root tensile strength test. The root tensile tests were conducted to find out the degree of reinforcement force and the additional root cohesion that a particular plant species can offer positively towards slope stability. The test results were used to evaluate quantitatively the root strength characteristics which are explained in Section 4.6.3.

**Table 6-1** Preliminary results of root tensile strength testing

| Plant genus | Test | Mean diameter (mm) | | | Distance to break point from top edge (mm) | Load (kg) | Tensile Strength (Mpa) |
|---|---|---|---|---|---|---|---|
| | | Top | Middle | Bottom | | | |
| **Calliandra** | Test_01 | 8.70 | 8.60 | 8.80 | 5 | 60 | 10.09 |
| **Artocarpus** | Test_01 | 12.00 | 12.85 | 12.00 | slipped | 40 | 3.38 |
| | Test_02 | 12.55 | 13.10 | 12.95 | slipped | 50 | 3.85 |
| | Test_03 | 12.90 | 12.65 | 12.50 | slipped | 80 | 6.33 |
| **Eucalyptus** | Test_01 | 8.40 | 8.40 | 8.30 | 3 | 240 | 43.65 |
| | Test_02 | 7.85 | 8.25 | 7.95 | 3.5 | 180 | 35.66 |
| | Test_03 | 6.60 | 5.70 | 5.60 | 4 | 30 | 10.73 |
| **Cinchona** | Test_01 | 9.00 | 8.60 | 8.55 | slipped | 80 | 13.41 |
| | Test_02 | 9.90 | 10.20 | 10.25 | slipped | 60 | 7.46 |
| | Test_03 | 9.30 | 9.80 | 10.00 | slipped | 60 | 8.12 |
| **Bauhinia** | Test_01 | 13.95 | 13.20 | 12.45 | slipped | 60 | 4.38 |
| | Test_02 | 6.76 | 6.00 | 7.60 | 11 | 40 | 11.06 |
| | Test_03 | 5.00 | 5.65 | 4.70 | 12.5 | 20 | 9.73 |
| | Test_04 | 9.65 | 10.45 | 10.05 | slipped | 220 | 27.73 |
| **Tea (*Camellia sinensis*)** | Test_01 | 13.25 | 13.15 | 13.90 | slipped | 30 | 2.12 |
| | Test_02 | 9.75 | 9.95 | 10.50 | 11 | 20 | 2.51 |
| | Test_03 | 9.55 | 8.75 | 8.00 | 13 | 20 | 3.31 |
| **Azadirachta** | Test_01 | 4.78 | 5.18 | 6.10 | 13.5 | 40 | 17.79 |
| **Clidermia** | Test_01 | 6.50 | 5.03 | 3.90 | 11.5 | 20 | 9.63 |
| **Osbeckia** | Test_01 | 6.10 | 4.65 | 4.50 | 12 | 20 | 9.85 |
| **Lantana** | Test_01 | 11.00 | 5.05 | 4.35 | 12 | 20 | 5.51 |

The tensile strength/root diameter relationships of the eleven test genera are shown in **Figure 6-1**. As reported in several studies (e.g. Operstein & Frydman, 2000; Norris, 2005; Mattia et al., 2005; Bischetti et al., 2005), root tensile strength generally decreases with increasing root diameter (D). However, the number of tests conducted is not adequate to draw the well-established power law equation.

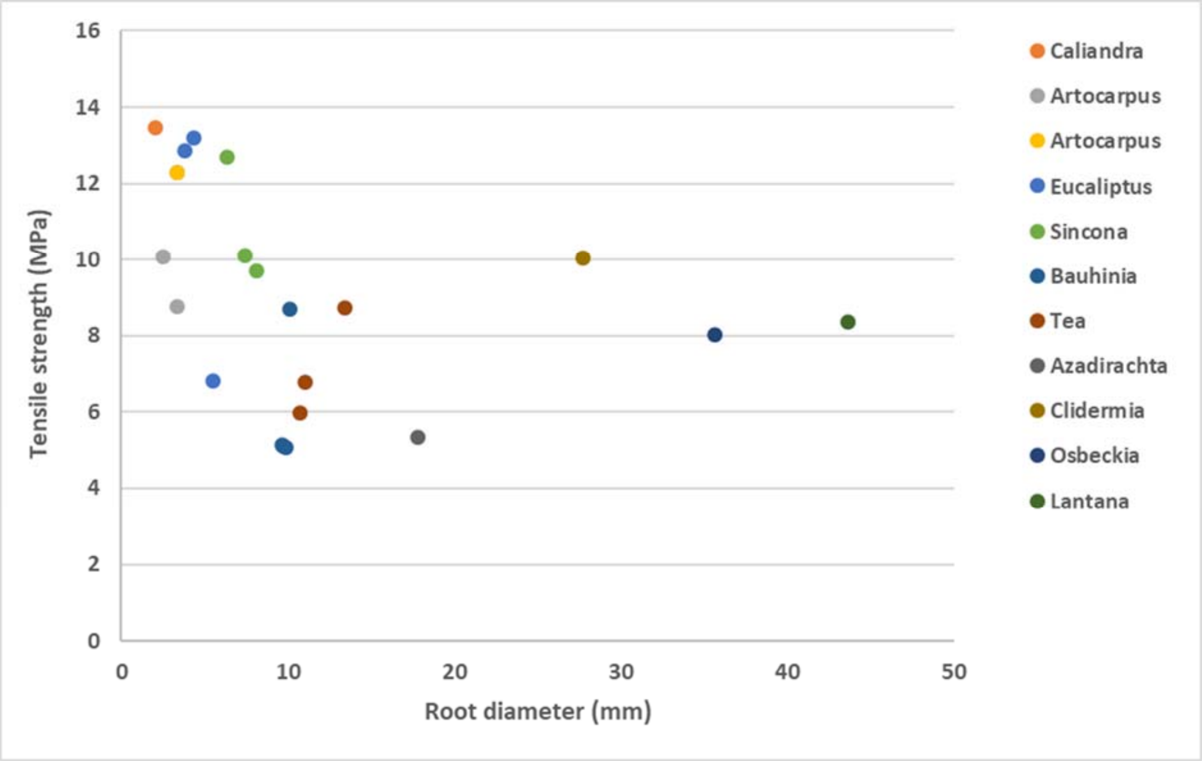


**Figure 6-1** The tensile strength/root diameter relationship for eleven test genera

## 6.2 Limitations of bioengineering solutions

The root and morphological traits of the 11 genera were examined with regard to their desirability for fixing soil on slopes. Each species possessed one or several traits which were desirable for improving slope stability, but no one species possessed a suite of traits that were ideal for fixing soil. Moreover, some of the species that showed many desirable traits were ecologically unsuitable due to their invasive growth characteristics. The information presented in the plant manual is only a guide to select appropriate plant species (or genera) in the absence of sufficient scientific evidence for plant selection. This guidance indicates that practitioners can always test a known or unknown plant for suitability and develop a framework to establish it, as appropriate.

Soil bioengineering is not appropriate for all sites and situations. Problems with using vegetation include failure to survive and grow, vulnerability to drought, soil nutrients and sunlight deficiencies may affect establishment and growth, newly established plants may be uprooted by overland flow or damaged by pests, diseases, or wildlife. Special management measures may therefore be required to ensure long-term project success.

## 6.3 Recommendation and perspectives

Practitioners should consider long-term slope stabilization and landslide risk reduction strategies and project-specific parameters for plant selection. In addition to plant traits, important selection parameters include soil conditions, topography, climate, vegetation in the surrounding environment, land use, economics, social environment, and effectiveness. A detailed trait guidance for all proposed plant species is not available; however, the indexes presented in **Table 4-3** and **Table 5-1** can be used to identify the strengths and weaknesses of proposed plant species. This guide presents a strategy and information to assist professional judgment in selecting effective plant species for slope stabilization and landslide risk reduction.

It is also important that one understands the concept behind the bioengineering treatment, and how it is installed, to ensure that it is placed in the appropriate location.

Studies into bioengineering properties of native and common plants of Sri Lanka are rare and there is an urgent need for laboratory, field, and simulation studies. This report and the recommendations of the plant manual will help to improve and expand the content of the current literature.

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# 8 Annexures

*Attached as separate volumes*