Assessment of the role of vegetation as part of Ecosystem-based Risk Reduction Measures used for shallow-landslides in Rasuwa district, Nepal

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February, 2017

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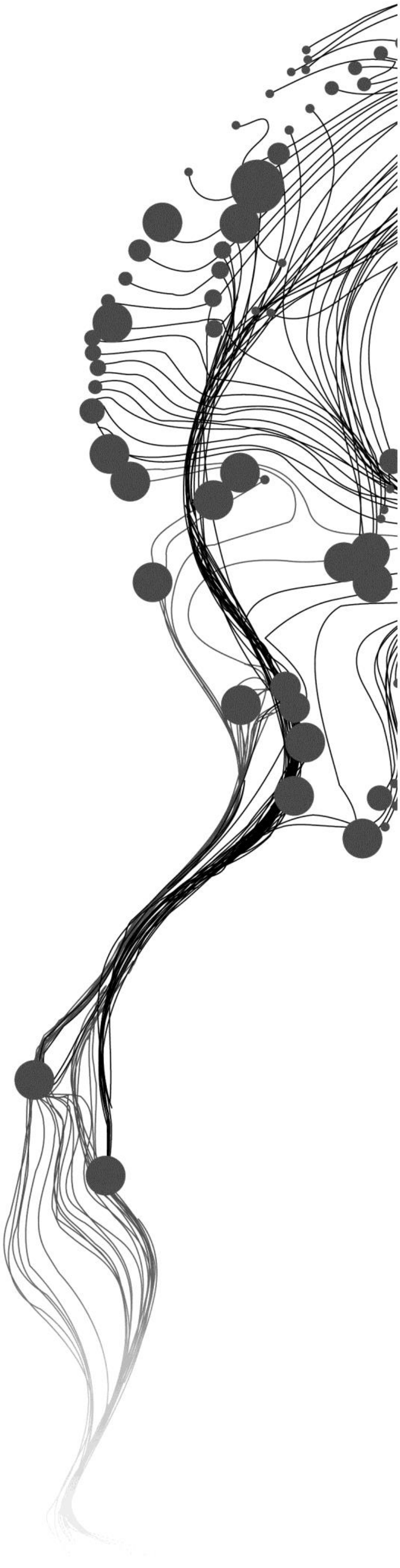

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ABSTRACT

Given its location, topography, and climatic conditions, Rasuwa District is prone to landslides leading to damage economic loses and even fatalities. To cope with this kind of hazards, bio-engineering is considered a good alternative as the management of ecosystems can provide benefits, stabilizing slopes as well as providing food, raw materials or medicinal resources, among others. In this study we analyzed the mechanical effects of 17 plant species on slope stability. The additional benefits they can provide to the local community population were also investigated. Root cohesion and surcharge effects were analyzed with the Infinite Slope Model and the Factor of Safety (FOS) was calculated for a hypothetical slope configuration. *Thysanolanea maxima* is a grass which shows the best performance among the grasses increasing the FOS since their roots can reach 0.7 m depth. In the case of bushes *Vitex negundo* is the species that can provide better stability. Finally, *Salix tetrsperma* stands out among the trees providing greater reinforcement thanks to their root cohesion, although it is also the tree with the greatest surcharge, however this effect is not significant. Different combinations of species were also analyzed in a small watershed using the STARWARS-PROBSTAT software. A combination of different species provides better stability than the presence of a single one in this case grass, shrubs, and trees. The benefits reported by local people that can be obtained from the different species suitable for slope stability are mainly its use as fodder. However, additional medicinal benefits are mainly reported in the literature. So, when it is consider to implement bio-engineering works it is suggested to make combinations of species and not monocultures, considering also the benefits they can provide to the community.

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1. INTRODUCTION

1.1. Background

Landslides are defined as the movement of rocks, soil, and organic material downslope under the effects of the gravity (Highland & Bobrowsky, 2008). They occur under several climatic and topographic conditions, caused either by human activities or natural forces as: volcanic activity, earthquakes, and water (Highland & Bobrowsky, 2008). This kind of hazard has generated billions of monetary losses in the last decade, affecting millions of people around the world (Guha et al., 2016).

Nepal is a country with a mountainous terrain located in the middle third of the Himalayas, which has the conditions that can make the country to be prone to landslides, such as steep and rugged land surfaces and extreme climatic conditions like the monsoon season (Sill & Kirkby, 2013). Landslides in Nepal provoke huge damage, block rivers, close roads, and also resulted in many casualties (Stauth, 2016).

In order to decrease damage caused by landslides, Disaster Risk Reduction (DRR) activities should be developed using systematic methodologies and propose alternatives to reduce disasters (UNISDR, 2015). Solutions to reduce disaster risk go from avoiding construction of infrastructure on steep slopes, regulating land use, till great engineering structures, depending on the kind of landslide (Highland & Bobrowsky, 2008). However another less invasive and less costly options can be used.

One of the options to deal with problems caused by landslides is Ecosystem-based Disaster Risk Reduction (Eco-DRR) defined as the "sustainable management, conservation and restoration of ecosystems to reduce disaster risk, with the aim to achieve sustainable and resilient development" (Estrella & Saalismaa, 2013). Sustainable management of natural resources to reduce risk from landslides allows obtaining other benefits beyond providing natural protection, such as run off reduction, erosion control, climate change mitigation, soil and water protection and recharge, biodiversity protection, biomass accumulation, climate regulation, nutrient enhancement, food, materials, aesthetic enjoyment, among others (CNRD-PEDRR, 2013; Wei et al., 2016), therefore Eco-DRR is considered a profitable investment (Tarolli, 2013).

Vegetation, an important part of ecosystems, is an element that plays a role on slope stability reducing the probability of landslides through their different structures and characteristics morphological and physiological (Papathoma-Koehle & Glade, 2013; Stokes et al., 2009). In general terms, this is called bio-engineering which refers to the use of plant structures (such as cuttings, roots and stems) to provide stability to slopes and reduce for example shallow landslides (Schiechti, 1985). Vegetation and its effects have been studied in several researches; for example by planting directly seeds of shrubs and see how their roots and their mechanical parameters such as root tensile strength, root shear resistance, and root diameter, reduce landslide susceptibility (Hu et al., 2013), or how vegetation can reduce pore water pressure in soil due different root architectures (Ng et al., 2015); just to mention some examples.

Hydrological and mechanical effects of vegetation influences slope stability. Among these two, mechanical effects such as reinforcement by root cohesion and surcharge have shown a role modifying slope stability (Pollen & Simon, 2005). In this study it is analysed the mechanical effects (root cohesion and surcharge) of different plant species present in Rasuwa District, Nepal and it is discussed about the benefits they can provide to the community in order to provide guidance in the selection of species useful for slope stabilization as well as useful to the community, in the framework of Eco-DRR.

1.2. Problem statement

Nepal is a country with one of the most precipitous territories in the world, around 83% of its territory is covered by hilly and mountainous terrain, because it is situated between the Indian and Eurasian plates (Goverment of Nepal, 2016a). Due its topography and location, in the country landslides are frequent and have caused huge damage. For example, the earthquake and its aftershocks occurred on April 25th, 2015, triggered around 4,312 landslides. The damage caused by the event left around 9,000 deaths, 22,000 injuries, 460 km of roads affected, more than 100 houses, and proximately USD 7 billion economic loses; affecting mainly the central part of Nepal (Sheresta et al., 2016) where Rasuwa district is located.

In Rasuwa District, most of its population live in poor and vulnerable conditions, developing their normal social and economic activities in a territory with the aforementioned characteristics. Moreover, because people has the need to access to health care, education, markets, among other services, rural roads are constructed, also causing instabilities of slopes (Devkota et al., 2014). The problem of landslides related to the topography, climatic conditions (monsoon rains), and human activities (Dahal & Hasegawa, 2008), made necessary the search for solutions or alternatives to cope with landslides.

Traditional engineering techniques can be used to control landslides and reduce them, nevertheless its applicability require considerable monetary investments and over time its effectiveness is reduced like any other civil works (Devkota et al., 2014). Bio-engineering is a less expensive and long term alternative which can bring more benefits than just stabilizing the slope, being able to improve the quality of life of people living in these areas prone to landslides in the region, appropriate for a developing country like Nepal (Lammeranner, Rauch, & Laaha, 2005).

Although in the country the use of bio-engineering has been used for almost 30 years, the studies on the performance of different species used for slope stability present in the country are few. In some cases the the researches published are mostly focused in practical experience (Dhital et al., 2013); on some other cases, the data presented can be considered as outliers (Gupta, 2016), due the values presented fall beyond the values reported in other publications related with soil reinforcement by roots. Also studies about strategies for reducing landslide hazard and its relationship with the environment are still rather rare.

Due its geographic location, Rasuwa District has varied climatic zones in short distances which makes to have a wide variety of plant species that can be used for bio-engineering reducing shallow landslides in the area, and also the benefits provided by those species can be used by people in the community. So with this research is expected to provide utile information about suitable native vegetation for slope stability, and the benefits that those species can provide to the local community. The information generated can be used for selection of suitable vegetation to reduce landslide hazard in Rasuwa district, so the stake holders could be able to take decisions based on more fundament. Due the characteristics of the study area, its long history in landslide hazards, and its diversity of plant species, this research is an important approach for ecosystem-based disaster risk reduction in the area. It is hoped to provide useful information that serves to plan and implement better measures for slope stabilization in Nepal.

1.3. Research objectives

The main objective of this study is to evaluate the role of different plant species in stabilizing areas susceptible to shallow-landslides and their relation with the ecosystem trough the benefits they can provide in a Nepalese mountain environment (Rasuwa district, Nepal).

To achieve this objective, the specific objectives are the following:

1. To generate list of plant species used suitable for slope stabilization in Rasuwa District
2. To identify, and describe the benefits provided by plant species suitable for slope stability in the study area
3. To analyse the role of different plant species on slope stability through the use of a physical model that incorporates the mechanical and hydrological aspects of vegetation.

The following research questions will be addressed according to each seated objective:

- Which plant species are used for slope stability in Nepal?
- What is the documented vegetation diversity of Rasuwa district suitable for slope stability?
- What properties (morphological) those species have, playing a role in slope stability?
- How can these characteristics be translated in mechanical and hydrological properties that can be used in slope stability analysis?
- What is the effect of vegetation on slope stability depending on different species analysed?
- What are the benefits provided by different plant species used for slope stability?

1.4. Thesis outline

The thesis is composed of 5 chapters. A brief description of each chapter is given in *Figure 1-1*.

Introduction

- Chapter 1 is a general introduction. It includes a description of the motivation to carry out the research project, as well as the stated objectives.

Literature review

- Chapter 2 includes a review of the theoretical background. First the effect of vegetation on slope stability trough different proceses is described, giving emphais in mechanical effects. Then the characteristics of vegetation that affect slope stability are mentioned. After, there is description of the models used to calculate the factor of Safety of an slope including the influence of vegetation. Finally, a section describing the vegetation used in Slope Stability and the benefits that it can provide is included.

Plant species used for slope stabilization in Nepal

- In Chapter 3 it is described the study area as well as the methodology followed to obtain a list of plant species, their characteristics and benefits that they can provide. The list of species is used to evaluate their performance on slope stability.

Modelling the effect of vegetation on slope stability

- In Chapter 5 the role of different plant species on slope stability is analyzed. In the chapter it is described how the ifnormation regardin root cohesion and surcharge was obtained. Then this two parameter were includen in an infinite slope model to calulate the Factor of Safety of an hyphotetical slope varying soil depth and slope angle. A slection of four species was done and its effects were combined under different scenarios to analyze how they perfomr togheter. Finally these scenarios were taken into a GIS and modeled in a catchment in Rasuwa District unsing STARWARS+PROBSTAB model.

Conclusions and recommendations

- The finidings are summarized and some recomendations are suggested for further scientific investigation in Chapter 5.

Figure 1-1. Overall thesis outline.

2. LITERATURE REVIEW

The beneficial effect of vegetation on slope stability has been demonstrated in many research results. Vegetation helps to reduce erosion (Marden et al., 2014) and also to reduce the susceptibility to shallow landslides due to the mechanical and hydrological effects it provides which influence the soil properties (Schmidt et al., 2001; Stokes et al., 2009). In this chapter a review of how vegetation can play a role on slope stability and the processes involved is presented, as well as vegetal characteristics according to different plant group forms related with such effects, giving emphasis on the aspects of root cohesion and surcharge which will be analysed in the subsequent chapters.

2.1. Effect of vegetation on slope stability

Vegetation, which is an essential component of ecosystems, plays a role in slope stability by reducing the probability of landslides through their different morphological and physiological characteristics (Papathoma-Koehle & Glade, 2013; Stokes et al., 2009). Those characteristics can be translated into hydrological and mechanical effects (See *Figure 2-1*), which have been studied by various researchers; demonstrating in different ways that vegetation is an important component in the stabilization of slopes. Such hydrological effects are interception, reduction of kinetic energy, evapotranspiration, flow reduction, and infiltration. Among the mechanical effects are: increasing shear strength, reduction of erodibility, anchoring soil to firm strata, weight surcharge, and wind load (Morgan & Rickson, 1995).

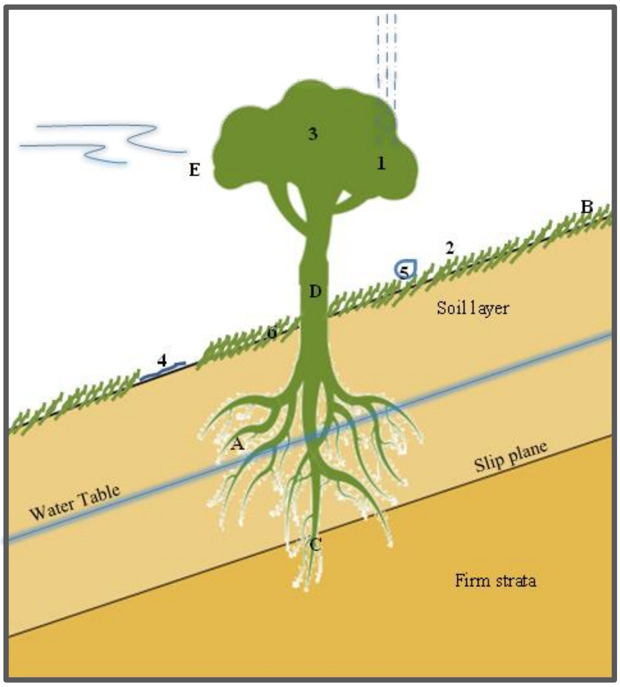

Figure 2-1: Effects of vegetation on slopes. Hydrological effects: 1) Interception of rainfall, 2) Reduction of kinetic energy, 3) Evapotranspiration, 4) Reduction of velocity of water 5) Increase of drop size localized, 6) Infiltration Mechanical effects: A) Increasing of shear strength, B) Reduction of erodibility, C) Anchoring into firm strata, D) Weight surcharge, E) Wind load. (Morgan & Rickson, 1995).

2.1.1. Hydrological effects of vegetation on slope satiability

Hydrological effects of vegetation on slope stability allow modifying the surface water regime through processes such as rainfall interception, surface water runoff, and infiltration. It also modifies the soil water properties trough evapotranspiration. These processes will be reviewed in the next sections.

2.1.1.1. Interception

In a rainfall event, precipitation can be divided in two portions assuming that it falls vertically. The first part is the rainfall which reaches the soil surface after passing the gaps in foliage of vegetation, this is called direct throughfall. The other portion is the rainfall intercepted by the canopy cover which does not pass the gaps (Morgan & Rickson, 1995). This interception of rainfall diminishes the available rainfall for infiltration (Stokes et al., 2008), until the canopy rainfall storage capacity is exceeded (Yu et al., 2012).

Depending on the characteristics of the canopy cover, interception will vary; so if a rainfall event continues, then the storage capacity of vegetation could be exceeded, consequently drainage from the leaves of plants will start (dripfall) and flow along other vegetal structures such as branches and stems (stemflow) (Stokes et al., 2008). There are researches suggesting that plant degradation (reduction in the above ground-biomass) significantly reduces canopy rainfall storage capacity which in turn can modify the hydrological conditions of the ecosystem (Yu et al., 2012).

An analysis of interception in forests in Nepal was carried with data of rainy season. The results showed that natural forest performs better intercepting rainfall than planted pine forest (Ghimire et al., 2012) (See Table 2-1). Their results were obtained by direct measurements in the field of each parameter indicating that natural communities can intercept more rainfall than planted ones. Alternative methodologies to estimate rainfall interception are available when it is not possible to make direct quantitative assessments. These methodologies include use of remote sensing data and are useful when areas on a small-scale are assessed (de Jong & Jetten, 2007). The importance of this process relies in that it modifies the water balance, and also because it is related with other processes such as evaporation, transpiration, and surface runoff (de Jong & Jetten, 2007).

Table 2-1. Percentage of rainfall interception by natural and planted forests in Nepal (Ghimire et al., 2012).

Forest type	Troughfall (%)	Stemflow (%)	Interception (%)
Natural forest	76.2	1.4	22.4
Planted pine forest	83.0	0.5	16.5

2.1.1.2. Infiltration

Vegetation may decrease the amount of runoff and giving chance to infiltration, being an important element in this process contrary to what happens in a bare soils (Morgan & Rickson, 1995). Organic matter, root growth and decaying roots help to maintain a continuous pore system in the soil, increasing the infiltration rate (Morgan & Rickson, 1995).

A comparison between bare soil and a vegetated area with natural grass cover exposed to a simulated rainfall shows that the presence of different grass species reduce runoff and increase the infiltration rate. This because the grasses make the surface have a rough appearance and roots create a network of channels in the soil (Zhan et al 2007) (See *Figure 2-2*). Their research also showed that when a rainfall event occurred in a bare area, the soil particles were easily detached and then transported down slope by surface runoff, causing erosion.

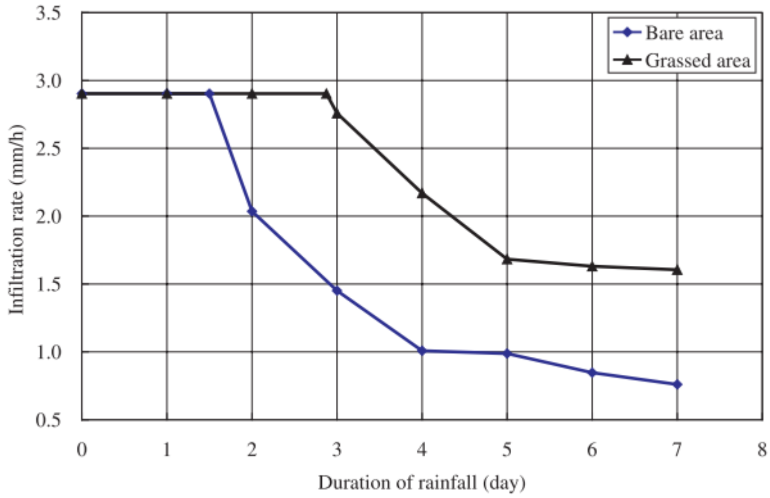

Figure 2-2. Infiltration rate of two areas with vegetation and without vegetation (Zhan et al., 2007).

The same effect was observed in another study where it was stated that the presence of grasses allows having higher permeability providing more infiltration and also reducing runoff, helping to conserve soil and water. But on the other side, this effect increased the pore water pressure reducing the factor of safety (Jotisankasa et al., 2014).

2.1.1.3. Evapotranspiration

Evapotranspiration is the combination of two processes where water is lost from the soil. On the one hand it is lost from the soil surface by evaporation and on the other hand from the vegetation by the process known as transpiration. These two processes occur at the same time, so it is difficult to distinguish between them (Allen et al., 1998). Vegetation and evapotranspiration has a strong influence on soil moisture and hence on slope stability (Stokes et al., 2008) because it modifies the ground water table (Wang et al., 2014).

Evaporation can occur in a variety of surfaces like rivers, pavement, soil and wet vegetation. In this process the liquid water is converted to water vapour and removed from the surface. In the case of transpiration, the liquid water taken by the roots is retained in the plant tissues and then vaporized usually through the stomatal aperture located in the leaves (Allen et al., 1998). Evapotranspiration is dependent on some aspects such as the result of the wind distribution and the surface roughness, so this process varies according to the atmospheric conditions, soil surface, and type of vegetation (Stokes et al., 2008).

Evapotranspiration is a difficult process to estimate, nevertheless it can be calculated by physical models or with water balance calculations using controlled conditions, among others (Stokes et al., 2008; Yu, et al., 2016). A study made on the tree *Scheffllera heptaphylla* which is distributed in Asia, shows that transpiration increases when leaf area index (LAI) is higher (LAI is a dimensionless index defined as the ratio one-sided green leaf area per unit ground surface). In the same research it was observed that evaporation decreases because the radiant energy from the sun is intercepted by the trees so it does not fall upon the soil. Also, comparing a bare soil with presence of the trees it was observed that evapotranspiration increases (Garg, et al., 2015). In physical models to calculate evapotranspiration, LAI, and interception capacity (parameters of vegetation usually employed to calculate evapotranspiration) can be obtained from direct measurements in the field or by use of remote sensing data (Yu et al., 2016).

Evaporation variations among seasons have been observed in several researches. In a study made in a tropical transitional forest in Brazil, the results show that evapotranspiration is lower in the dry season, increases in the transition season, and the highest value is present in the wet season (Vourlitis et al., 2002). For a hill evergreen forest in northern Thailand, evapotranspiration shows opposite results, where the highest rate of evapotranspiration is present in the dry season with around 3-4 mm d^{-1}, while in the wet season the values round around 2-3 mm d^{-1} (Tanaka et al., 2003). Such results can be the effect of different factors such as the type of vegetation, vegetation cover, precipitation regime, atmospheric evaporative demand, soil type, among other factors present in each area (Stokes et al., 2008).

2.1.2. Mechanical effects of vegetation on slope stability

Different processes influence the mechanical properties of soil modifying slope stability. Such processes are: wind load, anchoring, surcharge, and increasing shear strength, which are related with the presence of vegetation. In the next sections these effects on slope stability will be reviewed.

2.1.2.1. Wind load

One of the processes that can have negative effects on the stability of a slope is the effect of the wind on the vegetation. Wind can exert pressure on vegetation and then be transferred to the soil, increasing loading and reducing resistance to failure (Morgan & Rickson, 1995). In general the wind affecting pastures or shrubs does not represent a considerable threat, however when dealing with trees this effect becomes considerable (A. Gupta, 2016). Moreover, it is suggested that wind loading is going to be significant only if the velocity of wind exceeds 11 m/s (Morgan & Rickson, 1995).

The findings of Gupta (2016) show that in circumstances when trees have deep roots and heavy winds push them, the slope stability decreases drastically, but if the effect of wind is not exerted over the canopy then the presence of trees enhance better slope stability. In this case, the effect of wind on trees was related to the wind velocity itself, canopy shape, air density, crown length, crown width, height to crown base, and crown length.

2.1.2.2. Anchoring

Roots can provide anchoring, reinforcing the soil structure (Suarez, 1998), joining soils that are unstable to strata that have greater stability, so that the roots act as reinforcement piles. The anchoring will depend on the profile of the slope, and composition of subsurface layers. For example, the anchorage can occur between individual soil layers, and also where the soil layer is located on weathered rocks with cracks which will allow the roots to penetrate and anchor the soil to the rock (Tsukamoto & Kusakabe, 1984) (See *Figure 2-3*).

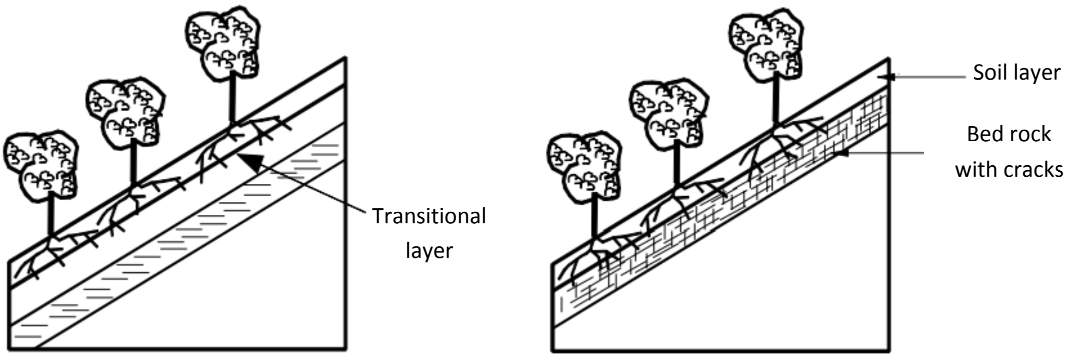

Figure 2-3. Root anchorage in two soil profiles. Left: anchorage between transitional layers. Right: anchorage of soil to bed rock. Modified from Suarez (1998) and Tsukamoto & Kusakabe (1984).

In a study made in Indonesia it was suggested that the best way to stabilize deep seated landslides is to plant a mixture of deep rooted trees which can help to anchor the soil to firm strata, and grasses whose roots help to reinforce top soils. The effect of anchoring by the roots of the trees was calculated using the Index of Root Anchoring (IRA; calculated by dividing the square of the diameter of vertical roots over the square of tree diameter at breast height (DBH)). The results showed that unpruned coffee present the best IRA (7.7) which could provide better anchor and increase stability than trees with frequent pruning which developed roots in surface layers of soil (Hairiah et al., 2006).

Another example showing how vegetation can anchor soil is the study developed by Riestenberg (1994). In this study two species of trees were analyzed: sugar maple and white ash. Sugar maple cannot stabilize deep seated landslides because its roots develop laterally and it does not possess a tap root. While the white ash has well developed roots in the first centimeters depth, but also a tap root which can penetrate soils ticker than 1 m. The results show that root of the white ash species can penetrate the clay colluvium, cross the shear zones and anchor the first layer of soil (colluvium) to the bedrock, in the same way as Tsukamoto & Kusakabe (1984) suggested.

2.1.2.3. Surcharge

Another impact on slope stability due presence of vegetation is surcharge, which adds weight to the slope increasing instability in superficial soils (de Blasio, 2011; Norris & Greenwood, 2006). Usually this effect is seen in trees because grasses and other herbs do not provide additional weight (Morgan & Rickson, 1995). Vegetation surcharge refers to the weight of an individual tree or the weight of all vegetation as a whole (Stokes et al., 2008). Such weight depends on the species present in certain area as well as its diameter and height. Although vegetation can increase surcharge on a slope, it is small compared to soil, so it has not a significant influence on slope stability (Stokes et al., 2008). While the weight of the vegetation can have a negative effect because it exerts a downslope stress, on the other hand this can also be a positive effect because the increment of the mass interacting with the frictional angle of the soil increases the stress in the perpendicular component on the slope, this increases the frictional resistance of the soil to sliding (Morgan & Rickson, 1995).

In a research made on riparian vegetation along the Mississipi River, surcharge of trees was calculated and divided by the root plate area, and then the factor of safety was assessed. It was found that when surcharge of trees increased, the factor of safety decreased. This was proven because trees that provide more surcharge the factor of safety decreased 7% and when the surcharge of a tree is low the factor of safety is reduced by 3%. It was reported that in average the maximum surcharge provided by a tree was 1.2 kPa. It was concluded that even when the effect of surcharge is negative, it is not significant compared with other factors of vegetation as root cohesion (Simon & Collison, 2002).

Another study carried out in Latrobe River in Victoria, Australia, shows similar results as in the previous example. The effect of surcharge of the largest tree in the study area *Acacia dealbata* was assessed by the factor of safety using the infinite slope model. This tree provides in average a surcharge of 0.81 kPa when the biomass of the tree is 250 kg and when the tree has a biomass of 1,596 kg it can provide 5.06 kPa. The effect of surcharge on a slope with an angle of 50° showed that when there is no presence of a tree the factor of safety is 0.96, when the surcharge of an average tree is included the factor of safety decreases to 0.93 and with a large tree the factor of safety decreases even more to 0.8. This negative effect is also observed when slope angle is increased diminishing the factor of safety in each of the scenarios. It was concluded that that the effect of surcharge is negative but secondary and small compared with other destabilizing forces (Abernethy & Rutherfurd, 2000b).

In the previous examples the main parameter used to estimate the surcharge was biomass. There are several ways to calculate biomass of a tree. The most accurate way to calculate it is directly to harvest it, dry it in an oven and then weight the dry matter. Such an approach is not only destructive, but also requires the expenditure of time, human and capital resources (Hunt, 2009). Other practical methods to estimate this parameter is the use of allometric curves that extrapolate the results of measurement of standing trees (Jenkins et al., 2004). The allometric equations are those that allow predicting the biomass of a tree from characteristics easy to measure such as diameter at breast height (DBH) or its height (Picard et al., 2012). Those characteristics can be measured directly in field or can be obtained from remote sensing, where with the use of airborne laser scanning the height of a tree can be measured and then the DBH is obtained from a relationship with the height (Fallah & Karslıoğlu, 2009).

2.1.2.4. Increasing shear strength

The presence of roots in the soil can increase the shear strength of the soil, because their frictional anchoring causes the roots develop tensile resistance to shearing. This is described below.

Root cohesion

One of the elements that provide stability to soil is cohesion, which increases the shear strength (de Blasio, 2011). Cohesion is termed as the resistance force per unit area, resulted from the electrostatic bonds between clay and silt particles (de Blasio, 2011). This cohesion can be increased by the effect of vegetation adding apparent cohesion to the soil thanks to the root reinforcement, which can be increased by the presence of roots causing tensile resistance to shearing (Deoja, et al, 1991). This reinforcement depends on the strength of the roots and their density in the soil as well as its architecture (Leung et al., 2015; Sanhueza & Villavicencio, 2012). For this, many studies analyse the role of vegetation on slope stability, being root system the most recurrent aspect analysed (Clague, 2009; Comegna et al., 2013; Stokes et al., 2007).

To be able to evaluate and quantify the effect of vegetation reinforcing the soil, a series of methods have been developed and applied, to measure or estimate root reinforcement. In the first case, this characteristic can be measured using in situ direct shear tests (See *Figure 2-4*), which consists in the use of a machine with a steel frame, a steel shear box, hydraulic jack and pump, dial gauge and proving ring. In this case, the shear resistance is measured by monitoring the horizontal displacement of the shear box (Teerawattanasuk et al. , 2014).

Other way to measure cohesion is in a laboratory, by means of triaxial compression tests, where a soil sample is collected from the field and then tested in laboratory with a triaxial compression system. The sample is packed in a cylindrical shape in an impervious membrane and then confining to pressure and loaded axially to failure in compression. The root cohesion is evaluated by subtracting the cohesion of the sample with presence of roots minus the cohesion of the sample without roots (Zhang, Chen, & Jiang, 2014). Interesting results were found in the last study, in which is proved that vertical roots add more cohesion to the soil than horizontal roots (35 kPa versus 11 kPa respectively for the tree *Robinia pseudoacacia*). The issues that can be seeing in this kind of approaches is that in the first case, root cohesion is evaluated in the first centimeters depth of soil and it is a difficult task because soil and anchoring of roots can be disturbed; in the second case root cohesion is evaluated by the presence of a single root in the sample.

Figure 2-4. In situ direct shear test (Teerawattanasuk et al., 2014).

The estimation of root cohesion requires modelling, for example the relationship between roots, its characteristics and the type of soil. In literature, two models to estimate cohesion are widely used: the Fiber Bundle Model (Pollen & Simon, 2005), and the Wu and Waldron's Model (Waldron, 1977; Wu et al., 1979).

The Fiber Bundle Model (Pollen & Simon, 2005) is one of the models most used to calculate root cohesion. In this model it is assumed that the roots are not broken at the same time, because they can break depending on how the load is distributed on the bundle of parallel fibers, since the maximum load resisted by them is less than the sum of the strength of each fiber. This is explained as follows. In the first instance, an increasing load is distributed in the same way over all the fibers in the bundle until one of them is broken (according to its tensile strength). Then, the load that was supported by that fiber is redistributed to the other fibers that are still intact, and the same process is repeated until the last fiber is broken. This model proposes a good approach to estimate root cohesion, nevertheless it has some weak points. In the model it needs to be chosen one of two assumptions: if the load can be redistribute to the fibers that are close to the broken one or the load can be redistributed not just to the neighbor fibers but all the fibers according to their diameters (Mao et al., 2012).

The other most used model to calculate root cohesion is the Wu and Waldron's Model (Waldron, 1977; Wu et al., 1979), which is based on the Coulomb equation where it is stated that the sear strength of the soil, S, depends on the frictional forces, and cohesion. S is represented by the cohesion of the soil and the apparent cohesion that roots using the following formula:

$$S = (c' + c_R{}') + (\sigma - u)tan\phi'$$

Equation 1

In this equation c' is the effective soil cohesion, c_R' is the apparent cohesion provided by the roots, σ is the normal stress due the weight of soil and water, *u* is the soil pore water pressure, and ϕ is the effective angle of internal friction. In the model it is assumed that the roots are cylindrical and elastic, they break at the same time and also it is assumed that they are perpendicular to the shear plane. So when the soil is sheared by an amount x in an angle of shear χ, the tensile strength of the root is mobilized, which can be separated in two components: tangential component, and normal component (See *Figure 2-5*).

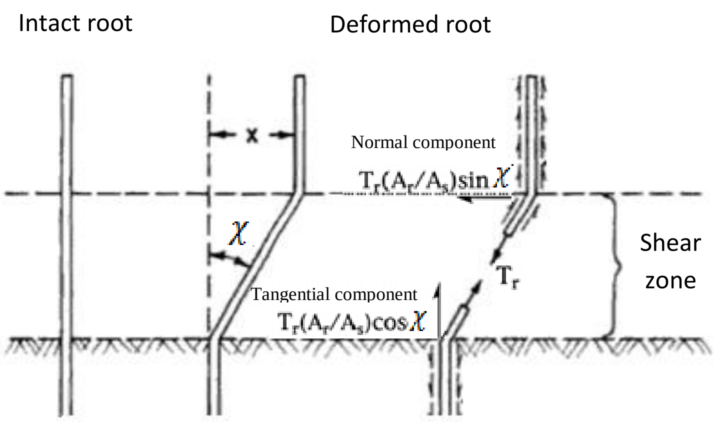

Figure 2-5. Diagram of a perpendicular root in the root reinforcement model. Definition of the variables can be seeing in Equation 2 and Equation 3. Modified from Gray & Sotir, (1996), and Schmidt et al., (2001).

In the previous equation root cohesion c_R' including diameter variability is calculated considering the next equation according to Waldron (1977) and Wu et al., (1979):

$$c_R = a \sum_{i=1}^{N} T_{ri} \left(\frac{A_{ri}}{A_s}\right)$$

Equation 2

Where T_{ri} is the tensile strength for roots in diameter class i, A_{ri}/A_s is the root area ratio or the proportion of root cross sectional area of a root to soil cross sectional area in class i, and N is the number of classes of root diameter. In the last formula the parameter α is the mobilized tensile resistance in root fibers or root orientation factor, expressed as follows:

$$a = sin\chi + cos\chi tan\phi'$$

Equation 3

Where χ is the root distortion angle from the vertical, and is ϕ is the angle of internal friction of the soil. Wu et. al. (1979) suggested that the value of α varies from 1.0 to 1.3 when 25°<φ<45° and 40°<χ<70° so in this case a value of 1.2 was taken into account as a median value and according to the value of φ assigned for the infinite slope stability model used in this research. The perpendicular model is a useful simulation of the orientation of the roots because it estimates an average of all the possible orientations that they can have in the ground (Gray & Sotir, 1996).

Equation 2 and *Equation 3* can be combined to make a simple equation to estimate the total mobilized tensile strength including the mean tensile strength of the roots (*Tr*) and the root area ratio (RAR) to represent the increase of shear strength due the presence or roots (Leung et al., 2015):

$$c_R = 1.2\, T_r.\, RAR$$

Equation 4

Reported values of root cohesion differ considerably even for the same species depending on the method followed. For example, studies carried out measuring root cohesion of *Chrysopogon zizanioides* (synonymous: *Vetiveria zizanioides*). In a study where the root cohesion was estimated using Equation 4 the values at depths of 0-0.1 m reached more than 1,280 kPa (Machado et al., 2015), while in a study where this parameter was measured in situ with direct shear tests the value reached a maximum of 8 kPa (Teerawattanasuk et al., 2014) (See *Figure 2-6*). The higher values reported by Machado et al. (2015) can be explained because the model used assumes that all the roots break at the same time and that the tensile strength of the roots is multiplied by the root area ratio of the grass at a given depth. Being the main parameters involved in the equation, it must be considered that the results of the model represent the maximum possible increase in shear strength (De Baets et al., 2008).

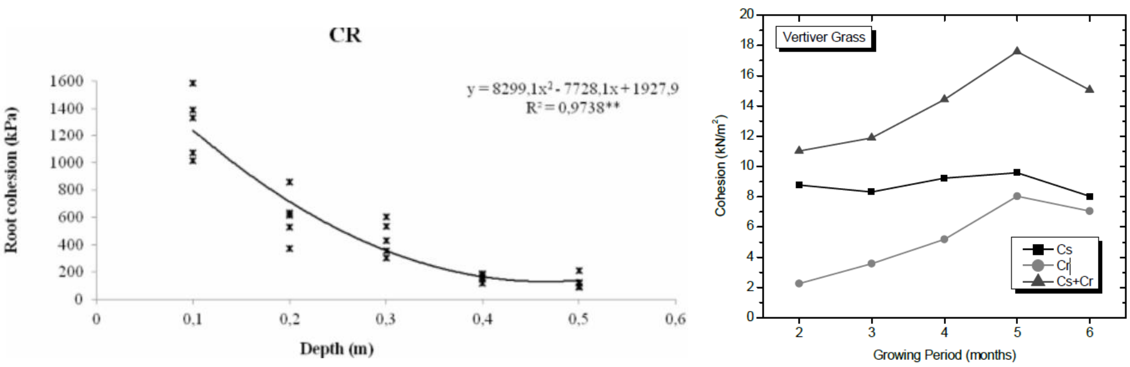

Figure 2-6. Root cohesion values for vetiver grass obtained with different methods. Left, c_R was calculated by a the Wu and Waldron's Model (Machado et al., 2015). Right, c_R was obtained from direct shear test (Cs: soil cohesion, Cr: root cohesion, Cs+Cr: combination of Cs and Cr) (Teerawattanasuk et al., 2014).

Results of Teerawattanasuk et al. (2014) also reveal that root cohesion of *Vetiveria zizanioides* varies depending on the age, increasing according to the growing period (See *Figure 2-6*). In the figure a decrease on root cohesion is shown in the sixth month. The authors explain that this value is related with the beginning of the rainy season.

Tensile strength

Root tensile strength is one of the factors included in the models to calculate root cohesion. This characteristic is dependent on the plant species, root characteristics such as diameter, and the environmental factors where it grows (Gray & Sotir, 1996). For example, Yang et al. (2016) analyzed the effect of root moisture on the tensile strength of different tree species, which are usually used for slope stability in mountainous areas in China. Their results showed that root moisture can have a significant influence on tensile strength. The weakest roots where those extremely dry because they do not present elasticity. The roots that present a better tensile strength were those that loose certain moisture, compared with their initial moisture content.

There is a relationship between root diameter and root tensile strength. Several researchers made on different species have found that root tensile strength decreases as root diameter increases, so that small roots are more resistant in tension (Bischetti, et al. 2009; De Baets et al., 2008; Lateh, Avani, & Bibalani, 2015; Leung et al., 2015; Schmidt et al., 2001; Tosi, 2007). Genet et al. (2005) found also that there is a relationship between cellulose content and root tensile strength; more cellulose percentage leads to more tensile strength.

Root tensile strength is measured with different instruments and in different ways. If tests are carried out in a laboratory, roots are collected from the field (generally with a diameter between 0.1-7 mm). In some cases tensile strength is measured immediately after sampling, but if it is not possible, then they are preserved using alcohol solution and then tested (Bischetti et al., 2009; De Baets et al., 2008). Sophisticated apparatus can be employed to measure tensile strength, such as the universal tensile and compression test machine (See *Figure 2-7*). In the apparatus the root is clamped in screw clamps with rubber strips and sand paper to improve the adhesion in the clamps and then a tensile force is exerted by gears, then tensile strength is calculated by dividing the peak force applied by the cross sectional area of the root (De Baets et al., 2008).

Figure 2-7. UTS apparatus to perform root tensile strength tests (De Baets et al., 2008).

Sometimes is not possible to carry out the test using such machines, so optional devices are developed (See *Figure 2-8*). In such devices the mechanism is almost the same. In this case the roots are clamped between two mobile steel jaws and the ends of the roots are embedded in cork and glue to avoid damage and slips. One of the jaws is fixed to a scaffold, the other jaw hangs freely with a vessel. The vessel is filled with water until the weight of it breaks the root. When the root fails the water flux to the vessel is immediately stopped and then the water volume is measured and the weight calculated which represents the peak load. Tensile strength is also calculated dividing the load by the cross sectional area of the root (Pohl, 2010).

Figure 2-8. Device designed to measure tensile strength (Pohl, 2010).

A study made by Hu et al., (2013) in the Qinghai-Tibetan Plateau, mechanical parameters as root tensile resistance, root shear resistance, and root diameter, of shrubs to reduce landslide susceptibility were assessed. The methodology followed in the study consisted in planting seeds of the species selected, and after two years of growth the soil properties, architecture and root distribution were measured in the laboratory. The study concluded that specifically two of the five species analysed were more effective reducing shallow landslides due their anatomical structures, especially root diameter. *Atriplex canescens* presented an average tensile strength of 40.28 MPa with an average root diameter of 1.93 mm, while *Caragana korshinskii* had an average tensile strength of 26.46 and average root diameter of 1.67 mm. in the tests for both cases root tensile strength decreased as root diameter increased.

Tensile strength may also vary in the same species. From *Table 2-2* it can be observed that the same species present a wide range of root tensile strength values. This variability shown by each author can be explained because root tensile strength is related with root diameter. The variability between different authors can also be explained because they used different root diameters to test tensile strength, the age of the grass when it was measured is different, and also probably the different devices to measure it affect the results provided.

Table 2-2. Root tensile strength values of Vetiver grass according to different authors.

Root diameter range (mm)	Tensile strength range (MPa)	Test device	Source
0.6-1.7	27-54	Rudimentary	(Sanjaya Devkota, 2017)
0.4-2.7	16-353	Universal Press	(Machado et al., 2015)
0.25-2.9	4.31-58	Rudimentary	(Teerawattanasuk et al., 2014)
0.2-1.3	14-44	Pull out test in field	(Voottipruex et al.,2008)

Root area ratio

Root area ratio (RAR) is one of the other important elements used to calculate root cohesion. This factor varies between species, within the same species located in different areas, and in three dimensions, as a general trend it decreases as soil depth increases. The values range between 0-0.5% (Bischetti et al., 2009; De Baets et al., 2008; Leung et al., 2015).

One technique to estimate RAR consit in to take samples or root-permeated soil and at various depths and measure the root biomass per unit voulme (Gray & Sotir, 1996). Other way consist in measure directly using trench walls which can be orientated perpendicular and paralell to the profile, where the root exposed in the vertical side of the trenches are mapped by overlaying an acetate gridded on the wall (Böhm, 1979). It is necessary to assume that the area ratios are the same in all directions when RAR is used to calculate the factor of safety using the infinite slope model (Gray & Sotir, 1996).

In several researched the roots at different depths are grouped into different diamterer classes and the number of roots in each interval is recorded, then the root areas of a each single root is summed. The cross section vaires depending on the plant specie, assuming that all root have a circular cross section (Leung et al., 2015; Preti & Giadrossich, 2009).

2.2. General aspects of vegetation on slope stability

The processes mentioned above are related to plant structures such as roots, an element in which this section will be focused given the scope of the research.

2.2.1. Plant form

There are more than 300,000 plant species which can perform the photosynthesis process divided in multiple subgroups. A scientific way to classify them is through their taxonomic group (Kingdom, Phylum, Class, Order, Family, Genus, and Species) (Shipunov, 2016). Another way of classification is based on the tissues that help to transport water and minerals (Xylem and Phloem). Plants that have such tissues are called "vascular plants" (they develop true roots, stem and leaves), while "nonvascular plants" do not own those tissues, such as mosses (Fernández, 2010).

Within the group of vascular plants two groups can be recognized: Gymnosperms and Angiosperms. Gymnosperms present seeds that do not develop inside a fruit (for example pines); Angiosperms develop fruits with seeds. Angiosperms group is divided in Monocotyledonous whose seeds have a single primordial leaf (e.g., grasses); and Dicotyledonous whose seeds have two primordial leaves (e.g., broadleaf plants) (Fernández, 2010).

Plant classification may be varied, but also a distinction can be done based on the form and structures they have. In civil engineering there is an easy way to classify the type of plant, which use mainly three groups: trees, shrubs and grasses (Coppin,et al., 2007).

Trees are considered as those woody plants larger than 3 meters that grow from a single upright main trunk with branches in the upper part forming a crown. Shrubs are considered as plants of substantial stature with perennial growth. They are smaller than a tree but sometimes they overlap with this group and they are characterized because of their fairly dense and well-branched stems (Coppin et al., 2007).

Another group of plants are grasses. They are members of the Poaceae family, presenting linear leaves with parallel venation typical of monocotyledons (Levetin & McMahon, 2008). Grasses can reproduce themselves by producing new stems from the bases of existing ones. They are a versatile and widespread group of plants which are most commonly used for engineering purposes (Coppin et al., 2007).

2.2.2. Roots

Roots are generally the non-photosynthetic part of the plant, and they have a variety of functions. Among these functions the uptake and conduction of water from the soil to all the other plant structures are the most important purpose. Linked to it, absorption of minerals is another vital function. Also, roots allow the anchorage of the plant to the soil and in some cases it helps to propagate as a way of reproduction. Other functionalities of roots are the storage of food and mobilization of these reserves for the metabolism of the plant and the production of plant growth regulators (Scott, 2008). Though roots are an important structure of the plant, they are frequently neglected when studying plant organs (Scott, 2008). Nevertheless in studies on slope stability, this plant structure plays an important role as will be shown in the next sections.

In general the roots can be divided in two groups: true roots, and adventitious roots, depending if they develop below or above ground. True roots can be subdivided in two main types according to their form: taproots and fibrous roots (See *Figure 2-9*). There can be other root forms, but these are specializations of the two main divisions. As a general rule, Monocotyledons present only fibrous roots, whilst Dicotyledonous can present both types (Scott, 2008).

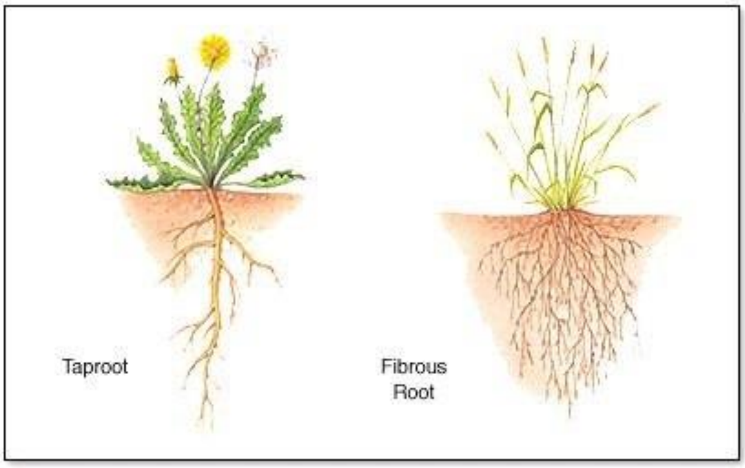

Figure 2-9. Different forms of true roots in plants. Monocotyledons present only fibrous roots, whilst dicotyledonous can present taproots or fibrous roots.

Taproots show a main root which can reach large depths and present many lateral roots. The diameter of the main root is thick in the top portion, and tapers to the bottom in the growing base. Fibrous roots are made up with many roots with equal diameter. These kinds of roots do not penetrate deep into the ground but spread out widely (Scott, 2008).

Root architecture refers to the spatial configuration of the root system such as the geometric deployment of root axes. In this configuration generally small or fine details are not included (Lynch, 1995). Uniform, triangular, exponential (hearth-shaped), and plate, are some of the main types of root architecture presents in vegetation (See *Figure 2-10*) (Ng et al., 2015). It is not easy to determine the architecture of a root system; it shows variation between species because it is genetically determined, and even within different parts of a single root system of the same individual the architecture varies (Lynch, 1995). On the other hand, external factors also affect its development and growth such as availability of air and soil nutrients, soil moisture and permeability, variation of groundwater table, soil compactness, among others (Stokes et al., 2008). Diversity of root architecture is therefore an intriguing aspect of the morphology of plants (Di Iorio et al., 2005; Lynch, 1995).

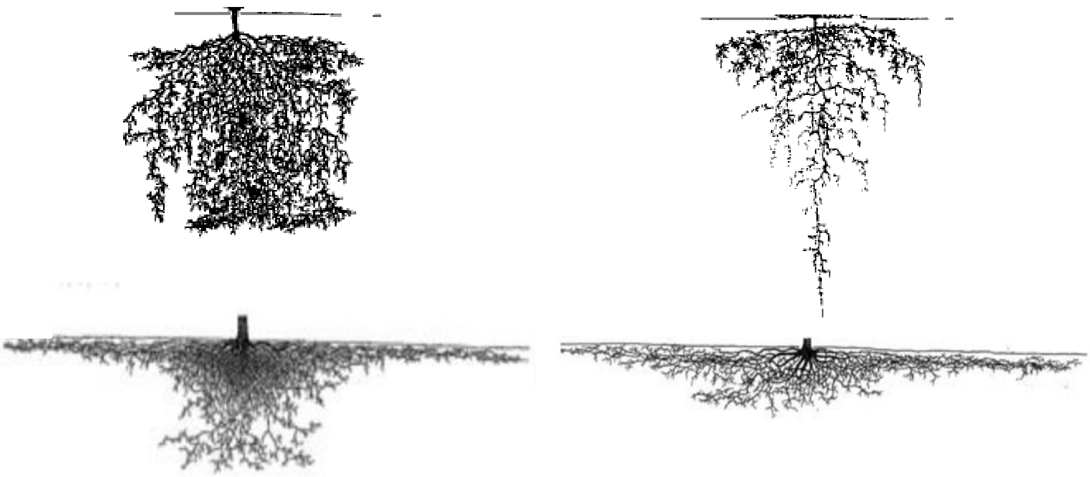

Figure 2-10. Main types of root architecture. Above left: uniform. Above right: triangular. Bottom left: Exponential. Bottom right: plate (Kutschera & Lichtenegger, 1997)

Nutrient supply affects root development. For example, root length of tomato plants showed an increment when they were exposed to bacteria that helps to absorb more nutrients (phosphorus), necessary for the development and metabolism of the plant (Sánchez,et al., 2012). In another case, when plants are exposed to drought they can increase root depth to reach deep soil layers and find the water table as an adaptive root trait (O'Toole & Bland, 1987).

Leung et al. (2015) suggest that the roots of shrubs have a diameter lower than roots of trees, and root system of trees extend deeper into the soil. In general it is not common that roots of plants penetrate greater than 2 meters into the soil. Actually, 80 to 90% of the roots is present in the first 60 centimeters of depth (See *Figure 2-11*) (Crow, 2005).

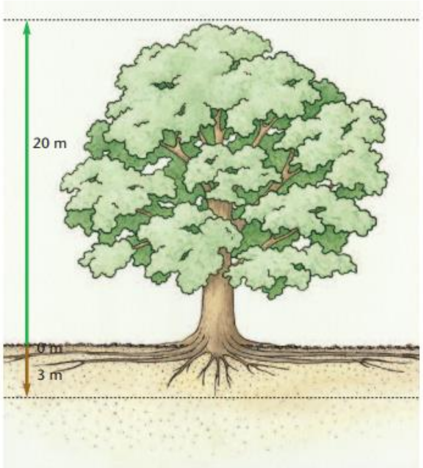

Figure 2-11. Representation of a tree root system (Crow, 2005).

2.2.3. Vegetation: communities and succession

Plants species are not in the environment as individual entities, but are interacting with other plants and animals forming dynamic communities with recognizable assemblages. Plant communities are defined as a uniform environment with a relatively constant floristic composition and structure, which can be distinguished from another surrounded communities (Bakker & van der Maarel, 2009).

Though it seems communities can stay stable, they are dynamic assemblages with a constant turnover of individuals, because the changes in climate, ground conditions, grazing, etc. make the communities adapt to the new circumstances (Coppin et al., 2007). Plant communities can show a three-dimensional structure depending on the spatial arrangement of the morphological elements. This can be based on the size of the dominant plants (trees, shrubs, grasses), its temporal arrangement (perennial, deciduous) and its spatial distribution (continuous or scattered cover) (Bakker & van der Maarel, 2009).

As it was mentioned before, communities are dynamic; such changes can be driven by environmental factors such as climate, soil, and also management regime. One of the most important kinds of change in communities is the natural succession. In this process, a plant community develops towards a climax stage through several progressive stages (Coppin et al., 2007). Climax is the potential natural vegetation which would develop under the present climatic, soil an historical conditions if all human activities were removed (Tüxen, 1956 as cited in Coppin et al., 2007).

As an example of a natural succession process, the mountain region of Nepal shows that grasses are replaced by trees to regenerate a forest, following a gradual decline in disturbance (L. N. Sharma, Vetaas, Chaudhary, & Måren, 2014). A study analyzing the effect of natural succession and its consequences on slope stability stays that this progression limits the surface processes declining the mass wasting after a long time of suspended human activities (Cammeraat, van Beek, & Kooijman, 2007).

In a Nepalese environment, where landslides are frequent and bare slopes with raw minerals, weathering elements and fragments of rocks are present, probably the first species in colonize those areas will be pioneer grasses and shrubs such as *Artemisa vulgaris*, *Saccharum spontaneum* and *Vitex negundo*. They will establish easily on infertile soils and will provide the conditions for other species to be established in the area. This because its presence will increase the permeability of the soil and its foliage will cause reduction of evaporation, as well as it will reduce the impact of the drops reducing erosion; besides their roots will provide soil reinforcement and promoting soil conservation for successor species. After a period of approximately two years these species will be gradually replaced by large woody shrubs and trees like *Melia azedarach* and *Butea minor* which tend to provide shade under their crown avoiding that the pioneer species remain present. These species will be replaced as well by other species with longer life-span such as *Alnus nepalensis* following a natural succession (Howell, 1999a).

2.3. Modelling slope stability

2.3.1. Infinite slope stability model

Factor of safety (FOS) is a commonly used index to describe the stability of a slope. It is defined as the ratio of the resistance of the soil mass along a potential slip plane to the shear force; this means shear strength as numerator and shear stress as the denominator (Morgan & Rickson, 1995). A slope is stable when the value of FOS is >1; if the value is <1 it is considered unstable.

To analyze how effective a species (with certain characteristics) can enhance slope stability, the FOS can be calculated trough the infinite slope model. This model shows the forces that prevent the slope from failing divided by the forces that make the slope fail. These forces can be expressed as follows:

$$FOS = \frac{c' + (\gamma z - \gamma_w h_v) cos^2\beta \; tan\phi'}{\gamma z \; sin\beta \; cos\beta}$$

Equation 5

Where, *c'* is the effective cohesion (in drained conditions) of the soil (kN/m^2); γ is the bulk unit weight of soil (kN/m^3); z is the depth of soil to shear plane (m); γ_w is the density of water (kN/m^3); h_v is the height of groundwater level above shear plane (m); β is the slope angle (degrees); and ϕ' is the effective angle of friction (degrees) (Leung et al., 2015; Morgan & Rickson, 1995). The parameters expressed in the equation are illustrated in *Figure 2-12*.

2.3.2. Infinite slope stability model including the effects of vegetation

Slope stability can be modified due the influence of vegetation; these influences can be included in the calculations of the factor of safety (Morgan & Rickson, 1995):

$$FOS = \frac{(c' + c'_R) + \{[(\gamma z - \gamma_w h_v) + W] cos^2\beta + Tsin\theta\} tan\phi' + Tcos\theta}{[(\gamma z + W) sin\beta + D] \; cos\beta}$$

Equation 6

Such influences are: enhanced effective soil cohesion due to soil reinforcement by roots (c'_R); surcharge due to weight of the vegetation (*W*); tensile root force acting at the base of the slip plane (*T*); angle between roots and slip plane (*θ*); and wind loading force parallel to the slope (*D*) (Morgan & Rickson, 1995).

Some researches used the infinite slope stability model to analyse the effect of vegetation. For example, Leung et al. (2015) Simon & Collison (2002), and Preti & Giadrossich (2009) included in the infinite slope model the effect of root cohesion and surcharge; while Riestenberg (1994) included the effect of the roots providing anchoring to the soil. Each of the researches adopted the infinite slope model to their own researches according to the variables they analysed.

All the variables mentioned in Equation 6 can be analysed with the infinite slope model. However a simplification can be done to analyze the effect of the cohesion contributed by the presence of roots in the soil and the surcharge of vegetation using the following formula:

$$FOS = \frac{(c' + c'_R) + \left((\gamma z - \gamma_w h) + W\right)\cos^2\beta \tan\phi'}{(\gamma z + W)\cos\beta \sin\beta}$$

Equation 7

Here, c'_R is the root cohesion or enhanced shear stress due to the presence of roots (kN/m^2); and W is the weight of vegetation (kN/m^2) (See *Figure 2-12*).

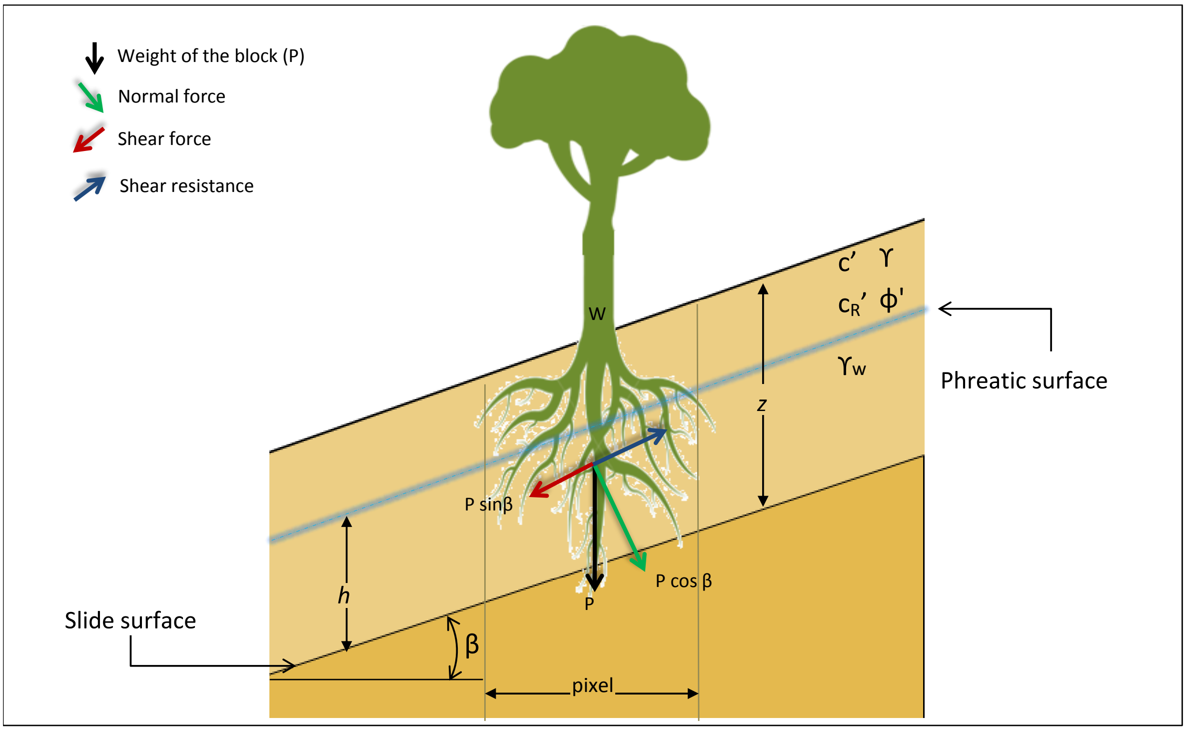

Figure 2-12. Schematization of the parameters applied in the slope stability analysis. c': effective cohesion of the soil, γ: bulk unit weight of soil, z: depth of soil to shear plane; γ_w: density of water, h: height of groundwater level above shear plane; β: slope angle, ϕ': angle of friction, W: weight of vegetation, and c'_R is the root cohesion or enhanced shear stress due to the presence of roots. Last two parameters are due presence of vegetation.

The infinite slope model can be incorporated into a Geographic Information System and model by computer the stability of a given slope which helps to interact with different scenarios in a spatial way. Different models have actually have been developed to assess or analyze the factor of safety of a slope. For example, TRIGRS (Transient Rainfall Infiltration and Grid based Regional Slope Stability Analysis). It is based in the infinite slope model but it does not take into account the role of vegetation (Baum et al., 2002). SINMAP (Stability Index Mapping) is a model which is run in the software Arc View®. It is also based in the infinite slope model and includes the root cohesion parameter; nevertheless it does not calculate the temporal probabilities of failure of a slope because it works with a steady-state hydrology model (Pack et al., 1998). STARWARS+PROBSTAB model includes several parameters where vegetation plays a role such as: root cohesion, crop factor, canopy storage, trough fall ratio, and potential evapotranspiration (van Beek, 2002). This model was compared with the other two previous models by Kuriakose (2006) and showed that it has a better performance in the prediction of unstable slopes. Therefore, this model can be considered for the evaluation of the effect of vegetation on the stability of the slopes in this study.

2.4. Vegetation used on slope stability and their benefits

Ecosystems are important for disaster risk reduction since they have the potential to influence in the frequency and magnitude of hazard events, the exposure of people and their belongs to hazards, and vulnerability trough the sustainable ecosystem management (Renaud et al., 2013). When ecosystems are degraded, the impact of natural hazards may be increased because for example, physical processes that regulate de magnitude and frequency of the hazard are altered (Estrella & Saalismaa, 2013). Regarding landslides, vegetation can reduce the probability of their occurrence through the different processes described in previous sections.

Ecosystem-based disaster risk reduction refers to the sustainable use of ecosystems to reduce disaster risk and achieve sustainable development (Estrella & Saalismaa, 2013). Ecosystems can provide multiple services which can be the direct or indirect benefits people obtain from nature (Estrella & Saalismaa, 2013). Those benefits can be summarized in provisioning, regulating, habitat, and cultural and amenity services (TEEB, 2010) (See *Table 2-3*).

Table 2-3. Ecosystem services (TEEB, 2010).

PROVISIONING SERVICES
Food (e.g. fish, game, fruit)
Water (e.g. for drinking, irrigation, cooling)
Raw Materials (e.g. fiber, timber, fuel wood, fodder, fertilizer)
Genetic resources (e.g. for crop-improvement and medicinal purposes)
Medicinal resources (e.g. biochemical products, models & test-organisms)
Ornamental resources (e.g. artisan work, decorative plants, pet animals, fashion)
REGULATING SERVICES
Air quality regulation (e.g. capturing (fine) dust, chemicals, etc.)
Climate regulation (incl. C-sequestration, influence of vegetation on rainfall, etc.)
Moderation of extreme events (e.g. storm protection and flood prevention)
Regulation of water flows (e.g. natural drainage, irrigation and drought prevention)
Waste treatment (especially water purification)
Erosion prevention, and slope stability
Maintenance of soil fertility (incl. soil formation)
Pollination
Biological control (e.g. seed dispersal, pest and disease control)
HABITAT SERVICES
Maintenance of life cycles of migratory species (incl. nursery service)
Maintenance of genetic diversity (especially in gene pool protection)
CULTURAL AND AMENITY SERVICES
Aesthetic information
Opportunities for recreation & tourism
Inspiration for culture, art and design
Spiritual experience
Information for cognitive development

Many studies analyze the role of vegetation in slope stability (included in regulation services), being root system the most important aspect considered. Nevertheless, other benefits that vegetation used for slope stability can provide is still incipient, so it is important to develop research on this research field since vegetation not only role over abiotic processes in situ, but also it influences the environment surrounding (Stokes et al., 2009).

The benefits that can be obtained from vegetation are diverse. One of the direct benefits obtained from vegetation is the provision food, both for human consumption and for farm animals. It can also be used in the construction of households, or furniture (TEEB, 2010). Vegetation also can provide cultural or religious benefits, since many species are used in spiritual rituals (Turin, 2003). Regarding to human well-being, vegetation can be used in health matters, as there is evidence that shows that plants are used for medicinal and therapeutic purposes (Turin, 2003). On the other hand also provides environmental benefits such as the regulation of climatic processes or the treatment of contaminated water sources, as well as mitigating the effects of natural hazards. Vegetation also offers opportunities for recreation and tourism by providing aesthetic spaces which can serve as inspiration for culture, art and design (TEEB, 2010).

Studies about bio-engineering strategies to reduce landslide hazards including the benefits vegetation can provide have not been fully developed. As the study area is highly prone to landslides and has a wide diversity of ecosystems, this research is an important approach for ecosystem-based disaster risk reduction in the area, hoping to provide useful information that serves to plan and implement better measures for slope stabilization in Nepal.

3. PLANT SPECIES USED FOR SLOPE STABILIZATION IN NEPAL

In this section the study area is presented and a description is given on how references and fieldwork were combined to obtain a list of plant species used in this study to analyse their effect on slope stability. An overview is given of their main characteristics, with a focus on root characteristics, as well as the potential benefits they can provide in a Nepalese mountain environment.

3.1. Study area

The study is located in the south of Rasuwa District, Nepal, between the coordinates 85°08' and 85°16" East and 27°58', and 28°06' North (See *Figure 3-1*). The altitude of the area ranges from 710 (masl) at the flow of the Trisuli River up to more than 2,000 (masl), with a mountainous relief, predominantly rural. Average temperatures during the coldest month is 16.2 ° C (January) and the hottest month is 28.8 ° C (June). Rainfall during the rainy season can reach a monthly average of 132 mm. (Goverment of Nepal, 2016b).

The study area is located in the physiographic region Middle hills, where altitudes can vary considerably within short distances; since in the river valleys are often very deep (around 500 m) and the ridge tops may be at 2000 m or more. The valleys usually are not inhabited, but the hill slopes generally are subject to terrace cultivation and inhabited by people grouped in single villages (Jackson, 1994a). Two climatic zones are identified, the subtropical which ranges between 1000-1700 m and the tropical which is below 1000 m. The subtropical zone is manly dominated by coniferous forest where the main specie is *Pinus roxburghii*; and the other main forest type in this zone is slope mixed hard-wood, whose main species are *Schima wallichii* and *Alnus nepalensis*. In the tropical zone the deciduous hill forest dominate, where the main species is *Shorea robusta* (Springate-Baginski et al., 2003).

Regarding its geology, it is located in the Kuncha formation which is exposed in the core of the Great Midland Antiform. Here it appears metamorphic rocks, such as phyllite, phyllitic metasandstone, amphibolite, schist, marbles, and gneisses (Dhital, 2015). In Nepal, the Main Central Trust is a fault where the Indian Plate is pushed under the Eurasian Plate, incrementing the metamorphic grade from the Lesser Himalaya to the Greater Himalaya influencing the study area (Searle et al., 2008).

Livelihoods in the study area are related mainly to agriculture, where people of the community develop this activity in terraces of farmland (See Appendix A). The middle-class households own also cattle and are depend on the farming. Poor households develop activities for example artisanal work and they collect Non-Timber Forest Products such as pine resin and many herbs which are marketed to local wholesalers. Richer households own local business but also terraces with farmland (Springate-Baginski et al., 2003).

The rugged terrain, its geology and the heavy rainfall amounts during monsoon season, combined with the activities developed by local people make the area prone to landslides. So measures to address this problem must be taken into account such as bio-engineering.

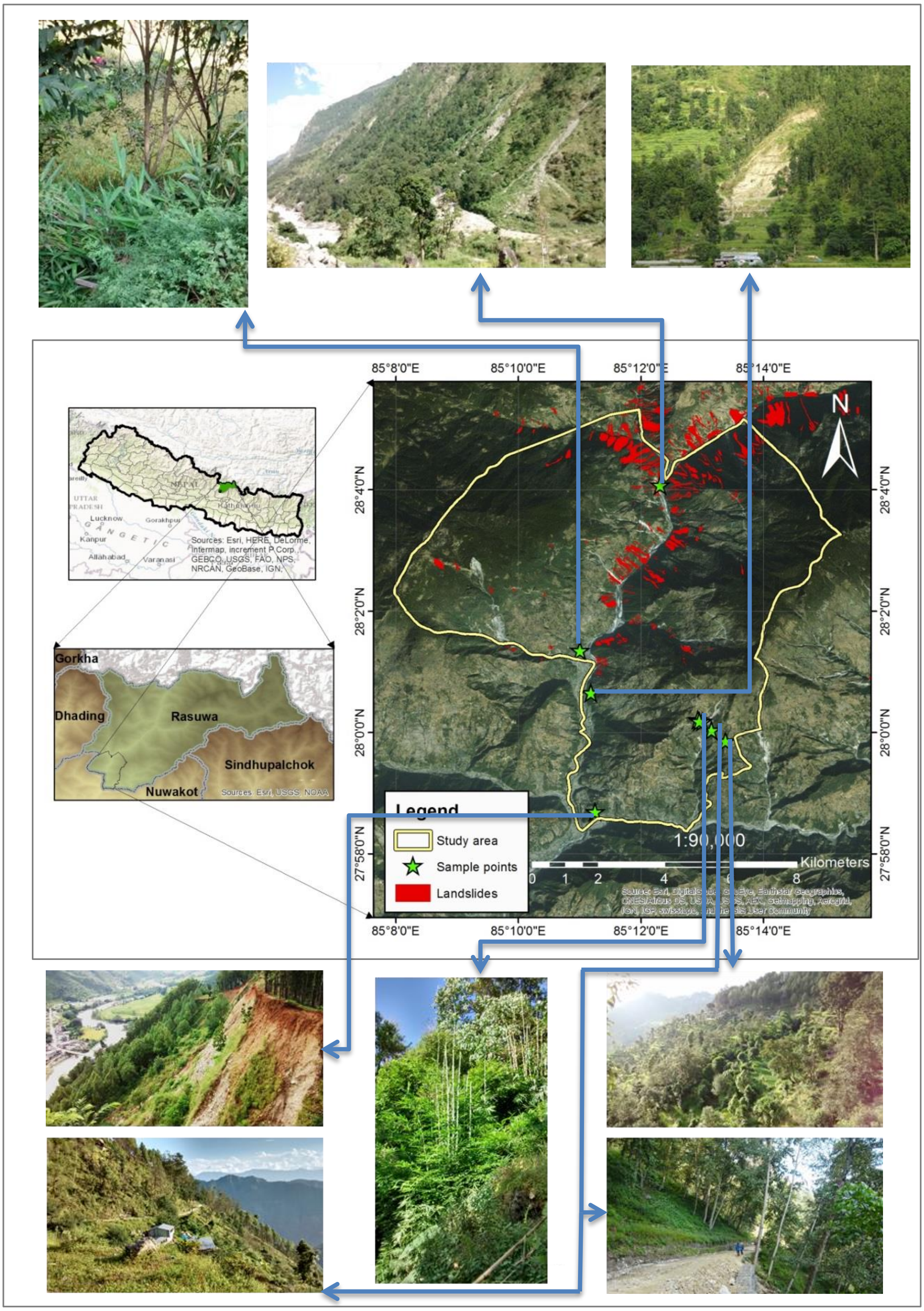

Figure 3-1. Location of the study area and sample points.

3.2. Getting a list of plant species used for slope stability

To generate a list of plant species used for slope stabilization in Nepal, a bibliographic research was made including textbooks, handbooks, journals, theses, using mainly a web search engine. Previous works done related to the role of vegetation on slope stability in Nepal were reviewed considering that Nepal has a large history of bioengineering approaches applied for at least 20 years (Devkota et al., 2014). The results obtained from fieldwork were compared with that information from literature.

3.2.1. Fieldwork

Fieldwork was carried out during October 2016, Nepal. The main purpose was to explore the study area, obtain information from key informants about plant species used for slope stability, and to know the importance and benefits that people obtain from those species. During the first week of fieldwork two workshops were attended. The first one was the Scientific Larning Eschange on Landslide Management & Bio-engineering in Nepal: Data to Landslide Mitigation – New Venues for Collaboration. The second one was Ecosystem Protecting Infrastructure and Communities, National Workshop on Eco-DRR for Improving Community Resilience. In those workshops contacts e information was retrieved which was used to have a better idea about the bio-engineering in Nepal. The last workshop included a visit to Pokhara were it was visited two sites where bio-engineering was used for reduction of soil erosion (See *Figure 3-2*). In this field visit it was observed that the participation of local people is a vital factor to develop this kind of strategies, because when people are involved and take bio-engineering projects as their own, their maintenance will be carried out regularly since people gain benefits from these strategies, both economic and in safety by reducing soil erosion.

Figure 3-2. Bio-engineering technique applied in Pokhara, Nepal.

In the study area, Rasuwa district was explored from Dhunche in the North to Laharepauwa in the South along the Pasang Lhamu Highway. There, it was observed that mainly in the northern part the landslides presented there were mainly deep seated, so vegetation cannot provide reinforcement to the soil. For this reason it was decided to focus on the southern part of the district where more shallow landslides were observed.

In the south part of the district, eight non-structured interviews (Rojas, 2006) were done to key informants who included local experts who have worked with bioengineering measures, as well as community people. They were considered as an important source of information. Selection of key informants was done with the snowball technique were a first person helped to identify other people who had a relation with bio-engineering or plant species used for slope stability.

The non-structured interviews consisted in open questions related with the experience the interviewed had with plants used for slope stability. The interview did not have an order stablished, acquiring conversation characteristics. The conversation developed spontaneously and informally in the subject, with the purpose to inquire which species they recognize to be used for slope stability and what are the benefits that can be obtained from them (See Appendix B).

The key informants guided us to the zones prone to landslides and where bio-engineering were implemented (See *Figure 3-1*). The sample areas were selected according to the expertise of the interviewed person, who was able to recognize the areas where bio-engineering techniques were applied. During the visits to the areas, the key informants showed and named the species recognized as used in bio-engineering, then the name of the species that they recognized as used for slope stability was recorded including the benefits the interviewed mentioned. In general, the common nepali name of the species used for slope stability was provided. The information provided was compared with the species reported in the literature used for slope stability in Nepal and then selected just those used with that purpose.

Once the final list of species was obtained, another bibliographical research was done to search benefits that these species provide besides slope stability. For example, as fodder or fuel, construction of houses, for aesthetic, recreation, medicinal or religious use. This information was added to the information provided by key informants. Also, information about root length, root architecture, and crown area was searched on literature. In some cases field observation was the resource. The aim of the inventory was to have a list of possible vegetal species and their respective characteristics, to be used for the analysis of slope stability, described in the next chapter.

3.3. Species used for slope stability in the study area

In the literature search, two main documents were found which compile a list of species that are used in bio-engineering in Nepal: Howell, (1999b) and Devkota et al. (2014). Basically Howell (1999) is the basis of the other document. In this 167 species are congregated into four different groups: grasses (35 species), shrubs (57 species), bamboos (6 species), and trees (69 species). The lists of species include information about the common name of the species, their distribution, form of propagation and some additional characteristics. But they do not include information about the characteristics of roots such as tensile strength that is useful for slope stabilization.

During the field work, a total of 33 species were mentioned by the people interviewed. Of these, 17 plant species were identified as useful for bio-engineering in the literature. Of the total of 17 species, two correspond to grasses, two bamboos, five shrubs, and eight trees. In Appendix C it is shown the list of the species reported as well as a brief description with relevant data.

3.3.1. Characteristics

In *Table 3-1* it is shown the information compiled about root characteristics useful for the analysis of slope stability and crown area used to calculate the area where the roots can extend, which is related with the distribution of the weight of a tree (See Chapter 4). In this table just information about root length and root architecture is shown. Root tensile strength and root area ratio values were obtained from other species (See Chapter 4) and they were not included in this chapter due the information was not possible to be retrieved directly from the species present in the study area, so that information had another treatment. As can be observed, for several species the information was not available, due in many cases there is no research done in the underground structure of the plants. In the case of information about crown area, it was just retrieved for trees. The lack of information about the characteristics of the root system of the different species shows that there is still much work to be done on studies of species used in bio-engineering for slope stability, for species already reported as useful in that aspect.

Table 3-1. Plans species with information about root length, root architecture and crown area.

	Scientific name	Root length (m)	Root architecture	Crown area (m^2)	Root area (m^2)
Grasses	*Chrysopogon gryllus*	0.3 (Gupta, 2016)	Fibrous (Scott, 2008)	-	
	Thysanolaena maxima	0.75 (Neupane, 2005)	Fibrous (Scott, 2008)	-	
Bamboos	*Bambusa balcooa*	0.7*	Fibrous (White & Childers, 1945)	-	
	Drepanostachyum intermedium	0.3 (Stapleton, 1994)	Fibrous (White & Childers, 1945)	-	
Shrubs	*Berberis asiatica*	0.35 (Hudek, 2013)	Tap root (Hudek, 2013)	-	
	Buddleja asiatica	4 (Tallent-Halsell & Watt, 2009)	Extensive network (Tallent-Halsell & Watt, 2009)	-	
	Colebrookea oppositifolia	0.2 (Devkota et al., 2008)	Tap root (Devkota et al., 2008)	-	
	Vitex negundo	5 (Howell, 1999a)	Tap root (Howell, 1999)	-	
	Woodfordia fruticosa	-	-	-	
Trees	*Acacia catechu*	2 (Howell, 1999a)	Taproot (Howell, 1999a)	4.58 (Singh, 2001)	6.87
	Alnus nepalensis	2 (Howell, 1999a)	-	11.34 (R. P. Sharma, Vacek, & Vacek, 2016)	17.01
	Ficus semicordata	-	-	1.4 (Bahadur, 1992)	2.1
	Melia azedarach	2 (Howell, 1999a)	Taproot (Tourn, Menvielle, Scopel, & Pidal, 1999)	11.52 (Mishra, Nautiyal, & Nautiyal, 2009)	17.28
	Morus alba	1.4 (Verma, Kohli, Kaushal, & Chaturvedi, 2014)	-	15 (Velázquez-Martí, Sajdak, & López-Cortés, 2013)	22.5
	Pinus roxburghii	1.5 (Dupuy et al., 2003)	Tap root (Dupuy et al., 2003)	19 (Khanduri & Sharma, 2002)	28.5
	Salix tetrasperma	-	-	19.6*	29.4
	Schima wallichii	-	-	19.6*	29.4

*Field observation

3.3.2. Benefits

With regard to the benefits that the plant species can provide to the population (See Appendix C), the results of the interviews show that they obtain mainly provisioning benefits; due the use that is mainly given to the species is fodder. In some cases, it is reported that some of them are used for construction of houses (*Bambusa balcooa*, *Pinus roxburghii*, and *Schima wallichii*). Two of the species were reported as particularly good on slope stability (*Thysanolaena maxima* and *Vitex negundo*). In terms of the benefits reported in the literature, in general these were expanded, mainly in the medicinal aspects and all of them in regulating services since they are already reported as useful for slope stability. However, in another cases the list of benefits was barely expanded (*Chrysopogon gryllus, Thysanolaena maxima, Drepanostachyum intermedium, Melia azedarach,* and *Salix tetrasperma*). Apparently the benefits they can provide are limited.

The benefits reported by the people of the study area and those reported in the literature were grouped into the different groups (See *Table 3-2*) that TEEAB (2010) makes of ecosystem services. The main kind of ecosystem service reported by local people corresponds to provisioning. Local people did not report any provisioning benefit for three species. Three species were reported were included in regulating services since they emphasize the use of the specie on slope stability. They did not mentioned any service for habitat neither for cultural or amenity.

Table 3-2. Resume of benefits of different plant species used for slope stability in the study area grouped in main services types.

Scientific name	Provisioning		Regulating		Habitat		Cultural and amenity	
	F	L	F	L	F	L	F	L
Chrysopogon gryllus	x	x		x				
Thysanolaena maxima	x	x	x	x				
Bambusa balcooa	x	x	x	x				
Drepanostachyum intermedium	x	x		x				
Berberis asiatica	x	x		x				
Buddleja asiatica	x	x		x				x
Colebrookea oppositifolia	x	x		x				
Vitex negundo		x	x	x				
Woodfordia fruticosa		x		x				
Acacia catechu		x		x				
Alnus nepalensis	x	x		x				
Ficus semicordata	x	x		x				
Melia azedarach	x	x		x				
Morus alba	x	x		x		x		
Pinus roxburghii	x	x		x				x
Salix tetrasperma	x	x		x				
Schima wallichii	x	x		x				

F: Field work, L: Literature.

In the study area local people report limited benefits that the species can provide. Nevertheless, the benefits they obtain can be extended if the information and guidance is provided to them. The sustainable use of the different species by the community should be included when slope stabilization works are done.

4. MODELLING THE EFFECT OF VEGETATION ON SLOPE STABILITY

It has already been mentioned in previous sections that vegetation fulfills certain functions that regulate processes involved in the stability of slopes. In this section, the role of different species that occur within the study area in Rasuwa district in Nepal, will be will analyzed from two points of view mainly. The first, considering the reinforcement in the soil, induced mainly through the root systems (cohesion); and the second, through the overload added by the presence of vegetation (surcharge). Hydrological aspects were not included in this research due the lack of data.

To carry out this task, the infinite slope model was used to evaluate the effect of the vegetation on slope stability. The methodology followed in this research and their respective results obtained will be described in this chapter.

4.1. Infinite slope stability model analysis

To analyze how effective a species (with certain characteristics) or combination of species can enhance slope stability, the Factor of Safety (FOS) was calculated trough the infinite slope model. This factor was calculated by using *Equation 7* described in Chapter 2.

The infinite slope model allows to analyze the effect of different characteristics of vegetation. However given the scope of this study, the effect of vegetation was focused on analysing the effect of the cohesion contributed by the presence of roots in the soil and the surcharge of vegetation. The data necessary to run the model was derived from literature for the different plant species and included in the formula to see how the FOS changed according to the different parameters.

The calculus of FOS and the effect of vegetation (root cohesion and surcharge) were analyzed taking into account different circumstances, varying soil depth and slope angle:

1. Analysis of FOS including root cohesion in a hypothetical slope with:

a) All the soil parameters fixed,
b) All the soil parameters fixed except soil depth,
c) All the soil parameters fixed except slope angle.

2. Analysis of FOS including surcharge of trees in a hypothetical slope with:

a) All the soil parameters fixed,
b) All the soil parameters fixed except soil depth,
c) All the soil parameters fixed except slope angle.

- Finally an analysis considering different scenarios was performed combining the effect of four plant form groups: grasses, bamboos, shrubs and trees.

4.2. Data collection for the infinite slope model

Since in this research it was not possible to perform the necessary tests to measure root cohesion and surcharge, the values were estimated with information obtained from literature or trough mathematical equations.

4.2.1. Root cohesion estimation

Root cohesion

Among the two main models used to estimate root cohesion, the Wu and Waldron Model was selected due the capability to parameterize it (See *Equation 4*). In this model the main parameters to estimate root cohesion are Root Area Ratio (RAR) and Tensile strength. Information about RAR for the different species here analyzed was not available, so RAR was assumed according to values present in literature (*Table 4-1*). In literature it was not possible to find information about how RAR is distributed in bamboos, so in this case it was decided to take the same values as for grasses since they belong to the same family (Poaceae) and they present similar root architecture (fibrous).

Table 4-1. RAR mean values for different plant forms.

Plant form	Soil depth				Source
	0.1 m	0.3 m	0.7 m	1 m	
Grass (*Lygeum spartum*)	0.0020	0.0002	0.00002	-	(De Baets et al., 2008)
Bamboo	0.0020	0.0002	0.00002	-	Assumed
Shrub (*Berberis aquifolium*)	0.0004	0.0003	0.00020	0.00010	(Hudek, 2013)
Tree (*Larix decidua*)	0.0020	0.0010	0.00020	0.00005	(Bischetti et al., 2009)

Tensile strength

For the different species analyzed in this research it was not possible to carry out the necessary tests to measure tensile strength, so mean tensile strength values were retrieved from literature. Nevertheless, for the specific species analyzed in this project there is no research made on the mechanical characteristics of their roots, so an alternative was taken. If information about mean tensile strength of the root of the species was not available, then information about other species from the same genus with similar characteristics was taken into account. In some cases, the information was still not available, so the power function showed in *Equation 8*

and the values proposed by Mao et al., (2012) (See *Table 4-2*) were used to estimate values of tensile strength for herbaceous plants, shrubs, and trees. Where α and β are empirical constants depending on species, in this case plant group and *d* is the root diameter.

$$Tr = \alpha d^{-\beta}$$

Equation 8

Table 4-2. Empirical constants used to estimate tensile strength for different plant groups (Mao et al., 2012).

Plant form	α	β
Trees	39.63	0.70
Shrubs	29.23	0.69

Herbs	21.05	1.15

4.2.2. Surcharge

In this research direct methods to measure the weight of a tree were not possible to carry out. So, other practical methods were used to be able to obtain the data required in this study by using allometric curves that make use of characteristics of trees such as diameter at breast height.

Data to analyze the effect of vegetation due to surcharge was also obtained from secondary sources, as in the case of root cohesion. Some of the species here analyzed counted with specific biomass tables from the Community Forest Management from Nepal (Tamrakar, 2000), so from such tables the information was retrieved. Therefore, it was not necessary to calculate such information with allometric equations.

In this study, for those species whose information was not retrieved directly from literature, the calculation of its biomass was carried out using the allometric regression shown in the next equation:

$$bm = e^{a+b\ ln\ DBH}$$

Equation 9

Where *bm* is the total aboveground biomass (kg), *DBH* is the diameter at breast height (cm), *e* is the exponential function, *ln* is the natural log base "e" (2.718282), and *a* and *b* are regression coefficients for each species group (See *Table 4-3*). In all the cases, information about DBH for each species was retrieved from literature and considered as the mean value.

Table 4-3. Regression equation coefficients to calculate total above ground biomass (Jenkins et al., 2004).

Species group of hardwood	a	b
Aspen/alder/cottonwood/ willow	-2.2094	2.3867
Mixed hardwood	-2.4800	2.4835

Once the calculations of biomass were done, total weight units of the trees were multiplied by the gravity to estimate the force that they exert, and then divided by the root surface of the tree presented in *Table 3-1*. Finally the units were transformed to obtain the parameter *W* required in the infinite slope model in kN/m^2 or kPa. It was not possible to find information about the horizontal extension of the roots of the different species of trees in the study area. Nevertheless the extension was assumed, since there is evidence suggesting that the extension of tree roots is 1.5 higher than the crown of the tree (Suarez, 1998).

4.3. Results of moddelling the effec of vegetation on slope stability

4.3.1. Species analysed

In this research a total of 17 species and the effect of their mechanical characteristics on slope stability were analysed. Among the total of 17 species, two belong to the bamboo group, two are grasses, five are shrubs, and eight are characterized as trees (*Table 4-4*).

Table 4-4. Species located in the study area, their common name and the plant form they belong. The last row shows the species from which information about tensile strength was obtained to perform FOS analysis.

Scientific name	Common nepali name	Plant form	Similar species with data about tensile strength to calculate root cohesion
Chrysopogon gryllus	Salimo	Grass	*Chrysopogon zizanioides*
Thysanolaena maxima	Amliso	Grass	*Thysanolaena maxima**
Bambusa balcooa	Bamboo	Bamboo	*Bambusa distegia*
Drepanostachyum intermedium	Nigalo	Bamboo	*Chimonocalamus dumosus*
Berberis asiatica	Chutro	Shrub	*Berberis aquifolium*
Buddleja asiatica	Bhimsen Pate	Shrub	-
Colebrookea oppositifolia	Dhurseli	Shrub	*Colebrookea oppositifolia*
Vitex negundo	Simali	Shrub	*Vitex negundo**
Woodfordia fruticosa	Dhayero	Shrub	-
Acacia catechu	Khayer	Tree	*Acacia mangium*
Alnus nepalensis	Utis	Tree	*Alnus subcordata*
Ficus semicordata	Khaniyo	Tree	*Ficus microcarpa*
Melia azedarach	Bakaino	Tree	*Melia azedarach**
Morus alba	Kimbu	Tree	*Morus alba*
Pinus roxburghii	Pinus	Tree	*Pinus tabulaeformis*
Salix tetrasperma	Bainsh	Tree	*Salix caprea*
Schima wallichii	Chilaune	Tree	-

* Species present in the study area with information on literature about tensile strength. (-) Information is not available.

Buddleja asiatica, *Schima wallichii*, and *Woodfordia fruticosa* were not included in the analysis of the effect of root cohesion on slope stability because it was not possible to retrieve information about their root system and their mechanical characteristics (tensile strength, neither root diameter) and also it was not possible to find information about another species related with them with similar characteristics. For *Melia azedarach*, *Thysanolaena maxima*, and *Vitex negundo* it was possible to get information about tensile strength from literature. For *Morus alba* tensile strength was calculated. *Chimonocalamus dumosus* does not belong to the same genus as *Drepanostachyum intermedium*; nevertheless its above ground characteristics are similar to *C. dumosus*, so it was decided to take this species into consideration to perform the analysis of root cohesion (hereafter only *Drepanostachyum* will be written although it is known that the value of tensile strength corresponds to *Chimonocalamus*). Information about tensile strength for the rest of the species had to be obtained from other species but from the same genus.

With regard to surcharge, trees were the only species analyzed, since it is assumed that the surcharge that grasses or shrubs can add to a slope is not significant. In this case it was possible to obtain information about diameter at breast height for the specific species located in the study area, so it was not necessary to search for other species with similar characteristics to the present in the study area as in the case of root tensile strength. The DBH that was considered in the analysis was the average for adult individuals.

Summarizing the previous information, 14 species were included in the analysis of factor of safety when the presence of the roots in the slope aggregate cohesion to the soil; and eight species of trees were included in the analysis of factor of safety by adding load to the slope due to the presence of vegetation. The results of these analyzes will be described in the following sections.

4.3.2. Root cohesion analysis

4.3.2.1. Tensile strength

Tensile strength values of the species and similar species located in the study area range from 12 MPa to 83 MPa. The species with the lower value of tensile strength are *Melia sp.* and *Pinus sp.* (12 MPa), while *Chrysopogon sp.* is the species with the highest tensile strength value (83 MPa) (*Table 4-5*).

In this study the analysis and tests required to calculate this parameter for each species was not executed, and due the lack of information for the species in the study area, just the mean tensile strength value of roots of the species was the value considered to calculate root cohesion.

For almost all the species, tensile strength values were found in literature (for themselves or similar species). In the case of *Morus sp.* the value of tensile strength was calculated by applying the Mao et al., (2012) formula, and empirical constants to estimate tensile strength (See *Equation 8*

, and *Table 4-2*). The diameter used to calculate this value was the mean root diameter of roots of second order (4 mm) for the specie *Morus alba* since it was the low diameter reported by the authors for the specie (Liu et al., 2016). The calculus of this value could be under or overestimated since in the report where the data was obtained just the mean diameter was given and because root tensile strength is dependent on species, root diameter, and moisture (Yang et al., 2016).

Table 4-5. Species and similar species of those located in the study area and their tensile strength values retreived from literature.

Scientific name	Plant form	Tensile strength (MPa)	Source
Chrysopogon sp.	Grass	83	(Machado et al., 2015)
*Thysanolaena sp.**	Grass	58	(Neupane, 2005)
Drepanostachyum sp.	Bamboo	18	(Hui & Zhang, 2013)
Bambusa sp.	Bamboo	23	(Hui & Zhang, 2013)
Berberis sp.	Shrub	19	(Hudek, 2013)
*Vitex sp.**	Shrub	20	(Long et al., 2012)
Colebrookea sp.	Shrub	38	(Devkota et al., 2008)
*Melia sp.**	Tree	12	(Cheng-Cheng, 2007)
Pinus sp.	Tree	12	(Yang et al., 2016)
Alnus sp.	Tree	16	(Naghdi et al., 2013)
Ficus sp.	Tree	16	(Deoja et al., 1991)
Acacia sp.	Tree	43	(Lateh et al., 2015)
Salix sp.	Tree	47	(Bischetti et al., 2005)
Morus sp.	Tree	15	Calculated with the formula proposed by Mao et al., (2012)

* Species present in the study area with information on literature about tensile strength.

On average, grasses were the ones with the highest tensile strength (70.5 MPa), followed shrubs (25.7 MPa), trees (23 MPa), and finally bamboos (20.5 MPa). The value of tensile strength has been studied for several species, and in all cases it is stated that this property is inversely proportional to the root diameter, increasing when diameter decreases (Bischetti et al., 2005; Lateh, Avani, & Bibalani, 2014; Machado et al., 2015). Also, it is stated that root tensile strength varies according to the species, age, and the specific factors of soil where it develops such as moisture, season, and altitude (Gray & Sotir, 1996). A plant can present a variety of root diameter, but the values presented in this study and retrieved from literature, represent the mean values for the species selected, so it is considered that these values can reflect the characteristics regarding tensile strength of each species.

4.3.2.2. Root cohesion calculation

Root cohesion of the species ranges from high values such as 199.2 kPa (*Chrysopogon sp.*), until low values as 0.7 kPa (*Melia sp.* and *Pinus sp.*) (See *Table 4-6*). This variability of the values depends on depth were it was calculated; root cohesion decreases as the depth increases because root area ratio of the species also decreases with depth. The highest values of root cohesion are present in the first 0.1 m depth into the soil, where some species can exceed 100 kPa until 199.2 kPa; two trees and two grasses are included in this range. At depths of 0.3 m the values range from 4.3 kPa to 56.4 kPa. When root cohesion is calculated at 0.7 m, the values of root cohesion for the different species range from 0.3 kPa to 11.3 kPa. At this depth, roots of a grass, a bamboo, and two shrubs species have already lost their capacity to provide cohesion to the soil. If root cohesion is calculated at a depth of 1 m, the values range from 0.7 kPa to 2.8 kPa. Roots of all grasses, bamboos, and two shrubs do not reach a meter depth.

Table 4-6. Root cohesion values calculated at different depths for the different species analysed.

Scientific name	Plant form	c_R at 0.1 m (kPa)	c_R at 0.3 m (kPa)	c_R at 0.7 m (kPa)	c_R at 1 m (kPa)
Chrysopogon	Grass	199.2	19.9	0.0	0.0
Thysanolaena	Grass	139.2	13.9	0.7	0.0
Drepanostachyum	Bamboo	43.2	4.3	0.0	0.0
Bambusa	Bamboo	55.2	5.5	0.3	0.0
Berberis	Shrub	9.12	6.8	0.0	0.0
Vitex	Shrub	9.6	7.2	4.8	2.4
Colebrookea	Shrub	18.24	0.0	0.0	0.0
Melia	Tree	28.8	14.4	2.9	0.7
Pinus	Tree	28.8	14.4	2.9	0.7
Alnus	Tree	38.4	19.2	3.8	1.0
Ficus	Tree	38.4	19.2	3.8	1.0
Acacia	Tree	103.2	51.6	10.3	2.6
Salix	Tree	112.8	56.4	11.3	2.8
Morus	Tree	36	18.0	3.6	0.9

Comparing root cohesion between the same plant forms it can be observed that among grasses *Chrysopogon* has the best performance in the first 0.1 m depth compared with *Thysanolaena*. At 0.3 m depth, the difference between them is 6 kPa, and at 0.7 m *Chrysopogon* does not provide any additional cohesion because its root cannot reach more than 0.3 m depth. Bamboos have almost the same root cohesion in the first 0.1 m depth whose difference between them is 12 units. At 0.3 m the difference is 1.2 units; and by 0.7 m depth root cohesion of *Drepanostachyum* is null because its roots do not reach that depth. Roots of any of the species of this group can reach 1 m depth (See *Figure 4-1*).

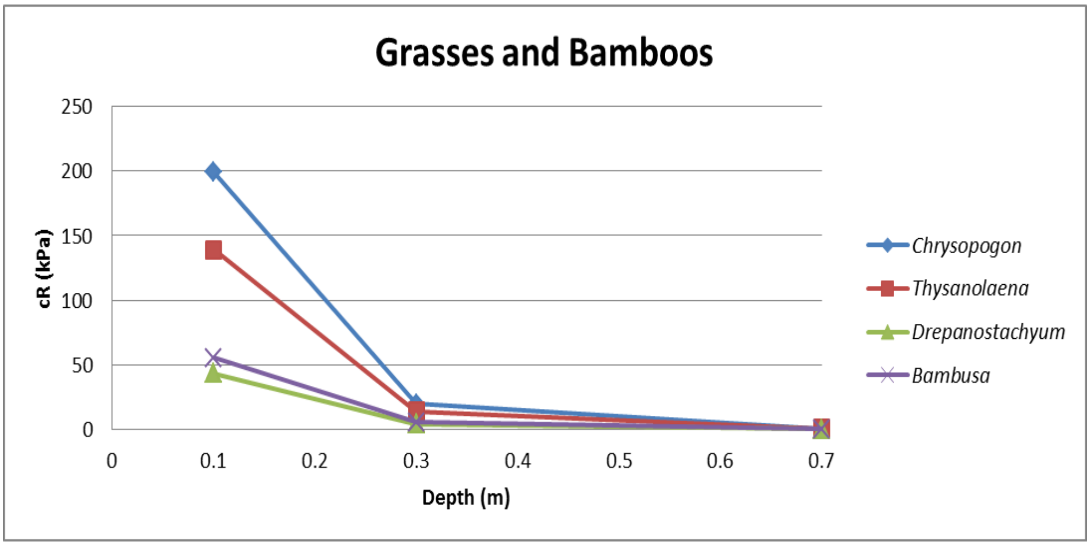

Figure 4-1. Additional cohesion provided by the presence of roots across the soil profile for grasses, and bamboos present in the study area.

In the case of shrubs, *Berberis* and *Vitex* have almost the same values of root cohesion until 0.3 m depth. Just *Vitex* species, their roots can reach 1 m depth. Altouhg, *Colebrookea* presents a high value of root cohesion in the first 0.1 m depth, compared to the other two species of shrubs, this quality is lost since 0.2 m depth, which is the maximum length that its roots can reach (See *Figure 4-2*). In comparison to the groups of grasses and bamboos, shrubs perform better at greater depths than the species in those groups.

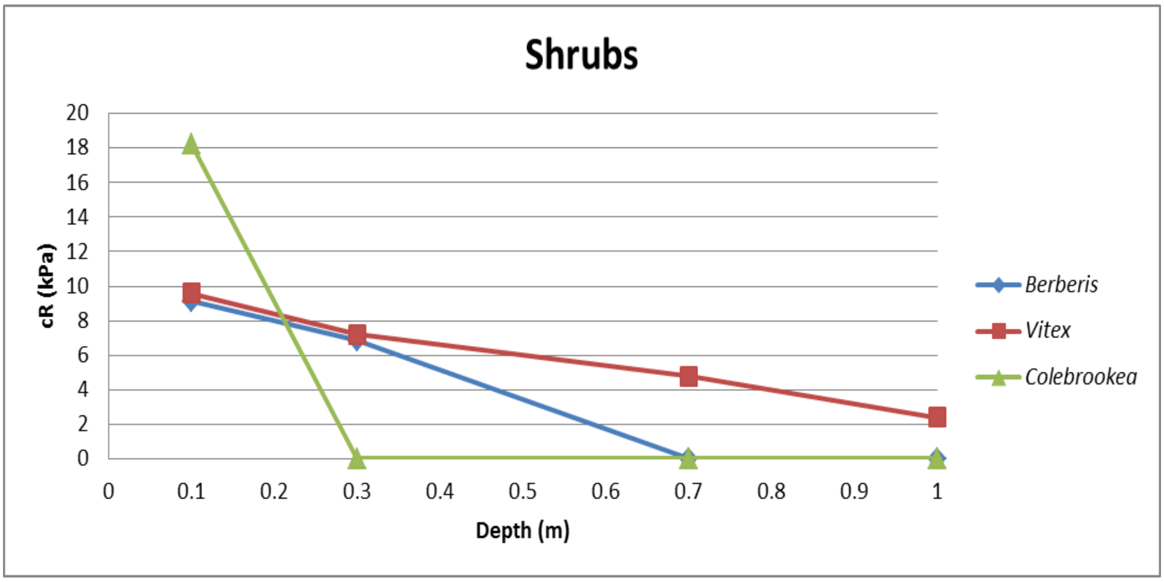

Figure 4-2. Additional cohesion provided by the presence of roots across the soil profile for shrubs present in the study area.

Values of root cohesion for trees are extreme. In one side, there are species with relative low values of root cohesion in the first 0.1 m depth (28.8 to 38.4 kPa for *Melia*, *Pinus*, *Alnus, Morus,* and, *Ficus*), another second group with high values on root cohesion is observed, which includes *Acacia* and *Salix*,. The same pattern is observed along the soil profile till the 1 m depth, although the difference between these values is smaller (See *Figure 4-3*), a difference of 2.1 kPa between the highest value and the lowest is showed at that depth.

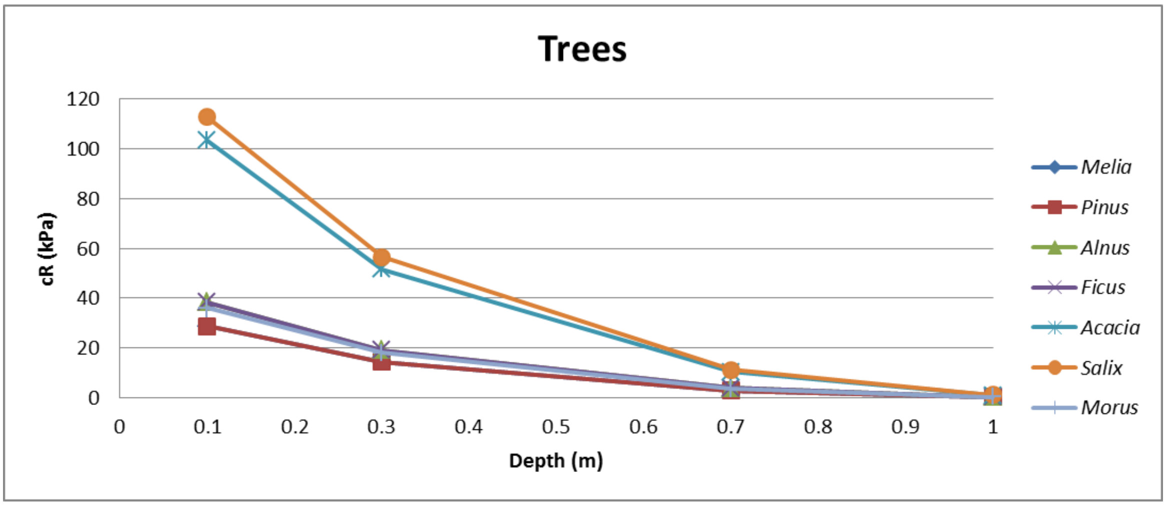

Figure 4-3. Additional cohesion provided by the presence of roots across the soil profile for trees present in the study area.

All the previous values of root cohesion were obtained using *Equation 4*, taking into consideration tensile strength of each species and root area ratio of the plant group. Values of Root Area Ratio were assigned according to the plant group and obtained from to literature, with representative values for grasses (De Baets et al., 2008), shrubs (Hudek, 2013), and trees (Bischetti et al., 2009). In literature the variability of RAR values for several species is high even with the same plant group form or even the same species in different locations (Bischetti et al., 2009), but in general these values range between 0-0.5%, which was considered in this research.

Values of root cohesion varied regarding depth into the soil, decreasing as the soil depth increases. This tendency is observed in other studies made for other species (Bischetti et al., 2009; De Baets et al., 2008; Leung et al., 2015). The high values of this species in the first centimeters depth are related with the values of RAR used to calculate this variable. Similar results were found in the study made by Machado et al., (2015), where values of c_R in the first centimeters depth (0-10) reached the 1280 kPa for grasses. Other similar results were found by De Baets et al. (2008), they found the maximum value of root cohesion (304 kPa) for the species Rush (*Juncus acutus*) in the first ten centimeters depth. Both researches used the same methodology to obtain root cohesion as the one here presented.

4.3.2.3. Effect of root cohesion on slope stability, calculating the factor of safety

With the information presented previously, the Factor of Safety was calculated including the effect of root cohesion. In this section the results of modeling the Factor of Safety including the effect of vegetation how vegetation modifies the slope stability due the presence of roots adding cohesion to the soil. These according different circumstances (varying soil depth and slope angle) mentioned in section 4.1.

1.a) Analysis of FOS including root cohesion, soil parameters fixed.

In a first analysis, all the values of root cohesion retrieved were included in the infinite slope model according to the *Equation 7* to make a sensitivity analysis and observe how root cohesion can affect slope stability. For this, all other values of the slope were fixed, and it was considered in all cases that the root cohesion calculated reach the shear plane. It was decided to include all the values of root cohesion at different depths in order to observe how the FOS changes depending on those different values.

The calculus of the Factor of Safety when a slope is assumed with the characteristic shown in the *Table 4-7*, gives a value of 0.98, indicating that the slope is unstable. When the values of root cohesion are added to the equation, the factor of safety increases considerably when root cohesion is calculated at a depth of 0.1 m, exceeding FOS values of 5, for example when root cohesion of *Chrysopogon* (199.2 kPa) is present. The minimum increment due to the presence of vegetation and its effect on slope stability by increasing cohesion is 1.01 (3.1%) for *Melia*, and *Pinus* with a value of root cohesion of 0.7 kPa. Values of root cohesion of all shrubs and five trees calculated at shallow depths (0.1 m) do not increase the FOS value more than 5 (values of root cohesion below 38.4 kPa) (See *Figure 4-4*). In general it was observed that when values of root cohesion are high the FOS value increases as well.

When FOS is calculated with values of root cohesion obtained at depths of 1 m (where the shear plane of the hypothetical slope is present), the increase in FOS is between 30.7% and 7.8%. In this case the tree *Salix* shows a better performance increasing FOS, followed by the tree *Acacia*, the shrub *Vitex,* and the trees *Ficus*, *Alnus*, *Morus*, *Pinus* and *Melia*. The rest of the species (grasses and bamboos) do not provide any additional cohesion at depths of 1 m (See *Figure 4-4*).

Table 4-7. Parameters assumed in a slope with 1 meter depth soil. Description of each of the parameters can be seen in Equation 5.

Slope parameters						
c' (kPa)	Υ (kN/m³)	z (m)	Υ_w (kN/m³)	h_v (m)	β (°)	φ' (°)
7	19	1 m	9.8	1 m	50	30

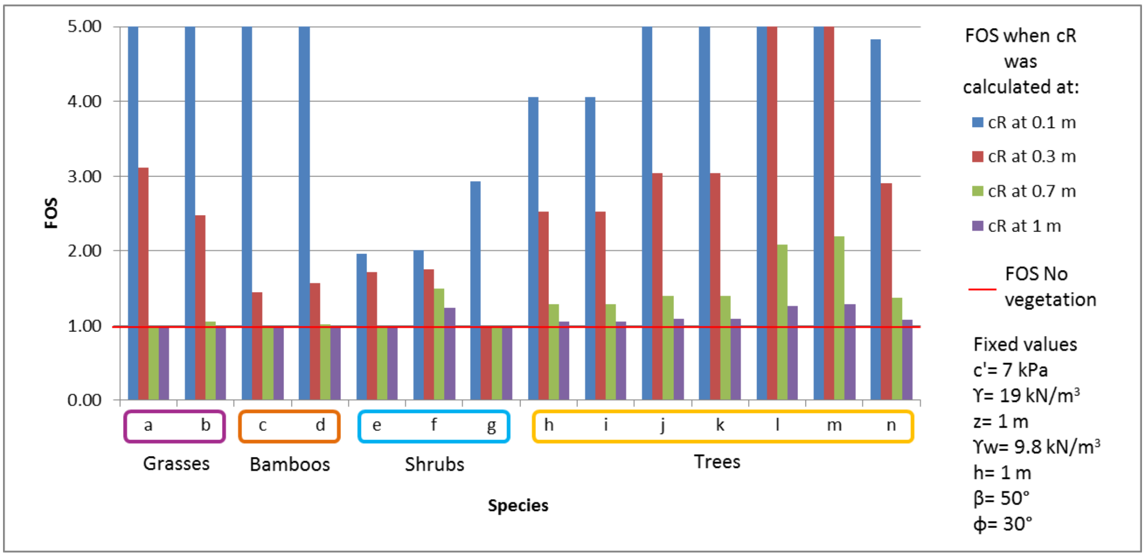

Figure 4-4. Factor of safety of a slope including root cohesion for different depth per species assuming that root cohesion effect up to 1 meter depth, although it has been calculated at different depths.

a: Chrysopogon b: Thysanolaena c: Drepanostachyum d: Bambusa. e:Berberis f: Vitex g: Colebrookea
h: Melia i: Pinus j: Alnus k: Ficus l: Acacia m: Salix n: Morus

1.b) Analysis of FOS including root cohesion, soil parameters fixed. Soil depth variable.

The second scenario analysis was carried out considering the same conditions on the slope showed in *Table 4-7*, varying the soil depth at 0.3 m, 0.7 m and 1 m including the respective values of root cohesion. *Figure 4-5*, *Figure 4-6*, and *Figure 4-7* show how the factor of safety varies according to depth, depending on how root cohesion provides stability to the slope according the different species analyzed for grasses and bamboos, shrubs, and trees respectively.

As can be observed in *Figure 4-5*, in the first 0.3 m depth grasses incrase the value of the Factor of Safety from 7.11 (*Thysanolaena*) until 9.24 (*Chrysopogon*) while bamboos do it from 3.68 (*Drepanostachyum*), until 4.11 (*Bambusa*), even that, the FOS increase is 91.7% compared with a bare slope with the presence of this bamboo, because the value of Factor of Safety is almost the double than without vegetation. At 0.7 m depth, *Chrysopogon* and *Drepanostachyum* do not increase the value of FOS, due their roots cannot reach those depths. Nevertheless, *Thysanolaena* and *Bambusa* still can increase this factor by 8.9% and 3.5% respectively. None of the species of grasses or bamboos analyzed can reach a depth of 1 m, losing their capacity to enhance the stability of a slope at that depth, so the Factor of Safety at 1 m depth is equal than a FOS without vegetation.

In the case of shrubs, in the first 0.3 m of soil depth, the value of the Factor of Safety is increased to a maximum of 4.71 by the presence of the *Vitex* shrub. The shrub species that provides the lowest improvement in slope stability at that depth is *Berberis*, with an increase in FOS value of 4.58. *Colebrookea* shrub does not increase the value of FOS due their roots cannot reach a depth higher than 20 cm. So its presence does not provide benefit on slope stability further than the first 0.2 m depth. Only *Vitex* species can reach depths of 0.7 m and 1 m. In this case, its presence increases the Factor of Safety value to 1.93 and 1.24 respectively (See *Figure 4-6*).

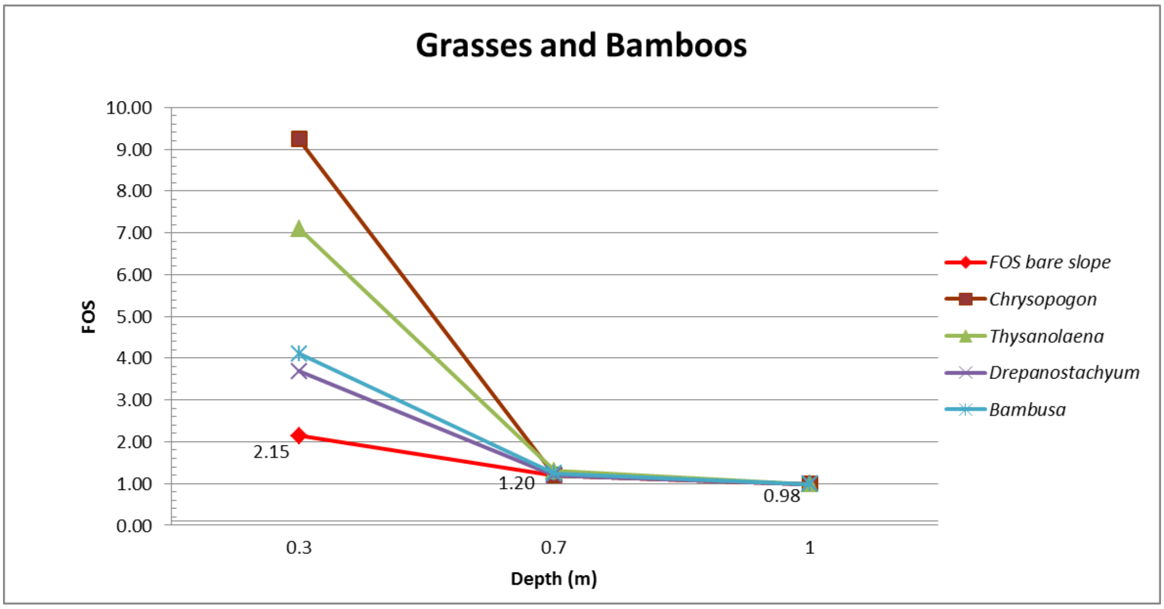

Figure 4-5. Factor of safety distribution of a hypothetical slope with contribution of cohesion of different species of grasses and bamboos present in the study area.

Figure 4-6. Factor of safety distribution of a hypothetical slope with contribution of cohesion of different species of shrubs present in the study area.

As can be observed in *Figure 4-7*, all the species of trees reach depths of 1 m, which makes this group the only one that can improve the stability of the slopes at considerable depths by adding cohesion to the soil. In general, at any depth *Salix* is the species that shows a better performance in comparison with other tree species, increasing the value of the Factor of safety to 22.2, 2.92, and 1.28 at depths of 0.3, 0.7 and 1 m respectively. In second place is *Acacia*, which increases the Factor of Safety value by 1.26 (28.1%) at 1 m depth. Acacia is followed by *Alnus* and *Ficus*, both increasing the FOS value to 1.09 (10.4%). Next species is *Morus* wich increases the FOS value to 1.08 (9.8%). Finally, *Melia* and *Pinus* are the tree species that contribute the least in cohesion to the soil; even so, they can increase the FOS value to 1.06 (7.8%).

Figure 4-7. Factor of safety distribution of a hypothetical slope with contribution of cohesion of different species of trees present in the study area.

In all cases (this means: grasses, bamboos, shrubs, and trees) the FOS decreases with depth. This tendency is also observed in a slope without vegetation, because the soil depth increases. This increase on the soil thickness causes that the destabilizing forces on the slope increases, reducing the safety factor and causing instability. In the case of the presence of vegetation, the reduction in the factor of safety when soil depth increases is explained because the cohesion provided by the species also decreases with the depth. The effect of the different species improves the value of the Safety Factor, thanks to the cohesion provided by them, is particularly large in shallow depths for grasses and trees. These values of cohesion are directly related to the root area ratio and tensile strength of the different species, thus explaining these results.

1.c) Analysis of FOS including root cohesion soil parameters fixed except slope angle.

In the previous section the effect of root cohesion and different soil depths was analyzed. In this section, root cohesion and different slope angles was analyzed. For this, the other characteristics were fixed as in the *Table 4-7*, except the angle of the slope, which changed between 20-50°. Values that were considered for root cohesion were those calculated at 0.1 m depth. Species whose roots do not reach the 1 meter depth were removed from this analysis: *Chrysopogon*, *Thysanolaena*, *Drepanostachyum*, *Bambusa*, *Colebrookea,* and *Berberis*.

Figure 4-8 and *Figure 4-9* show the trend of how the factor of safety behaves when the angle of the slope is varied. For shrubs, root cohesion increases the value of FOS until 2.31 (*Vitex*), when the slope has an angle of 20°. In the case of trees, the FOS value increased to 2.38 when *Salix* is present which provides the best value of FOS. The presence of roots in the soil provides cohesion, which increases the safety factor. In both groups, FOS decreases progressively until the slope has an angle of 50°.In this case, the decrease in the value of the factor of safety when the slope increases and its relation to the presence of vegetation adding cohesion must be carefully analyzed. It can be observed that species that have higher values of root cohesion provide greater slope stability. As well, the value of the FOS decreases as the angle of the slope increases. This is explained because the forces that provide slope stability decrease as the angle of the slope increases.

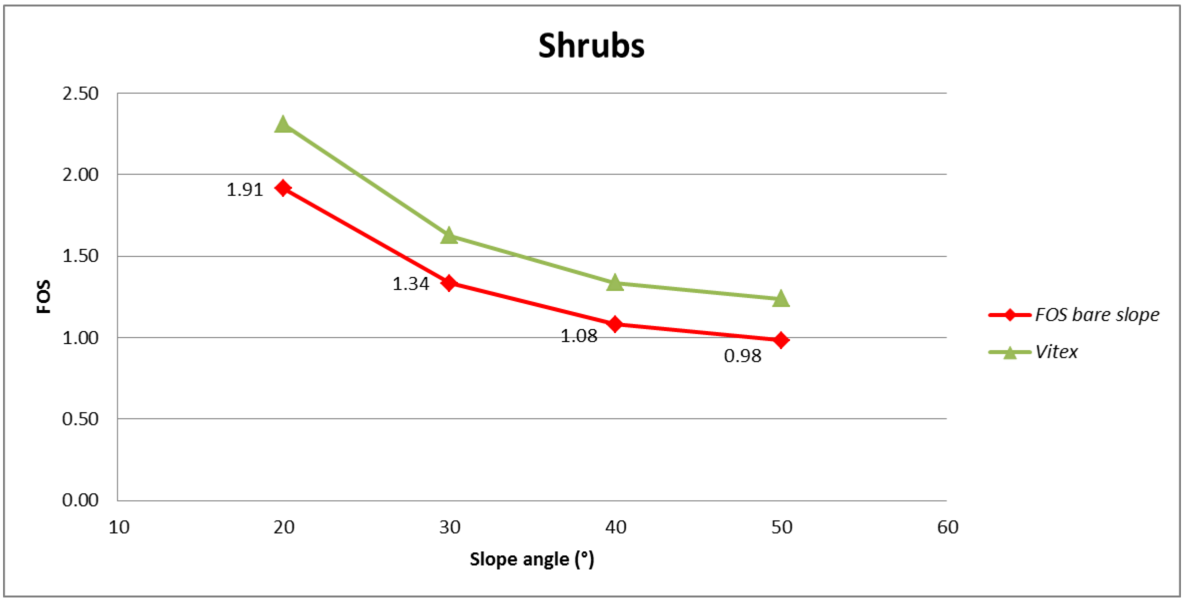

Figure 4-8. Factor of safety distribution on different slope angles of a hypothetical slope with contribution of cohesion of different species of shrubs present in the study area.

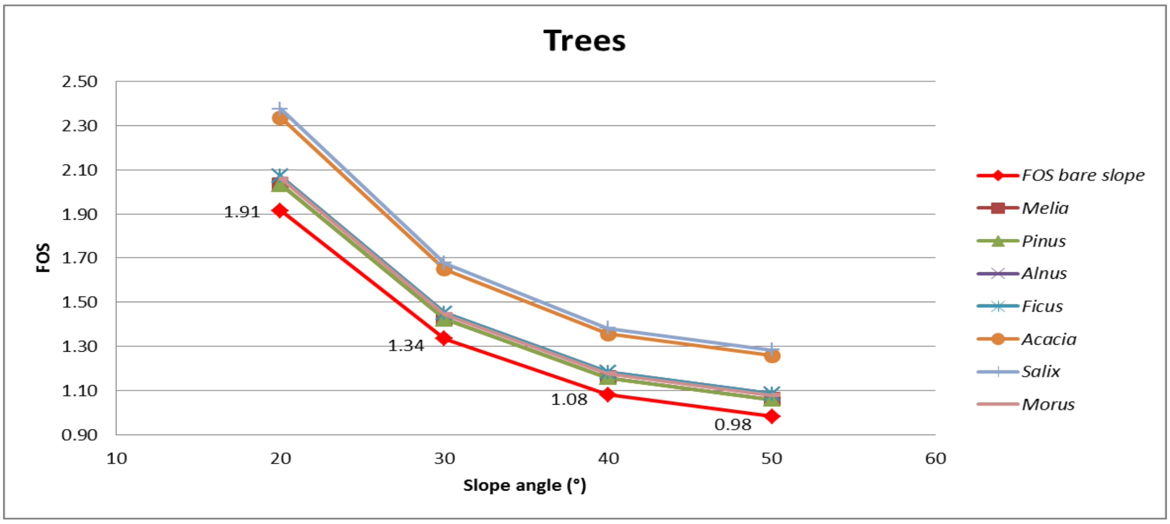

Figure 4-9. Factor of safety distribution on different slope angles of a hypothetical slope with contribution of cohesion of different species of trees present in the study area.

4.3.3. Surcharge analysis

In this section the effect of surcharge added by presence of trees is analyzed. For almost all the species of trees the biomass was retrieved directly from literature. For *Melia azedarach*, *Morus alba*, and *Salix tetrasperma* it was necessary to calculate the biomass trough *Equation 9,* where *M. azedarach* and *M. alba* were classified as Mixed hardwoods and *S. tetrasperma* was considered in the group of Aspen/alder/cottonwood/willow. The size of the individuals was selected as an average of an adult. DBH and biomass change with age, so it was decided to include the analysis of surcharge of one of the species and its different DBH and biomass. The root area was changed proportional to the DBH (See *Table 4-9*).

The results of surcharge for the different species of trees ranged from 0.03 kPa for *Melia azedarach* to 0.27 kPa for *Salix tetrasperma* (See *Table 4-8*). Surcharge of each species is related their biomass which at the same time is related with DBH, also it is related with the distribution of the root area presented in Chapter 3. As it can be seen, not always a high DBH means a high biomass, since this value also its related with the wood density of each species (Hunt, 2009). Similar values of surcharge were reported for riparian trees which an average tree, can exert a force of 0.81 kPa (Abernethy & Rutherfurd, 2000b).

Table 4-8. Tree species and values of DBH, Biomass, and surcharge.

Scientific name	DBH (cm)	Source of DBH	Biomass (Kg)	Source of Biomass	W (kPa)
*Melia azedarach**	10.6	(Waggy, 2009)	29.5	Calculated	0.02
Acacia catechu	9	(Oo, Shin, Oosumi, & Kiyono, 2006)	37.0	(Tamrakar, 2000)	0.05
Pinus roxburghii	26	(R. K. Sharma, Sankhayan, & Hofstad, 2008)	161.0	(Tamrakar, 2000)	0.06
*Morus alba**	30	(Jackson, 1994b)	390.3	Calculated	0.17
Ficus semicordata	7.3	(Jackson, 1994b)	21.7	(Tamrakar, 2000)	0.08
Alnus nepalensis	28	(Barakoti, 2005)	234.8	(Tamrakar, 2000)	0.14
Schima wallichii	26	(Shrestha, Devkota, & Keshar, 2015)	581.0	(Tamrakar, 2000)	0.19
*Salix tetrasperma***	49	(Afzal & Akhtar, 2013)	1187.0	Calculated	0.40

* Mixed hardwoods ** Willow

Table 4-9. Surcharge of Alnus nepalensis according to DBH.

Scientific name	DBH (cm)	Root area (m^2)	Biomass (Kg)	Source of Biomass	W (kPa)
	10	6	21.7		0.04
	20	12.1	107.6		0.09
Alnus nepalensis	30	18.1	275.7	(Tamrakar, 2000)	0.15
	40	24.2	593		0.24
	50	30.3	908		0.29

2.a) Analysis of FOS including surcharge of trees, soil parameters fixed.

The analysis of the factor of safety considering just the effect of surcharge added by the presence of trees and the values of a slope considered in *Table 4-7*, indicates that it has a negative effect. As the overload due to the presence of vegetation increases, the FOS value decreases (*Figure 4-10* and *Figure 4-11*).

The value of the factor of safety when a tree of *Melia azedarach* with a surcharge of 0.02 kPa is added to the equation, does not increase or decrease significantly the factor of safety (FOS=0.982) compared with a slope without considering the effect of vegetation (FOS=0.983); even when the load added by a species with is a high value of surcharge of 0.40 kPa the FOS value is equal to 0.973 decreasing this FOS in 1%, a low variation compared with the variation that root cohesion causes in FOS, as this factor acts partially on the resistance and the driving forces (van Beek, 2002).

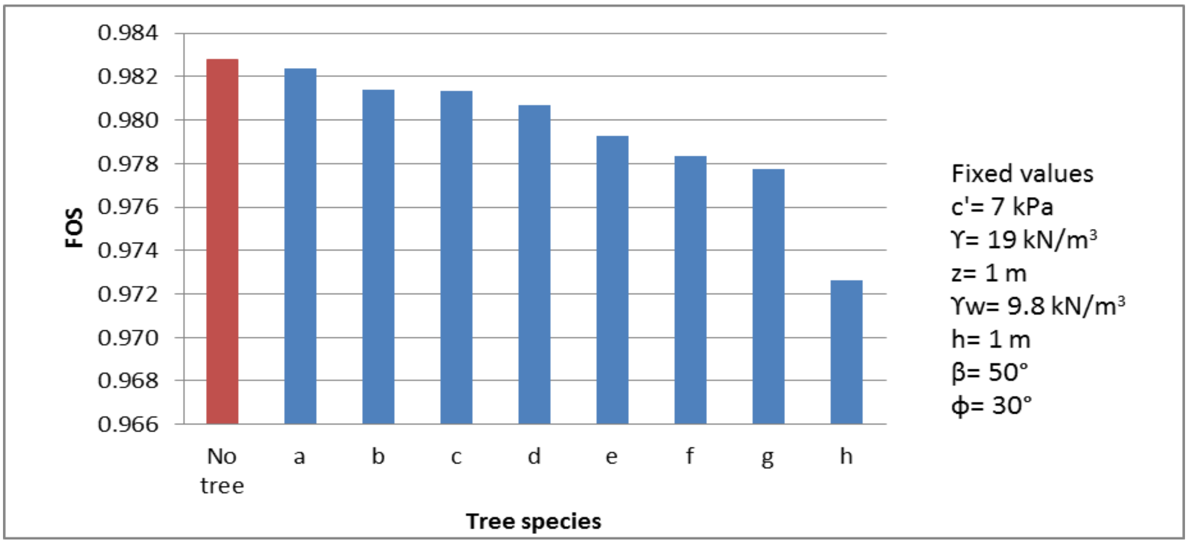

Figure 4-10. Effect of vegetation on the factor of safety when surcharge of different species is added to a slope. Load of the species increases from left to right.

a: Melia azedarach | *c: Pinus roxburghii* | *e: Alnus nepalensis* | *g: Schima wallichii*
b: Acacia catechu | *d: Ficus semicordata* | *f: Morus alba* | *h: Salix tetrasperma*

In *Figure 4-11* it is presented FOS considering one species (*Alnus nepalensis*) being one of the species which can add more load compared with the other species. As can be observed the minimum load that can provide to the slope is 0.04 kPa reducing the FOS value to 0.982 (0.1% less) and maximum load is 0.29 kPa which reduces the Factor of Safety value to 0.975 (0.8% less). This means that young trees do not provide significant effect on slope stability as well as mature trees.

The destabilizing effect of weight of vegetation also has been seen in other researches made in riparian trees. Abernethy & Rutherfurd, (2000) made an infinite slope stability analysis and they found that trees present in riverbanks are a source of instability, due the surcharge they provide to the slope. However, although the presence of vegetation is a negative factor in slope stability, they concluded that the effect is minimal, in agreement with the results of the analysis presented here for the different species analyzed. Other researches show that the effect of weight of vegetation can have a negative or positive effect on slope stability, this effect is related with the soil and slope parameters present (Steinacher et al., 2009).

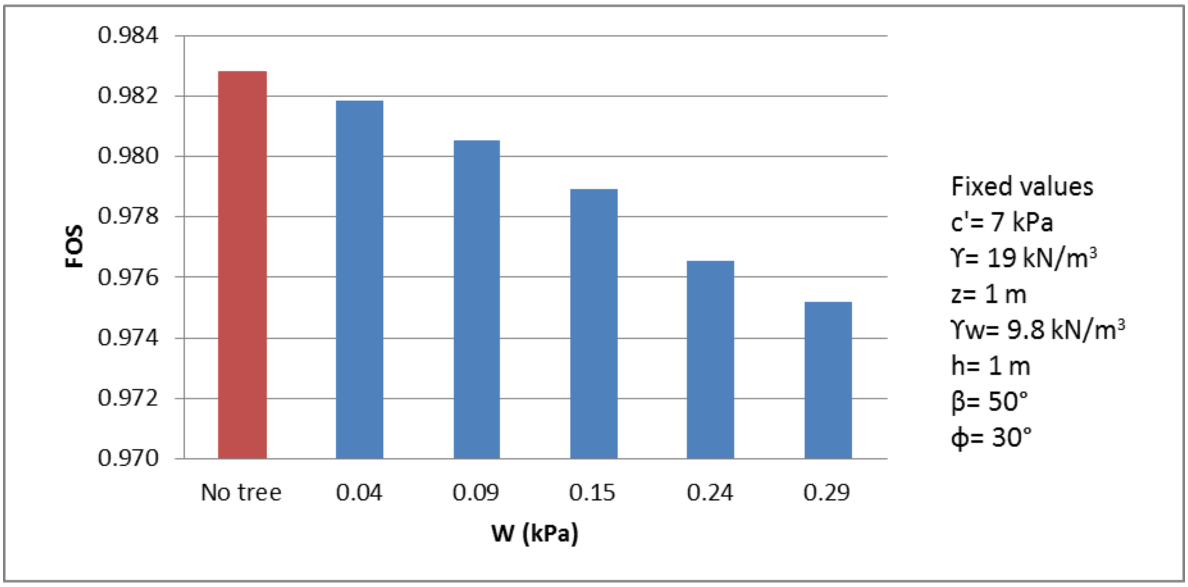

Figure 4-11. FOS calculated when surcharge of Alnus nepalensis with different DBH is added.

2.b) Analysis of FOS including surcharge of trees, soil parameters fixed except soil depth .

Analyzing the effect of surcharge and different soil depth, it was observed that the factor of safety is higher at soil depths (0.3 m) where the species with a low surcharge (*Melia azedarach)* present a better performance in slope stability than those with higher weight such as *Salix tetrasperma,* whose value of factor of safety decreases in 5% at shallow depths (0.3 m). As in the case of root cohesion, soil depth has a negative effect on slope stability diminishing the FOS as depth increases. At shallow depths the variation between the FOS with and without trees is maximum 5% less. As the soil depth increases the deviation in the safety factor decreases becoming less noticeable, and the effect of surcharge by vegetation becomes imperceptible. This is because the effect that the overload of a tree can contribute is small compared to the soil depth factor, which represents a higher incidence in the FOS by increasing the soil weight according to the FOS equation.

2.c) Analysis of FOS including surcharge of trees, soil parameters fixed except slope angle.

When the Factor of Safety is calculated taking into consideration different slope angles and the effect of surcharge, it is observed that in general the factor of safety decreases as the slope angle increases reaching a maximum value of 1.914 for *Melia azedarach* in a slope of 20° (no difference on FOS value compared with a slope without tree) and a lower value of 1.908 for *Salix tetrasperma* in a slope of 20° (0.3% less compared with a slope without tree). Even with an increase on the slope angle the FOS value does not differs significantly compared with a bare slope. At steep slopes of 50° the decrease in the Factor of Safety when *Salix tetrasperma* (species with the highest surcharge value) is present is 0.7% compared to slopes without vegetation.

In general the results presented in this project are similar to those presented by Abernethy & Rutherfurd (2000a), and Leung et al. (2015). In both cases the factor of safety decreases as the slope angle increases. Results presented by Abernethy & Rutherfurd (2000a), indicate that the effect of the added load by the presence of trees on the slope decreases the safety factor, but does not affect the stability of the slope considerably. Results presented in this research are according with those in literature, because the difference between FOS values with vegetation and without vegetation are quite similar. Vegetation and its surcharge do not provide a significant difference in the stability of the slope, so its presence is not entirely negative.

4.3.4. Combination of plant species

An analysis was carried out considering the effect of different plant species on an the slope stability, using the infinite slope method. We calculated the FOS of an infinite slope with the same characteristics as those mentioned in *Table 4-7*. A selection of species was made for the combination. The species were selected according to those that provided the highest values of root cohesion and that reach the greatest rooting depth in each plant group. The selection was as follows: in the case of grasses *Thysanolanea*, for bamboos *Bambusa*, for shrubs *Vitex,* and for trees *Salix*. In the analysis, the values of the FOS were compared considering four different scenarios (See*Table 4-10*). In the scenarios with vegetation root cohesion and surcharge parameters of the species were included.

Table 4-10. Scenarios considering combination of different plant species.

Scenario	Plant group	Root cohesion (kPa)			Surcharge (kPa)
		0.3 m	0.7 m	1 m	
1	No vegetation	0	0	0	0
2	G	13.9	0.7	0	0
3	G+B	19.4	1	0	0
4	G+S	21.1	5.5	2.4	0
5	G+S+T	77.5	16.8	5.2	2.4

G: Grass, B: Bamboo, S: Shrub, T: Tree.

As can be observed in *Figure 4-12*, in the scenario where vegetation is not present the FOS value is the lowest among all different scenarios, decreasing as soil depth increases. In the second scenario, where just the presence of grass provides additional cohesion, it can be observed that the FOS value increases considerably in the first 0.3 m depth. At 0.7 m depth the FOS increases just from 1.3 to 1.41, compared with a slope without vegetation, since this grass can provide limited root cohesion at such depth. At 1 m depth the scenario for grass shows the same FOS value as in the scenario without vegetation, as the roots do not reach that far So grass shows a good performance at shallow depths but has no effect anymore at depths larger than 70 cm.

In the third scenario grasses and bamboos are evaluated together. Compared to the previous scenario the presence of both species increases the value of the FOS at 0.3 m and 0.7 m depth. However, as in the previous case, its presence does not provide stability in deeper soils. Compared with the scenario with grass and bamboo the fourth scenario provides higher values in FOS. FOS value increases at the three different depths considered, because roots of the shrub (*Vitex*) can reach depths of up to four meters. The presence of the shrubs increases the cohesion, and increases the Factor of Safety at depths of 1 m, where the roots of grass and bamboo cannot reach (See *Figure 4-12*).

In the last scenario, where a combination of trees, grass and shrubs is considered, the FOS increases even more compared with the previous scenarios, due the additional cohesion provided by each species. In the first 0.3 m the FOS value can increase more than 10. At 0.7 m the FOS value is 3.77. In both cases the shear plane is reinforced by the presence of roots from all three species present. At 1 m the FOS value increases to 1.52 thanks to the presence of the roots of shrubs and trees.

In the different scenarios, the lateral distribution of the roots was not taken into account, since it is assumed that in the infinite slope the characteristics of the unit area are homogeneous. Nevertheless the characteristic of the horizontal root distribution of the different species is different, so the reinforcement is also different as it was observed in the vertical analysis. For example the clumps of some grasses are as small as 30 cm; in the case of *Vitex,* it can reach a meter diameter (Howell, 1999a) but also grasses can be distributed homogeneously in the soil. In the case of bamboos, *Bambusa* can develop an extensive fibrous root system (White & Childers, 1945). For trees, their roots can reach a distance from the stem of 2 m (depending on the specie and the DBH), so root reinforcement decreases as the distance from the stem increases (Schwarz, Cohen, & Or, 2012). In this case a single tree can provide reinforcement in an area were the roots distribute. This is important when an analysis using GIS is done, since the size of the pixel (which is considered as a homogeneous unit) must to be considered at least according to the distribution of the roots of the species that is considered to analyse.

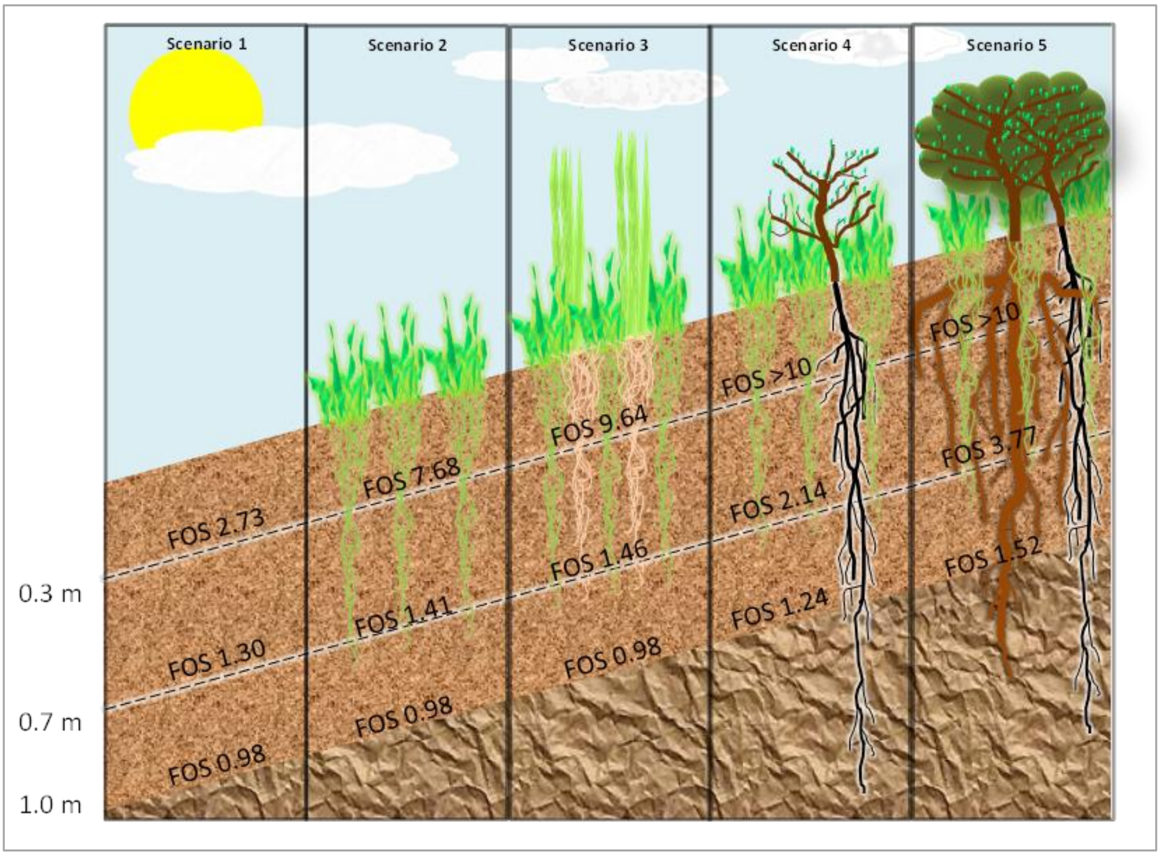

Figure 4-12. Scheme of FOS with different scenarios in a hypothetical slope.

4.3.5. Modelling the effect of vegetation in GIS

The same scenarios were applied in a GIS environment using the STARWARS + PROBSTAB model (van Beek, 2002), in order to obtain a spatial representation of the possible performance of the combination of the different plant species under different combinations of slopes, soil depths and water conditions. A small catchment from Rasuwa District (See *Figure 4-13*) was selected for testing the five scenarios outlined in *Table 4-10*. The selection of the catchment was based on the sample sites of vegetation. The soil depth model, parameterization and adjustment of the STARWARS-PROBSTAB model were done by Guo (2017), and we provided the root cohesion parameters. The model was executed for one rainfall period, using the rainfall record from 2015 as rainfall input, and a pixel size of 30 m. The final output of the model was FOS values for each pixel.

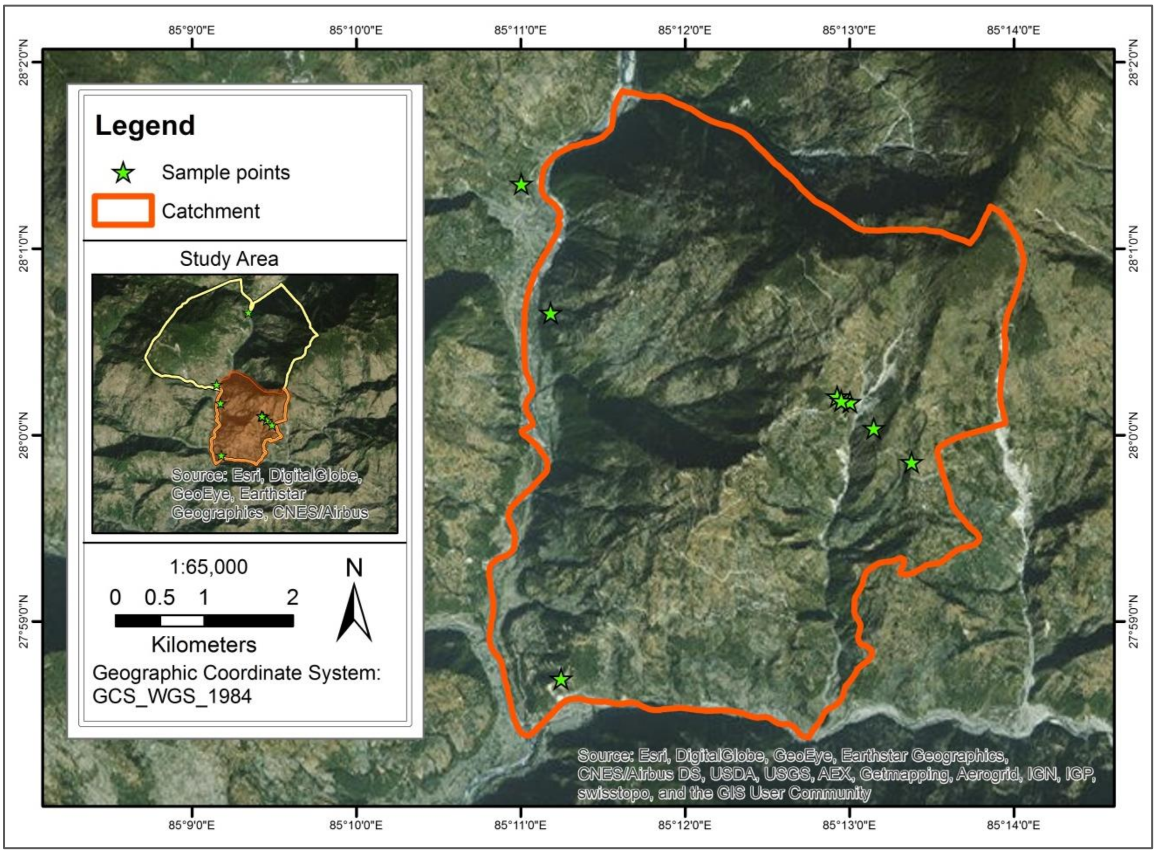

Figure 4-13.Catchment where the effect of different combinations of plant species were tested.

The different scenarios were simulated in the catchment and the results were expressed in percentage of pixels with 1 day or more with a FOS < 1, and pixels with a FOS ≥1. Only the results were shown when the slip plane surface is at 0.7 and 1 m, since at 0.3 m all the pixels showed a FOS>1, meaning stable slopes. In *Table 4-11* it can be observed how the different combinations of species perform according to the different slide surface depths. In both cases the percentage of pixels with a FOS<1 decreases when a combination of different species add root cohesion (See *Table 4-11*). The percentage of pixels with a FOS<1 in a slope without vegetation is higher when the slip surface is at 1 m; this can be seen visually in *Figure 4-14* and *Figure 4-15*.

A comparison between the scenarios which include vegetation, and the scenario without vegetation shows that at 0.7 m slide surface, the presence of the optimal grass species reduces the percentage of pixels with FOS<1 with 1.05%. The presence of a grass and a bamboo species together reduces the percentage of unstable pixels with 1.57%. The combination of a grass and a shrub species reduces the percentage of unstable pixels with 5.35%. Finally, the best combination that reduces the percentage of unstable pixels (FOS<1) is scenario 5, which includes grass, shrub, and tree species combined (*Table 4-12*). In *Figure 4-14* it can be observed that the scenario with no vegetation and the scenario with grass and shrub shows the largest difference. We did not show scenario 5, with the three plant groups, because this combination reduces the number of pixels with FOS<1. Root cohesion higher than 16.8 kPa will provide stability in all the prone zones to sliding. These values of root cohesion can be provided by a combination of different plant species.

We compared the percentage of pixels with FOS<1 between the scenario without vegetation and the scenarios with vegetation with the sliding surface depth at 1 m. The results show that scenarios 2 and 3 do not decrease the percentage of pixels. This is because their roots do not reach that deep and therefore cannot increase cohesion at those depths. Scenarios 4 and 5 decrease the percentage of unstable pixels with 3.85 and 7.88% respectively (See *Table 4-12Table 4-12. Percentage of difference with respect to the scenario without vegetation.*). In scenario 4 just the shrubs are providing root cohesion, since as it was already mentioned, roots of grasses do not reach 1 m depth. In scenario 5 both shrubs and trees contribute to provide the cohesion, and this is the scenario which reduces the percentage of pixels with FOS<1 most (See *Figure 4-15*).

Table 4-11. Percentage of pixels with a FOS<1 and a FOS≥1 in the catchment under different scenarios considering different values of root cohesion.

Scenarios	**Plant group**	**Sliding Surface depth**			
		0.7 m		1 m	
		% FOS <1	% FOS ≥1	% FOS <1	% FOS ≥1
1	No vegetation	6.68	93.32	15.50	84.50
2	G	5.64	94.36	15.50	84.50
3	G+B	5.12	94.88	15.50	84.50
4	G+S	1.34	98.66	11.65	88.35
5	G+S+T	0.00	100.00	7.62	92.38

Table 4-12. Percentage of difference with respect to the scenario without vegetation.

Scenarios	**Plant group**	**Sliding Surface depth**	
		0.7 m	1 m
1	No vegetation	-	-
2	G	1.05	0.00
3	G+B	1.57	0.00
4	G+S	5.35	3.85
5	G+S+T	6.68	7.88

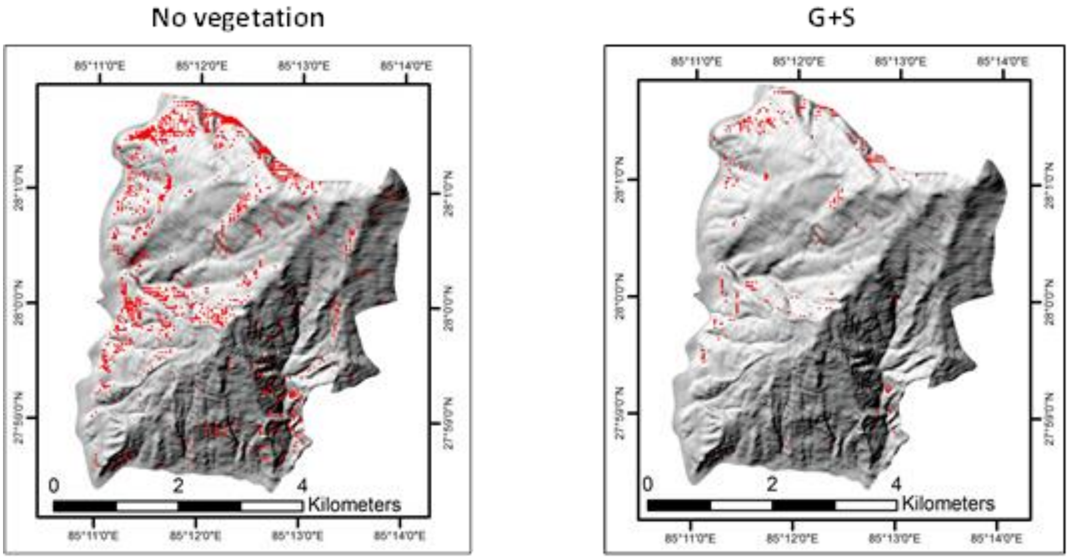

Figure 4-14. FOS at 0.7 m slide surface. Left: scenario without vegetation. Right: scenario with a combination of species with grass and shrubs. Red spots are pixels with FOS<1.

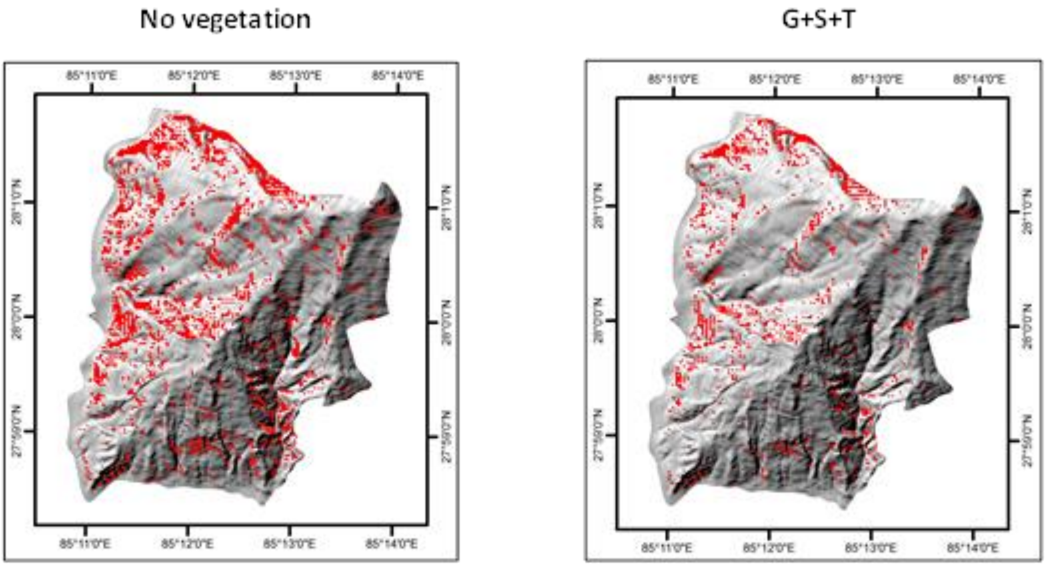

Figure 4-15. FOS at 1 m slide surface depth. Left: scenario without vegetation. Right: scenario with a combination of grasses, shrubs, and trees. Red spots are pixels with FOS<1.

As can be observed in *Figure 4-14* and *Figure 4-15* the modelled unstable area in the catchment is too large, as there were not that many unstable areas in 2015, even not after the occurrence of the earthquake. So the modelling is too pessimistic and the parameters should be further calibrated. But they do show the trend of different vegetation types reducing unstable zones.

Evidence that a combination of different plant species enhances slope stability has been provided by Hairiah et al. (2006) and Teerawattanasuk et al. (2014). In the first case it was shown that trees provide stability because their deep roots allow anchoring the soil to firm strata, while grasses provided stability to the top soils. In the case of the study made by Teerawattanasuk et al. (2014) it is shown that with in situ direct shear tests, the roots of vetiver grass provide more root cohesion than ruzi grass roots. Nevertheless, when the test was carried out taking into consideration the combination of both species, this resulted in a great development of shear strength for soil reinforcement. This results suggest that the presence of a mix of several species in a given area is preferable than the presence of single species.

4.4. Considerations regarding vegetation and its effect on slope stability

Until now it has been observed that root cohesion decreases with depth and that some shrubs and trees have a better performance on slope stability thanks to the soil reinforcement due to the presence of roots in deep soils. Regarding surcharge, the negative effect that trees can provide to slope stability can be considered very limited. Considering these two characteristics and the root length of the species a ranking was done to summarize which species have a better performance to stabilizing a slope (See *Table 4-13*).

The ranking indicates that *Vitex negundo* has the best characteristics, since their roots can reach considerable high depths, it has good root cohesion and does not provides surcharge to the slope. This species prefers to develop on river banks in moist soils, wastelands or deciduous forests (Orwa, Mutua, Kindt, Jamnadass, & Simons, 2009), but also it can grow in dry stony sites or hot dry road cuts (Howell, 1999a). When the plant is exposed to water stress its roots can extend deep into the cracks of the bedrock, providing anchoring effect as well (Li et al., 2007). Regarding its hydrological aspects Wang et al., (2014) showed that their leaves have high adhesion of water drops, thus controlling rainfall interception. In terms of evapotranspiration, this plant presents higher values of evapotranspiration in the rainy season (monthly evapotranspiration in August 150-250 mm) with a relatively high value of LAI in that month as well (Fan & Zhang, 2009). The benefits reported by the local people of this species were limited to slope stability. Nevertheless in literature this species have a large list of medicinal benefits, which can be used by the local communities, and other benefits like hedges. Considering its properties, it can be suggested as the best species among the species analyzed in this research.

The ranking of species is an approach to select the species needed in the stability of a slope. Nevertheless, when actions are needed to provide stability to a slope, certain aspects must be considered. The speed of growth of the different species, the soil depth in the slope, and other soil site specific characteristics must to be taken into account. For example, in this case the species which have a fast growth are the grasses; they can be planted in soils that have been affected recently by a landslide or a fast enhancing of the slope is required. Since they are pioneer species they do not require fertile soils to grow. Bushes can be planted in the first stages also; *Vitex negundo* is a good example of a shrubs species for slope stability with a fast growth and good performance. Pioneer species are good in the first stages after slope failure. Nevertheless a work of bio-engineering should follow a natural succession so after the development of pioneer species such as grasses and shrubs, it must give way to long-lived species that can provide more stability to slopes, in this case trees.

In this study we must take into account that the values of root tensile strength and root area ratio to calculate root cohesion were retrieved from literature, and in some cases calculated; so this values must to be taken with caution and as a reference, also because it is reported that the values calculated for root cohesion with the model utilized should be considered as the maximum values of root cohesion that species can provide. Actual measurements on tensile strength of two of the species here analyzed were provided by Devkota (2017). For *Chrysopogon gryllus* and *Thysanolaena maxima* the values of tensile strength ranged between 21.6-32.9 MPa and 16.7-25.4 MPa respectively. In the case of *Chrysopogon gryllus* the difference of values reported here and by Devkota (2017) can be explained because the specie used to retrieve the parameter was different than *C. gryllus*. On the other side, the different value reported here by *Thysanolaena maxima* was retrieved from a study which studied that specie (Neupane, 2005). Such differences may be due the different root diameter used to calculate tensile strength. In the case of Devkota (2017) the roots with maximum value of tensile strength (25.4 MPa) had a mean diameter of 0.8 mm, while in the case of Neupane (2005) the roots with the maximum value of tensile strength (160.5 MPa) had a mean diameter of 0.5 mm. Such difference could be due also by the different devices to measure them.

Table 4-13. Ranking of the species according to their performance enhancing slope stability. High values indicate a better performance.

Scientific name	Plant form	Ranking root lenght	Ranking c_R at 1 m	Ranking surcharge	Total
Vitex negundo	Shrub	9	5	9	23
Acacia catechu	Tree	8	6	7	21
Melia azedarach	Tree	8	2	8	18
Thysanolaena maxima	Grass	5	1	9	15
Alnus nepalensis	Tree	8	4	3	15
Morus alba	Tree	7	3	5	15
Bambusa balcooa	Bamboo	4	1	9	14
Ficus semicordata	Tree	6	4	4	14
Pinus roxburghii	Tree	6	2	6	14
Salix tetrasperma	Tree	6	7	1	14
Berberis asiatica	Shrub	3	1	9	13
Drepanostachyum intermedium	Bamboo	2	1	9	12
Chrysopogon gryllus	Grass	2	1	9	12
Colebrookea oppositifolia	Shrub	1	1	9	11
Schima wallichii	Tree	-	-	2	-

5. CONCLUSIONS AND RECOMMENDATIONS

The study has significant results in terms of plant species that have a better performance stabilizing slopes basically on shallow landslides. However, the lack of direct data on root area ratio, tensile strength, as well as the model used to estimate root cohesion makes the results to be taken with caution because these types of factors are specific, even varying between the same species. The results can be taken as indicative and as an approximation of the performance of plant species that have been reported as useful in slope stabilization but for most of them no specific studies have been done.

The main benefit that local people can obtain from plant species used for slope stability is provisioning, either as raw materials or medical resources according to results obtained in fieldwork and the literature.

Thysanolanea maxima (grass), *Bambusa balcooa* (bamboo), *Vitex negundo* (shrub), and *Salix tetrasperma* (tree) are the species with higher values of root cohesion among their plant group and the plant species whose roots can reach higher depths. *Salix tetrasperma* is the specie which which can add more surcharge to the slope among tree species.

The FOS is increased when additional cohesion is provided by the roots of the plant species. Surcharge has a negative effect on the value of FOS but it is minimal. In both cases the FOS value decreases as soil depth, and slope angle increases.

The presence of a single plant species does not increase the value of the FOS as a combination of different plant groups does. The best combination of plant species included one species of each group of grasses, shrubs and trees.

Future research should focus in quantifying the additional benefits that plant species used for slope stability can provide to the community and assess their potential economic benefit. It is also recommended to measure tensile strength and root area ratio of the species here presented specifically in the study area and including lateral root cohesion. Surcharge added by trees would also be included; such information could be derived by using remote sensing for example. Such information can be incorporated in the analysis of FOS and validate the information provided here. Hydrological aspects should also be included to provide a complete assessment of the role of vegetation on slope stability.

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6. APPENDIX

A. Livelihood on Middle hills in the study area.

B. Interviews with key informants.

C. List of plant species reported by people in fieldwork and description.

	Scientific name	Common nepali name	General description
Grasses	 *Chrysopogon gryllus*	Salimo	Perennial grass forming tough tussocks, the culms can reach 1.5 m tall, and it develops in mountain slopes (Shouliang & Phillips, 2006). It grows in hot, dry and arid, generally sunny environments being drought resistant. It does not demand fertile soils so it is highly competitive (Eleftheriou & Noitsakis, 1978).
Grasses	 *Thysanolaena maxima*	Amliso	Large clumping grass resembling a bamboo whose clumps can have a meter or more in diameter reaching 2 meters in height with a massive root system. It distributes in damper areas of forest and grows well in dry, stony sites; and some hot but humid areas. It can propagate from rhizome cuttings and the seeds are difficult to germinate in nurseries (Howell, 1999a).
Bamboos	 *Bambusa balcooa*	Bamboo	Thick-walled bamboo, dense branching, which can reach a diameter of 16 cm and a height of 25 m; with an extensive fibrous root system (White & Childers, 1945), it is tolerant to dry conditions (Stapleton, 1994). In Kathmandu flowers have been seen but no seeds, so propagation is by culm cuttings (Jackson et al., 1987).
Bamboos	 *Drepanostachyum intermedium*	Nigalo	Bamboo whose culms can reach 4 m tall and a diameter of 2 cm, but usually they are not very straight. Generally it is found in evergreen oak and chesnut forest or cultivated in subtropical farmlands. In the forest it can present small sized due browsing. It has an easy propagation at subtropical altitudes(Stapleton, 1994). It can survive in dry conditions, planted in gullies or between rocks and on waste land (Jackson et al., 1987).
Shrubs	 *Berberis asiatica*	Chutro	Evergreen shrub which can reach 1.8-4 m height and the bark 10 cm diameter. (Srivastava et al., 2004). It develops in grassy and rocky slopes and open hillsides in the drier areas. It can grow in poor loamy soils preferably in dry or moist soils. Seeds is the best propagation but it can be also propagated by cuttings of half-ripe wood (PFAF, 2012)
Shrubs	 *Buddleja asiatica*	Bhimsen Pate	Perennial shrub ranging between 1-8 meters which develops in open places regularly at the edge of open forests or woodlands (Ping-tao & Leeuwenberg, 1996). Some individuals can live up 40 years (Sheppard et al., 2006). is a great colonizer of dry open ground in mountainous areas due it has a fast growth and an extensive root system, so it is useful as a pioneer specie thanks its high disturbance tolerance (Gentili et al., 2011; Waranusantigul et al., 2008). It develop an extensive network of fine roots which can reach a depth of 4 meters underground (Tallent-Halsell & Watt, 2009).

	Scientific name	Common nepali name	General description
	 *Colebrookea oppositifolia*	Dhurseli	It is the only specie in the Colebrookea genus (Ishtiaq et al., 2016). It is a shrub with many erected branches (Quattrocchi, 2012), which can reach between 1-3 m tall (Ishtiaq et al., 2016).
	 *Vitex negundo*	Simali	Shrub with several branches, sometimes it can reach a height of 5 meters with a growth moderately to fairly fast. It distributes along river banks in moist soils, wastelands or deciduous forests (Orwa et al., 2009), but also it can grow in dry stony sites or hot dry road cuts (Howell, 1999a).
	 *Woodfordia fruticosa*	Dhayero	Shrub which can reach 3.5 m high with long and spreading branches (Das et al., 2007). It grows in dry sites in in the lower middle mountain valleys in very steep sites including rocky slopes. Its propagation is by seeds and it cannot develop from hardwood cuttings (Howell, 1999a).
Trees	 *Acacia catechu*	Khayer	Tree which can reach 15 meters in height with a relatively slow growth, 10 meters after 55 years (Department of the Environment and Heritage & CRC for Australian Weed Management, 2003). Present naturally in mixed deciduous forests, commonly in sandy soils of riverbanks (Global Invasive Species Database, 2016). In Nepal, the specie is commercially threatened with a status of protected (Tamang & Chapagain, 2016).
	 *Alnus nepalensis*	Utis	Deciduous tree which can reach 30 meters (Barakoti, 2005), with a rapid growth of 145 cm per year (Negi, 2013). It is tolerant to different stress presented in degraded soils (Ferrari & Wall, 2004), and associated to unstable slopes with rocky strata; so it seems to be a specie present in primary succession in Nepal (Negi, 2013). It regenerates naturally in landslide affected slopes, freshly exposed, and degraded soils (Sharma et al., 1998). It is susceptible to wind damage (Orwa et al., 2009).
	 *Ficus semicordata*	Khaniyo	Deciduous tree for a short time in the year, which requires spaces with good availability of light. It is tolerant to frost and easily killed by fire. In eroded slopes is one of the first species which regenerates naturally. It can be propagated by seeds; hardwood cutting is also possible. It has a relatively fast growth (3.4 m after 18 months) and at the eight year it can reach a height of 6 meters and a DBH of 7.3 cm (Jackson, 1994b). The mean crown diameter of ten year old trees is 2.35±1.2 m (Bahadur, 1992).

	Scientific name	Common nepali name	General description
	 *Melia azedarach*	Bakaino	Deciduous tree which can reach 10 meters tall or the wild forms until 40 m (Hua & Mabberley, 2008; Jackson, 1994b), and a DBH of 10.6 cm (Waggy, 2009), and crown area of 11.52 m² (Mishra et al., 2009). It grows relatively fast in moist forest associated to Schima-Castanopsis forests, being light-demanding. It can survive in shallow soils, but it grows better in deep soils well-drained and fertile soils. They are liable to damage for fire and hard winds, being uprooted and the stems broken (Jackson, 1994b).
	 *Morus alba*	Kimbu	Deciduous tree which can reach large dimensions in suitable sites, but it can also develop in poor soils in a wide range of climatic conditions. It is one of the fastest-growth fodder trees (reaching 2.7 m in 34 months), where for a good growth it must to be planted in loamy soils.
	 *Pinus roxburghii*	Pinus	Tree three-needle pine which can reach a height of 21-50 meters tall (Jackson, 1994b; Sharma et al., 2008). It is distributed in sheltered valleys in the foot hills and sometimes in dry upper valleys, sometimes forming pure pine forest or sometimes associated to *Shorea robusta*. It is very tolerant to poor soil conditions, so it can grow even in hard, eroded red clay loams and it tolerates a wide range of pH; but it does not grow well in soils with bad drainage. It is susceptible to diseases (Jackson, 1994b).
	 *Salix tetrasperma*	Bainsh	Deciduous tree which can reach a height of 14 meters (Afzal & Akhtar, 2013) with a fast growth of 2-2.5 annual diameter increment (Jackson, 1994b). In Nepal is found along the streams. It is light demanding and can resist frost. It can grow in dry conditions and be propagated by cuttings but it must to be protected from grazing (Howell, 1999a).
	 *Schima wallichii*	Chilaune	Large deciduous tree grows best in moist soil and in areas with high rainfall; sometimes it can resist certain amount of drought. It can regenerate very well. Its propagation is by seedlings from nursery (Howell, 1999a).

D. Benefits of different plant species used in bio-engineering for slope stability. Reported by local people and literature.

	Scientific name	Benefits mentioned by local people	Benefits from literature
Grasses	*Chrysopogon gryllus*	Fodder	Fodder (Tuna et al., 2004).
	Thysanolaena maxima	Fodder, slope stability	Fodder, brooms (Howell, 1999a).
Bamboos	*Bambusa balcooa*	Construction of houses, baskets, fodder, slope stability	Used for scaffolding and construction of house wall and slope stabilization (Stapleton, 1994), and reported as edible (Choudhury et al., 2012). Production of mat, baskets, musical instruments, paper, tooth brush, brooms, fodder, fuelwood, and insect repellent for cattle (Bhatt et al., 2003).
	Drepanostachyum intermedium	Fodder	Used in weaving to elaborate several kind of baskets (Jackson et al., 1987), used as fodder (Stapleton, 1994) and weaving (Howell, 1999a)
Shrubs	*Berberis asiatica*	Fodder, food, medicinal	Medicine: treatment of respiratory, aural and gastrointestinal diseases (Srivastava et al., 2004). In general it has been reported that the plant can treat a wide variety of diseases (Furrianca et al., 2015). For fencing because its sizeable thorns. Fruits are edible (Turin, 2003).
	Buddleja asiatica	Fodder	Fodder, fuelwood, rituals (Turin, 2003). Medicine: treatment of fever, ache, diarrhea and articular rheumatism (Chen et al., 2005). Source of perfume (Ping-tao & Leeuwenberg, 1996). Phytoremediation of heavy metal-contaminated soils (Waranusantigul et al., 2008).
	Colebrookea oppositifolia	Medicinal	The juice of young bud is used to remove leeches from nose of cattle (Tamang & Sedai, 2016). It has antimicrobial, antifungal, and anti-inflammatory effects, so it can be able to treat headaches, dermatitis, fever, and urinary problems (Ishtiaq et al., 2016).
	Vitex negundo	Slope stability	The juice of the leaves of this shrub is used to treat cough and constipation (Tamang & Sedai, 2016). It can be used for hedges and firewood (Howell, 1999a). A review of the medicinal uses of this plant shows that can treat a large list effects due its effects such as vermifuge, anti-inflammatory, antiseptic, diuretic, among others (Tandon, 2005).
	Woodfordia fruticosa	-	Juice of this plant can work against stomach ache (Uprety et al., 2011). A review of this plant show a wide variety of diseases where it can works such as dysentery, leucorrhoea, menorrhagia, diarrhea; also it is used to treat wounds and toothache, among others (Das et al., 2007). It can also be used for bedding and firewood (Howell, 1999a)
Trees	*Acacia catechu*	-	Crude dyeing (in silk, cotton, canvas, paper and leather to a dark-brownish color), leather tanning (Green & Food and Agriculture Organization of the United Nations, 1995). Fodder, fuelwood, house posts, agricultural implements and wheels(Global Invasive Species Database, 2016; Uprety et al., 2011). Medicine: treatment of respiratory and

	Scientific name	Benefits mentioned by local people	Benefits from literature
			gastrointestinal diseases (Global Invasive Species Database, 2016; Uprety et al., 2011).
	Alnus nepalensis	Fooder, fuel	Fodder, fertilizer, wood used for furniture, construction of houses, and beehives (Turin, 2003). Fuelwood, and used for shifting agriculture allowing soil fertility (Sharma et al., 1998). Slope instability indicator (Negi, 2013).
	Ficus semicordata	Fodder	Is used as fodder (Howell, 1999a; Jackson, 1994b). The juice of the plant is used to rehydrate the body and decrease warmness (Tamang & Sedai, 2016). A review of the medicinal uses of the plant suggest that can be used to treat diarrhea, headache, fever, earache, ulcer and gastric problems (Kaur et al., 2016).
	Melia azedarach	Fodder	Is used as a fodder, timber used for furniture, fuelwood, (Jackson, 1994b).
	Morus alba	Food	Usually used as a fodder, but the fruits are edible (Jackson, 1994b). In some cases, latex is used as anthe-helmintic for cattle (Tamang & Sedai, 2016). It is cultivated to feed silkworms (J.-R. Wang, Song, & Du, 2014). It is reported that this plant can help to treat several diseases such as cold, influenza, eye infections, or be used as and antirheumatic, antispasmodic, diuretic (PFAF, 2012).
	Pinus roxburghii	Construction of houses, fodder	The resin of the tree is used to cure mumps (Tamang & Sedai, 2016). It is reported to be good as antiseptic, diuretic, herbicide, fuel wood, building of houses; the resin is used to manufacture turpine (Jackson, 1994b). Small branches can be used as torches, in some cases they are used in exorcism rituals or other rituals (Turin, 2003)
	Salix tetrasperma	Fodder	It can be used as fodder, weaving, and timber (Howell, 1999a).
	Schima wallichii	Construction of houses, fodder	The medicinal use juice of bark of this tree is related in the treatment gastritis problems (Tamang & Sedai, 2016). Wood is used for furniture, and firewood. Timber is excellent for house construction (Turin, 2003). A paste extracted from the plat can be used for fish poisoning (Uprety et al., 2011).