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Quantitative Assessment of Root Anchorage and Binding Capacities of Teak and Pine for Shallow Landslide Mitigation in Sukabumi, Indonesia

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ABSTRACT

Shallow landslides pose a persistent hazard in tropical forest landscapes, particularly under increasing climate variability. This study evaluated the mechanical and biological effectiveness of five forest species—*Tectona grandis* (teak), *Pinus merkusii* (pine), *Melaleuca leucadendra* (cajuput), *Hevea brasiliensis* (rubber), and *Paraserianthes falcataria* (albizia)—in preventing shallow landslides through root-soil interactions. Ten replicate samples were collected using a purposive sampling method for each species and age class combination. This study was conducted in February 2023, analysing the Root Anchorage Index (RAI) and Root Binding Index (RBI) at age classes (4, 5, and 6 years). Laboratory tests of organic matter quality focused on nitrogen content, C/N ratio, lignin, and polyphenols. The results showed that teak roots have a very high RBI (14.635), indicating superior soil binding capacity, while pine roots showed the highest RAI (1.005), indicating strong anchorage potential. Both species also showed low decomposition due to high lignin and C/N values, strengthening their role in long-term slope stability. Species selection in reforestation and slope rehabilitation is essential, especially on latosol soils. Further research on root biomass and species-soil interactions is needed to support practical mitigation efforts in landslide-prone areas.

1. INTRODUCTION

Global climate change has emerged as a pressing concern, evidenced by rising global temperatures that affect all regions, including Indonesia and the island of Java. The average global temperature has increased by approximately 2℃ above pre-industrial levels. According to estimates, developing countries require an annual investment of approximately USD 6 billion solely for disaster risk management. Climate change adaptation forms a critical component of the 2030 Sustainable Development Agenda, particularly within Goal 13, which emphasises enhancing resilience and adaptive capacity to climate-induced hazards. Among the most significant natural disasters linked to climatic variability in Indonesia are landslides.

A lack of preparedness and adaptive measures toward natural hazards inevitably leads to heightened disaster risks. Environmental degradation—particularly deforestation—often intensifies community vulnerability rather than mitigating it. Likewise, unregulated urban expansion into hazardous zones, such as steep slopes or flood-prone lowlands, significantly increases risk exposure. Over time, populations tend to normalise slow-onset disasters, inadvertently accepting them as routine despite the escalating socioeconomic losses they incur [1].

Landslides are primarily triggered by rainfall [2-14], a finding consistently supported in numerous studies. Forested areas with sparse vegetation cover are particularly vulnerable to landslide impacts during intense precipitation [15]. In Indonesia, where the average annual rainfall ranges from 1,000 to 4,000 mm, regions with deforested or poorly managed forest areas face significantly elevated landslide risks.

West Java is one of Indonesia's provinces with the highest landslide disaster rates, with Sukabumi Regency being one of the most frequent. The National Disaster Management Agency (BNPB) reported 369 landslides in Sukabumi Regency between 2020 and 2025.

Forest ecosystems mitigate such hazards by intercepting rainfall, retaining water within the soil matrix, and gradually releasing it into downstream systems. This process significantly reduces surface runoff and improves slope stability [15-17].

In addition to climatic factors, variables such as land use intensity, vegetation type [18, 19], Human-induced activities—including deforestation—play a significant role in triggering landslides [2, 14, 19-21].

Landslides are also one of the consequences of deforestation [22]. Deforestation leads to increased landslide frequency due to the control of forest roots on slope stability. Numerous studies have highlighted how root systems enhance soil cohesion, particularly in sloped environments, making sustainable forestry practices integral to landslide mitigation strategies. Landslides are typically classified into deep-seated and shallow categories [10], with shallow landslides characterised by a failure depth of less than two meters.

Previous studies have highlighted the crucial role of vegetation in mitigating landslides and soil erosion through mechanical and hydrological mechanisms. Vegetation is pivotal in mitigating landslides and soil erosion by enhancing slope stability through both mechanical and hydrological effects [23]. One of the key mechanisms lies in the root systems, which significantly improve soil cohesion and shear strength; among various species, *Pinus merkusii* has demonstrated the highest soil-root cohesion [24]. Building on this, emphasised that vegetation with interlocking root systems can effectively reduce landslide risk in vulnerable areas [24]. Further supporting this, vegetation is particularly beneficial in lowering soil movement during the rainy season, owing to its dual mechanical and hydrological functions [25]. However, the overall effectiveness of vegetation in slope stabilisation is influenced by several factors, including root architecture, soil conditions, and plant species characteristics.

Vegetation is widely recognised as an eco-friendly and cost-effective approach to slope stabilisation, primarily through its mechanical and hydrological influences on soil strength. Root systems enhance soil cohesion and shear resistance, reducing the risk of shallow landslides. However, despite growing interest in nature-based solutions, challenges such as the time required for vegetation to establish and the need for continuous maintenance remain significant limitations. Moreover, while previous studies have demonstrated the general benefits of vegetation for slope stability, empirical data on the root reinforcement performance of specific tree species in particular soil types—such as latosols—are still limited [25]. Addressing this research gap, the present study quantitatively assesses root anchorage and binding capacities of *Tectona grandis* (teak) and *Pinus merkusii* (pine) in latosol soils. These two species are commonly used in reforestation programs across landslide-prone regions, including Sukabumi, Indonesia. The findings are expected to contribute to species-specific recommendations for shallow landslide mitigation and support adaptive land management strategies in response to increasing environmental challenges.

This study investigates explicitly shallow landslides and aims to evaluate the mechanical contribution of tree roots using the Root Anchorage Index (RAI) and Root Binding Index (RBI). These indices are applied to analyse root strength in teak (*Tectona grandis*) and pine (*Pinus merkusii*), the primary commercial forestry species managed by the state-owned enterprise Perhutani. Teak and pine have long served as the economic backbone of Indonesian forestry, not only due to their high commercial value in timber and non-timber products but also for their ecological services. Teak is cultivated predominantly for its high-density wood, while pine is managed for timber, non-timber, and resin derivatives such as gum rosin and turpentine. Additional species—cajuput (*Melaleuca leucadendra*), rubber (*Hevea brasiliensis*), and albizia (*Paraserianthes falcataria*)—were included in this study to provide a comparative framework for assessing root strength across species. The involvement of forestry enterprises was limited to logistical support and access to field sites, ensuring the objectivity of the study's scientific findings.

1.1 Study area

This study was conducted in the Sukabumi Forest Management Unit (Kesatuan Pemangkuan Hutan or KPH Sukabumi), one of the management units under the Perhutani Regional Division of West Java and Banten. KPH Sukabumi comprises six forest sections (BKPH): Bojong Lopang, Cikawung, Jampang Kulon, Lengkong, Pelabuhan Ratu, and Sagaranten, as shown in Figure 1. Administratively, KPH Sukabumi is located within Sukabumi Regency, West Java Province, Indonesia.

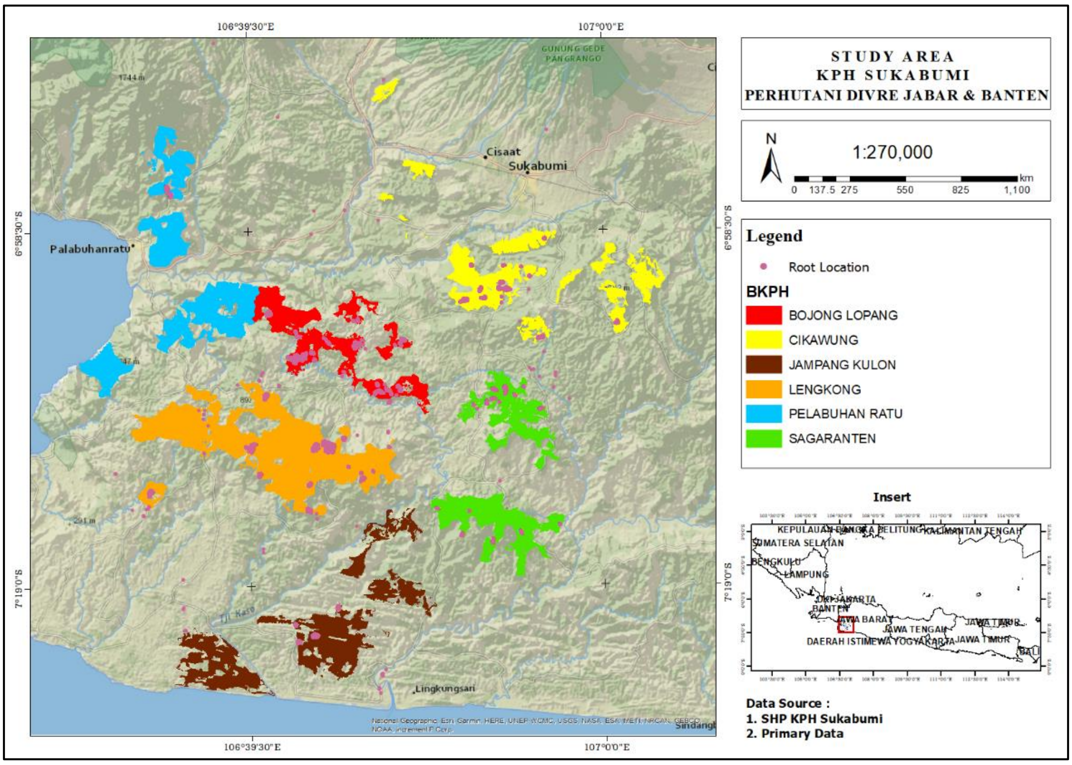

Figure 1. Study area in KPH Sukabumi

2. METHODS

Field data were collected in February 2023 within the forest management unit of Sukabumi, West Java, Indonesia. This location was selected due to the presence of various forestry species, including *Tectona grandis* (teak), *Pinus merkusii* (pine), *Melaleuca leucadendra* (cajuput), *Hevea brasiliensis* (rubber), and *Paraserianthes falcataria* (albizia). The diversity of species and maturity stages made it an ideal setting to evaluate the mechanical properties of tree roots in stabilising shallow landslides.

2.1 Tools and materials

The tools used in this research are a soil survey set, stationery, metre, bow, hoe, knife, hammer, graph paper, sample ring, and direct root strength tool including an identification guide, tally sheets, hoes, crowbars, soil forks, measuring tapes, rulers, calipers, smartphones, hypsometers, and writing tools. As for materials in the form of tree samples from the plant species *Tectona grandis* (teak), *Pinus merkusii* (pine), *Melaleuca leucadendra* (cajuput), *Hevea brasiliensis* (rubber), and *Paraserianthes falcataria* (albizia), aged 4, 5, and 6 years. Root samples of Root diameter data in vertical and horizontal positions are used as primary data.

2.2 Measurement

The study utilised a combination of primary field measurements and secondary data, including the planted species' survival rates and the site's general environmental characteristics. The core focus was to measure two indices that reflect root mechanical function: the Root Anchorage Index (RAI) and the Root Binding Index (RBI).

2.3 Procedures and sampling

As depicted in Figure 2, the procedure began with identifying landslide-prone slopes. Sampling plots were established, and representative species were selected for excavation. Roots were carefully exposed to avoid breakage and facilitate accurate measurement. Then, the soil type, organic matter content, and the calculation of RAI and RBI values were analysed.

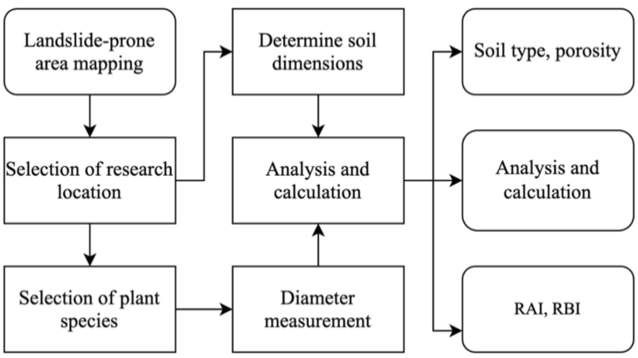

Figure 2. Work procedure of RAI and RBI measurement

Sample plants in each observation lane were dug at the root area and observed and measured according to the parameters used. Trees with high economic value were prioritised for the observations and compared to bush fallow vegetation. The parameters used in this study are root characteristics consisting of the Root Anchorage Index (RAI) and Root Binding Index (RBI). The method of measuring root diameter was carried out by measuring at a distance of 1 cm from the base of the root, both vertically and horizontally. The stem diameter is measured at a height of 130 cm for the tree and pole level [26]. These two indices are essential for determining the plant type that mitigates soil movement and erosion [23]. Some vertical roots were collected as samples to measure wood density and assess lignin and polyphenol contents, employing the same analytical methods.

2.4 Inventory of tree root systems

Tree root diameter samples were obtained by digging the soil to the deepest root. Horizontal roots (dh) are those with < 45% of their roots directed toward the soil, while vertical roots (dv) are those with > 45% of their roots directed toward the soil. The measured data are the diameters of each dh and dv (Figure 3).

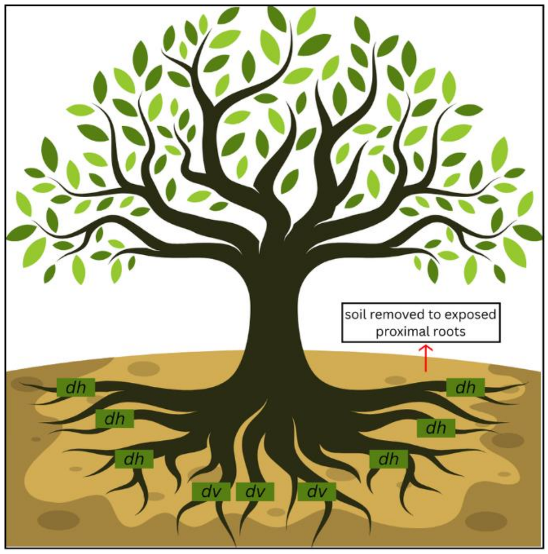

Figure 3. Schematic diagram of the distribution of proximal roots

2.5 Root excavation

Root excavation is carried out carefully to avoid root damage and is carried out in stages, starting from the west side and then moving eastward to prevent the plant from collapsing. This process involves digging the soil 50 cm from the outer edge of the crown. Excavation is carried out in small increments, every 10 cm, using a small shovel and brush until all the roots are exposed (Figure 4).

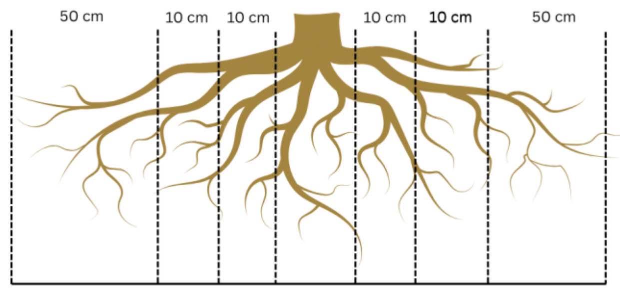

Figure 4. Excavation stage scheme

The selection of root samples was based on a purposive sampling method in the Sukabumi FMU area. Root samples were taken at ages 4, 5, and 6 from live plants with the best phenotypes for each species (trunk straightness, diameter, and plant height).

2.6 Sample criteria

The selection criteria for sample trees in this study focused on dominant species classified under the company's commercial category, with age classes of 4, 5, and 6 years. These criteria are selected based on the stability of root growth dynamics at a certain age in preventing landslide hazards. Studies have shown that tree roots can significantly increase soil cohesion, with effectiveness varying by species, age, and forest management practices [27]. Moreover, the distribution of root biomass changes as trees age; younger trees tend to have roots clustered near their base, while older trees exhibit a more even spread. Fine roots adjust their biomass in response to environmental conditions and stand age, rather than changing their spatial distributions [28].

To minimise disturbance to soil integrity, particularly in erosion-prone areas, only trees exhibiting exposed root systems on the soil surface were targeted for sampling. This approach not only ensured accessibility but also reduced the risk of additional mechanical damage to surrounding vegetation and soil. The data used in this study were obtained from each target tree species and age class, with ten individual samples collected for each category. For example, ten pine trees were sampled for age 4, ten for age 5, and ten for age 6. The same sampling procedure was applied to the other tree species included in the study. This approach was taken to enhance statistical reliability and to address variability within groups.

The research was conducted across five sub-forest Management Units (BKPHs): Bojonglopang, Lengkong, Jampang Kulon, Sagaranten, and Cikawung. These sites were selected based on the availability and distribution of the target age classes (4 to 6 years) within the managed forest landscape. The selected BKPHs provided a representative cross-section of both environmental and silvicultural conditions relevant to the study objectives.

2.7 Data analysis

Measurements were made using the Root Anchoring Index and Root Binding Index methods to prove how forestry multi-enterprise crop commodities can withstand landslide natural disasters. The Index of Root Anchoring (RAI) is the ratio of horizontal root diameter to stem diameter. The Index of Root Binding (RBI) is the ratio of vertical root diameter to stem diameter. The root distribution of plant species can be described through RAI and RBI values. The RAI value is used to determine the condition of vertical rooting, while the condition of horizontal rooting is determined using the RBI value. This research has practical implications for understanding and managing the risk of natural disasters in forestry [8, 9].

The second proof is obtained by examining the organic matter content of each root. Roots with high organic matter quality will be easily decomposed and break easily. Conversely, if the roots have low organic matter quality, they are more robust and do not break easily [29]. Each plant sample was measured for horizontal root diameter (to calculate RBI), vertical root diameter (for RAI), and stem diameter [30]. A horizontal root is the angle between the root and the horizontal plane of less than or equal to 45°, while a vertical root is more than 45°. The equations used to calculate RAI and RBI are:

$$RAI = \frac{\sum dv^2}{\sum db^2} \quad (1)$$

$$RBI = \frac{\sum dh^2}{\sum db^2} \quad (2)$$

where,
RAI: Root Anchoring Index
RBI: Root Binding Index
dv: vertical root diameter
dh: horizontal root diameter
db: stem base diameter

After obtaining the average, the RAI and RBI scores were grouped into classifications (Table 1).

Table 1. Classification of RAI and RBI values [30]

Category	RAI	RBI
Low	< 0.5	< 0.5
Medium	0.5 – 1.8	0.5 – 1.5
High	> 1.8	> 1.5

In addition to the RAI and RBI values, the organic matter quality of the roots was also analysed. The criteria for high-quality organic matter are:

- N content > 2.5%
- C/N content < 20%
- lignin < 20%
- polyphenols < 2%

Various studies have widely acknowledged that roots play a pivotal role in strengthening the soil [8-12], and the C/N ratio of plants also affects the soil C/N ratio [31-36]. This understanding forms the basis of our research.

3. RESULTS AND DISCUSSIONS

According to the Forest Sustainability Management Plan KPH Sukabumi for 2023-2032, the research area comprises two dominant soil types: latosol and grumusol. Latosol soils are distributed across all Sub-Forest Management Units (BKPH), whereas grumusol soils are localised in the Bentang Barat Forest Subdivision of BKPH Sagaranten. All sampling locations for root index measurements in this study were on latosol soils. Latosol soils are typical of tropical rainforest ecosystems and are characterised by high porosity, generally between 40% and 60% [37], depending on site conditions and land management practices. This high porosity facilitates root penetration and gas exchange, promoting plant growth and overall soil ecosystem function. However, latosols are often nutrient-poor and require active soil management to sustain fertility and vegetation cover.

Additionally, latosol soils in the study area have a moderately acidic pH, typically ranging from 5.0 to 5.8, influencing nutrient availability and microbial activity essential for root development. The bulk density is relatively low, averaging around 0.9 to 1.1 g/cm³, indicating a loose soil structure that supports deeper root penetration and reduces mechanical resistance. Moreover, the shear strength of these soils is moderate, generally between 25 and 35 kPa, which affects the soil's ability to resist deformation and contributes to slope stability, an essential factor in assessing the anchorage capacity of tree roots in landslide-prone terrains.

The root system, a vital link between plants and soil, has been largely unexamined but is of immense practical importance. Plant roots are essential in strengthening the soil, preventing adverse soil movements, stabilising the plant itself, preventing soil erosion, and stabilising slopes. The mechanical stabilisation of soil slopes through tree roots depends mainly on the strength properties of the roots and their growth pattern in the soil. The effect of tree roots on slope stability can be considered in terms of their strength and distribution in the soil [14, 16, 17]. These findings have significant implications for soil management and conservation practices.

3.1 Standing conditions in KPH Sukabumi

The tree stands in the Sukabumi Forest Management Unit and represents a commercial species in the Indonesian timber trade. The existing species include *Tectona grandis* (teak), P*inus merkusii* (pine), *Melaleuca leucadendra* (eucalyptus), *Hevea brasiliensis* (rubber), and *Paraserianthes falcataria* (albizia) with varying age classes and areas. Table 2 outlines the specific characteristics of the sampled areas, including species composition, age distribution, and site conditions.

Table 2. Composition of plant species aged 4, 5, and 6 years

Species	Sub-FMU	Age (Ha)			Total (Ha)
		4	5	6	
JPP	Jampang Kulon	304.88	161.31	0	466.19
Rubber	Bojong Lopang	0	0	45.18	45.18
Cajuput	Sagaranten	211.27	0	17.4	228.67
Pine	Bojong lopang	195.73	644.4	57.75	317.88
	Cikawung	109.48	21.52	67.68	198.68
	Lengkong	390.36	109.13	10.20	509.69
	Sagaranten	35.34	15.46	82.68	133.68
Albizia	Bojong Lopang	101.57	0	0	101.57

3.2 Root Anchorage Index (RAI) and Root Binding Index (RBI)

The results of the Root Anchorage Index (RAI) and Root Binding Index (RBI) analysis for five tree species of various ages are presented in Table 3. These metrics provide insights into the mechanical behaviour of root systems in stabilising soil under shallow landslide conditions. Our analysis revealed that RAI and RBI values for pine species generally increase with tree age, suggesting that older pine trees develop stronger anchoring and soil-binding capabilities.

However, this trend was not consistent across all species, primarily due to differences in the age composition of the sampled individuals.

This study analysed the RAI and RBI values of different tree species for soil stabilisation. Root samples from various tree species were collected, and their RAI and RBI values were measured. The results are presented in Table 3. We observed that the RAI and RBI values for pine species increase as the age increases. However, this is only sometimes true for other species since this was not done in the field due to differences in age composition for each species. Table 4 summarises each species' average RAI and RBI values and classifies them based on their stabilisation potential.

Table 3. RAI and RBI values at various types, ages, and diameters

Species	Age	Dbh (cm)	RAI	RBI
Pine	4	11.2	0.273	0.154
	5	14.8	0.474	0.385
	6	14.0	0.672	0.613
	7	4.6	5.208	2.944
Albizia	6	16.8	0.408	0.868
Rubber	15	26.0	0.534	0.076
Cajuput	7	20.8	0.131	0.137
Teak/JPP	5	13.6	0.086	9.940
	6	12.8	0	24.026

Table 4. Mean values of RAI and RBI and their categories

Species	Dbh (cm)	RAI		RBI	
		Value	Category	Value	Category
Pine	13.1	1.005	Medium	0.719	Medium
Albizia	16.8	0.408	Low	0.868	Medium
Rubber	26.0	0.534	Medium	0.076	Low
Cajuput	20.8	0.131	Low	0.137	Low
Teak/JPP	13.3	0.086	Low	14.635	High

On the other hand, the cajuput (*Melaleuca Leucadendron*) tree presents a more balanced performance between RAI and RBI. With its RAI slightly surpassing its RBI, at 0.131 and 0.137, respectively, it suggests that the cajuput species possesses a more evenly distributed ability to anchor its roots and bind the soil. This versatility makes it a potentially intriguing species for soil stabilisation in various environments.

Conversely, the *Hevea brasiliensis* (rubber tree) displays a more robust anchoring ability, with an RAI of 0.534. However, its RBI is notably lower at 0.076, indicating that while the rubber tree's root system is more effective at anchoring, it has a relatively low capacity to bind the soil. This finding suggests that further research and evaluation may be needed before considering the rubber tree for specific applications that demand strong absorption or binding properties.

Finally, albizia (*Paraserianthes falcataria*) and pine (*Pinus merkusii*) show the highest overall values in the chart. *Paraserianthes falcataria* has a balanced relationship between its RAI (0.408) and RBI (0.868), with a slightly more vital ability to bind soil than to anchor roots. Pine stands out with a firm root anchoring ability (RAI of 1.005) and a decent soil binding ability (RBI of 0.719). Pine is a particularly effective species for soil stability and erosion prevention.

The chart underlines the different strengths of these five species in soil stabilisation. While teak/JPP excels at binding the soil, species like pine and rubber show a more balanced or robust performance in root anchoring. The variation in RAI and RBI values underscores the importance of species selection for specific soil stabilisation needs, highlighting the significance of our work in this field.

A comparative analysis of RAI and RBI across the five species is shown in Figure 5. These indices are essential for understanding the ability of tree species to stabilise soil and prevent erosion. The RAI measures the strength of the root system when anchoring the tree, which is crucial for avoiding uprooting and maintaining stability. At the same time, the RBI assesses the root system's ability to bind the soil particles together, contributing to soil stability by preventing soil erosion. The chart shows a significant difference between the RAI and RBI values of the Tectona grandis (Teak) tree. Its RAI is relatively low at 0.086, suggesting that its root system is less effective in anchoring the tree. However, its RBI is very high at 14.635, indicating that while its root system does not anchor the tree firmly, it does bind the soil particles very effectively, which implies that teak may help stabilise soil in environments where soil binding is the primary concern.

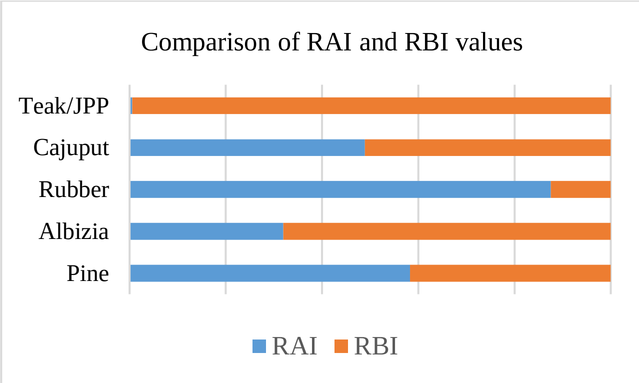

Figure 5. Comparison of RAI and RBI values

The analysis reveals that different species have distinct strengths, making them suitable for varying purposes. Pine and albizia demonstrate balanced performance, whereas Tectona grandis dominates binding efficiency. Conversely, species like rubber and cajuput may require further evaluation before being utilised for specific applications that demand strong absorption or binding properties. It highlights the importance of choosing suitable species for targeted ecological or industrial applications.

Regarding the classification of RAI and RBI values [30], as shown in Table 4, rubber species with an average diameter of 26 cm have medium and low RBI values. Cajuput species with a diameter of 20.8 cm, RAI, and RBI values are included in the low criteria. Pine, with an average diameter of 13.1 cm, is categorised as a medium class (medium) with both RAI and RBI values. As for the albizia species, with an average diameter of 16.8 cm, the RAI value is in the low category, but the RBI value is in the medium category. Teak, with an average diameter of 13.3 cm, has a low RAI value but a high RBI value.

The very high RAI value for teak species is because the root samples studied for Teak Plus Perhutani (called JPP) species mostly do not have tap roots. Jati Plus Perhutani (JPP) is a superior variety of teak trees developed by Perhutani through vegetative propagation methods, primarily through shoot cuttings and tissue culture techniques. These two methods allow faster plant propagation and produce seedlings with the same genetic characteristics as the parent tree, so the quality and durability of JPP seedlings are more guaranteed.

Rubber species had the lowest Root Binding Index compared to the other species studied. It is thought to be because rubber species have a root system consisting of a taproot, lateral roots attached to the taproot, and fibrous roots. In 3-year-old plants, the depth of the taproot has reached 1.5m. The taproot length of 3-year-old and 8-year-old rubber trees was about 1.5 meters and 2.5 meters, respectively. When the plant is 7 years old, the taproot has reached a depth of more than 2.5 meters. It was found that 3-year-old trees have lateral roots that extend up to 6-9 meters, and 7-8-year-old trees have lateral roots that are more than 9 meters long [10-13].

Rubber plants are dicotyledonous plants with a root system consisting of taproots, lateral roots attached to the taproot, and root fibres. The taproot strengthens the plant so that it does not collapse quickly, and the taproot is firmly stuck into the soil, while the lateral roots and root fibres attached to the taproot absorb water and minerals from the soil.

Pine species, although the types and methods of research are different, in China's Beigou forest (800-1600 m a.s.l.), through root removal tests, *Pinus tabulaeformis* (25 years old) was the least effective in strengthening/anchoring the soil compared to other species (*Betula platyphylla*, *Quercus mongolica*, *Larix gmelinii*, and *Ulmus pumila*) [10]. Ferera, in 2009 [38-42], states that trees with extensive root index values are needed to maintain cliff stability. The data above shows that pine species, although categorised as a medium for RAI and RBI values, have a higher average root index than albizia, rubber, and cajuput. Pine's root index has a higher RAI value than teak, but the RBI value remains below. Table 3 also shows that the older the plantation, the higher the RAI and RBI values, thus maintaining slope stability. However, increased RAI is only sometimes followed by increased RBI [43].

Dewi et al.'s [44] research in 2015 showed an RAI value of 0.94 and an RBI value of 0.51. They mentioned that pine trees can anchor themselves firmly to the ground and grip the soil quite well, even better than jackfruit (*Artocarpus heterophyllus*) and melinjo (*Gnetum gnemon*) species for RBI values.

Teak species had the lowest RAI value compared to other species (0.086) but the highest RBI value. It is likely because the teak species planted is Perhutani Teak Plus, which results from tissue culture propagation, so it has a firm grip but relatively no tap roots. In teak (*Tectona grandis*), the phenomenon of high Root Binding Index (RBI) but low Root Anchorage Index (RAI) is closely related to the configuration of the root system. Teak with high RBI usually has a large root biomass, especially in well-developed lateral roots, while taproots are underdeveloped or weak. This condition causes the total mass of roots that bind the soil to be quite large, so the RBI is high, but the structure and depth of the roots that support the tree mechanically are not optimal, so the RAI is low. Such root systems tend to produce dense root networks at the soil surface, are practical at binding soil and preventing erosion, but are less effective at providing mechanical stability against physical disturbances such as strong winds. In other words, the dominance of large lateral roots without the support of a strong taproot results in a heavy but less architecturally complex root system, resulting in low tree anchoring ability (RAI) despite high soil binding ability (RBI) [45].

Trees that allocate more biomass to lateral roots than taproots generally have a large total root biomass (high RBI). However, because the taproot is underdeveloped or weak, the root system is less complex and has low mechanical strength (low RAI). This explains why teak trees, predominantly lateral roots with a poorly developed taproot, exhibit high RBI but low RAI.

A high RAI indicates a solid and stable root system that supports the tree to prevent it from collapsing, while a low value suggests potential instability. Meanwhile, a high RBI indicates the ability of the roots to bind the soil well, which is vital for preventing erosion and strengthening soil stability. However, it does not necessarily correspond to the tree's mechanical resistance to wind.

3.3 Organic matter content

To complement the mechanical root index analysis, laboratory assessments were conducted to evaluate the quality of organic matter in teak and pine roots. Parameters analysed included total nitrogen (N), carbon-to-nitrogen (C/N) ratio, lignin content, and polyphenol concentration—factors that influence root decomposition and mechanical resistance. Differences in test results for teak and pine roots are shown in Table 5.

Table 5. Comparison of organic materials between teak roots and pine roots

Parameter	Teak Roots (%)	Pine Roots (%)
Carbon	3.02	1.45 – 3.75
Nitrogen	3.17	9.26
Lignin	28.91	20.5 – 25.8
C/N Ratio	16.25	15.66 – 40.50

According to established criteria [46], high-quality organic matter should possess N content > 2.5%, C/N ratio < 20, lignin < 20%, and polyphenols < 2%. Based on these benchmarks, both teak and pine roots exceed acceptable lignin and polyphenol thresholds, suggesting that their root tissues are not readily decomposable. This structural resistance contributes to their functional longevity in providing soil cohesion and mechanical support, even under high-moisture conditions. The high lignin content observed in teak (28.91%) further reinforces its role in long-term slope stability through persistent soil binding despite its low RAI.

Conversely, the higher RAI observed in pine, combined with a lignin content within the moderately decomposable range, makes it suitable for applications requiring anchorage and gradual nutrient cycling.

These findings confirm that both teak and pine species exhibit root traits effective in shallow landslide mitigation, albeit via distinct mechanisms—binding versus anchoring.

3.4 Diagram of a typical root system

A general overview of teak and pine root systems typically shows a prominent taproot accompanied by an extensive network of lateral roots. The differences between the two types of roots (Table 6). In both teak and pine, root development begins with a robust taproot that anchors the tree and reaches deep for nutrients, complemented by lateral roots that expand outward to enhance stability and nutrient absorption. Teak roots are primarily distinguished by their considerable depth and broad horizontal reach. In contrast, the balance between the taproot and lateral roots in pine can vary based on the soil type.

Table 6. Different types of roots

Tree Type	Root System Type	Characteristics
Teak (*Tectona grandis*)	Taproot system with extensive lateral roots	- The taproot grows deep (3 – 4.5 m) for strong anchorage and deep soil nutrient absorption. - Lateral roots spread widely (up to ±9 m), adding stability and aiding absorption. - Initially focused on the taproot, it then develops numerous lateral root branches as it grows.
Pine (*Pinus merkusii*)	Primarily taproot system	- Initially, a main taproot appears, growing deeply to anchor the plant. - Secondary and tertiary lateral roots appear later, and their pattern depends on the soil type. - In sandy or peaty soils, the dominance of the taproot may diminish as lateral roots develop more.

3.5 Vegetation selection for recommendations

For landslide-prone areas, it is recommended to use vegetation with root systems that are able to provide mechanical stability as well as strong soil binding, through a combination of Root Anchorage Index (RAI) and Root Binding Index (RBI) values. Plants with high RAI usually have deep and sturdy taproots, which can resist shear forces and prevent trees from falling or mechanical landslides. On the other hand, plants with a high RBI have a large root biomass with dense lateral roots, which are effective in binding soil grains and increasing soil cohesion, reducing the risk of erosion and surface landslides.

The results show that the ideal root system to reduce landslide risk is one that combines strong deep roots (increasing RAI) with abundant and dense lateral roots (increasing RBI). Deep anchoring roots provide high mechanical stability, while lateral roots strengthen soil structure horizontally and help improve soil hydrology by accelerating the post-rainfall drying process, thereby reducing water saturation that can trigger landslides [47].

Therefore, tree vegetation with deep taproots and good lateral root development is highly recommended to be planted in landslide-prone areas, as it can provide optimal soil reinforcement and slope stabilisation. In addition, roots with good mechanical properties (such as flexural and tensile strength) as well as complex root architecture (e.g., degree of branching and root area ratio) also contribute greatly to reducing landslide susceptibility [48].

Thus, vegetation selection in landslide-prone areas should consider these two parameters (RAI and RBI), so that the plants are not only effective in binding the soil but also mechanically strong enough to resist forces that can trigger landslides.

4. CONCLUSIONS

Teak roots have a very high RBI (14.635), indicating superior soil binding capacity, while pine roots showed the highest RAI (1.005), indicating strong anchorage potential. The comparative analysis of root index values across five primary forest species in KPH Sukabumi reveals distinctive traits in their capacity to mitigate shallow landslides. Pine (Pinus merkusii) exhibited the highest Root Anchorage Index (RAI), demonstrating strong anchoring performance, while teak (Tectona grandis) presented the highest Root Binding Index (RBI), indicating superior soil-binding capability.

The structural resilience of both species is supported by their root organic matter quality, characterised by high lignin content and low decomposition rates. These attributes make pine and teak especially effective in slope stabilisation through anchorage and soil binding.

Based on these findings, a combined planting strategy is recommended to optimise slope protection. Teak is suggested to be primarily planted on the middle and lower slopes where soil binding is critical, while pine can be prioritised on the upper slopes to maximise anchorage against shallow slips. A tentative planting ratio of teak to pine at approximately 2:1 may be considered to balance their complementary mechanical functions and economic benefits.

Further research is recommended to quantify root biomass and its correlation with slope stability, to prove that soil strength is directly proportional to the increase in root biomass. Additionally, an in-depth investigation is needed into how different soil types—particularly latosols—interact with specific root structures to inform species selection for reforestation and slope rehabilitation projects.

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REFERENCES

[1] Slettebak, R.T. (2012). Don't blame the weather! Climate-related natural disasters and civil conflict. Journal of Peace Research, 49(1): 163-176.

[2] Dai, F.C., Lee, C.F., Ngai, Y.Y. (2002). Landslide risk assessment and management: An overview. Engineering Geology, 64(1): 65-87. https://doi.org/10.1016/S0013-7952(01)00093-X

[3] Guzzetti, F. (2003). Landslide hazard assessment and risk evaluation: Limits and prospectives. In Proceedings of the 4th EGS Plinius Conference, Mallorca, Spain.

[4] Hojat, A., Arosio, D., Ivanov, V.I., Longoni, L., Papini, M., Scaioni, M., Tresoldi, G., Zanzi, L. (2019). Geoelectrical characterisation and monitoring of slopes on a rainfall-triggered landslide simulator. Journal of Applied Geophysics, 170: 103844. https://doi.org/10.1016/j.jappgeo.2019.103844

[5] Marin, R.J., García, E.F., Aristizábal, E. (2020). Effect of basin morphometric parameters on physically-based rainfall thresholds for shallow landslides. Engineering Geology, 278: 105855. https://doi.org/10.1016/j.enggeo.2020.105855

[6] Camera, C.A.S., Bajni, G., Corno, I., Raffa, M., Stevenazzi, S., Apuani, T. (2021). Introducing intense rainfall and snowmelt variables to implement a process-related non-stationary shallow landslide susceptibility analysis. Science of The Total Environment, 786: 147360. https://doi.org/10.1016/j.scitotenv.2021.147360

[7] Greco, R., Comegna, L., Damiano, E., Marino, P., Olivares, L., Santonastaso, G.F. (2021). Recurrent rainfall-induced landslides on the slopes with pyroclastic cover of Partenio Mountains (Campania, Italy): Comparison of 1999 and 2019 events. Engineering Geology, 288: 106160. https://doi.org/10.1016/j.enggeo.2021.106160 10.101

[8] Jang, S.J., Kim, S.W., Kim, M., Chun, K.W. (2021). Evaluating the effect of root cohesion on shallow landslides for physically based modeling. Sensors and Materials, 33(11): 3847-3862. https://doi.org/10.18494/SAM.2021.3606

[9] Kalubowila, P., Lokupitiya, E., Halwatura, D., Jayathissa, G. (2021). Threshold rainfall ranges for landslide occurrence in Matara district of Sri Lanka and findings on community emergency preparedness. International Journal of Disaster Risk Reduction, 52: 101944. https://doi.org/10.1016/j.ijdrr.2020.101944

[10] Liu, S., Ji, X., Zhang, X. (2022). Effects of soil properties and tree species on root–soil anchorage characteristics. Sustainability, 14(13): 1-19. https://doi.org/10.3390/su14137770

[11] Chang, R., Fu, B., Liu, G., Yao, X., Wang, S. (2012). Effects of soil physicochemical properties and stand age on fine root biomass and vertical distribution of plantation forests in the Loess Plateau of China. Ecological Research, 27(4): 827-836. https://doi.org/10.1007/s11284-012-0958-0

[12] Ben Sim, K., Lee, M.L., Wong, S.Y. (2022). A review of landslide acceptable risk and tolerable risk. Geoenvironmental Disasters, 9(1). https://doi.org/10.1186/s40677-022-00205-6

[13] Tanyaş, H., Hill, K., Mahoney, L., Fadel, I., Lombardo, L. (2022). The world's second-largest, recorded landslide event: Lessons learnt from the landslides triggered during and after the 2018 Mw 7.5 Papua New Guinea earthquake. Engineering Geology, 297: 106504. https://doi.org/10.1016/j.enggeo.2021.106504

[14] Vishnu, C.L., Oommen, T., Chatterjee, S., Sajinkumar, K.S. (2022). Challenges of modeling rainfall triggered landslides in a data-sparse region: A case study from the Western Ghats, India. Geosystems and Geoenvironment, 1(3): 100060. https://doi.org/10.1016/j.geogeo.2022.100060

[15] Bhattacharjee, K., Behera, B. (2017). Forest cover change and flood hazards in India. Land Use Policy, 67: 436-448. https://doi.org/10.1016/j.landusepol.2017.06.013

[16] Zal, N., Bastrup-Birk, A., Bariamis, G., Scholz, M., et al. (2015). Water-retention potential of Europe's forests. A European overview to support natural water-retention measures. European Environment Agency Technical Report, 13: 2015. https://www.eea.europa.eu/publications/water-retention-potential-of-forests.

[17] Moos, C., Peter, B., Graf, F., Mattli, J., Rickli, C., Schwarz, M. (2014). How does forest structure affect root reinforcement and susceptibility to shallow landslides? Earth Surface Processes and Landforms, 41(7): 951-960. https://doi.org/10.1002/esp.3887

[18] de Jesús Arce-Mojica, T., Nehren, U., Sudmeier-Rieux, K., Miranda, P.J., Anhuf, D. (2019). Nature-based solutions (NbS) for reducing the risk of shallow landslides: Where do we stand? International Journal of Disaster Risk Reduction, 41: 101293. https://doi.org/10.1016/j.ijdrr.2019.101293

[19] Phillips, C., Hales, T., Smith, H., Basher, L. (2021). Shallow landslides and vegetation at the catchment scale: A perspective. Ecological Engineering, 173:106436. https://doi.org/10.1016/j.ecoleng.2021.106436

[20] Cohen, D., Schwarz, M. (2017). Tree-root control of

shallow landslides. Earth Surface Dynamics, 5(3): 451-477. https://doi.org/10.5194/esurf-5-451-2017
[21] Sestras, P., Bilaşco, Ş., Roşca, S., Dudic, B., Hysa, A., Spalević, V. (2021). Geodetic and UAV monitoring in the sustainable management of shallow landslides and erosion of a susceptible urban environment. Remote Sensing, 13(3): 385. https://doi.org/10.3390/rs13030385
[22] Diehl, J.A., Asahiro, K., Hwang, Y.H., Hirashima, T., Kong, L., Wang, Z., Yao, H., Tan, P.Y. (2022). A CHANS approach to investigating post-disaster recovery potential in rural Japan. Journal of Disaster Research, 17(3):453-463. https://doi.org/10.20965/jdr.2022.p0453
[23] Sittadewi, E.H., Tejakusuma, I.G. (2019). Peranan arsitektur akar tanaman dalam mitigasi bencana gerakan tanah dan erosi. Jurnal Sains dan Teknologi Mitigasi Bencana, 14(1): 54-61.
[24] Zayadi, R., Putri, C.A., Irfan, M.N., Kusuma, Z., Leksono, A.S., Yanuwiadi, B. (2022). Soil reinforcement modelling on a hilly slope with vegetation of five species in the area prone to landslide in Malang, Indonesia. Environmental Research, Engineering and Management, 78(3):56-72. https://doi.org/10.5755/j01.erem.78.3.30670
[25] Judijanto, L., Suparwata, D.O. (2025). Peran vegetasi dalam mengurangi risiko pergerakan tanah di musim hujan. Jurnal Geosains West Science, 3(01):21-27. https://doi.org/10.58812/jgws.v3i01.2048
[26] Setiawan, O., Narendra, B.H. (2012). Strychnos lucida R. Br. Root System for Landslide Control. Jurnal Penelitian Kehutanan Wallacea, 1(1): 50-61. https://doi.org/10.18330/jwallacea.2012.vol1iss1pp50-61
[27] Giadrossich, F., Schwarz, M., Marden, M., Marrosu, R., Phillips, C. (2020). Minimum representative root distribution sampling for calculating slope stability in Pinus radiata D.Don plantations in New Zealand. New Zealand Journal of Forestry Science, 50. https://doi.org/10.33494/nzjfs502020x68x
[28] Saaty, T.L. (2005). Analytic hierarchy process. Encyclopedia of Biostatistics. https://doi.org/10.1002/0470011815.b2a4a002
[29] Istomo, Dwisutono, A.N. (2016). The species structure and composition stand with root system of plants in karst area in Bantimurung-Bulusaraung National Park, Resort Pattunuang-Karaenta. Jurnal Silvikultur Tropika, 7(1): 58-67. https://doi.org/10.29244/j-siltrop.7.1.%25p
[30] Hairiah, K., Widianto, W., Suprayogo, D., Van Noordwijk, M. (2020). Tree roots anchoring and binding soil: Reducing landslide risk in Indonesian agroforestry. Land, 9(8): 1-19. https://doi.org/10.3390/LAND9080256
[31] Ziemer, R.R. (1981). Roots and the stability of forested slopes. In Proceedings of the International Symposium on Erosion and Sediment Transport in Pacific Rim Steeplands, 132: 343-361.
[32] Schmidt, K.M., Roering, J.J., Stock, J.D., Dietrich, W.E., Montgomery, D.R., Schaub, T. (2001). The variability of root cohesion as an influence on shallow landslide susceptibility in the Oregon Coast Range. Canadian Geotechnical Journal, 38(5): 995-1024. https://doi.org/10.1139/cgj-38-5-995
[33] Ghestem, M., Veylon, G., Bernard, A., Vanel, Q., Stokes, A. (2014). Influence of plant root system morphology and architectural traits on soil shear resistance. Plant and Soil, 377: 43-61. https://doi.org/10.1007/s11104-012-1572-1
[34] Capilleri, P.P., Motta, E., Raciti, E. (2016). Experimental study on native plant root tensile strength for slope stabilisation. Procedia Engineering, 158: 116-121. https://doi.org/10.1016/j.proeng.2016.08.415
[35] Ogilvie, C.M., Ashiq, W., Vasava, H.B., Biswas, A. (2021). Quantifying root-soil interactions in cover crop systems: A review. Agriculture, 11(3): 218. https://doi.org/10.3390/agriculture11030218
[36] Liu, X., Wang, Y. (2021). Probabilistic simulation of entire process of rainfall-induced landslides using random finite element and material point methods with hydro-mechanical coupling. Computers and Geotechnics, 132: 103989. https://doi.org/10.1016/j.compgeo.2020.103989
[37] Tiessen, H., Moir, J.O. (2007). Characterisation of available P by sequential extraction. In Soil Sampling and Methods of Analysis. https://doi.org/10.1201/9781420005271-33
[38] Abe, K., Ziemer, R.R. (1991). Effect of tree roots on a shear zone: Modeling reinforced shear stress. Canadian Journal of Forest Research, 21(7): 1012-1019. https://doi.org/10.1139/x91-139
[39] Ip, J. (2011). The role of roots in slope stability. University of British Columbia. https://doi.org/10.14288/1.0075519
[40] Samarappuli, L., Yogaratnam, N., Karunadasa, P., Mitrasena, U. (1996). Root development in *Hevea brasiliensis* in relation to management practices. Journal of the Rubber Research Institute of Sri Lanka, 77: 93-111.
[41] Putranto, R.A., Kusuma, Z., Leksono, A.S., Yanuwiadi, B., Irfan, M.N. (2012). Differential gene expression in different types of Hevea brasiliensis roots. Plant Science, 183: 149-158. https://doi.org/10.1016/j.plantsci.2011.08.005
[42] Shara, D., Izzati, M., Prihastanti, M. (2014). Perkecambahan biji dan pertumbuhan bibit batang bawah karet (Hevea brasiliensis Muell Arg.) dari klon dan media yang berbeda. Jurnal Biologi, 3(4): 60-74.
[43] Ferera, A. (2009). Inventarisasi dan karakterisasi akar pepohonan yang berpotensi mengurangi longsor. Doctoral dissertation, Universitas Brawijaya.
[44] Dewi, W.S., Sudiarto, A., Sugiharto, Y., Purwanto, B.H., Susiloningtyas, D. (2015). Hydrological performance of pine tree, melinjo and jackfruit for rehabilitation of catchment area of slope of Mt. Merapi, Indonesia after 2010 Eruption. Journal of Environmental Earth Science, 5(8): 173-179.
[45] Sinacore, K., Hall, J.S., Potvin, C., Royo, A.A., Ducey, M.J., Ashton, M.S. (2017). Unearthing the hidden world of roots: Root biomass and architecture differ among species within the same guild. PLoS ONE, 12(10): e0185934. https://doi.org/10.1371/journal.pone.0185934
[46] Chávez-Rosales, J.S., Pintor-Ibarra, L.F., González-Ortega, N., Orihuela-Equihua, R., Ruiz-Aquino, F., Luján-Álvarez, C., Rutiaga-Quinones, J.G. (2021). Basic chemical composition of Pinus spp. sawdust from five regions of Mexico, for bioenergetic purposes. BioResources, 16(1): 816-824. https://doi.org/10.15376/biores.16.1.816-824
[47] Alberti, S., Leshchinsky, B., Roering, J., Perkins, J., Olsen, M.J. (2022). Inversions of landslide strength as a proxy for subsurface weathering. Nature Communications, 13: 6049.

https://doi.org/10.1038/s41467-022-33798-5
[48] ADPC 2020. Guidance Document on Use of Nature-Based Solutions for Site-specific Landslide Risk Mitigation, Nature Based Landslide Risk Management Project in Sri Lanka. https://www.adpc.net/igo/category/ID1644/doc/2020-qULw50-ADPC-Guidance_Document.pdf.