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Vetiver root cohesion at different growth sites in Bogor, Indonesia

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Abstract. *Fata YA, Hendrayanto, Erizal, Tarigan SD, Wibowo C. 2022. Vetiver root cohesion at different growth sites in Bogor, Indonesia. Biodiversitas 23: 1683-1692.* The plant root system, including the root system of vetiver grass, plays a critical role in enhancing soil cohesion, shear strength, and vegetated slope stability. Numerous studies on mechanical reinforcement of vetiver grass-roots have been conducted, with the majority of studies focusing on ground-planted vetiver with good maintained or naturally grown vetiver, while mechanical reinforcement of vetiver grass roots planted in landslide areas at various growth sites with less maintenance is still uncommon. The purpose of this study was to examine the vetiver grass-roots cohesion that grew in the different growth sites that had been affected by landslides. Vetiver grass root samples were collected in January 2021, at the age of 8 months. Vetiver grass roots were collected from vetiver plants growing in the affected landslide areas of (a) bareland, (b) shrubland, and (c) bushland. The root tensile strength of root samples was determined using a Universal Testing Machine (UTM) with a capacity of 3 tons, and the measurement accuracy of the load cell was 1/10000. The test was conducted in accordance with ASTM D638-14 guidelines. Three repetitions were performed on roots representing the root length class of 10 cm. The results indicated that the growth sites influenced the morphological and architectural properties of the vetiver grass-roots. The vetiver grass that grew in bushland exhibited a higher root density than bareland or shrubland. The roots were denser and had a greater range of lengths. Short roots less than 10 cm in length were the most prevalent, and the majority of them were found near the soil surface. The greater the soil depth, the less the quantity of roots. The tensile strength (T_R) tends to get smaller with longer roots, and vetiver grass roots grew in bareland have the highest T_R (15-59 MPa) relative to their growth in bushland (9-37 MPa) and shrubland (16-29 MPa). The ratio of root fiber area to root growth area (RAR) also tends to get smaller with deeper roots. Likewise, is the tensile strength increasing caused by roots (t_R) and root cohesion (C_R) which are a function of RAR. The C_R of vetiver roots growing in bushland (0.015-0.275 kPa) were relatively higher than those growing in bareland (0.02-0.168 kPa) and shrubland (0.002-0.028 kPa) in the same root length class, at the same depth.

Keywords: Vetiver grass, growth sites, tensile strength, root area ratio, root cohesion

INTRODUCTION

The roots of vegetation can increase soil organic matter, soil particle bonding, and soil aggregate stability (Cazzuffi and Crippa 2005; Rahayu et al. 2020), and the root system can also increase subsurface lateral flow in the rhizosphere in macroporous networks that can trigger preferential flows (Zhang et al. 2015). The influence of roots on the stability of soil aggregates is a function of the increase in soil cohesion by apparent root cohesion or root cohesion (C_R) which is a function of the root tensile strength (T_R) and the root area ratio (RAR). The increase in soil cohesion by roots is the most dominant influence shown by many studies that consider root cohesion parameters in slope stability analysis (Frei 2009; O'Loughlin and Ziemer 1982 in Fata et al. 2021; Nguyen et al. 2018).

Root cohesion is affected by vegetation type, plant age, soil conditions, climate, land management, and the environment. The vegetation type affects the morphology and characteristics of roots such as tensile strength, length, diameter, water content, root depth (Cazzuffi and Crippa 2005; Adhikari et al. 2013), stem diameter (Mehtab et al. 2021), and plant spacing (Ni et al. 2019). Shrubs and bushes have greater root cohesion than perennials (Cazzuffi and Crippa 2005; Leung et al. 2015).

The age of the plant affects T_R and the root length. The older the plant, the greater the root tensile strength (Voottipruex et al. 2008; Rajesh et al. 2017), but it can also reduce RAR, and the decaying root can further reduce root cohesion (Meng et al. 2014; Tadsuwan et al. al. 2017). Meanwhile, external conditions might influence vegetation growth and root production. Mechanical root reinforcement is effective only in the shallow depths, where most of the root biomass is present (Ni et al. 2018).

Vetiver grass-roots enhanced soil shear strength by up to 139% at 0.15 m depth and up to 47% at 0.75 m depth (D'Souza et al. 2019). The soil shear strength enhancement provided by vetiver root cohesion can increase slope stability up to five times greater than soil without root reinforcement (Jaikaew and Nokkaew 2019). Shearing resistance increases steadily as root content in the soil increases. Roots generate a fiber matrix, and as matrix density and fiber variation increase, so does the strength value (Gopinath et al. 2015).

Many root cohesion models have been carried out, including root cohesion modeling by Waldron et al. (1977), Wu et al. (1979) ((O'Loughlin and Ziemer 1982; Wilkinson et al. 2002; Vanacker et al. 2002 in Fata et al. 2021); Nguyen et al. 2018), Wu and Waldron model (WWM) (Tadsuwan et al. 2017), fiber bundle model (FBM) introduced by Pollen and Simon (2005) (Adhikari et al. 2013; Mehtab et al. 2021), and root bundle model (RBM) by Schwarz et al. (2010) (Zhou and Qi 2019).

Modeling root cohesion applies the different assumptions/hypotheses. The WWM assumes that all roots extend vertically and all roots that cross the shear plane break simultaneously (Waldron 1977) and Wu et al. (1979). Another model is the FBM considers the damage to root elements sequentially according to their respective tensile strengths (Wang et al. 2019). The RBM models the root reinforcement by considering the tortuous root geometry that affects the dynamic friction between the roots and the soil (Schwarz et al. 2010).

Wu model is the most widely used model with simple static assumptions, which means that the Wu model estimates maximum root reinforcement at a single instance in time when all of the roots contained in the soil matrix have reached their maximum tensile strength. This assumption tends to overestimate root strength indicated by a higher root cohesion value than other methods (Pollen and Simon 2005; Wang et al. 2019). Meanwhile, Wu's simple model gives better predictions for species with low root diameter distributions, such as grass plants (Coppin and Richards 1990 and Gray and Sotir 1996) in (Thomas and Pollen-Bankhead 2010). The value of root cohesion is also influenced by the method used in determining the root area ratio (RAR) and root tensile strength (T_R).

The role of vetiver roots in increasing soil cohesion and soil strength has been extensively studied. Root cohesion in San Francisco, America, using Böhm's monolith method at vetiver age of 24 months is 126-1600 kPa (Machado et al. 2015). In Italy (Cazzuffi and Crippa 2005) and Bangladesh (Hoque 2019), using shear strength laboratory tests, the root cohesion is 0-64 kPa. In Thailand (Teerawattanasuk et al. 2014; Voottipruex et al. (2008) and Malaysia (Hengchaovanich and Nilaweera 1996) using in situ shear strength test, the root cohesion at vetiver age 2-24 months is 1.28-29.43 kPa. Moreover, the Wu method, which is used to calculate root cohesion in various countries such as America (Machado et al. 2015), Thailand (Jotisankasa et al. 2015), and Spain (Mickovski and Beek 2009) at vetiver age 4-24 months, have a root cohesion of 0-1600 kPa. Root cohesion can also be obtained by adopting the characteristics and parameters of roots from previous studies and regression equation models such as the study in Bangladesh (Islam et al. 2020; Islam and Badhon 2020), Thailand (Nguyen et al. 2018), and Indonesia (Hamdhan et al. 2020; Kurniawati and Wulandari 2020; Muntohar et al. 2017).

Study on vetiver grass root cohesion has been carried out using vetiver grass roots that are naturally grown (Cazzuffi and Crippa 2005; Islam and Badhon 2020; Jotisankasa et al. 2015; Hoque 2019) and which grow in well-managed areas (Islam et al. al. 2020; D'Souza et al. 2019; Nguyen et al. 2018; Muntohar et al. 2017), while research on vetiver grass-roots cohesion in planted landslide areas with different growth sites characteristics have not been widely carried out, while the effectiveness of roots in soil strengthening is influenced by soil conditions and climate (D'Souza et al. 2019) as the growth sites characteristics. In Indonesia, studies related to vetiver grass root cohesion due to measuring the root tensile strength from landslide rehabilitation areas are still not available. This research is aimed to examine the impact of vetiver grass growth in different growth sites of landslide areas overgrown with bare, shrub, and bushland on root cohesion.

MATERIALS AND METHODS

Study area

The study area is in Sukajaya Sub-district, Bogor District, West Java Province, Indonesia. The study area is a mountainous area of Mount Salak, which experienced a landslide triggered by high rainfall, especially occurred on January 1st, 2020. The rehabilitation was carried out from mid-January to July 2020 by planting vetiver grass (Figure 1).

Vetiver grass sampling

Vetiver grass sampling was carried out in January 2021 at the vetiver grass planting location in April 2020 (vetiver grass was aged eight months). Vetiver grass samples were selected from 3 different growing conditions, namely (a) bareland, (b) shrubland, and (c) bushland (Figure 2). Bareland was the former landslide slope of landslide depth of >1.5 m with a slope steepness of >45%. Shrubland was the former landslide slope of landslides depth of 0.5-1.5 m with a slope steepness of 15-45%. Bushland was the former landslide slope of landslides depth of <0.5 m with a slope steepness of <15%. The area and depth of the samples plot of vetiver are adjusted to the size of the vetiver grass and the depth of their roots. In this case, the samples size for vetiver grass in bareland, shrubland, and bushland were respectively being 20x20, 30x30, and 40x40 cm^2 and the depth of 50 to 70 cm.

The vetiver grass roots tested for tensile strength were taken from locations (a), (b), (c) (Figure 2). 6, 3, 3 vetiver grass samples were taken purposively to represent the heterogeneity of plant growth conditions and the need for root samples (Figure 4). The vetiver grass samples were then soaked in water for 14 days and air-dried before the root tensile strength test.

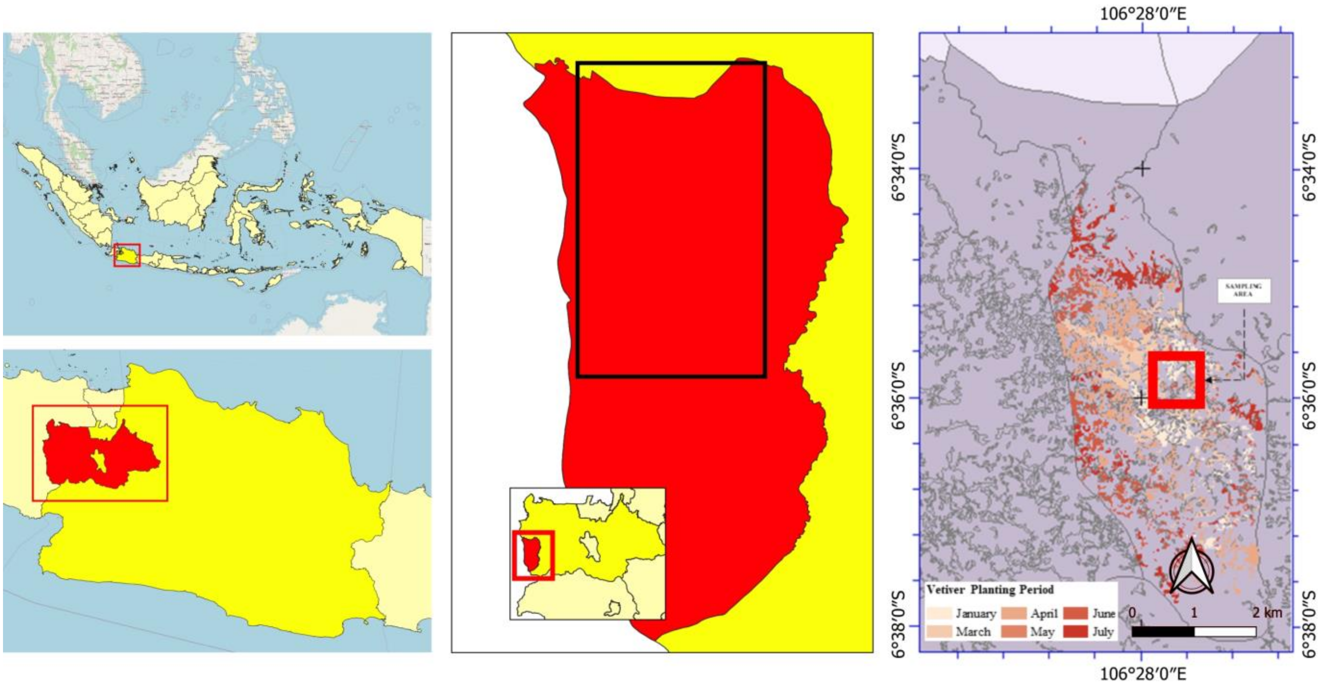


Figure 1. Study area in Sukajaya Sub-district, Bogor District, West Java Province, Indonesia

A B C

Figure 2. The vetiver grass sample locations: A. Bareland, B. Shrubland, C. Bushland

Data analysis

Root preparation

Roots were sampled from the vetiver grass samples representing the length class of 10 cm intervals. Three root samples were selected of each length class as the measurement replications. Before testing, the root sample's diameter, length, and water content were measured. A caliper was used to measure root diameter, while the gravimetric technique was used to assess soil water content directly. Water content is the weight difference between the air-dry weight of the root sample measured before testing and oven-dry weight measured after testing the root tensile strength. Furthermore, the percentage of moisture content was obtained based on the gravimetric method by calculating the ratio between the weight of water (wet weight-dry weight) with the weight of wet roots.

Root tensile strength test

The root tensile strength test was performed by measuring the maximum force (F_{max}) required to break the roots (kgf) using a 3 tons capacity of Universal Testing Machine (UTM) at a room temperature of 25ºC. The root tensile strength test used the ASTM D638-14 criteria to determine the test speed based on the root diameter class of 1.25 mm/min (D_{root} <1.8 mm). Prior to performing the measurement, the UTM instrument was calibrated. The accuracy of root tensile strength is 1/10000.

To avoid root slippage during testing, the fixing clamps made of a pair of steel grooved beams were used. Additionally, black rubber was added between the clamps to fill the cavity between the groove and the root, preventing root slippage. If roots are broken near or in a clamping position during testing due to root slippage, the experiment was repeated using new roots with the same diameter and length.

A B C

Figure 3. A. Schematic diagram of vetiver grass-root tensile strength test setup, B. actual setup on tensile strength test of vetiver grass-root, C. the break-up vetiver root after the test

The schematic diagram of the vetiver root tensile strength test setup is presented in Figure 3 (A), the actual setup on tensile strength test of vetiver roots, and the break-up vetiver root after the test are presented in Figure 3 (B) and (C) respectively.

Root tensile strength (T_R) was calculated based on equation (1) (Gray and Sotir 1996 in Teerawattanasuk et al. 2014).

$$T_R = \frac{F_{max}}{\pi\left(\frac{D^2}{4}\right)} \quad 1$$

Where T_R is the root tensile strength (kgf/cm^2), F_{max} is the maximum force required to break the root (kgf), and D is the root diameter (cm^2).

Root cohesion analysis

Root cohesion (C_R) was calculated using equation (2) (Wu et al. 1979).

$$C_R = t_R(\sin\theta + \cos\theta tg\varphi) \quad 2$$

$$t_R = T_R\left(\frac{A_R}{A}\right) \quad 3$$

$$C_R = T_R \, {}^{A_R}\!/_{A}(\sin\theta + \cos\theta tg\varphi) \quad 4$$

$$C_R = 1{,}2t_R \quad 5$$

$$A_R/A = RAR = \sum_{i=1}^{n} \frac{\pi \times d_i^2/4}{a_i \times h_i} \quad 6$$

Where C_R is root cohesion, and t_R is the increase in tensile strength caused by roots. The T_R is the average tensile strength of roots (MPa), A_R/A is the root area ratio (RAR), where A_R is the root fibers area (mm^2), and A is the effective soil cross-sectional area (mm^2). The value of $(\sin\theta + \cos\theta tg\varphi)$ range from 1 to 1.3, a value of 1.2 was selected by Wu et al. (1979) and also used in this study, d is root diameter (mm), a is cross-sectional width (mm), h is root depth (mm), i is the number of roots.

RESULTS AND DISCUSSION

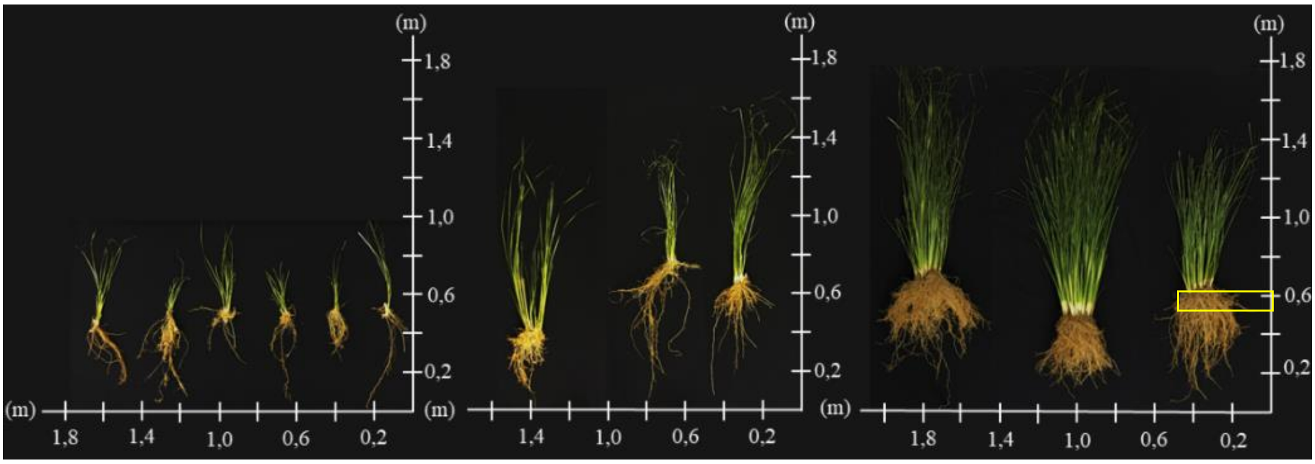
Vetiver grass-root characteristics

The characteristics of vetiver grass at the growth sites, which include root length (l), diameter (d), water content (Θ), the maximum force required to break the root (F_{max}), root tensile strength (T_R), number of roots (i), cross-sectional width (a), and root depth (h) of each root length class at bareland, shrubland, and bushland are presented in Table 1, whereas the root architecture is presented in Figure 4.

According to Table 1, vetiver grass roots growing in shrubland have the longest roots, reaching 70 cm, while those growing on bareland and bushland have the shorter roots, reaching 48 cm. However, the number of vetiver roots growing in bushland is huge, reaching >100 roots, nearly twice that of shrubland and four times that of bareland. The root length in root length class 30-40 cm was not found in bareland. The diameter of vetiver grass roots (d) varies according to root length class and growth sites. However, there is a tendency for the diameter to increase with the length of the root (l). The water content ($\boldsymbol{\Theta}$) of vetiver grass roots varies in each root length class and their growth sites. There is no clear relationship between moisture content and diameter, and root length. The highest Θ of grass root was found in vetiver grass roots growing in shrubland, which reached 10%. The high Θ of vetiver grass-root in shrubland was suggested due to the presence of shallow water table indicated by the appearance of springs on shrubland, while in bareland and bushland, there were none. The seepage of the shallow water table is suggested to cause the higher soil water content; therefore, more water is available for vetiver grass-root.

Table 1. Vetiver grass-root characteristics

Location	Length Class (cm)	*l* (cm)	*d* (mm)	*Θ* (%)	F_{max} (kgf)	T_R (MPa)	*i* (roots)	*a* (cm)	*h* (cm)
Bareland	0-10	7.1 ± 0.9	0.70 ± 0.36	5 ± 4	1.3 ± 0.7	48.3 ± 43.6	10	16.4	8.1
	10-20	17.2 ± 2.2	1.03 ± 0.45	5 ± 4	2.0 ± 0.5	21.0 ± 10.0	8	22.6	19.6
	20-30	23.5 ± 2.2	0.40 ± 0.10	4 ± 4	0.9 ± 0.8	59.2 ± 29.2	2	11.2	25.3
	30-40	-	-	-	-	-	-	-	-
	40-50	44.2 ± 5.2	1.35 ± 0.64	6 ± 0	1.5 ± 0.4	15.6 ± 15.5	5	16.8	47.8
Shrubland	0-10	8.2 ± 1.5	0.87 ± 0.50	6 ± 2	1.9 ± 1.4	37.0 ± 22.9	20	23.4	9.9
	10-20	14.8 ± 2.1	0.77 ± 0.40	4 ± 4	1.1 ± 0.4	34.6 ± 23.2	11	32.4	17.1
	20-30	23.1 ± 1.3	0.97 ± 0.45	10 ± 1	1.9 ± 0.9	32.9 ± 24.2	7	32.4	23.9
	30-40	32.4 ± 2.1	0.87 ± 0.35	7 ± 0	1.7 ± 0.7	33.7 ± 19.1	2	17.8	34.7
	40-50	42.0 ± 1.0	1.23 ± 0.15	5 ± 4	1.6 ± 0.6	14.2 ± 7.8	3	12.0	43.0
	50-60	56.3 ± 1.4	1.23 ± 0.45	6 ± 2	1.7 ± 0.2	20.0 ± 14.6	2	17.0	57.4
	60-70	70 ± 0.0	1.20 ± 0.00	10 ± 0	1.1 ± 0.0	9.7 ± 0.0	1	12.0	70.0
Bushland	0-10	7.3 ± 1.2	0.97 ± 0.25	6 ± 2	1.5 ± 0.4	21.2 ± 5.6	50	42.2	8.1
	10-20	11.7 ± 1.0	0.97 ±0,70	5 ± 1	0.9 ± 0.7	29.1 ± 35.8	20	53.6	12.8
	20-30	24.1 ± 2.9	1.20 ±0.20	3 ± 3	2.1 ± 0.8	20.1 ± 10.8	15	61.0	26.0
	30-40	39.0 ± 0.7	1.03 ±0.59	3 ± 2	1.0 ± 0.3	17.2 ± 11.2	10	46.2	39.7
	40-50	42.9 ± 3.0	1.33 ±0.38	6 ± 1	2.0 ± 0.5	16.4 ± 8.0	9	39.2	41.8



A B C

Figure 4. The vetiver grass-root architecture in the location of: A. Bareland, B. Shrubland, C. Bushland

Based on the description of each characteristic of vetiver grass, the different growth sites show different morphological and architectural characteristics of vetiver grass roots. Vetiver grass that grows in bareland was the most stunted growth, while the vetiver grass that grows in bushland was the best growth among them.

Bareland location has experienced landslides with a depth of >1.5 m and a slope steepness of >45%, causing stunted growth of vetiver grass compared to vetiver grass on shrubland and bushland, which has landslide depth of <1.5 m and slope <45%. The deeper the landslide depth, the thinner the solum layer, which affects the soil's presence and diversity of nutrients beneficial for plant growth. The steeper slope affects the effectiveness of vetiver grass-roots in increasing slope stability, where vetiver on steep slopes (>45%) has lower slope stability than vetiver planted on a slope steepness of <45% (Jotisankasa et al. 2015).

The relationship between *d* and T_R of vetiver grass roots is a negative exponential relationship with a determinant coefficient (R^2) of 0.71-0.79 (Figure 5). A negative exponential correlation, in which the diameter increase with decreasing T_R, is a result of the model used (Eq-1), and R^2 will be greater if the F_{max} is closely related to *d* (R^2 >0.83). The relation between vetiver grass root *d* and T_R in three growth sites has the R^2 of 0.71-0.79 (<0.83), indicating a weak relationship between *d* and F_{max}. As shown in Figure 6, the relationship between *d* and F_{max} has an R^2 of just 0.2685-0.3402.

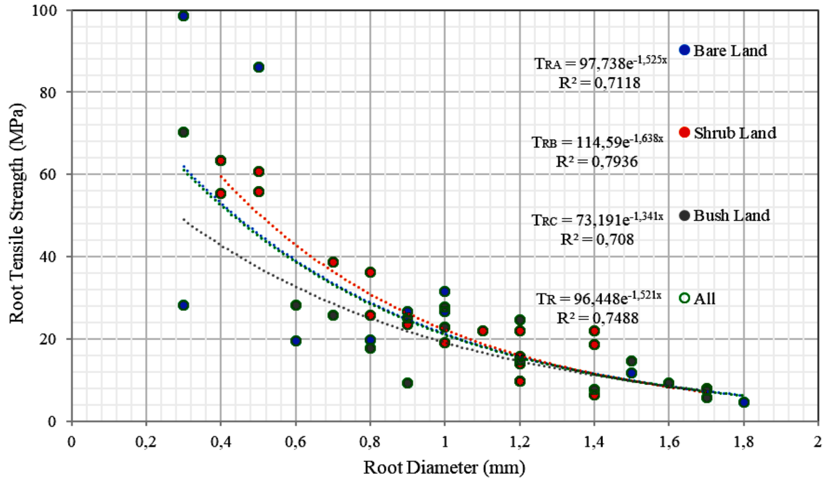


Figure 5. The relationship between root diameter (d) and root tensile strength (T_R) of vetiver grass growth in bareland, shrubland, and bushland

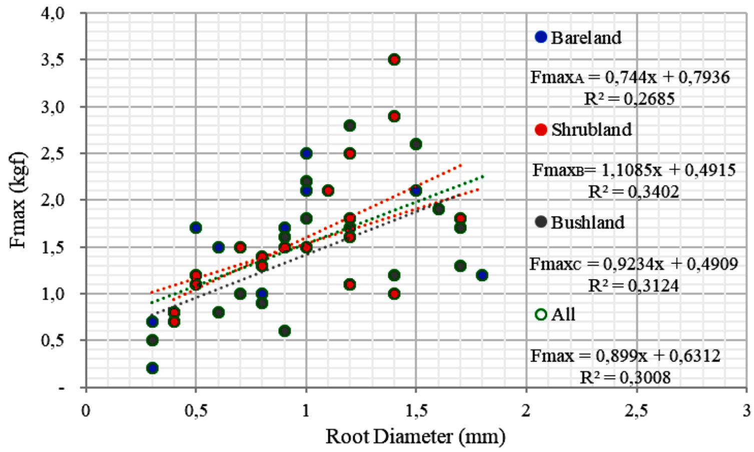


Figure 6. The relationship between root diameter (d) and maximum force required to break the root (F_{max}) of vetiver grass growth in bareland, shrubland, and bushland

Additionally, Figure 5 demonstrates that the T_R value is more spread out in the diameter range of 0.3-0.6 cm, especially in bareland. This is because the F_{max} value is more diverse in this diameter range (0.2 to 0.7 kgf); it is suggested that F_{max} is influenced not only by root diameter but also by root length, water content, and other factors. Zhang et al. (2019) revealed that the root tensile strength decreased linearly with increasing water content and root diameter. The difference in root tensile strength at the same diameter may also be caused by the difference in chemical and biological content of the roots, as mentioned by Ng et al. (2019), such as the lignin and cellulose content in roots (Zhang et al. 2014). Fine roots and thinner root structures have high cellulose content resulting in higher mechanical strength than coarse roots (Machado et al. 2015).

Vetiver grass-root cohesion

The average RAR, T_R, t_R, and C_R values for each root length class at bareland, shrubland, and bushland growth sites are presented in Table 2 and graphically presented in Figure 7.

According to the data in Table 2 and Figure 7, RAR and C_R, as well as T_R, tend to decrease as the root length class increases. Longer roots penetrate deeper into the soil, but the quantity of roots is less in deeper areas, resulting in a smaller RAR. Bushland has the highest RAR of 0.108%. This figure is nearly twice as high as the RAR in shrubland and five times as high as the RAR in bareland. Meanwhile, the greatest T_R value was observed in bareland, at 48.3 MPa, more than twice the T_R found in bushland (21.2 MPa). The T_R value of vetiver grass roots in shrubland was a maximum of 37 MPa. The C_R values, a function of RAR and T_R in bushland, shrubland, and bareland, were maximum 0.275, 0.228, and 0.168 kPa, respectively. These findings demonstrate that RAR contributes significantly more to C_R than T_R.

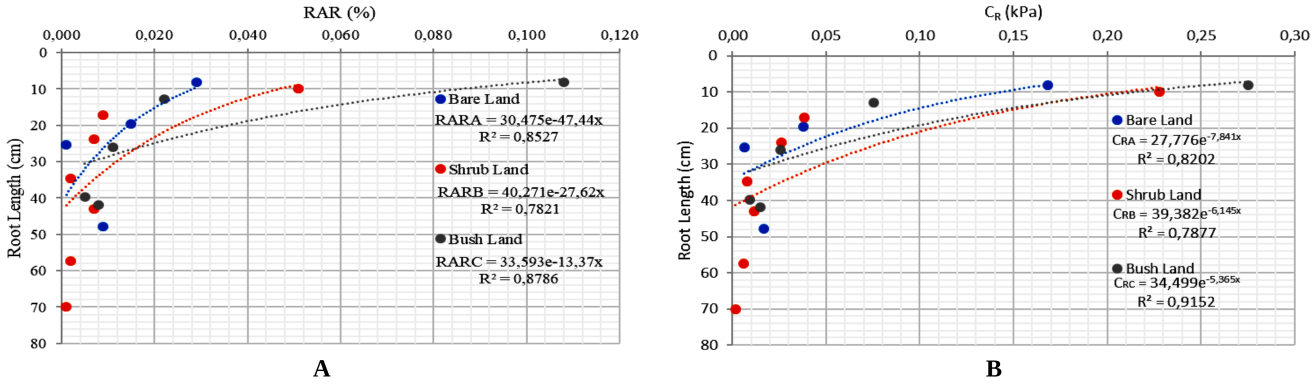


Figure 7. The relationship between root length class: A. Root Area Ratio (RAR), B. Enhancement Cohesion by Root (C_R)

Table 2. The vetiver grass-root contribution in soil strengthening

Location	Root length class (cm)	RAR (%)	T_R (MPa)	t_R (MPa)	C_R (kPa)
Bareland	0-10	0.029	48.3	1.4	0.168
	10-20	0.015	21.0	0.5	0.038
	20-30	0.001	59.2	0.1	0.006
	30-40	-	-		-
	40-50	0.009	15.6	0.1	0.017
Shrub Land	0-10	0.051	37.0	1.9	0.228
	10-20	0.009	34.6	0.3	0.038
	20-30	0.007	32.9	0.2	0.026
	30-40	0.002	33.7	0.1	0.008
	40-50	0.007	14.2	0.1	0.012
	50-60	0.002	20.0	0.0	0.006
	60-70	0.001	9.7	0.0	0.002
Bush Land	0-10	0.108	21.2	2.2	0.275
	10-20	0.022	29.1	0.6	0.075
	20-30	0.011	20.1	0.2	0.026
	30-40	0.005	17.2	0.1	0.009
	40-50	0.008	16.4	0.1	0.015

Discussion

The root morphology and properties of vetiver grass growing in different growth sites at the same plant age demonstrated variation, as shown in Tabel 1 and Tabel 2. The growth of vetiver grass root length in landslide areas of bareland, shrubland, and bushland was relatively slow. At the age of eight months, the roots length only reaches 50-70 cm, while the 4-month-old vetiver grass can reach the root length of 40 cm (Kurniawati and Wulandari 2020), even though in Bangladesh, the 6-month-old vetiver grass can reach the root length of 120 cm (Islam et al. 2020), and in India, at 12 months old can reach the root length of 120 cm with good maintenance (D'Souza et al. 2019). The root diameter of vetiver grass-roots in landslide areas of bareland, shrubland, and bushland ranged from 0.3-1.8 cm, on average 0.99 mm. This diameter range is almost the same as the diameter of vetiver grass growing in Bangladesh (Islam et al. 2020) and India (D'Souza et al. 2019). As shown in Table 2 and Table 3, the T_R of vetiver grass-roots growing on bareland, shrubland, and bushland in landslide areas was generally higher than the T_R of vetiver grass roots that were well planted managed, as well as naturally grown vetiver. The RAR of vetiver grass roots growing on bareland, shrubland, and bushland in landslide areas, on the other hand, was much lower than the RAR of well-managed vetiver grass plantation and naturally grown vetiver grass roots. The RAR values of vetiver grass roots growing on bareland, shrubland, and bushland in landslide areas range from 0.001 to 0.108%. Meanwhile, the RAR of ground planted vetiver grass of 6-12 months age range from 0.01-0.57% (D'Souza et al. (2019; Islam et al. 2020), and for 24 months old, the RAR reached 3.31% (Hengchaovanich and Nilaweera 1996). The RAR of naturally grown vetiver grass roots also reached 3.5% (Hoque 2019).

As a result of the very low RAR, the C_R values in bareland, shrubland, and bushland of landslide areas were very low compared to the C_R values of well-planted and maintained vetiver grass and vetiver grass that grew naturally. The C_R values in bareland, shrubland, and bushland of landslide-affected land were the highest at 0.275 kPa, generally, less than 0.05 kPa, whereas the C_R of well-planted and maintained vetiver grass and vetiver grass that grew naturally was greater than 1 kPa, even exceeding 1000 kPa (Machado et al. 2015).

Morphology and root production, as measured by the number of roots per unit area, root length that can penetrate deep into the soil, and root tensile strength, are important factors in the function of vetiver grass as a mechanical reinforcement of soil and slopes. Root growth is an important aspect to consider in land rehabilitation practice so that it can be effective in increasing slope stability. Vegetation-provided mechanical root strengthening through their root characteristics. Planting and maintenance of vetiver grass must be done with care to ensure that the roots of the vetiver grass grow well and produce high T_R, RAR, and C_R values.

Table 3. Research recapitulation of the vetiver grass root cohesion

Investigators	Locations	Age (month)	D (mm)	Length (m)	T_R (MPa)	RAR (%)	C_R (kPa)
Islam et al. (2020)	Ground planted Vetiver (Bangladesh)	1-6[c]	1.1-1.35[b]	0.05-1.2[b]	13.3-16[c.1]	0.01-0.079[c.1]	1.92-12.6[c.1]
Mickovski and Beek (2009)	Ground planted Vetiver (Spain)	6[c]	0.3-1.4[c]	0-0.3[c]	2-17[c.8]	0.034-0.11[b.c]	2.4[c.2.7]
D'Souza et al. (2019)	Ground planted Vetiver (India)	12[c]	[a]	0.15-1.2[c]	85 [c.2]	0.15-0.57[c.2]	[a]
Muntohar et al. (2017)	Ground planted Vetiver (Indonesia)	[b]	0.8[b]	0.025-0.6[b]	0.019[b]	0-2.1[c.1]	0-25[c.1]
Machado et al. (2015)	Ground planted Vetiver (San Francisco. USA)	24[c]	0.4-2.7[c]	0.1-0.5[c]	16-353[c.5.8]	0-0.024[c.6]	126-1600[c.6.7]
Voottipruex et al. (2008)	Ground planted Vetiver (Thailand)	4-24[c]	0.2-1.3[c]	[a]	14-44[c.1]	[a]	29.43[c.2]
Nguyen et al. (2018)	Ground planted Vetiver (Thailand)	[a]	[a]	1[b]	[a]	[a]	3[b]
Kurniawati and Wulandari (2020)	Ground planted Vetiver (Indonesia)	1-4[c]	[a]	0-0.6[c]	[a]	[a]	[a]
Hengchaovanich and Nilaweera (1996)	Ground planted Vetiver (Malaysia)	24[c]	0.2-2.2[c]	0.15-0.5[c]	40-180[c.1]	0.52-3.31[c.7]	1.28-8.92[c.2]
Islam and Badhon (2020)	Naturally grown Vetiver (Bangladesh)	[a]	0.3-1.2[c]	>0.2[c]	20-115[c.3]	[a]	3-14[c.1]
Hoque (2019)	Naturally grown Vetiver (Bangladesh)	[a]	0.2-2.2[c]	<0.1756[c]	[a]	1-3.5[a]	0-64[c.4]
Cazzuffi and Crippa (2005)	Naturally grown and ground planted Vetiver (Italy)	[a]	0.5-2[c]	[a]	22-58[c.8]	[c.10]	15[c.4]
Hamdhan et al. (2020)	Indonesia[a]	[a]	[a]	[a]	44.64[b]	[b]	15-200.88[c.1]
Teerawattanasuk et al. (2014)	PVC planted Vetiver (Thailand)	2-10[c]	0.25-3[c]	0.1[c]	4.31[c.8]	[a]	2-7.8[c.2]

Note: [a]: Uknown/Not specified. [b]: Addopted value. [c]: [1]Regression model from other research; [2]In situ shear test; [3]Block test; [4]Laboratory test; [5]Cylinders method; [6]Böhm's monolith method; [7]Wu method; [8]UTM test; [9]Transparent sheet method; [10]Hypothetical curves

It is a difficult task in and of itself to plant vetiver grass to strengthen slopes of landslide areas. On the one hand, good vetiver grass growth necessitates maintenance; on the other hand, landslide areas typically have a shallow solum, are steeper than previously, and are unstable, necessitating extra caution when planting and maintaining it, particularly when it rains or after a few days of rain, which may cause landslides. However, proper vetiver grass planting can contribute to its recovery over time by limiting additional soil loss, enabling organic matter to accumulate, and fostering tree growth, which will finally stabilize it through mechanical reinforcement of soil and slopes by roots system of vegetation.

In conclusion, the growth sites influence the shape, architecture, features, and production of vetiver grass roots, as well as the slope's mechanical reinforcement. The root area ratio (RAR) of vetiver roots growing in landslide areas overgrown by bushland was greater than the RAR of vetiver grass roots growing in shrubland and bareland, whereas the root tensile strength (T_R) of vetiver roots growing in landslide areas bareland was greater than the T_R of vetiver grass roots growing in shrubland and bareland. The root cohesion (C_R) of vetiver roots growing in landslide areas overgrown bushland was significantly greater than the root cohesion (C_R) of vetiver grass roots growing in shrubland and bareland. Vetiver grass's RAR has a stronger influence on C_R than on T_R.

The C_R of vetiver grass roots growth in landslide sites overgrown by bushland, shrubland, and bareland in the range 0.002-0.275 kPa was significantly lower than the C_R of well-managed vetiver grass plantations and naturally occurring vetiver grass growth.

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