

Soil Bioengineering Using Vetiver for Climate-Adaptive Slope Repair: Review

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Abstract: An increase in precipitation due to climate change has given rise to the number of landslide occurrences. Vetiver, which is a perennial grass, is becoming increasingly popular all over the world as a vegetation-based soil bioengineering tool for preventing landslides. Sunshine Vetiver grass, also known as *Chrysopogon zizanioides* is noninvasive and does not compete with other indigenous plants growing in the area. Even though it is a tropical grass, Vetiver can grow in a wide range of climate conditions, including those that are quite harsh in terms of both soil and climate. The roots can grow up to 3 m in length in a dense bushy root network under optimal conditions. In this review, the authors have studied the impact of Vetiver on landslide mitigation as a climate-adaptive slope repair tool based on the research undertaken so far. Furthermore, the authors have addressed the future potential and constraints associated with the use of Vetiver for landslide mitigation. It is seen that the use of Vetiver reduces pore water pressure. The high tensile strength of Vetiver roots provides reinforcement for slopes and enhances soil shear strength. Vetiver increases saturated hydraulic conductivity and reduces surface runoff and slip surface depth. Being a vegetation-based climate-adaptive technology, this grass exhibits great promise in its ability to effectively address landslide problems. However, the magnitude of the root impact diminishes as the depth increases, rendering Vetiver a more promising remedy for shallow landslide occurrences. In addition, Vetiver grass has a wide range of practical uses due to its unique characteristics, which provide additional benefits. Employment of Vetiver is cost-effective compared with traditional engineering methods, and it requires less initial maintenance, which implies that community-based initiatives can effectively address landslide prevention through Vetiver implementation. DOI: [10.1061/NHREFO.NHENG-2014](https://doi.org/10.1061/NHREFO.NHENG-2014). © 2024 American Society of Civil Engineers.

Practical Applications: Vetiver grass has a long bushy network of roots that can grow up to 3 m in length. The Sunshine Vetiver grass is not invasive and does not compete with indigenous plants. Although Vetiver is a tropical grass, this grass can survive in various climates and soil conditions. Vetiver is a vegetation-based climate-adaptive technology that can prevent slope failure and reduce surface runoff. Additionally, growing Vetiver can generate income for local communities because the fragrant roots can be utilized in the extraction of essential oils for the perfume industry and from the manufacture and trade of other commodities derived from Vetiver. The grass's green leaves contribute to the aesthetic appeal of the landscape. Implementing Vetiver on slopes does not require heavy machinery and is cost-effective compared with traditional engineering methods. It also requires less initial maintenance, making it an ideal solution for community-based initiatives aiming to address slope failure prevention through Vetiver implementation.

Author keywords: Natural hazard-induced disasters; Landslide; Rainfall; Soil bioengineering; Vegetation; Vetiver.

Introduction

A landslide is a broad term used to describe the gravitation induced downward movement of soil. The term landslide is sometimes employed interchangeably with other terminology such as mass movement and slope failure to categorize various types and magnitudes of landslide disasters (Highland and Bobrowsky 2008).

Because the impacted areas are typically on a small scale or regionally, the impact of landslides is sometimes underestimated compared with other natural disasters (such as earthquakes, storms, or flooding) (Kalia 2018). From January 2004 to December 2016,

4,862 landslide disasters have been reported resulting in a total of 55,997 fatalities (Nix et al. 2006). Between 2008 and 2017, more than 3 million people have been impacted by landslides resulting in losses of more than USD 2.7 billion (Segoni et al. 2018). Landslides account for 17% of global fatalities resulting from natural hazard-induced disasters, and during the period from 1993 to 2002, they ranked as the seventh leading cause of death among natural hazard-induced disasters, resulting in an average of over 940 fatalities per year (Lacasse et al. 2005).

Landslides can be triggered by various mechanisms that induce displacement and exert stress on the slope (Sorbino and Nicotera 2013). Failures in slopes typically arise from three primary factors: geological phenomena (e.g., earthquakes and volcanic eruptions), hydrological events (such as heavy rainfall, storm waves, and quick snowmelt), and human interventions resulting from development activities (such as improper slope excavation and loading, rapid reservoir depletion, and blasting vibration) (Cruden 2018; Acharya et al. 2016; Dai et al. 2002).

Excessive rainfall has been identified as one of the hydrologic events that can cause landslides (Di Maio et al. 2021). Due to climate change and global temperature rise, in recent years the number of slope failures tends to rise alongside the increase in intense rainfall events (Haque et al. 2019; Tozato et al. 2022).

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In conjunction with the observed rise in precipitation levels, there has been a corresponding escalation in the occurrence of fatal landslides. During the time spanning from 1995 to 2014, an analogous upward trajectory was also noted in the occurrence of both landslides and intense rainfall from 2005 to 2014 compared with 1995–2004 (Haque 2019). It is anticipated that as the world warms, heavy precipitation will occur more frequently and with higher intensity. Given this potential, excess precipitation can be the most triggering factor for landslides exceeding earthquakes or slope undercutting (Crozier 2010).

The standard approach to slope protection employs civil engineering structures. However, traditional structure-based slope protection techniques are expensive, resource-intensive, and necessitate comprehensive site-specific research (Punetha et al. 2019). Along with that, by nature, the effectiveness of the materials declines as they age (Mohamed et al. 2022).

Soil bioengineering is one of the permanent techniques used for landslide mitigation and erosion control where plants or plant-based materials are used for slope protection individually or in conjunction with other slope protection methodologies (Gray and Sotir 1996; Schiechl and Stern 1996; Highland and Bobrowsky 2008). These techniques are cost-effective and more environmentally friendly compared with traditional methods of landslide mitigation. Vegetation is one of the most effective soil bioengineering techniques that has been used for reducing slope failure. Root fibers mechanically strengthen the soil by reinforcement, hence enhancing a variety of mechanical soil qualities (Nguyen et al. 2019). Through evapotranspiration, where soil moisture is absorbed by plant roots, vegetation can remove excess water from soil, resulting in a decrease in pore water pressure and an increase in the shear strength of the soil (Leknoi and Likitlersuang 2020). Additionally, the presence of roots can impact soil permeability and water retention behavior.

Among the plants employed in vegetation-based soil bioengineering for landslide prevention, Vetiver grass is regarded as an effective answer. Originating in subtropical India, South Asia, and Southeast Asia, this grass is a perennial herbaceous graminaceous plant. However, this plant shares several morphological traits with other aromatic grasses, including lemongrass, citronella, and palmarosa (D'Souza et al. 2019). Vetiver plants are adaptable to a variety of climatic and soil conditions. Despite being a tropical plant, it can thrive in a variety of temperatures and climates, including tropical, semitropical, and Mediterranean conditions.

Vetiver has been utilized efficiently for roadside stabilization throughout Africa, Asia, Australia, Latin America, and southern

Europe and has been used to stabilize railway ballast (Mickovski et al. 2005). Since the early 1900s, Vetiver has been utilized in the West Indies, South Africa, Brazil, and Fiji to protect slopes, improve embankments, and cuttings away of soil from agricultural regions (Hengchaovanich 2003). In Nigeria, Venezuela, Indonesia, Australia, and China, Vetiver has been found to reduce soil erosion and runoff more effectively than other plant species (Truong and Loch 2004). The World Bank extensively promoted Vetiver as a grass that would help farmlands conserve water and soil by reducing soil erosion. Many experts consider Vetiver as one of the most versatile crops of the 21st century (Maffei 2002).

Vetiver has a complex network of long, bushy roots. The root system consists of a large, thick, and rapidly expanding network of fibrous filaments that can reach a height of 3 m (Mickovski et al. 2005). In addition, Vetiver roots can drain surplus soil water through evapotranspiration and boost the soil's shear strength.

This paper summarizes the applicability of Vetiver grass as a climate-adaptive nature-based soil bioengineering strategy for mitigating landslides. The paper will explore Vetiver's characteristics as well as its many applications. Later, it will review the variation of Vetiver root properties based on climate and soil conditions. Based on previous published research works, the authors have combined the impact of Vetiver on various soil properties, such as soil shear strength, cohesion, soil improvement, horizontal displacement of slope, runoff reduction, erosion control, and so on, that are related to the landslide problem. It is to be mentioned that in the process, the authors restricted their review to peer-reviewed scientific journal articles, technical conference proceedings, and book chapters on pertinent topics, eliminating any gray literature. In total, 131 publications have been carefully studied, and based on the study, the authors have compared and evaluated the prospect of Vetiver technology for landslide mitigation, along with its limitations and future research potential.

Background

Global Temperature Rise and Excessive Rainfall

Since 1880, it is seen that the average increase in Earth's temperature has been approximately 0.14°F (0.08°C) per decade, resulting in a total rise of approximately 2°F. The pace has doubled since 1981 with an increase of 0.32°F (0.18°C) per decade (NOAA 2022). Fig. 1 illustrates the upward trajectory of temperature seen in both the US and across the world.

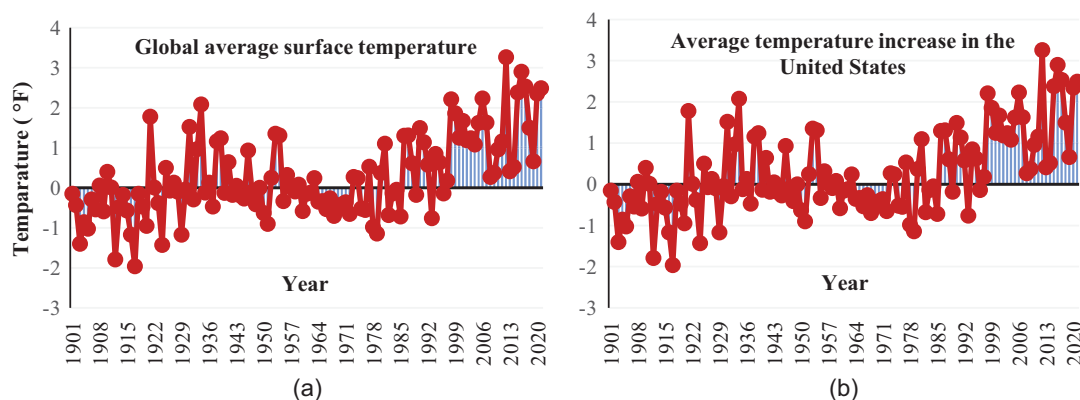


Fig. 1. Annual average surface temperature in comparison for the twentieth-century (from 1901 to 2020): (a) global temperature rise; and (b) temperature rise in the US. 1°F = −17.22°C. (Data from NOAA 2022.)

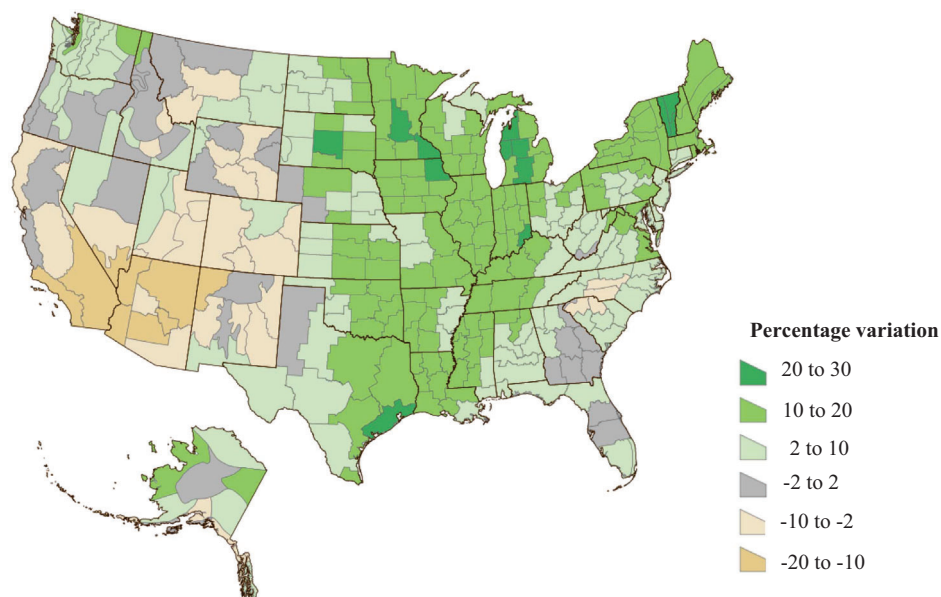


Fig. 2. Annual percentage variation of rainfall in the US. (Reprinted from USEPA 2023.)

The increase in temperature has a notable influence on precipitation because each degree of temperature rise results in a 7% increase in water-holding capacity (Battisti and Naylor 2009). Since the year 1901, there has been an observed upward trend in global precipitation, with an average increase of 0.1 cm each decade. Similarly, within the United States, precipitation has also experienced an upward trend at a higher rate of 0.51 cm per decade (USEPA 2023) where certain regions see a range of rainfall fluctuations, with an increase of 20%–30% (USEPA 2023) (Fig. 2).

Relation of Excessive Rainfall and Landslides

The increased water-holding capacity due to temperature rise has led to a rise in excess rainfall events, posing a serious risk for landslides on a global scale. In general, rain-induced landslides are usually caused by increased pore pressures and seepage (Wang and Sassa 2003) as the soil's moisture content rises and causes a decrease in the shear strength (Cho 2017). Most rainfall-induced landslides in highly permeable soil move rapidly. They are shallow and are triggered by heavy rainfall for a short period (Johnson and Sitar 1990). Whereas in low-permeability soil, rainfall can cause even deep-seated failures if the infiltration takes place for a long period (Cardinali et al. 2006). Compared with sand and silt, clay's shear strength diminishes rapidly (Stark and Duncan 1991).

In high-plasticity clay soil, long-term wetting and drying have a significant impact on the shear strength of the soil. Repeated wetting and drying can develop desiccation cracks in high-plasticity clay soil, which pave the way for water inside and reduce strength during rainfall (Skempton 1984). These cycles not only affect the fully softened strength of the soil, but it also reduces the vertical permeability (Ivok et al. 2021). For high plasticity clay the combination of the fully softened strength and rainfall works as a most probable case that develops landslides (Khan et al. 2016). Along with the shear strength, various natural soil properties, such as saturated hydraulic conductivity and soil water retention capacity are influenced by rainfall leading to increased surface runoff, soil erosion, and landslides (Cho 2014; Cai and Ugai 2004; Ran et al. 2012).

Soil Bioengineering as Climate-Adaptive Slope Stabilization

Soil bioengineering can be seen as a specific component of biotechnical stabilization where the primary structural and mechanical elements of the slope protection system are live plant parts, such as roots, stems, and branches (Highland and Bobrowsky 2008). Soil bioengineering mostly utilizes indigenous resources, like plant stems or branches, rocks, timber, and soil. Suitable vegetation for bioengineering purposes can be acquired from indigenous materials that are readily propagated. Furthermore, soil bioengineering systems are often seen as environmentally compatible during the building phase due to their limited need for equipment and workforce access, resulting in minimum disturbance.

Several methods are used for landslide reduction, including drainage, slope geometry modifications, retaining structures, etc. (Hutchinson 1977; Popescu and Sasahara 2009). The selection is often based on cost, landslide magnitude and frequency, and the related level of risk. In addition, climate change has increased global awareness of the gradual decrease in available resources and has made many who were previously unconcerned, proponents of sustainability. People are actively seeking eco-friendly and green engineering solutions (Bordoloi and Ng 2020), which makes soil bioengineering techniques feasible as nature-based alternatives to conventional hydraulic or civil engineering approaches (Kettenhuber et al. 2023). These ecological engineering techniques can improve the environment. In addition, the use of plants can stabilize the terrain while enhancing the landscape (Bischetti et al. 2021).

The soil bioengineering techniques work for landslide control by (1) catching eroding soil materials, (2) using vegetation cover or armoring to protect slopes, (3) planting roots that will serve as soil reinforcement, (4) supporting soil as a buttress in combination with structural elements like retaining walls, and (5) removing excess rainwater-related moisture by the evapotranspiration process initiated by vegetation (Fay et al. 2012). Unlike conventional approaches, these solutions can be executed with locally accessible materials and with minimal use of heavy equipment (Lewis et al. 2001). In addition, they contribute to the aesthetics of the highway

environment by limiting the environmental impacts of highway construction, maintenance, and operation.

Vegetation as a Soil Bioengineering Technique

Vegetation-based slope protection has been proven extremely effective for preventing shallow landslides, where the slip surface is within 1–1.5 m (Hengchaovanich 2003). The vegetative roots reinforce the soil and reduce the pore water pressure by taking in water for evapotranspiration (Krzeminska et al. 2019; Stokes et al. 2014), and the vegetation reduces the surface water runoff, provides protection against wind-induced soil erosion, reduces the impact of rain, and increases infiltration (Coppin and Richards 1990) (Fig. 3).

Numerous studies have investigated the impact of vegetation on landslides. Field research was conducted by Ziemer and Swanston (1977), Wu et al. (1979), Riestenberg and Sovonick-Dunford (1983), Reneau and Dietrich (1987), and Riestenberg (1994). Laboratory-based investigations were performed by Endo and Tsuruta (1969), Waldron (1977), Waldron and Dakessian (1981), and Waldron et al. (1983), and numerical modeling was executed by Sidle (1992) and Krogstad (1995) to solidify the impact of vegetative roots on landslide protection. The frequency of landslides has been observed to increase after vegetation was removed (Kuruppuarachchi and Wyrwoll 1992; Bishop and Stevens 1964; Gray 1981), and increased displacement has been observed on slopes with less vegetation in existing landslide locations. (DeGraff 1979; Swanston et al. 1988).

An Introduction to Vetiver Grass

Vetiver grass, also known as *Vetiveria zizanioides* and *Chrysopogon zizanioides*, is a tropical perennial herbaceous graminaceous plant that shares several morphological features with other fragrant grasses, including lemongrass, citronella, and palmarosa (D'Souza et al. 2019). Sunshine Vetiver is the only genotype permitted by the USDA for planting in the United States (US) because it has a low score of –8 for its tendency to become invasive, based on the fact that no volunteer seedlings have been documented from Sunshine conservation plantings in the Pacific Islands over 15 years (Joy 2009). According to the research conducted by the US Army Corps of Engineers on the invasive qualities of Vetiver, the plant may

release seeds, but the seeds do not germinate and grow seedlings under actual field conditions. Additionally, it has been discovered that Vetiver is a passive plant that avoids competition with native plant species. It produces excellent results in rich, fertile soils in humid regions but can also grow in infertile sandy lands where no native grass can grow. In the southern parts of the United States, Vetiver is an excellent option as a nature-based solution. However, its resiliency does not extend to cold and freezing weather conditions (Sharif 2000) because the rate of survivability is poor if the soil freezes and shading impacts the Vetiver growth. Typical ranges of stresses that Vetiver can withstand are a pH of 3.3–9.5 and temperatures from –15°C to 55°C (Danh et al. 2009). Fig. 4 presents Vetiver with roots grown in different soil and climate conditions.

Vetiver's Applications

In addition to its value in remediating slope instability, Vetiver shows higher resistance to erosion compared to the ground modification chemical polyhedral oligomeric silsesquioxanes (POSS) (Kidd et al. 2011), Vetiver plays a crucial role in a wide array of problems, such as phytostabilization, phytoextraction, and phytotiltration of heavy metals. It is an effective heavy metal accumulator, particularly of Pb and Zn (Antiochia et al. 2007), and helps eliminate cadmium and lead, prevalent contaminants in agricultural regions (Phusantisampan et al. 2016; Nanekar et al. 2015). Compared to other plants, it is effective against metals such as arsenic, copper, chromium, mercury, nickel, and selenium (Danh et al. 2010; Truong 1999). Table 1 presents the comparison of Vetiver with vascular plants in heavy metal absorption.

Due to its ability to remove heavy metal contaminants, it has been utilized effectively in mine site rehabilitations, landfill rehabilitations, contamination removal from landfill-generated waste, leachate treatments, and wastewater pollution management (Danh et al. 2009; Truong et al. 2010).

Vetiver can also treat crude oil-contaminated soil and crude oil sludge (Nanekar et al. 2015). It can eliminate trinitrotoluene (TNT) from soils treated with a urea chaotropic agent (Das et al. 2010). It has been found to have a significant impact on the reduction of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) in the treatment of palm oil mill secondary effluent (Darajeh et al. 2016). Vetiver efficiently removed contamination from surface water in Vietnam. Vertical flow constructed wetlands (VFCWs) can effectively remove 90% of the biochemical oxygen demand (BOD₅), more than 80% of chemical oxygen demand (COD) and after being treated with Vetiver, the surface water satisfies the standards for reuse in agricultural irrigation (Nguyen et al. 2023).

Vetiver is well-known for its fragrant qualities. The oil it produces is currently utilized commercially in the perfume and cosmetics industries and has been discovered to have therapeutic qualities that influence various vital physiological processes, including tissue remodeling, cholesterol metabolism, and tuberculosis (Han and Parker 2017; Saikia et al. 2012). The oil has also been found effective against insects such as subterranean termites (Zhu et al. 2001).

Farmers benefit from plantings of Vetiver, as its roots improve the condition of soil, boost crop yields by increasing infiltration (Dousset et al. 2016), enhancing water and nutrient retention (Babalola et al. 2007). It produces ash [Vetiver grass ash (VGA)] that contains roughly 7% more silica and seven times more potassium oxide (K₂O) than fly ash as tested in accordance with ASTM C191-92 (ASTM 1992) and ASTM 109-80 (ASTM 1980) requirements for a Class C pozzolana. VGA mortar is a suitable building material for chemically exposed foundations, maritime projects, sewers, and other structures (Nimityongskul et al. 2003).

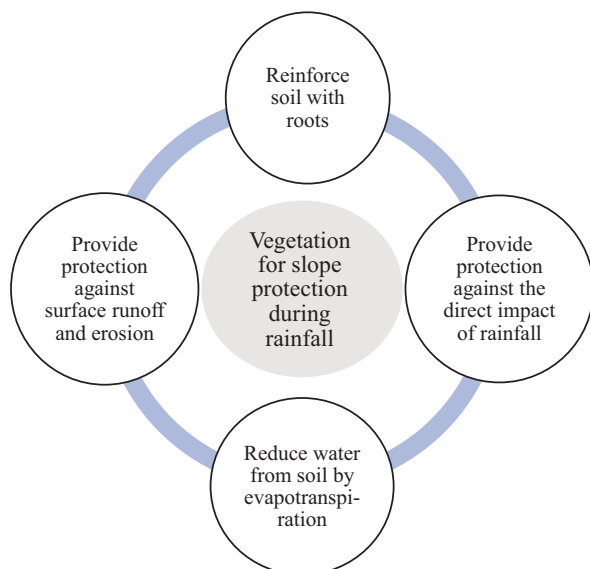


Fig. 3. Impact of vegetation on the soil.



Fig. 4. (a) Length of Vetiver roots [reprinted from Kim et al. (2022), under Creative Commons-BY-4.0 license (<https://creativecommons.org/licenses/by/4.0/>)]; and (b) Vetiver roots grown in poorly graded sand for 110 days (reprinted with permission from Springer Nature: Springer, *Innovative Infrastructure Solutions*, “A simple approach for estimating contribution of vetiver roots in shear strength of a soil–root system,” F. F. Badhon, M. S. Islam, Md. A. Islam, and Md. Z. U. Arif, © 2021).

Table 1. Comparison of heavy metal absorption capacity of Vetiver and vascular plants

Heavy metal	Threshold levels in soil (mg/kg)		Threshold levels in plants (mg/kg)	
	Vetiver	Vascular plants	Vetiver	Vascular plants
Arsenic	100–250	20	21–72	1–10
Cadmium	20–60	1.5	45–48	5–20
Copper	50–100	Not available	13–15	15
Chromium	200–600	Not available	5–18	0.02–0.20
Lead	>1,500	Not available	>78	Not available
Mercury	>6	Not available	>0.12	Not available
Nickel	100	7–10	347	10–30
Selenium	>74	2–14	>11	Not available
Zinc	>750	Not available	880	Not available

Source: Data from Danh et al. (2009).

and is used in ceramic production as a flux agent at low temperatures (600°C) to produce a glassy phase (Islam and Badhon 2017; Gnansounou et al. 2017). More than 120 countries rely on Vetiver for a variety of purposes, and its popularity is growing (Truong and Loch 2004).

Vetiver Grass for Climate-Adaptive Slope Repair

Many countries utilize Vetiver for slope protection (Mickovski and Van Beek 2009) because its long bushy root system boosts water penetration rates, provides gripping action to decrease sliding, and interacts with the soil to form a composite material that has high tensile strength (Dousset et al. 2016). In this study, through laboratory experiments, field monitoring, and numerical soil assessments performed under varying climatic and soil conditions, we examined the characteristics and behavior of Vetiver roots, namely (1) tensile strength; (2) pull-out strength; and (3) effects on soil cohesion, shear strength, hydraulic permeability, pore pressure, surface runoff, and the slope’s slip surface under conditions of excessive rainfall. The significance of Vetiver as a climate adaptive

solution for slope failure has become increasingly critical in light of the ongoing climate change. The utilization of Vetiver plantation in purpose of slope repair in the US state of Mississippi is illustrated in Fig. 5.

Tensile Property of Vetiver Roots

Vetiver’s long, bushy root system reinforces soil mechanically, and the soil’s tensile strength enables it to resist any horizontal forces that it encounters (Badhon et al. 2021). Similar to other types of root reinforcement, the contribution of Vetiver roots to the shear strength or root cohesion can be estimated by Eq. (1)

$$S_r = T_R \cdot (A_R/A) \cdot (\sin \theta + \cos \theta \tan \phi') \quad (1)$$

where T_R = mobilized root tensile stress on the root; A_R/A = root area ratio or ratio between the root and total area; ϕ' = friction angle of soil; and θ = angle of root deformation (Wu et al. 1979).

It is also necessary to accurately estimate the ultimate tensile strength of the Vetiver roots to predict the soil’s shear strength because the tensile strength mobilizes the force on a slope exerted by the movement (Islam et al. 2021). The shear strength of root-enforced soil can be calculated using Eq. (2)

$$\tau = S_r + c + \sigma \tan \phi' \quad (2)$$

where c = effective cohesion of soil; and σ = normal stress.

A constant value of 1.2 can be used for the added cohesion value provided by the roots replacing the later part of the Eq. (1) in a condition that the range of θ will be from 48° to 72° (Wu et al. 1979). In that case, the value of S_r can be obtained by using Eq. (3)

$$S_r = 1.2 \cdot T_R(A_R/A) \quad (3)$$

Several studies conducted to accurately detect and predict the tensile strength of Vetiver root systems have shown that its strength reduces as its diameter increases [Fig. 6(a)]. Smaller-diameter roots were shown to have greater tensile strength before rupture under tension; however, thicker roots were found to withstand lower tensile pressures. Badhon et al. (2021) measured the root tensile strength of 2-year-old Vetiver roots grown in low-plasticity clay,



Fig. 5. Vetiver grass used to stabilize a moving highway slope in Mississippi. (Image by Avipriyo Chakraborty.)

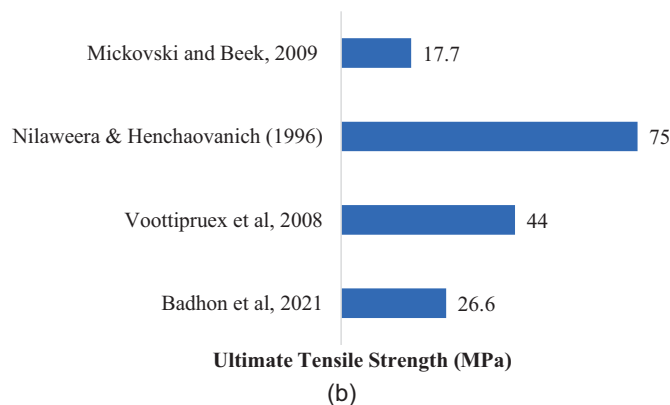
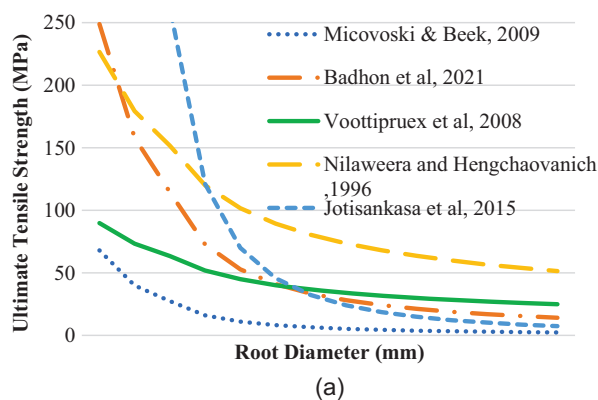


Fig. 6. Ultimate tensile strength values achieved by different studies on Vetiver roots: (a) variation of root strength with different diameter; and (b) variation of ultimate tensile strength achieved at different studies.

Voottipruex et al. (2008) studied Vetiver growth in poorly graded sandy soil based on the pull-out test, Mickovski and Van Beek (2009) studied Vetiver grown in clay for 6 months, and Jotisankasa et al. (2015) studied root strength on laboratory-grown Vetiver. The tests that they performed to determine Vetiver's root tensile strength had mixed results having a minimum root ultimate tensile strength of 17 MPa [Fig. 6(b)].

Although Nilaweera and Hengchaovanich (1996) determined that the root strength of Vetiver was higher than other grasses it was compared with, the results of later studies were more reliable due to significant improvement of the testing device and a more controlled strain. In addition, the meteorological and soil condition variations, as well as the age of the grass, may have impacted the root tensile strength.

Pull-Out Capacity of Vetiver-Rooted Soil

In root soil composite material, the root strength mobilizes the force generated by the soil's movement. A larger root system has a greater capacity for mobilization; however, the soil can fail at a lower strength than the tensile strength due to root slippage (Zhang et al. 2020). Slippage refers to the force necessary to separate a plant root from the soil when the soil is under stress, which is a limiting condition of loading on a slope against failure rather than only the root rupture (Waldron and Dakessian 1981). The pull-out strength is a tangential friction between roots and soil that is largely dependent on root bending, hairs and branches of roots, and root tensile strength at breakages rather than slope conditions (Abe and Iwamoto 1986; Tsukamoto 1986). The uprooting force in Vetiver-rooted soil increases with soil displacement until it reaches the maximum value, then declines due to root slippage or rupture [Fig. 7(a)].

Root spread has a significant impact on the pullout strength of Vetiver roots, as the value of force increases with greater root spread, as shown in Fig. 7(b) (Mickovski et al. 2005). However, there is still a research gap on Vetiver pull-out strength for a greater comprehension of the mechanical behavior exhibited by these roots when they fail. Further investigation is necessary regarding the effectiveness of Vetiver pull-out strength under varying soil conditions and the effect of water content variation on slippage.

Impact of Vetiver on Soil Shear Strength

The shear strength of soil consists of the cohesion or force that holds soil particles together and the resistance of the particles due to friction or interlocking when they slide over each other (Flerchinger et al. 2005). Eq. (4) can be used to calculate the shear strength of soil

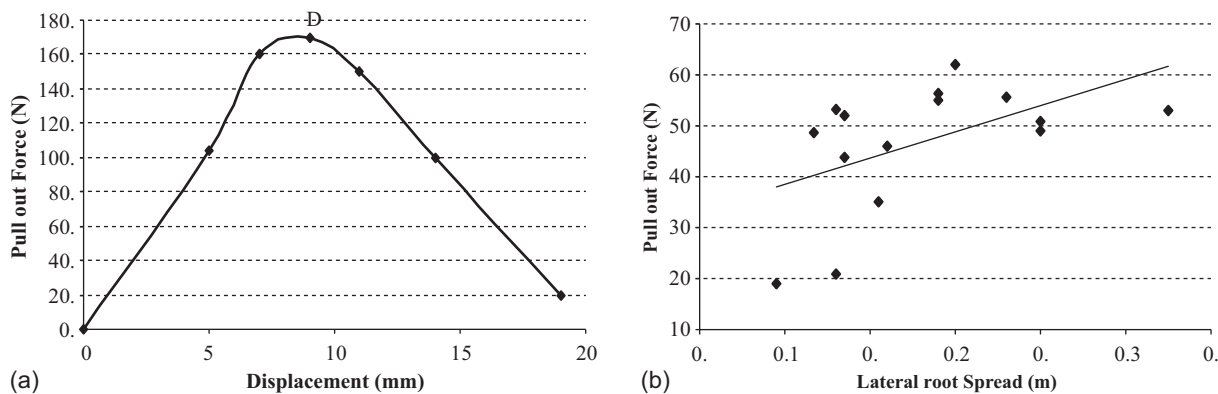


Fig. 7. Variations of pullout force of Vetiver roots: (a) with displacement; and (b) lateral root spread. (Reprinted with permission from Springer Nature: Springer, *Plant and Soil*, “Uprooting of vetiver uprooting resistance of vetiver grass (*Vetiveria zizanioides*),” S. B. Mickovski, L. P. H van Beek, and F. Salin, © 2005.)

$$\tau = c + \sigma' \tan \phi' \quad (4)$$

where c = cohesion of soil; σ' = effective stress; and ϕ' = friction angle.

Triaxial testing and direct shear testing are two methodologies that are widely used in geotechnical engineering to determine the shear strength properties of soil. They are used interchangeably despite potential variations in findings (Castellanos and Brandon 2013).

Numerous studies have employed direct shear testing to evaluate Vetiver's influence on the friction angle, cohesion, and shear strength of various soils under different climatic conditions (Rahardjo et al. 2014). Mickovski and Van Beek (2009) tested its impact on silt with clay soil in Spain, Islam et al. (2013) studied Vetiver-rooted soil in low-plasticity clay and silty sand in Bangladesh, and Ali and Osman (2008) studied its impact on sandy soil in Malaysia. Fig. 10(a) illustrates a field-scale direct shear test device used for studying Vetiver impact on soil shear strength.

All of the studies demonstrated that Vetiver increased the soil's cohesion and peak shear stress; however, the impact of Vetiver in friction angle increase has not been found that significant in direct shear testing (Fig. 8). In a study based on direct shear testing and conducted on sandy soil, Vetiver-rooted soil had higher peak shear stress values than nonrooted soil (D'Souza et al. 2019) [Fig. 9(a)]; however, it was observed that the peak stress values decreased with increased depth. The number of roots also decreases with increasing soil depth, leading to the conclusion that roots impact the soil shear strength up to the depth they grow.

The root area ratio (RAR) has a direct relationship with shear strength, as shown in Eq. (3); in Vetiver-rooted soil, it also appears root mass influences the peak shear stress. Experiments have shown that peak shear stress values rise with an increase in the RAR [Fig. 9(b)]. Compared with nonrooted soil, rooted soil can withstand greater strain, which means more deformation can take place in Vetiver-rooted soil than nonrooted soil before failure (Fig. 10).

A study based on triaxial testing that was conducted on poorly graded sand in Singapore's tropical environment revealed that Vetiver roots increased the cohesion value from 2 to 10 kPa and the friction angle from 29° to 34° , exceeding that of one of their local plants, orange jasmine (Fig. 11). Similar to the results of the direct shear tests, the triaxial testing showed that Vetiver-rooted soil can undergo greater deformation than the original slope before reaching peak shear stress in unsaturated soil conditions. Because the rooted soil exhibits ductile behavior before it collapses, it can serve as an early warning system for landslides.

Impact of Vetiver on Hydraulic Properties of Soil

Hydraulic Permeability of the Soil

The hydraulic permeability of soil plays a significant role in precipitation-induced landslides because it determines the degree to which water infiltrates unsaturated soil. When the permeability increases, infiltration increases and reduces the surface runoff and soil erosion; In rainfall conditions, soil water infiltration is controlled by the saturated hydraulic permeability value (Scanlan and Hinz 2010; Li et al. 2016). Soil with a higher saturated hydraulic permeability value absorbs more water and reduces surface runoff and erosion. According to the study conducted by Jotisankasa and Sirirattanachai (2017), Vetiver affects the saturated hydraulic permeability of soil, but the degree to which it affects it varies depending on the soil state. The value rises to a threshold in low-plasticity clay before declining, although no significant change has been observed in sandy clay soil.

Rajamanthri et al. (2021) conducted a study on poorly graded silty sand and poorly graded sand and observed an increase in the saturated hydraulic permeability value. Vetiver increases the soil's capacity to retain water to varying degrees because mature plants have greater capacity than younger ones. Root mass impacts the volumetric water content because upper slopes with more roots have higher saturated water content than the lower part of the slopes. There is no clear picture of how slope angles impact the water retention capacity, although some researchers have found that the water retention capacity on Vetiver-planted slopes increases with the slope angle. The research on the effect of Vetiver on saturated hydraulic conductivity is still insufficient, however, to make a definitive determination on the subject. There is a need for additional research into the effects of Vetiver on varied soil conditions.

Pore Water Pressure and Matric Suction

Matric suction influences the shear strength of unsaturated soils and is considered a cohesion component of unsaturated soil shear strength (Nam et al. 2011; Lu and Likos 2006). An increase in pore water pressure decreases effective stress and matric suction, thereby compromising the stability of a slope (Matsuura et al. 2008; Rahardjo et al. 2014). Based on a study using the Gtirana and Fredlund model, it was seen that Vetiver impacts unsaturated soil properties in poorly graded silty sand and poorly graded clayey sand because the air entry value decreased with an increase in the root mass (Rajamathri et al. 2021). On a poorly graded sand slope in the tropical environment of Singapore, however, Vetiver substantially reduced the pore water pressure and increased the

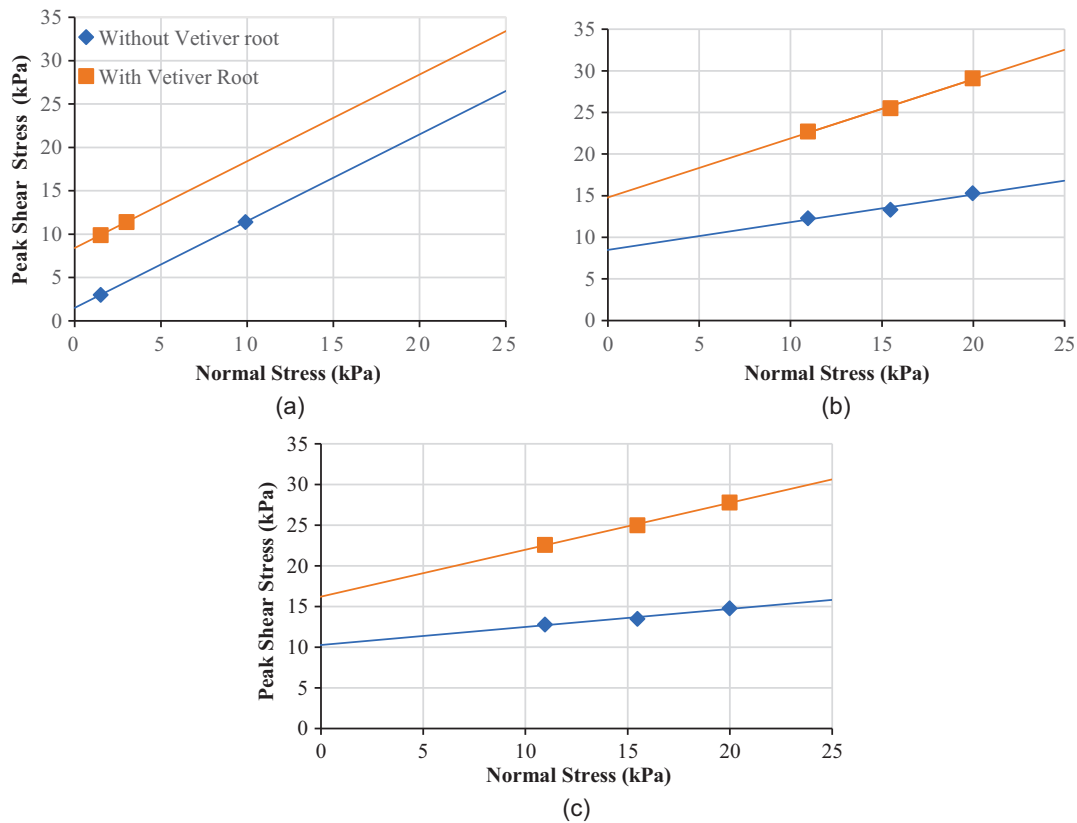


Fig. 8. Comparison of the shear strength of undrained nonrooted and Vetiver-rooted soil under normal loading conditions: (a) in silt with clay soil (data from Mickovski and Van Beek 2009); (b) in silty sand (values derived from Islam et al. 2013); and (c) in low-plasticity clay (data from Islam et al. 2013).

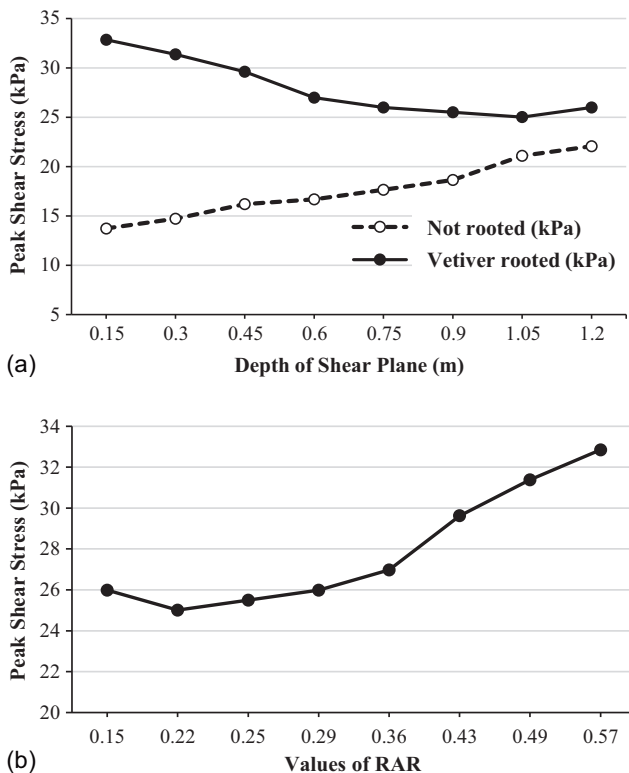


Fig. 9. Variations in peak shear stress values based on a direct shear test: (a) with depth; and (b) with root area ratio in Vetiver-rooted soil. (Data from D'Souza et al. 2019.)

shear strength (Fig. 12). The impact of Vetiver on unsaturated soil properties in different climates and soil conditions is still poorly understood and requires additional research.

Impact of Vetiver on Reduction of Slope Slip Surface

The duration, intensity, and pattern of a rainfall event, as well as the hydraulic conductivity of the saturated soil and initial and boundary conditions, increase the saturation level of the soil (Ali et al. 2014; Yoshida et al. 1991). Completely saturated soil reaches a stage of complete softening by decreasing shear strength and contributes to landslide. In unsaturated soil conditions, rainfall water infiltration decreases the matric suction and shear strength of the soil (Rahardjo et al. 1995). Heavy precipitation can also create perched water conditions that have the potential to reduce the soil's shear strength (Lee et al. 2009). Especially in marginal soil like high-plasticity clay, water paves into the soil through the desiccation cracks and causes landslide events (Khan et al. 2016).

Centrifuge modeling is beneficial because it allows researchers to examine physical models at a stress level that closely reflects the real-world situation. This is particularly important when dealing with landslides because gravity plays a significant role in slope failure (Taylor 2018). At 50g centrifugal acceleration, the pressures and tensions applied to the model are increased by a factor of 50. Therefore, if a 1-m-deep model represents 50 m of prototype soil, the vertical tension at the base of the model is similar to the vertical stress at a depth of 50 m below the surface of the earth (Center for Geotechnical Modeling 2019).

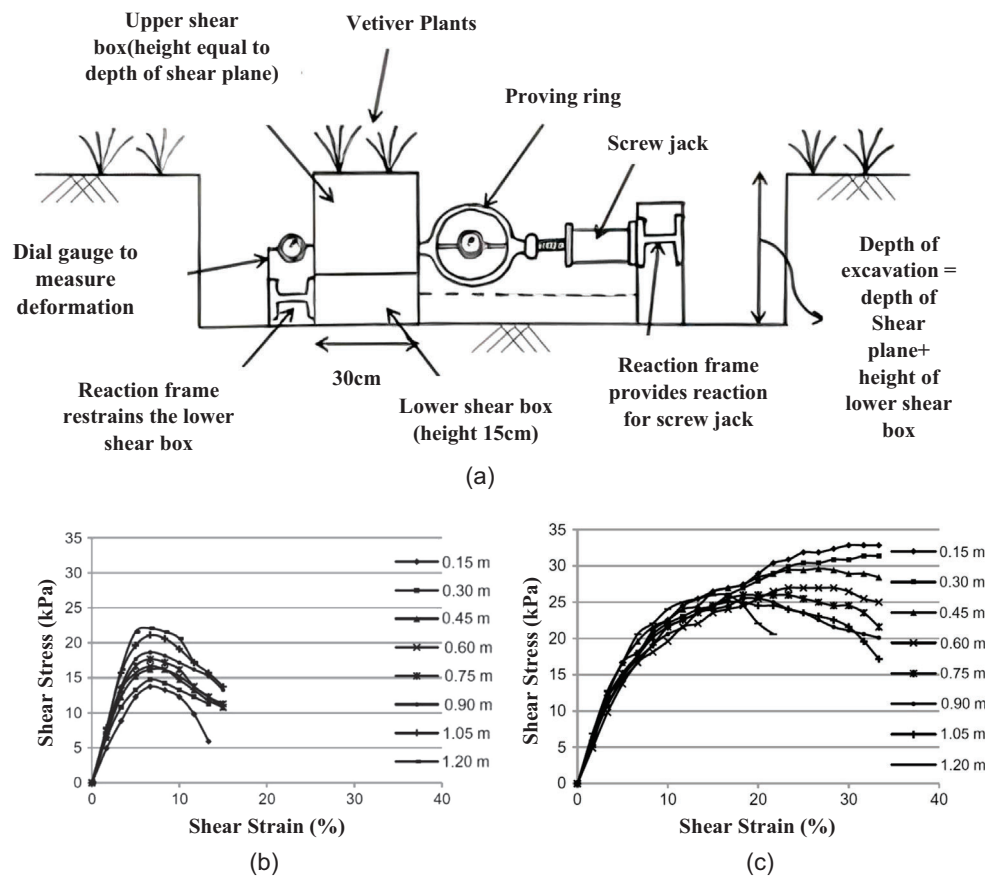


Fig. 10. Variations of shear stress on different strain conditions and depths: (a) field setup; (b) nonrooted soil; and (c) Vetiver-rooted soil. (Reprinted with permission from Springer Nature: Springer, *Ground Improvement Techniques and Geosynthetics*, “Assessment of vetiver grass root reinforcement in strengthening the soil,” D. N. D’Souza, A. K. Choudhary, P. Basak, and S. K. Shukla, © 2018.)

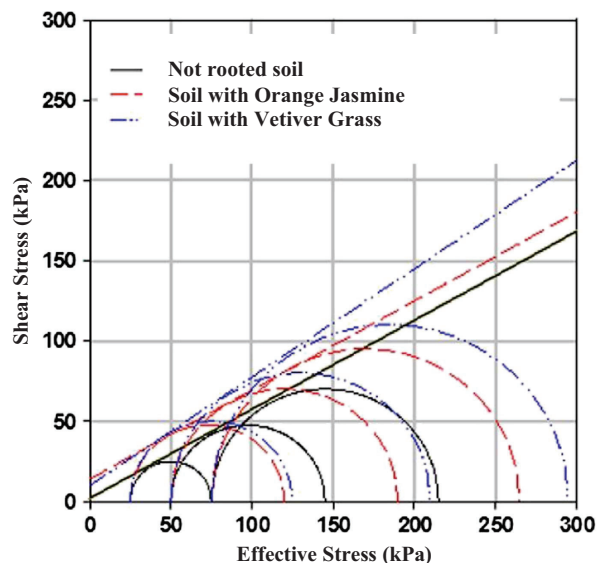


Fig. 11. Comparison of Mohr-Coulomb failure envelopes at zero matric suction with the original soil, soil reinforced with orange jasmine, and soil reinforced with Vetiver grass roots. [Reprinted from *Soils and Foundations*, Vol. 54 (3), H. Rahardjo, A. Satyanaga, E. C. Leong, V. A. Santoso, and Y. S. Ng, “Performance of an instrumented slope covered with shrubs and deep-rooted grass,” pp. 417–425, © 2014, with permission from Elsevier.]

Eab et al. (2015) conducted a study based on a 50g centrifugal acceleration model of a slope built of fine sand to determine the impact of Vetiver roots in excess rainfall conditions. Pore water pressure transducers (PWPs) and accelerometers (ACCs) were inserted in the soil layers to monitor the pore water pressure and horizontal displacement, which showed that Vetiver reduces the depth of the slip surface [Figs. 13(a and b)]. The horizontal displacement was reduced at both the top and toe of the slope, thereby preventing the slope from failing, but the reduction of displacement was greater in the toe [Figs. 13(c and d)].

Vetiver Impact on Reduction of Surface Runoff

Infiltration of soil is an important parameter of study for understanding slope stability, especially in excess rainfall conditions, as low infiltration increases surface runoff and causes soil erosion that can eventually trigger landslides. Numerous studies conducted under varying climate conditions have shown that Vetiver roots reduce surface runoff, and several have shown that they can reduce the surface discharge at various slope angles (Donjadee and Tingsanchali 2013; Sudhishri et al. 2008; Welle et al. 2006; Islam et al. 2020). Table 2 presents the surface runoff reduction in varying climate and soil conditions, which shows Vetiver can reduce surface runoff up to 69%. However, it is seen that a steeper slope makes the runoff decrease less effective. Although Vetiver-rooted slopes have a positive effect on reducing surface discharge, the impact of Vetiver on surface runoff reduction and erosion control requires more research.

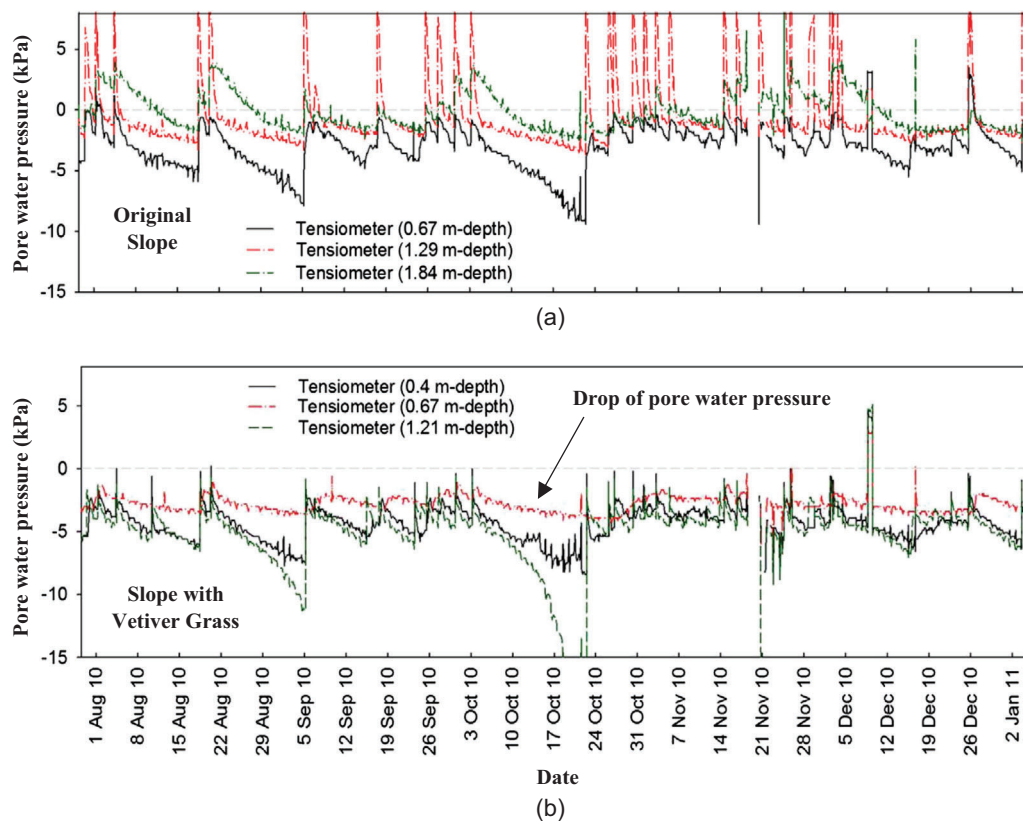


Fig. 12. Variations of pore water pressure at different depths: (a) in nonrooted soil; and (b) Vetiver-rooted soil. [Reprinted from *Soils and Foundations*, Vol. 54 (3), H. Rahardjo, A. Satyanaga, E. C. Leong, V. A. Santoso, and Y. S. Ng, "Performance of an instrumented slope covered with shrubs and deep-rooted grass," pp. 417–425, © 2014, with permission from Elsevier.]

Numerical Analysis of Vetiver Impact on Slope Repair

Numerous studies based on numerical analysis have explored the influence of Vetiver in preventing landslides. Factor of safety (FOS) value requirements should exceed or equal 1.5 in normal conditions and 1.2 in excess rainfall conditions (Wang et al. 2023). Mickovski and Van Beek (2009) and Sanguankao et al. (2014) performed limit equilibrium analyses using the Bishop method. Mickovski and Van Beek (2009) considered additional soil cohesion due to the presence of Vetiver roots; Sanguankao et al. (2014) did not. The results of both analyses showed that Vetiver increased the factor of safety on slopes. Rahardjo et al. (2014) compared slopes planted with Vetiver with slopes planted with native grass orange jasmine and found that the factor of safety values of the Vetiver-rooted soils were significantly higher compared with both the original slope and the slope with orange jasmine (Fig. 14).

Spears et al. (2023) studied Vetiver impact based on finite-element seepage analysis and limit equilibrium stability analysis considering the rainfall and seepage based on a high-plasticity clay levee slope. As a part of the study, Vetiver was planted on the levee slope and monitored for a 2-year period, which showed no visible crack on the levee section. Transient seepage analysis considering a return period of 100 and 500 years in Mississippi showed that Vetiver provided enough strength to the soil making the slope stable during a 4-day storm period (FOS = 1.4) compared with the unrooted soil (FOS = 0.6).

Another study based on the finite-element method has shown that the FOS of slopes planted with Vetiver grass increased from 1.15 to 1.5 (Mohammad et al. 2022). The analysis was done on

the impact of Vetiver grass planted on a high-plasticity expansive clay 3:1 slope in the hot, humid climate of Mississippi. Time-dependent slope movement along the depth was monitored with rainfall variations, and it was revealed that before the grass was planted, the slope experienced 10% movement; after it was planted, it remained static.

Overall Assessment of Vetiver Growth in Different Climate and Soil Conditions

Different Climate Conditions

The Köppen-Geiger climate classification, which is recognized as the most widely acknowledged climate classification map, has divided the Earth into multiple climatic zones (Peel et al. 2007). The map has presented distinct regions within the worldwide landscape, characterized by variations in vegetation types, precipitation patterns, and annual variations in air temperature. The initial letter designates the primary category according to vegetation type, namely, A for tropical, B for dry, C for mild temperate, D for snow, and E for polar. The second letter refers to the categorization according to precipitation, and the third letter corresponds to temperature (e.g., Cwa means mild temperate with dry winter and hot summer). The comprehensive breakdown of the climate zones is given in Table 3.

Fig. 15(a) depicts the various climate zones of the world, and Fig. 16 presents the mapping of US climate zones. According to the findings of the study, Vetiver exhibits the capacity to grow within climate zones categorized as A (tropical), B (dry), and C

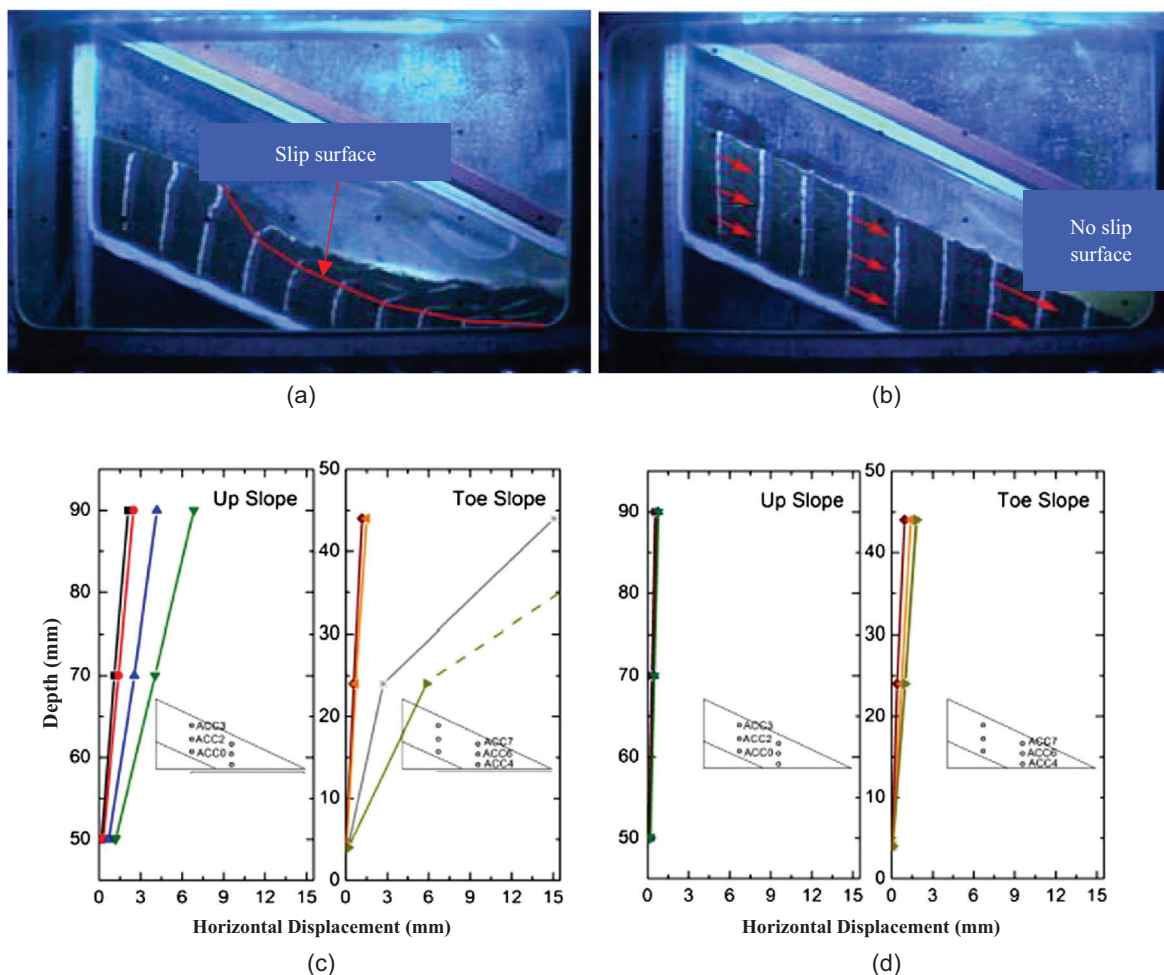


Fig. 13. Impact of Vetiver in rainfall condition compared with nonrooted soil: (a) slip surface in nonrooted soil; (b) slip surface in Vetiver-rooted soil; (c) horizontal displacement in unreinforced slope (up slope and toe slope); and (d) horizontal displacement in Vetiver-reinforced slope (up slope and toe slope). [Reprinted from *Soils and Foundations*, Vol. 55 (5), K. H. Eab, S. Likitlersuang, and A. Takahashi, "Laboratory and modelling investigation of root-reinforced system for slope stabilisation," pp. 1270–1281, © 2015, with permission from Elsevier.]

Table 2. Surface runoff reduction by Vetiver grass at different climate and soil conditions

References	Country	Climate	Soil type	Temperature (°C)		Annual rainfall (mm)	Slope (%)	Reduced runoff (%)
				Summer	Winter			
Donjadee and Tingsanchali (2013)	Thailand	Tropical	Sandy silt	28–33	20	512	30–50	31–69
Babalola et al. (2007)	Nigeria	Tropical	Alfisol (clay-enriched subsoil)	31.6	21.3	1,230	7	63
Welle et al. (2006)	Ethiopia	Subtropical	Sandy silt	25.6–28.2	7.1–15.5	661	9	62
Chaowen et al. (2007)	China	Subtropical monsoon	Sandy silt	30	9	966	17–20	63–71
Aziz and Islam (2023)	Bangladesh	Tropical monsoon	Sandy silt	30–35	20	2,085	37	21

(mild temperate). However, the growing potential of Vetiver in climate zones characterized by main groups D (snow) and E (polar), and subgroups–w (dry winter) and k (cold arid) is limited because of its low tolerance to cold temperatures and frost.

In the US, the potential Vetiver growth zone has been marked based on the USDA hardiness index and Annual Precipitation volume (Fig. 16); (USDA 2023). According to the USDA, Vetiver can grow in Hardiness zone 9 and higher. However, based on the available literature and current assessment, Vetiver grows and survives in

Hardiness zone 8. In addition, with an annual rainfall of 76 cm and higher, Vetiver can grow. As marked in the map, Vetiver has the growing potential throughout the southeastern and majority of south-central regions, in specific parts of Washington, Oregon, and California of the southwest and northwest of the US. Apart from the contiguous US, it can grow very well in the tropical island regions of Puerto Rico and Hawaii. However, the north-central and majority of the northwest portions of the US have a limited growth potential of Vetiver due to low temperatures and its reduced resistance to frost.

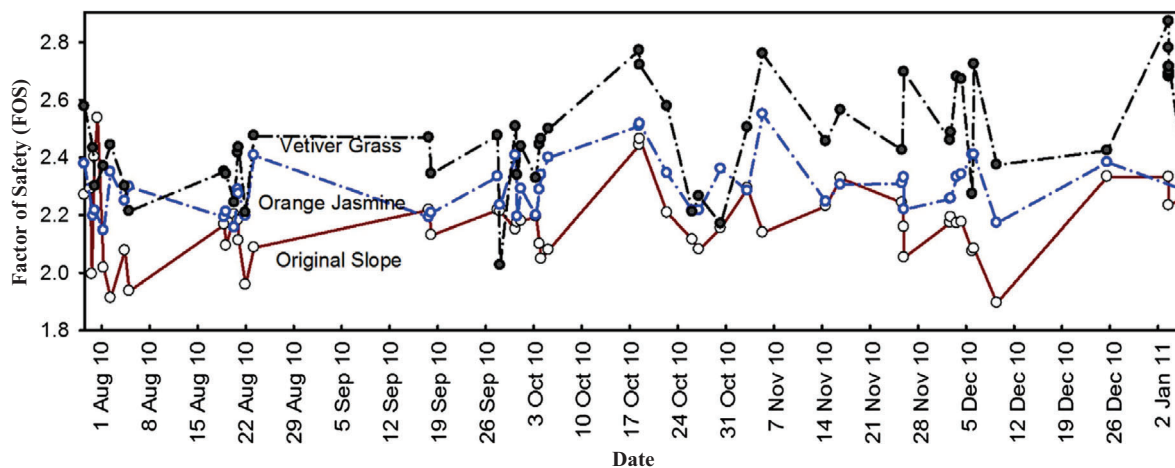


Fig. 14. Comparison of variations of factor of safety for poorly graded sandy soil slope planted with orange jasmine and Vetiver grass. [Reprinted from *Soils and Foundations*, Vol. 54 (3), H. Rahardjo, A. Satyanaga, E. C. Leong, V. A. Santoso, and Y. S. Ng, "Performance of an instrumented slope covered with shrubs and deep-rooted grass," pp. 417–425, © 2014, with permission from Elsevier.]

Growth of Vetiver in Different Soil Conditions

Fig. 17 illustrates the growth study of Vetiver in different soil conditions based on USDA soil classification and fine-grained soils based on unified soil classification system (USCS) soil classification. It is seen that Vetiver can grow very well in different soil conditions that include clay, silty clay, silty clay loam, silty loam, clay loam, sandy clay loam, and sandy loam. Vetiver can even grow in soil conditions with a high percentage of sand. Vetiver can grow well in high-plasticity clay and sandy silt conditions.

Both sandy silt and high-plasticity clay are prone to shallow slope failure because sandy silt exhibits low cohesion and shear strength; high-plasticity expansive clay experiences a reduction in soil shear strength because of the wet–dry cycle and shrink–swell behavior. The utilization of Vetiver can be a viable solution for addressing shallow slope failure due to its high growth potential in sandy silt and expansive clay. However, studies on Vetiver

growth in soil conditions with a greater portion of silt, particularly high-plasticity silt, are still insufficient and require more research.

Community Perception of Vetiver Impact on Slope Repair

In slope stability problems, over other conventional technologies, one of the major benefits of Vetiver is that the implementation of the grass does not require heavy machinery. This implies that any local community-based or individual action will be sufficient for planting Vetiver and protecting the slope from potential failure, especially in remote areas. The grass requires minimum initial maintenance and the cost involved in the implementation and maintenance of it is low compared with traditional structural solutions, which means communities with limited financial resources can more easily afford to implement Vetiver for failure protection.

Moreover, in addition to slope failure, Vetiver is a versatile plant that has various benefits including its cosmetic and therapeutic uses. Community-based initiatives can also cultivate Vetiver because growing Vetiver for different commercial products can create job opportunities for the local farmer-based community, particularly in areas where Vetiver-based goods like handicrafts and essential oils are in demand. For locals, harvesting, processing, and selling products related to Vetiver can become a source of income. The introduction of Vetiver farming may present chances for educational and practical training programs. The inclusion of local people in the design, planting, and upkeep of Vetiver can encourage their active participation in environmental preservation initiatives and facing future challenges of climate change.

However, awareness of Vetiver grass utilization in slope repair, other benefits, and its social impact are still limited. A sustainable framework through the development of community capacity, leadership, and networking for both governmental and nongovernmental organizations can increase awareness of its potential and ensure the efficient use of Vetiver grass.

Discussion

A thorough review of the existing literature indicates that Vetiver offers great benefits, and its use has the potential to transform how we stabilize slopes to prevent landslides. Some of the key findings are as follows:

Table 3. Climate group based on Köppen-Geiger climate classification map

Classification	Type	Name
Main group	A	Tropical
	B	Dry
	C	Temperate
	D	Snow
	E	Polar
Subgroup (based on precipitation)	f	Fully humid
	m	Monsoon
	s	Dry summer
	w	Dry winter
	W	Desert
	S	Slope
Subgroup (based on air temperature)	h	Hot arid
	k	Cold arid
	a	Hot summer
	b	Warm summer
	c	Cool summer
	d	Cold summer
	T	Tundra
	F	Frost

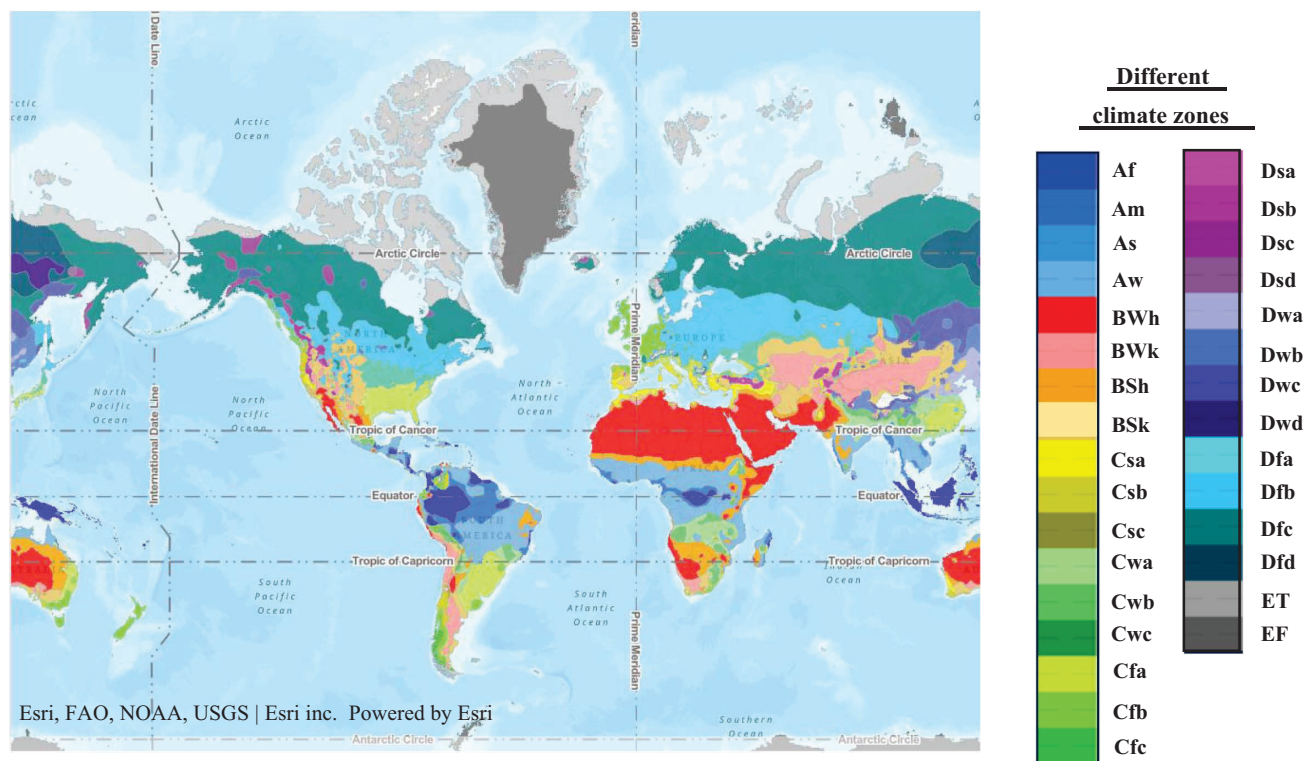


Fig. 15. Different climate zones all over the world based on [Koppen-Geiger Climate Classification Zones 2022](#). (Sources: Esri, FAO, NOAA, USGS.)

- Excessive rainfall is one of the major hydrological causes of landslides. The rising temperatures initiated by climate change have increased the number and intensity of rainfall events and exacerbated global concern about landslides. Soil bioengineering with vegetation is a nature-based permanent slope failure mitigation approach that can be an effective tool for preventing or at least mitigating landslides that are due to excess rainfall.
- Vetiver grass is an effective alternative to more traditional slope stabilization techniques because it affects a slope mechanically as well as hydrologically through reinforcement and evapotranspiration. Vetiver roots are bushy and can grow up to 3 m long. Those with smaller diameters have higher tensile strength before rupture, whereas those with a larger-diameter root can withstand less tensile stress. The ultimate tensile strength of a Vetiver root is a minimum of 17 MPa according to studies conducted in various regions with diverse soil conditions.
- Large-scale, small-scale, and in situ direct shear testing has shown that Vetiver roots improve soil's cohesion, friction angle, and peak shear stress. It has also been observed that they affect the failure strain. Vetiver-planted soil undergoes greater deformation than unrooted soil and exhibits ductile behavior, allowing the slope to withstand greater strain before failure. This characteristic of rooted Vetiver can provide an early warning of an impending landslide.
- Shear strength decreases in saturated soil conditions; however, the long roots of Vetiver absorb water in the soil and prevent it from becoming saturated. Although some research has been conducted on Vetiver-rooted soil using triaxial testing, more research is needed to determine its short- and long-term effects on the soil characteristics of slopes under various drainage conditions.
- Mature Vetiver can provide adequate anchorage to reduce the slope slip surface depth during rainfall events; however,

the impact is greater at the toe than at the top of the slope. Numerical analysis revealed that Vetiver affects the factor of slope safety values under various soil and climate conditions, but the degree of influence may vary based on how the roots are modeled, the roots' tensile strength, the modulus of elasticity, the consideration of root cohesion provided by the root reinforcement, the geometric shape of the slip surface, and other soil parameters.

- Vetiver decreases pore water pressure and enhances matric suction and soil shear strength. It increases soil-saturated hydraulic permeability, which can lessen rainfall-induced erosion and surface runoff. However, root mass affects air entry suction in unsaturated soil and soil water retention because some studies found that Vetiver increases the water retention capacity of the soil around the roots. Study on Vetiver's effect on soil hydraulic characteristics is still limited under varied climatic and soil conditions. Additional research work is required to fully understand how Vetiver impacts the hydraulic and unsaturated properties of the soil.
- Vetiver's root mass significantly impacts the soil, and the shear strength decreased as the number of roots in the soil decreased with depth, indicating that the effect of Vetiver is better suited to shallow landslide situations up to the length of the roots.
- Based on the Koppen Geiger classification system, Vetiver exhibits the capacity to grow within A (tropical), B (dry), and C (temperate) climate zones. However, the growing potential of Vetiver in climate zones characterized by main groups D (snow) and E (polar), and subgroups w (dry winter) and k (cold arid) is limited because of its low tolerance to cold temperatures and frost. In the US, Vetiver has high growth potential throughout the southeastern and majority of southcentral regions, certain parts of southwest and northwest, and in the tropical island regions of Hawaii and Puerto Rico. However, the

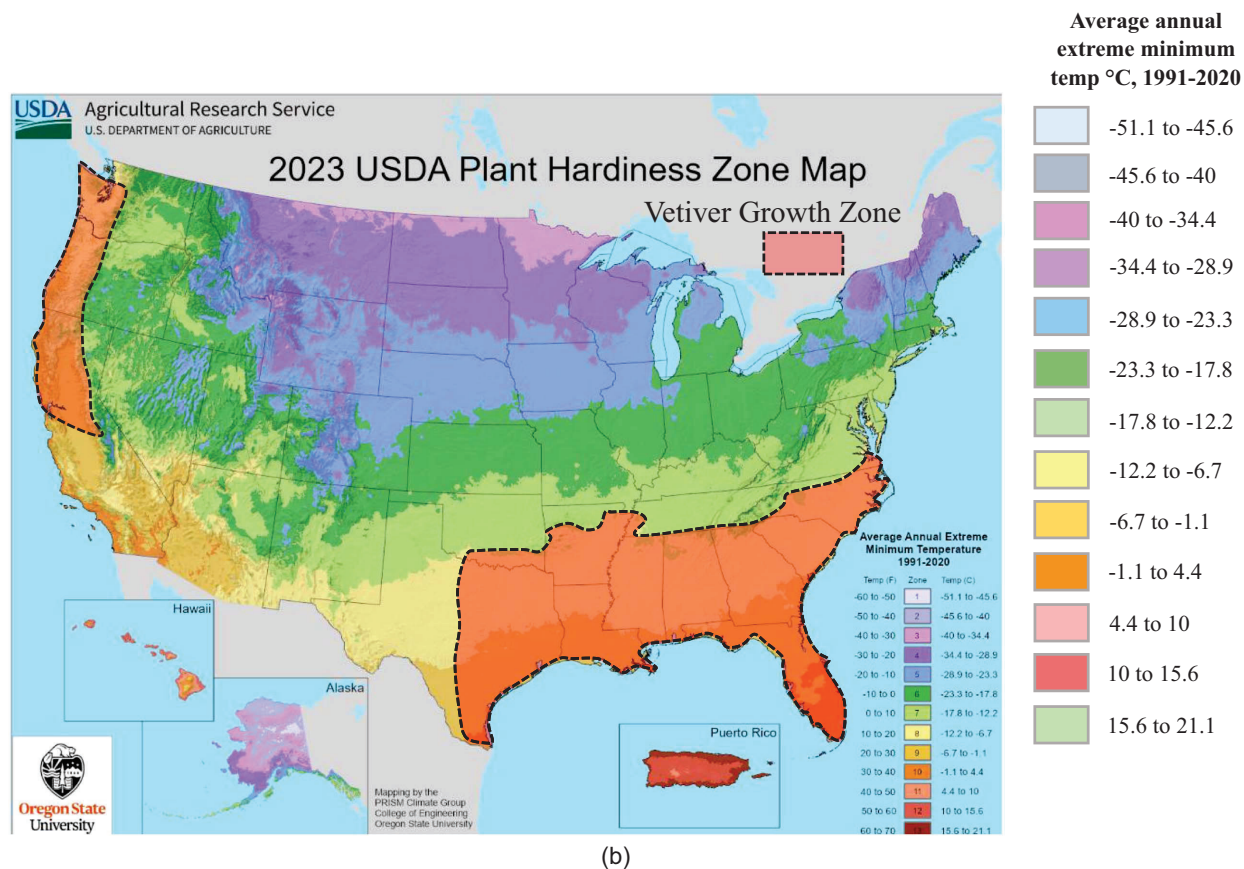
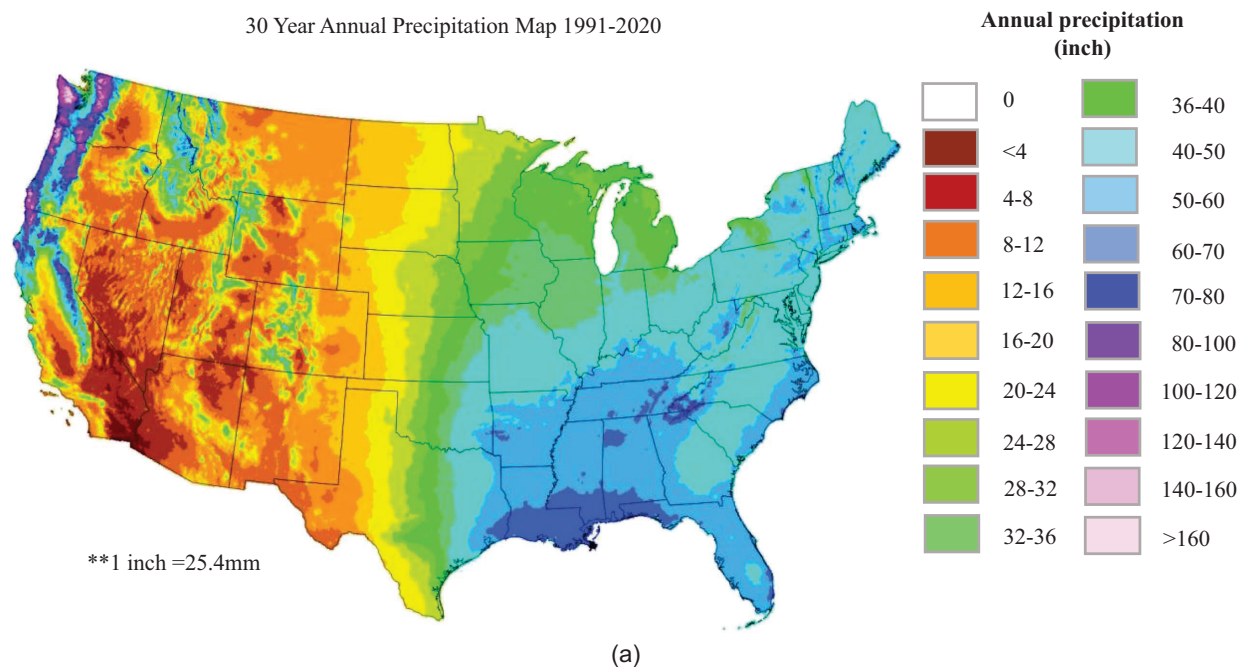


Fig. 16. (a) Annual 30-year normal precipitation map; and (b) US Hardiness Map with the location of Vetiver growth and application. (Copyright © 2022, PRISM Climate Group 2022, Oregon State University, <https://prism.oregonstate.edu>; Map created Feb 27, 2024 as instructed in the following link <https://prism.oregonstate.edu/terms/>.)

north-central and majority of northwest portions of the US have a limited growth potential of Vetiver due to low temperatures and its reduced resistance to frost.

- Vetiver can grow throughout a range of soil conditions, encompassing silty clay, silty clay loam, silty loam, clay loam, sandy

clay loam, and sandy loam and in soil conditions characterized by a substantial proportion of sand. High growth potential of Vetiver on sandy silt and high plasticity expansive clay renders it a promising solution for mitigating shallow slope failure in the slopes characterized by these soil types.

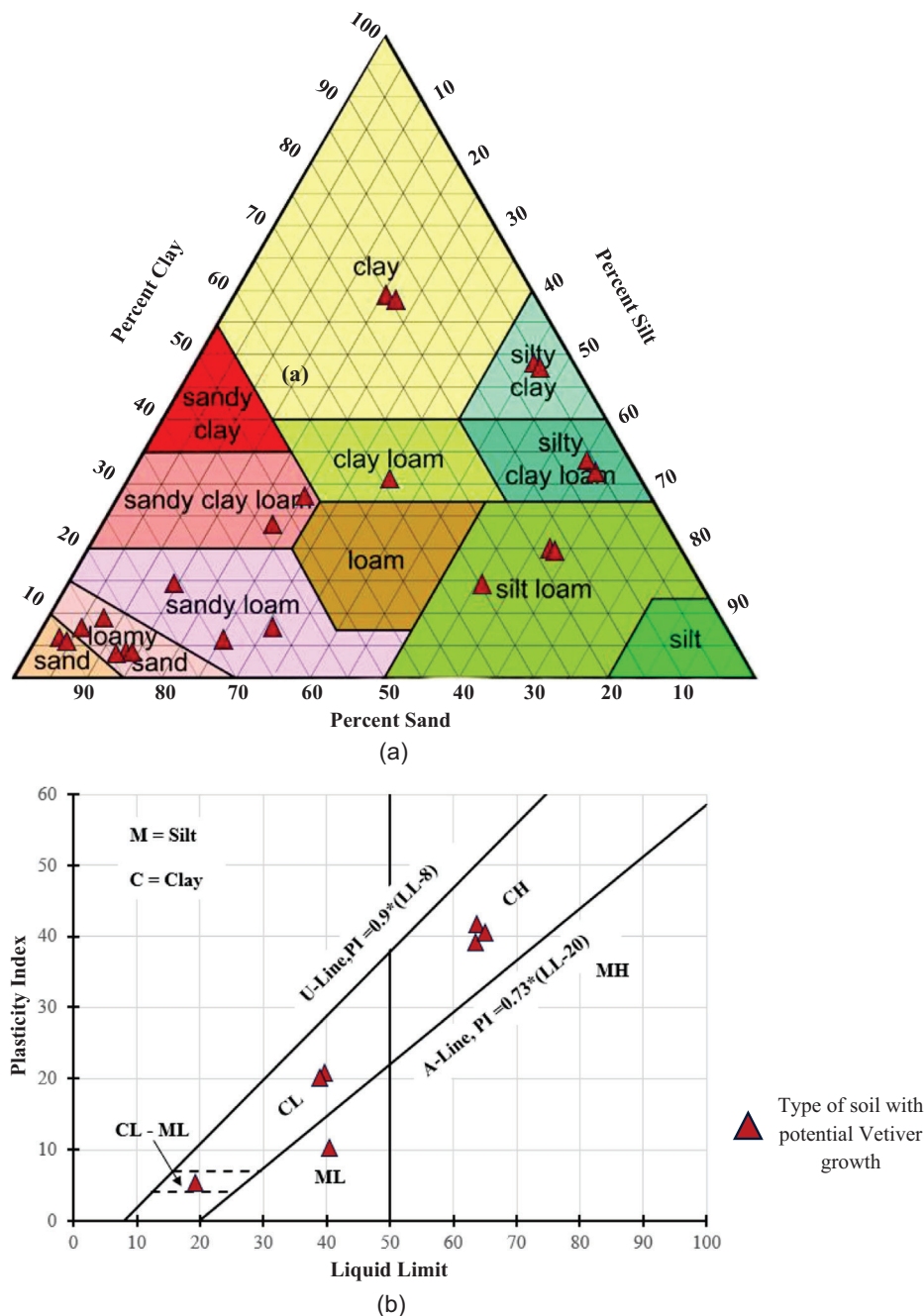


Fig. 17. Growth study of Vetiver at different soil conditions: (a) based on USDA soil classification; and (b) in fine-grained soil based on USCS classification system.

- It is vitally important to develop a proactive solution for preventing landslides because they all have the potential to be fatal and to have catastrophic effects on a variety of factors, including the economy, infrastructure, transportation, and human life. Sunshine Vetiver grass can be a potential solution that can be used alone or in conjunction with other slope stability techniques. However, as climate and soil conditions influence the biological growth of Vetiver, a location-specific study on root efficiency of slope repair can be done for more accurate application for slope repair with Vetiver. The implementation of Vetiver is cost-effective, requires minimal maintenance, is easy to implement without heavy machinery, long-lasting, and does not depreciate with time, like cement and rebar. In addition to

this, growing Vetiver has other commercial benefits that can benefit the local community.

Summary and Conclusions

Landslides are natural disasters that wreak devastation on human lives, infrastructure, and the economy, and their accelerating incidence, which is the result of more frequent and intense rainfall events, is causing concern across the world. Many countries are successfully using Vetiver grass as a plant-based soil bioengineering technique for repairing slopes, and the Sunshine genotype has been approved for use in the US because of its noninvasive nature.

There are many advantages to using Vetiver grass for slope reinforcement. It is affordable, perennial, long-lasting, easy to implement without the need for heavy equipment, and easy to maintain. Its long, bushy roots have a high tensile strength that reinforces slopes and prevents soil from becoming saturated through evapotranspiration. Vetiver enhances the soil cohesion and friction angle while decreasing pore water pressure, boosts the matric suction and shear strength of the soil, reduces the horizontal displacement and depth of the slip surface, and increase soil's saturated hydraulic permeability. Vetiver-rooted soil has ductile behavior under increasing loads and exhibits greater deformation before failure than nonrooted slopes, providing an early warning of a potential catastrophe. It can also be utilized alone or in conjunction with other slope stabilization methods.

Despite all the aforementioned advantages, Vetiver is better suited to shallow landslides because the roots have less impact at greater depths. More research is needed to investigate the impacts of Vetiver in unsaturated soil environments, on soil hydraulic characteristics, slope angles, and soil conditions because its impact may vary based on soil and meteorological conditions.

Data Availability Statement

All data and analysis for possible discussions and comparisons are available from the corresponding author upon reasonable request.

Acknowledgments

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Author contributions: Sadik Khan: Study conception and design, Analysis and Interpretation of results, Draft manuscript preparation. Avipriyo Chakraborty: Study conception and design, Data collection, Analysis and interpretation of results, Draft manuscript preparation. All authors reviewed the results and approved the final version of the manuscript.

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