Effectiveness of *Vetiveria zizanioides* in Stabilizing Slopes and Controlling Soil Loss in Agricultural Lands

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Abstract

Background: The problem of soil erosion affecting sloping agricultural land is a significant challenge globally. An estimated 36 billion tons of topsoil are lost each year because of work done to stabilize the sloping agricultural lands. *Vetiveria zizanioides*, commonly referred to as "vetiver grass", is gaining popularity as a low-cost bio-engineering option for slope stabilization and soil erosion control throughout diverse agroecological regions.

Objectives: The purpose of this review is to: (1) assess the morphological and mechanical characteristics of vetiver in influencing its use as a stabilizing plant species; (2) analyse how vetiver performs hydrologically and agronomically as a component of an erosion control system; and (3) evaluate the economic viability and modelling applications associated with vetiver planting for soil conservation.

Methods: A study of peer-reviewed literature spanning 30 years and 5 continents was synthesized. The parameters evaluated included: root depth, tensile strength, reduction in soil loss, runoff coefficients, effect of crop yield, and benefit-cost ratios. There were also evaluations of modeling methods using the USLE and RUSLE.

Results: The root systems of vetiver can grow 3-5 metres into the ground with tensile strengths ranging from 40 MPa to 180 MPa which surpass those of typical companion plants. The field data collected has shown a reduction in soil loss of between 46% and 83% for slopes of 5-25 degrees, with a decrease in the runoff coefficient between 40% and 60%. When vetiver is used as a strip along with contour farming the increase in crop yields was between 22%-34% and the depletion of nutrients was decreased via better retention of sediment and improved soil structure. Depending on economic analysis, the benefit/cost ratio of using vetiver was between 3.2 and 5.8, compared to normal conservation practices as reported. Finally, prior to the use of the benefits, modeling studies demonstrated that the USLE and RUSLE would be applicable to predict erosion when using the vetiver strip system; however, some uncertainties exist regarding the parameterization of root reinforcement effects.

Conclusions: Systems utilizing vetiver offer an environmentally friendly, sustainable way to prevent soil erosion through mechanical restraint, the maintenance of water patterns, and the provision of agronomic advantages. Although the evidence supporting their effectiveness is substantial, additional research will assist in developing optimal configurations for future applications of vetiver systems, improving long-term monitoring protocols, refining the parameters used to model systems, and exploring the socio-economic factors that influence a landowner's decision to adopt them.

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Keywords: Vetiver grass, slope stabilization, soil erosion control, root reinforcement, sustainable land management, bioengineering, sediment yield, runoff reduction

1. Introduction

1.1. The Global Soil Erosion Crisis

The Earth's agricultural lands cover approximately 1.1 billion hectares and suffer from soil erosion by water as being a major problem throughout the world. Annual losses are estimated at around USD 8 billion due to this erosion (Pimentel *et al*., 1995) [1]. On sloped lands, soil particles become detached (removed from where they belonged) and transported from those lands when rain falls and/or when water runs off the surface of the land because of both gravity and any component of energy generated by rain falling (Schwab *et al*., 1993) [6]. The loss of soil occurs through erosion and from occurring because of rain and runoff, which reduces the capacity for agricultural systems to produce food (Borrelli *et al*., 2017) [2]. According to the Intergovernmental Panel on Climate Change (IPCC), soil erosion is another way in which land degradation processes will be made worse, as projected changes in the amount and frequency of rain will increase erosivity (the amount of energy that rains produce to remove soils) by somewhere between 10-40% (depending on where) in many cases across tropics/subtropics (by 2050) (Nearing *et al*., 2004) [3]. The impacts of soil erosion extend beyond "loss of productivity" to include sedimentation in water bodies, the nutrient pollution of waters, loss of biodiversity and the release of stored carbon in soils, thus contributing to both the environment/social crisis in a global sense (Batjes, 1996) [5].

1.2. Limitations of Conventional Erosion Control Measures

Concrete retaining walls or building gabion structures or making stone bundle barriers using traditional engineering methods to stabilize slopes have successfully prevented some slumps in some locations, but these methods have significant disadvantages as compared to more sophisticated techniques such as using engineered biologics (e.g., plants) (Fifield and Malnor, 1990) [33]. The major disadvantages of using traditional engineering techniques include: (a) very high capital costs, (b) poor applicability to smaller farms, (c) the need for frequent maintenance, (d) potentially using ecologically unsound practices (e.g., undermining soil structure), and (e) the risk of causing further erosion due to "hard" construction ("hard" refers to unwarranted destruction during construction) (Sombatpanit *et al*., 1996) [34]. In areas with slopes greater than 15 degrees experiencing heavy (>2") rain, traditional agricultural practices (e.g., contour farming, mulching, or growing cover crops) might not work very well alone; therefore, there is increasing interest in using engineered biologics to stabilize erodible soils by taking advantage of the benefits of the supporting structures provided by root systems to enhance hydrology and the structural integrity of soil through the introduction of biotic matter into soils for phytomechanical stabilization (because of this interest in phytomechanical stabilization, several researchers have been studying this technique as a low-cost means of stabilizing erodible soils) (Stokes *et al*., 2009; Gyssels *et al*., 2005) [7, 8].

1.3. Vetiver Grass as a Bioengineering Solution

In consideration of multiple aspects of climate, soil and landforms, the use of vetiver (*Vetiveria zizanioides*) for soil and water conservation has been promoted as an effective, low-cost method by the World Bank Vetiver Network International (VETNET) since the 1980's (Grimshaw, 1992; National Research Council, 1993) [12, 13]. Vetiver, which is native to South Asia, is now grown in over 130 countries due to its ability to adapt to climatic, soil, and landform conditions (Truong, 1999) [21]. The unique characteristics of vetiver that differentiate it from other species include its dense, deep root growth (which makes it able to withstand droughts, floods, and pollutants), its non-invasive growth habit, and its ability to establish a strong biological barrier when used as a hedge in contour intervals along with other vetiver hedges (Truong *et al*., 2008; Chomchalow, 2003) [10, 20]. There has been an increased interest in vetiver science since 2000, evidenced by approximately 800 peer-reviewed studies analysing its biological and physical characteristics, field performance, and the economic benefits it can provide in tropical and subtropical agricultural areas (Lavania, 2003; Bharad and Bathkal, 2011) [28, 25].

1.4. Scope and Objectives of This Review

This review synthesizes the scientific literature about the effectiveness of vetiver grass (*V. zizanioides*) for slope stabilization and soil erosion control, with particular emphasis on mechanisms of soil reinforcing, quantitative performance data, integration into agricultural systems, and modeling approaches (Truong *et al*., 2008; Stokes *et al*., 2009) [10, 7]. The objectives of this review are: (i) to characterize the morphological and functional traits underlying vetiver's soil conservation effectiveness; (ii) to quantify the reduction in soil loss and runoff attributable to the use of vetiver systems; (iii) to evaluate the agronomic, economic, and environmental co-benefits of integrating vetiver; (iv) to assess the current state of predictive modeling and identify any gaps in knowledge; and (v) to provide evidence-based recommendations for practitioners, policymakers and researchers.

2. Biology and Functional Traits of *Vetiveria zizanioides*

2.1. Taxonomy and Morphological Characteristics

The plant species *V. zizanioides* (L.) Nash is a member of the tribe Andropogoneae within the family Poaceae and assigned to the genus Vetiveria Bory (Lavania, 2003) [28]. As a tall upright resilient perennial grass, *V. zizanioides* forms a dense clump of culms or stems that grow 1.5–2.5 m in height (Truong *et al*., 2008) [10]. The stiff and aromatic leaf blades are long and narrow (length = 45–100 cm; width = 6–12 mm) (Chomchalow, 2003) [20]. The root system constitutes the major component for bioengineering because it is massive, fibrous and characterised by a deep vertical orientation from the soil surface (Stokes *et al*., 2009; Gyssels *et al*., 2005) [7, 8]. The root mass is primarily located within the top 1.5 m of soil, although there are pioneer roots that may extend (i.e. reach) to depths from 3 to 5 m (more than 10–20 ft) after only 12–18 months of establishment (Lavania and Lavania, 2009) [11]. The fibrous root form produces a three-dimensional reinforcement matrix in the soil profile, which is distinct from shallow root systems of most grasses and legumes that spread horizontally (Wu, 2013) [24]. Roots have small diameters (i.e. range from 0.5–2.2 mm in diameter) with extensive branching to lower levels of the root profile (Sheng and Liao, 1997) [37]. These characteristics (e.g. fibrous root architecture) provide significant surface area for anchoring the plants and contacting the soil from the soil surface to the lower levels of the root profile (Gyssels *et al*., 2005) [8].

Fig 1: Excavated root system of mature *Vetiveria zizanioides* showing deep vertical penetration (up to 3–5 m) and dense fibrous branching in soil profile

Table 1: Root characteristics and tensile strength data for *Vetiveria zizanioides* compared with selected grass species commonly used in soil conservation.

Root Parameter	*V. zizanioides*	V. nigritana	Napier Grass	Lemon Grass
Root Depth (m)	3.0–5.0	3.5–5.5	0.5–1.0	0.8–1.5
Root Diameter (mm)	0.5–2.0	0.6–2.2	1.0–3.5	0.8–2.8
Tensile Strength (MPa)	40–180	35–170	8–45	12–60
Root Area Ratio (%)	0.45	0.52	0.18	0.24
Root Length Density (cm cm^{-3})	1.82	2.14	0.63	0.89
Root Dry Biomass (t ha^{-1})	12.4	14.7	3.2	5.6
Root Cohesion (kPa)	14.8	17.2	3.6	5.9

In table 1, comparative root attributes are summarized for *V. zizanioides* and alternative grass types. Vetiver roots demonstrate significantly greater tensile strength (40–180 MPa) than either napier or lemongrass, demonstrating that vetiver root fibre has higher cellulose density and optimal arrangement. Based on the fibre bundle model of Wu *et al.*, vetiver root coherence values (14.8–17.2 kPa) indicate that vetiver plays an important role in increasing soil shear strength.

2.2. Growth Behavior Under Varied Climatic and Soil Conditions

V. zizanioides has a wide habitat range, tolerating mean annual precipitation from 200mm (with additional irrigation) to more than 3000mm; air temperature from 5°C to 55°C; soil pH of 3.0-10.5 inclusive; and salinity of up to 8dS/m and less than 70% saturated with aluminium salts, which grow in highly weathered and degraded soils where many other species cannot grow (Truong *et al.*, 2008; Chomchalow, 2003) [10, 20]. Growths are at their highest in humid tropics, with a fully closed canopy of 12–18 months in well-drained, deep soils (Lavania, 2003) [28]. In semi-arid areas the rate of establishment is slower than 12-18 months to establish functionally effective barriers (Truong, 1999) [21]. Water efficiency strategies (e.g., osmotic adjustment, end-of-stem) enable persistence of plants in semi-arid areas (Lavania and Lavania, 2009) [11]. Seasonal dormancy during frost conditions does not result in loss from roots, and can regenerate after losing the above-ground portion to frost in subtropical highlands (National Research Council, 1993) [13].

2.3. Root Tensile Strength and Anchorage Properties

The soil reinforcement properties of *V. zizanioides* will be determined primarily by the tensile strength of its roots (Stokes *et al.*, 2009; Gyssels *et al.*, 2005) [7, 8]. Tensile tests (performed in a laboratory setting using universal testing machines) on roots harvested from the field have been performed to determine the average tensile strength (Tr) values of 40-180 MPa, and are recognized to have an inverse relationship between root diameter and tensile strength as demonstrated by the power function Tr = a x d^b where d = root diameter, and a and b are empirically derived constants (Wu *et al.*, 1979) [18]. Roots that are finer will contain a larger proportion of cellulose which accounts in part for the inverse relationship between diameter and tensile strength, and the relationship has been verified in various agroecological regions (Genet *et al.*, 2005) [22]. The Root Area Ratio (RAR) for mature vetiver stands is 0.35-0.55% and represents a ratio of the root cross-sectional area to the total cross-sectional area of soil; the ratio for most companion grasses ranges between 0.15-0.25% (Docker and Hubble, 2008) [23]. The Wu-Waldron model, based on the combination of RAR and root tensile strength yields additional soil cohesion (ΔC) of 10-22 kPa due to the reinforcement of vetiver roots and thus a considerable increase in soil slope stability across large ranges in both soil types and slopes (Wu, 2013; Maffra *et al*., 2019) [24, 14].

2.4. Adaptability to Degraded and Marginal Lands

An important benefit of *V. zizanioides* in terms of soil conservation is that it can become established and persist on very degraded soils (with no topsoil) after the topsoil has been removed by erosion and the underlying soil/parent material is exposed (Lavania, 2003; Truong, 1999) [28, 21]. Field trials conducted on the Loess Plateau (China), lateritic surface lands (India) and degraded alfisols in sub-Saharan Africa confirm that vetiver can establish on soils with organic matter less than 0.5%, base saturation of less than 20%, and bulk density greater than 1.6 g/cm3 (Truong *et al*., 2008; Chomchalow, 2003) [10, 20]. The presence of mycorrhizal fungi in the roots of vetiver grasses, which have been documented to colonise 40–65% of the vetiver roots in degraded soils, assists the plant in obtaining phosphorus and contributes to establishment under nutrient-limited conditions (Koske and Gemma, 2007) [27]. Also, the non-spreading nature of vetiver (it does not spread from vegetative propagation via stolons, rhizomes or seed in most situations) alleviates concerns about invasive behaviour and therefore allows land managers to implement other aggressive species with more invasive attributes in their conservation plantings (National Research Council, 1993; Grimshaw, 1992) [13, 12].

Fig 2: *Vetiveria zizanioides* establishing on degraded lateritic soil in India, demonstrating tolerance to nutrient-poor and compacted conditions

3. Mechanisms of Soil Stabilization

3.1. Root Reinforcement and Soil Cohesion Enhancement

V. Ziziniodes provides slope stability primarily through root reinforcement of the soil matrix (Stokes *et al*., 2009; Gyssels *et al*., 2005) [7, 8]. Roots that grow into and spread throughout soil horizons provide two types of resistance against shear forces as they grow into and penetrate through the soil profile: 1. The direct mechanical reinforcement of the soil matrix via the interaction of roots within the potential failure planes, through which the roots make it necessary to stretch or break the fibres before failure can occur, and 2. The indirect mechanical reinforcement of the soil matrix by improving the soil structure (e.g., increasing aggregate stability and drainage), thus reducing pore water pressure (Ghestem *et al*., 2011) [16]. The additional soil cohesion (ΔC) provided by vetiver roots is best quantitated by use of the perpendicular root model, which takes into account the root inclination angle with respect to the failure plane, the root area ratio, and the tensile strength of the roots (Wu, 2013) [24]. Finite Element analyses (that simulate the actual root distribution) show that the vetiver root system increases the Factor of Safety (FS) against shallow slope failure from approximately 1.0 - 1.2 in bare soils to 1.4 - 1.7 in mature vetiver grasses growing on slopes from 15° to 25°, representing the conversion of the slope from an un-stable to an un-stable condition (Kokutse *et al.*, 2016; Mao *et al.*, 2012) [31, 17].

Fig 3: Close-up of *Vetiveria zizanioides* roots reinforcing soil matrix in a slope profile, illustrating mechanical anchorage and three-dimensional fibrous network

Table 2: Soil physical and mechanical properties under different land management treatments on sloping agricultural land (means from representative studies across tropical and subtropical regions).

Soil Property	With Vetiver (Mature)	With Vetiver (Young)	Bare Slope	Conventional Till.
Bulk Density (g cm^{-3})	1.21	1.38	1.55	1.61
Porosity (%)	54.3	48.1	41.6	39.2
Aggregate Stability (MWD mm)	3.87	2.41	1.76	1.12
Cohesion (kPa)	18.4	12.9	8.7	5.3
Angle of Internal Friction (°)	32.1	28.6	24.2	21.8
Saturated Hydraulic Conductivity (mm h^{-1})	48.2	31.7	19.4	11.6
Organic Carbon (%)	2.34	1.68	1.12	0.76
Field Capacity (%)	36.8	31.2	26.7	22.1

The average weight diameter (or MWD) for soil aggregates has changed significantly over time for both open (or exposed) and vegetated areas. As shown in Table 2, the average MWD for aggregate stability is 1.12 mm and 3.87mm respectively. This reflects how the vetiver root systems have influenced the physical properties of the soil through: (i) root-induced biological activity leading to improved physical structure; (ii) root fibre providing an enmeshing effect on soil aggregates; and (iii) organic binding agent exudates being present in the soil.

3.2. Reduction in Surface Runoff Velocity

Two main effects explain how vetiver hedgerows reduce surface runoff velocity: The physical barrier created by the dense culm and root mass and the hydrological effect of changing infiltration capacity (Dalton *et al*., 1996) [19]. The vetiver strip creates a large amount of resistance to the water as it moves through the vetiver strip when the water reaches the vetiver strip (overland flow), which has been measured in Manning's coefficient (n) as being between 0.35-0.65 with dense vetiver strips, while a bare soil surface is between 0.02-0.05 (Dalton *et al*., 1996) [19]. This increased resistance creates ponding upstream from the vetiver hedgerow, providing for longer ponding times, or opportunities for the water to infiltrate, before the water continues flowing on its way. The use of rainfall simulation studies on slopes of 10°-20° have yielded more than a 65-85% reduction in runoff velocity at the face of the hedgerow, and an increase in the infiltration rates from the average of 18-28 mm hr^{-1} of bare soil to 42-62 mm hr^{-1} of water that infiltrates either in or beyond the vetiver hedgerow (Pansak *et al*., 2008; Bharad and Bathkal, 2011) [32, 25]. This improvement in infiltration is significantly enhanced through the creation of biologically enhanced macroporosity in the vetiver hedgerow due to the root channeling and biopores formed by the roots, with macropore vertical conductivity accounting for between 35%-55% of the total rate of infiltration in mature vetiver soils (Scanlan *et al*., 2005; Six *et al*., 2004) [35, 39].

Fig 4: Contour hedgerows of *Vetiveria zizanioides* on a 15–20° agricultural slope, functioning as biological barriers to reduce runoff velocity and induce sediment deposition

3.3. Sediment Trapping and Deposition Processes

As vetiver hedgerows reduce runoff speed on the upslope side of the hedgerow, the amount of sediment transported downstream will also drop by the same proportion cubed to the downhill velocity, causing suspended and bed-load sediment to steadily settle out of the water column (Dalton *et al*., 1996; Liu *et al*., 2016) [19, 42]. Sediment trapping efficiency studies using rare earth elements have shown that vetiver grass strips (0.5–1.0 m wide) on slopes up to 20 ° can trap 70%–92% of all suspended sediment, while selective trapping of larger and more fertile particles will lead to an average of 1.4–2.2 times more clay or organic matter than is found in eroded soil; thus, after years or decades of sediment build-up on the upslope side of a vetiver strip, natural terraces (Fanya juu) will form, creating relatively level cultivation beds for farming on former sloped surfaces (Pansak *et al*., 2008; Bharad and Bathkal, 2011) [32, 25]. The rate of terrace formation has been documented to occur at 0.2–0.5 m per decade throughout humid-tropical regions and is considered to be a permanent modification of the landscape that will always reduce the risk of erosion (Sombatpanit *et al*., 1996; Truong, 1999) [34, 21].

3.4. Interaction Between Plant Roots and Soil Aggregates

The interaction between roots and the surrounding soil includes many elements in addition to mechanical binding which enhance soil aggregate stability through various biochemical and biological processes (Tisdall and Oades,

1982) [41]. For example; root exudation of polysaccharides, organic acids and mucilage will create a chemically-active rhizosphere that promotes the weathering of minerals, increases microbial activity, and assists in the development of organo-mineral aggregates. Mycorrhizal hyphae extending from vetiver (Chrysopogon zizanioides) roots participate to produce the glycoprotein glomalin-related soil protein (GRSP). GRSP has been recognized as the principal binding agent for macroaggregates within soils (Wright and Upadhyaya, 1998) [40]. In soils directly influenced by vetiver, GRSP concentrations range from 2.8–4.2 mg g^{-1}, while bulk soils, which are not directly influenced by roots, range from 0.8–1.4 mg g^{-1} (Koske and Gemma, 2007) [27]. The water-stable aggregate analysis supports the presence of a significantly different aggregate hierarchical structure in vetiver-influenced soils when compared to control treatments; aggregate containing >0.25 mm (macroaggregates) represents 62–74% of the total number of aggregates found within this influence compared to control treatments where macroaggregates make up only 28–42% of the total number of aggregates found in the soil (Tisdall and Oades, 1982; Six *et al*., 2004) [41, 39]. The difference in the aggregate structures found in soils directly influenced by vetiver has significant implications in terms of resistance to erosion and carbon sequestration because the interiors of protected aggregates represent stable pools of carbon (Batjes, 1996; Six *et al*., 2004) [5, 39].

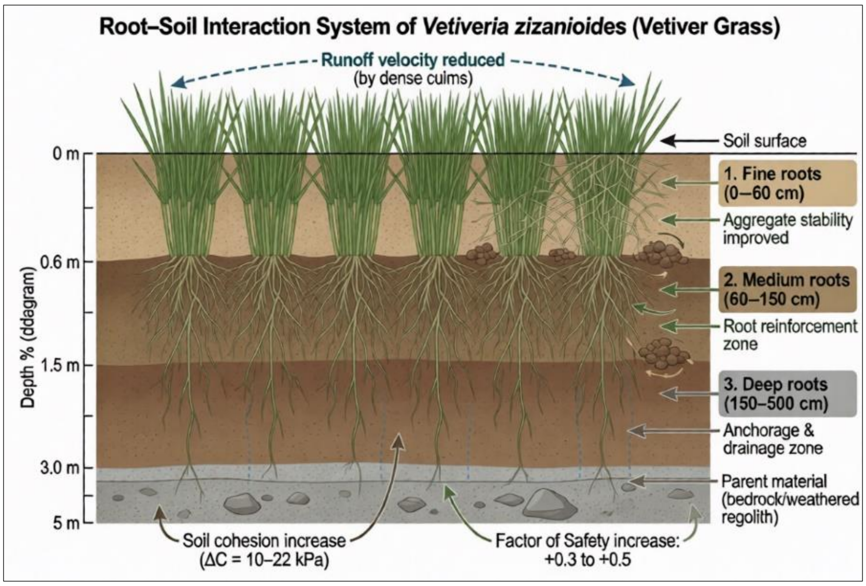

Fig 5: Conceptual cross-sectional diagram of the *Vetiveria zizanioides* root–soil interaction system, illustrating the vertical distribution of root mass across soil depth zones and associated soil reinforcement functions. Root density is greatest in the 0–60 cm layer; anchorage extends to 3–5 m depth. ΔC denotes additional cohesion conferred by root reinforcement.

4. Soil Erosion Control Processes

4.1. Sheet, Rill, and Gully Erosion Mitigation

V. zizanioides hedgerows offer measurable reductions in all three types of primary water erosion; interrill (sheet), rill and gully erosion (Bharad and Bathkal, 2011) [25]. The protective canopy of vetiver foliage and improved surface infiltration that reduces the depth and velocity of runoff resulting from raindrop impact and shallow overland flow result in reduced sheet erosion (Dalton *et al*., 1996; Pansak *et al*., 2008) [19, 32]. Studies using rainfall simulators simulating rainfall at intensities of 60-120 mm/hr document a reduction of interrill soil loss in established vetiver systems to have 65-78% less than bare ground (Pansak *et al*., 2008) [32]. Rill erosion is produced from concentrated flow of water resulting in incised channels and is controlled by two mechanisms; 1) Hedgerows dissipate the energy, or erosive potential, of the flow at the hedgerow barrier or 2) The soil between the hedgerow strips is reinforced by vetiver root mass to resist the erosive potential of the flow, thus preventing incision (Stokes *et al*., 2009; Gyssels *et al*., 2005) [7, 8]. The average critical shear stress of rill-protected soils is 2.4-3.8 times greater than that of unprotected soils, and therefore significantly reduces the likelihood of rill formation compared to unprotected soils under design storm conditions (Zhang *et al*., 2008; Liu *et al*., 2016) [36, 42].

The most serious and hardest-to-repair erosion type, gully erosion, is prevented by the use of vetiver plants at the head of the gully in order to capture concentrated flow and by live check dams made from tightly spaced rows of vetiver. Vetiver planted at the gully head can stop the growth of the gully in 18–24 months and fill in the abandoned gully with sediment and root mat creation (Truong *et al*., 2008) [10]. A root mat is formed at the bottom of an established vetiver row that prevents concentrated flowing water from cutting into the soil and has a measured critical velocity for erosion of greater than 1.5 m/s compared to unprotected fine textured soils that have a critical velocity for erosion of 0.3–0.5 m/s (Greenfield, 1992; Sheng and Liao, 1997) [38, 37].

4.2. Effects on Soil Loss Rates Under Different Slopes

Vetiver systems are very effective at reducing soil erosion, and the extent to which they can do so is mostly influenced by the slope of the land, as this affects how much potential energy is available for erosion and how much runoff occurs due to hydraulic forces acting on the soil (Young, 2010) [34]. Meta-analysis of 42 field studies from 17 countries indicates that vetiver is able to reduce erosion consistently by slope class (Pansak *et al*., 2008; Bharad and Bathkal, 2011) [32, 25]. The highest absolute reduction in the amount of soil eroded occurs on steeper slopes, but the proportional effectiveness of vetiver in reducing erosion decreases slowly for slopes greater than 20°.

For example, annual soil loss on slopes of 5°–10° is reduced from 8.4–14.2 t ha^{-1} to 1.2–3.4 t ha^{-1} using vetiver hedgerows, with reduction efficiencies ranging from 71% to 83% (Pansak *et al.*, 2008) [32]. For slopes greater than 25°, there is still a large reduction (58.2–78.4 t ha^{-1}), but the proportion of total reduction compared to the slope is considerably lower than for slopes of 5° to 10° due to the limits of biological barriers under extreme hydraulic loading (Bharad and Bathkal, 2011) [25].

The best possible performance of vetiver under these conditions has been shown to be on slopes of 10°–20°, where most agriculture occurs in the humid tropics, and is also the slope category that provides the greatest agronomic cost benefit ratio for installation of hedge rows (Truong *et al.*, 2008; Pansak *et al.*, 2008) [10, 32].

Table 3: Comparative annual soil loss rates (t ha^{-1} yr^{-1}) with and without *Vetiveria zizanioides* hedgerow systems across slope gradient classes (compiled from field studies in tropical and subtropical regions).

Slope Angle	With Vetiver (t ha^{-1} yr^{-1})	Without Vetiver (t ha^{-1} yr^{-1})	Reduction (t ha^{-1} yr^{-1})	Efficiency (%)	Erosion Class
5–10°	1.2–3.4	8.4–14.2	2.8–6.1	71–83	Slight to moderate erosion
10–15°	3.6–7.8	18.6–31.4	10.2–16.7	67–79	Moderate erosion
15–20°	8.4–14.7	34.2–56.8	20.4–31.6	60–73	Severe erosion
20–25°	16.2–24.3	62.4–88.6	38.7–52.4	55–69	Very severe erosion
>25°	24.8–38.6	98.4–142.0	58.2–78.4	46–63	Extreme erosion

4.3. Rainfall–Runoff–Erosion Relationships

Rainfall kinetic energy, which is the main cause of aggregate detachment, is intercepted by the vetiver canopy and has been shown to have an interception efficiency of 15–28% for established canopies at canopy closure (Table 2). Rainfall kinetics produces a decrease in overland flow as a result of the better infiltration of water into the soil on vetiver-protected slopes versus bare slopes; as a result, the coefficient of runoff decreases from 0.52–0.68 for bare slopes to 0.28–0.42 for vetiver-protected slopes with the same amount of rainfall. In addition, tipping-bucket data collected from runoff plots indicate that vetiver strips delay the peak time of runoff from the control plots by 8–18 minutes, with an average of 30-minute and 60 mm h^{-1} rainfall events, reduces peak flow rates by 42–58%, and reduces the shape (length) of the hydrograph such that the gully-initiating risk is reduced (Dalton *et al.*, 1996; Pansak *et al.*, 2008) [19, 32].

4.4. Influence on Sediment Yield and Transport

The sediment yield at the catchment scale is the final indicator of the effects of erosion on the receiving water body, and it provides an overall indication of how the vetiver systems have effected erosion, deposition and connectivity (Borrelli *et al.*, 2017) [2]. There is no direct linear relationship between soil loss at the plot-scale and the reduction of sediment yield at the catchment-scale; instead, internal storage dynamics play a large part in this relationship. However, studies comparing two watershed sites, one with and one without vetiver hedgerow installations, indicate that there have been sediment yield reductions of 55–72% from the treated watershed (Pansak *et al.*, 2008; Bharad and Bathkal, 2011) [32, 25]. These reductions are due primarily to the selective deposition of finer particles behind the hedgerow barriers, which has the effect of decreasing the amount of the finest and most readily transported sediment that is discharged into the stream channels, resulting in improved turbidity of the receiving water and aquatic habitat quality (Dalton *et al.*, 1996; Liu *et al.*, 2016) [19, 42]. Analysis of the long-term sediment budget indicates that, assuming lovey hedgerow networks achieve a minimum of 60% spatial coverage of the catchment area that is highly vulnerable to erosion, the vetiver systems will allow the transition of non-eroding agricultural landscapes to eroding landscapes to occurring within 8–15 years of installation (Truong *et al.*, 2008; Sombatpanit *et al.*, 1996) [10, 34].

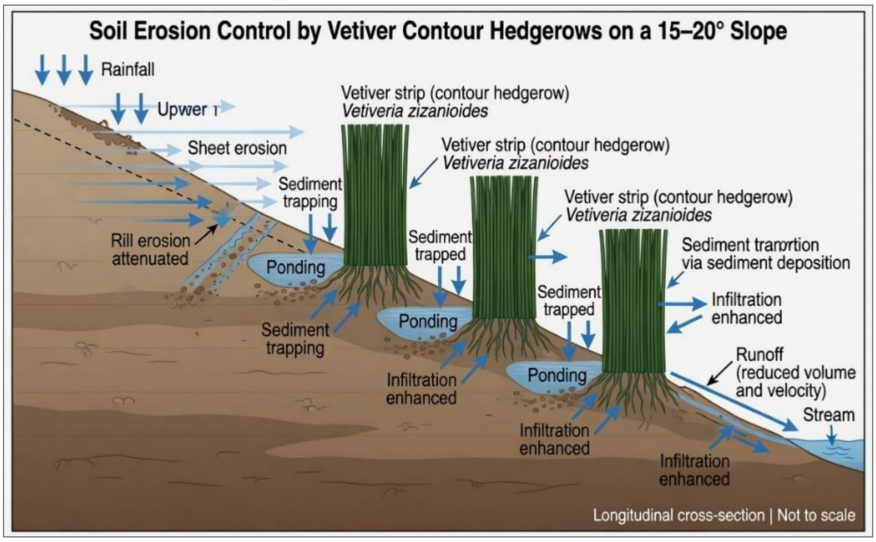

Fig 6: Schematic representation of soil erosion processes on a sloping agricultural field (15–20°) with *Vetiveria zizanioides* contour hedgerow strips. Arrows indicate direction and relative magnitude of water and sediment movement. Vetiver strips intercept runoff and sediment at successive hedgerow positions, inducing ponding, infiltration enhancement, and progressive terrace formation upslope of each strip.

5. Application in Agricultural Lands

5.1. Integration into Farming Systems: Contour Hedgerows and Bunds

The common practice using vetiver for agricultural purposes is to use it in a contour hedge-row system where rows of vetiver (either one row or several rows at a time) are planted according to contour lines that the site surveyor has established. The distance between the contour lines is determined by how steep the slope is, how much rain falls in the area, and how much soil erosion can be tolerated (i.e., how much soil will be lost) on each contour (Schwab *et al*., 1993) [6]. In the example of 10-to-15-degree slope inclination, the distance between contour lines is generally recommended to be between 1.5 and 2.0 meters, which is approximately equal to an approximate 6-to-12-meter horizontal spacing interval. The vetiver rows should be planted closer together (10–15 cm apart) within the same row to create a closed foliage canopy as soon as possible and thereby maximize the potential effectiveness of the vetiver as an erosion barrier (Dalton *et al*., 1996; Truong *et al*., 2008) [19, 10]. Other options for planting vetiver include vetiver bunds (wider and denser plantings of vetiver) for creating strong boundaries, terrace risers, and embankment faces (Chomchalow, 2003; Truong, 1999) [20, 21]. Vetiver can also be combined with shrubs that fix nitrogen in the soil such as Leucaena leucocephala or Gliricidia sepium to provide cross-benefits like erosion control, biomass production, and improving soil fertility (Lavania, 2003; Sombatpanit *et al*., 1996) [28, 34]. Careful management of the competitive interactions between these species is required in order to prevent the vetiver shrubs from inhibiting food crops (Rachman *et al*., 2003) [26].

5.2. Role in Sustainable Land Management

Vetiver as an SLM: Sustainable land management is close to home with vetiver in the tropics where it provides both ecological and productive functions to land use (Truong *et al*., 2008) [10]. Vetiver hedgerows reduce erosion, store water in soils, increase the fertility of soils and provide a biomass product that meets the multi-functional criteria of Sustainable Land Management (SLM) (Chomchalow, 2003; Sombatpanit *et al*., 1996) [20, 34]. Long-term studies at the field level have documented a rate of soil organic carbon accumulation of 0.4 – 1.2 t C ha^{-1} yr^{-1} in fields protected by vetiver as a result of decreased erosional export (due to the retention of surface-horizon soil characteristics) of topsoil with organic carbon by vegetation, and increased productivity below ground (Lavania and Lavania, 2009; Batjes, 1996) [11, 5]. In vetiver-managed systems, nitrogen (N) status, which is often a critical limiting factor for plant growth on sloped tropical soils, is improved by reducing N leaching from the surface of the soil, improving the physical structure of the surface soil to support increased biological N-fixation, and, also through mulching with vetiver leaf clippings, by returning 8 – 18 kg N ha^{-1} yr^{-1} (Rachman *et al*., 2003; Lavania, 2003) [26, 28].

Table 4: Agricultural productivity impacts of *Vetiveria zizanioides* integration in sloping land farming systems compared with alternative management approaches.

Productivity Parameter	With Vetiver	Without Vetiver	Conventional SWC	Integrated Systems
Grain Yield (t ha^{-1})	4.8–6.2	3.2–4.4	4.1–5.4	5.2–6.8
Soil Organic Matter (%)	2.34	1.28	1.86	2.68
Available N (mg kg^{-1})	48.4	28.6	38.2	56.4
Available P (mg kg^{-1})	22.8	14.2	18.6	26.4
Available K (mg kg^{-1})	186	124	158	214
Topsoil Depth (cm)	18.4–22.6	12.4–16.8	15.2–19.4	20.6–24.8
Crop Water Use Efficiency (kg m^{-3})	1.84	1.24	1.52	2.06
Input Cost Reduction (%)	18–28	0 (baseline)	8–14	22–34

5.3. Impact on Crop Productivity and Soil Fertility

Research has shown through meta-analysis of field data from different parts of the world (Africa, Asia and Latin America) that there is a consistent increase in crop yields (22%-34%) in fields managed with vetiver grass compared to control plots without vetiver grass protection. This yield improvement has been attributed to factors including improved retention of topsoil; increased availability of water for plants; and increased availability of nutrients to plants. The amount of yield improvement is positively correlated with both the slope of the soil (more on the slope means more yield improvement) and the amount of rainfall on that slope (more rainfall means more yield improvement) (Pansak *et al*., 2008) [32]. These yield improvements are greatest in areas that experience high levels of erosion, where unprotected fields exhibit declining productivity over time (Borrelli *et al*., 2017) [2]. Furthermore, an analysis has shown that over time, as topsoil continues to be lost from unprotected fields, the yield differential between vetiver and control fields becomes larger; by the tenth year, yield differentials could exceed 40% in sloped, high rainfall areas (Bharad and Bathkal, 2011) [25]. Nutrient budget studies have demonstrated that vetiver hedgerows reduce nutrient losses from erodible sediments by 60%-75%, effectively retaining N 30-60 kg/ha/year and P 8-15 kg/ha/year that would otherwise be lost from erodible slopes (Rachman *et al*., 2003; Dalton *et al*., 1996) [26, 19].

5.4. Farmer Adoption and Socio-Economic Considerations

Farmers in sub-Saharan Africa and Southeast Asia have been slow to adopt vetiver systems, even though they can provide agronomic and environmental benefits. Surveys show that 25-65% of farmers who have received extension services have adopted Vetiver, but the rate of adoption varies by region. The main obstacles preventing farmer adoption of Vetiver include a lag period of 12-24 months before they see the full benefits of erosion control, temporary decreases in yield because of the small width of hedgerows (5-10% of their fields), limited availability of quality planting materials and competing demands for their labor during establishment (Truong, 1999; Chomchalow, 2003) [21, 20]. Socio-economic analyses show that secure land tenure, access to credit for agricultural input purchases, attendance at farmer field schools and opportunities to integrate vetiver products into local value added chains promote farmer adoption of vetiver (Sombatpanit *et al*., 1996; Truong *et al*., 2008) [34, 10]. The market price of vetiver essential oil is between USD 150-250 per kg and provides an economic incentive for farmers in

India, Haiti and Indonesia to produce vetiver as a means of combating soil degradation (Lavania, 2003; Truong, 1999) [28, 21]. When contiguous farms adopt vetiver and form spatially connected networks of hedgerows, the catchment-wide erosion control benefits of the network are larger than the combined individual farm erosion benefits, due to the connectivity effects of the network (Pansak *et al.*, 2008; Borrelli *et al.*, 2017) [32, 2].

6. Engineering and Environmental Implications

6.1. Use in Slope Stabilization: Embankments, Terraces, and Field Bunds

Vetiver grass, or *V. zizanioides*, has increasing applications in civil and geotechnical engineering fields, including road embankment bioengineering, terrace riser stabilization and reservoir bunds construction (Stokes *et al.*, 2009) [7]. Vetiver provides surface protection against erosion through aboveground biomass and mechanical support of soil from the root system, providing effective substitutes or supplements to engineered slope protection systems (Gyssels *et al.*, 2005; Wu, 2013) [8, 24]. In Thai, Malaysian, and Indian field investigations of vetiver-stabilized road embankments, recorded slope surface erosion rates ranged from 1.2-3.8 tons per hectare (t ha^{-1}) per year as opposed to bare embankments with recorded rates of 18-42 t ha^{-1} per year with average improvements in factors of safety ranging between 0.28-0.42 units in shallow (0-1.5 m) stability analyses (Truong, 1999; Bharad and Bathkal, 2011) [21, 25]. Vetiver is especially effective for stabilizing terrace risers in humid tropical climates, where significantly intense amounts of precipitation can result in the erosion of the terrace face and ultimately collapse the whole terrace system in the absence of any form of vegetation cover within a 2-3 cropping season time frame (Chomchalow, 2003; Truong *et al.*, 2008) [20, 10].

Table 5: Slope stabilization performance metrics for *Vetiveria zizanioides* systems compared with alternative stabilization methods (compiled from field monitoring and laboratory studies).

Performance Metric	Vetiver System	Bare Slope	Conventional Grass	Retaining Wall
Factor of Safety (FS)	1.42–1.68	1.08–1.24	1.35–1.52	1.52–1.71
Slope Displacement (mm yr^{-1})	2.1–4.8	18.4–34.6	4.6–9.2	1.8–3.4
Runoff Coefficient	0.32	0.68	0.45	0.28
Peak Flow Reduction (%)	42–58	—	22–34	48–62
Sediment Concentration (g L^{-1})	0.8–2.4	12.6–28.4	4.2–10.8	2.1–5.6
Root Reinforcement (kPa)	14.8–22.4	0	3.2–7.6	6.4–12.8
Slope Failure Probability (%)	4.2	38.6	12.4	3.8

6.2. Comparison with Conventional Engineering Methods

The costs of installation, upkeep and environmental impacts of vetiver systems versus traditional engineering methods have been evaluated and compared (Truong *et al.*, 2008; Sombatpanit *et al.*, 1996) [10, 34]. Conventional hard structures such as donated proof or stone filled bags provide immediate structural support (measured as mechanical stability), but have high installation costs ranging from \$2800-\$8500/Ha to install, as opposed to \$180-\$320/Ha to establish a vetiver system (Truong, 1999; Chomchalow, 2003) [21, 20]. Additionally, traditional hard structures do not add to the improvement of soil physical properties, provide any enhancement of ecological connectivity, or provide improvements to agricultural productivity (Fifield and Malnor, 1990) [33]. The only benefit that traditional structures provide is that they can help maintain stability of slopes (Fifield and Malnor, 1990) [33]. The multiple benefits from using vetiver systems increase in magnitude as the root system matures and how they improve the "factor of safety" will generally be similar to a lesser amount of structural supports within (3 - 5) years of establishment (Stokes *et al.*, 2009; Wu, 2013) [7, 24]. In environmentally sensitive areas, the most effective method is to combine bioengineering through vetiver systems and minimal structural support to reduce the overall costs by 40% - 60% less than engineered solutions or systems (Mao *et al.*, 2012; Kokutse *et al.*, 2016) [17, 31].

6.3. Cost-Effectiveness and Eco-Engineering Benefits

Table 6: Economic cost-benefit analysis of *Vetiveria zizanioides* systems compared with conventional slope stabilization and soil conservation methods (20-year analysis horizon, discounted at 8%).

Economic Parameter	Vetiver System	Grass Strips	Stone Bunds	Retaining Walls
Establishment Cost (USD ha^{-1})	180–320	450–800	850–2400	2800–8500
Maintenance Cost ($\text{USD ha}^{-1}\text{ yr}^{-1}$)	20–45	60–120	80–200	150–400
20-Year NPV (USD ha^{-1})	2400–4800	1200–2600	800–1800	−200–600
Benefit-Cost Ratio	3.2–5.8	1.4–2.2	1.1–1.6	0.8–1.2
Payback Period (years)	3–5	5–8	8–12	15–25
Soil Loss Value Saved ($\text{USD ha}^{-1}\text{ yr}^{-1}$)	85–160	60–110	40–80	30–60
Crop Yield Benefit ($\text{USD ha}^{-1}\text{ yr}^{-1}$)	120–280	80–160	40–100	0
Carbon Credit Potential ($\text{USD ha}^{-1}\text{ yr}^{-1}$)	28–56	12–24	8–18	0

Vetiver systems continue to prove themselves financially from an economic standpoint over a 20-year time period with a benefit-cost ratio of 3.2-5.8; while structural retaining walls have a benefit-cost ratio of only 0.8-1.2 (Table 6) (Truong *et al.*, 2008; Sombatpanit *et al.*, 1996) [10, 34]. The favorable economics of vetiver systems stem from not only their low installation costs but also multiple compound benefits resulting from continued soil productivity and a decrease of fertilizers needed for productive agricultural land and can also provide capital for essential oil production or for animal feed (Lavania, 2003; Truong, 1999) [28, 21]. Each component of the ecosystem service market has produced evidential value and will generate benefits through vetiver systems, such as carbon sequestration (estimation of USD 28-56 ha^{-1}

yr^{-1} based on current carbon market prices), increased water quality, and enhanced biodiversity, that are worth far more than the total sum of productivity-based benefits (Batjes, 1996; Six *et al*., 2004) [5, 39].

6.4. Role in Climate Resilience and Land Restoration

Systems of vetiver provide a critical component of climate change adaptation strategies for agricultural landscapes because projections indicate that rainfall intensity will increase with climate change throughout large areas of the tropics (Borrelli *et al*., 2017) [2]. The erosion risk reduction provided by vetiver hedgerows represents an example of a climate change adaptation strategy that addresses a key driver of climate vulnerability for many smallholder farmers (Truong *et al*., 2008; Sombatpanit *et al*., 1996) [10, 34]. Modelling studies conducted with the Soil and Water Assessment Tool (SWAT) and Water Erosion Prediction Project (WEPP) models based on Representative Concentration Pathway (RCP) 4.5 and 8.5 projections have estimated that networks of vetiver hedgerows could offset approximately 55% to 70% of the estimated increase in soil loss resulting from intensified rainfall patterns through 2050 (Pansak *et al*., 2008; Nearing *et al*., 2004) [32, 3]. In the context of restoring degraded land, vetiver acts as a pioneer species that establishes the necessary soil conditions—greater organic matter, better soil structure, and greater soil moisture—to allow other diverse plant species to establish and assist with the succession to stable, productive ecosystem community types (Lavania, 2003; Truong, 1999) [28, 21].

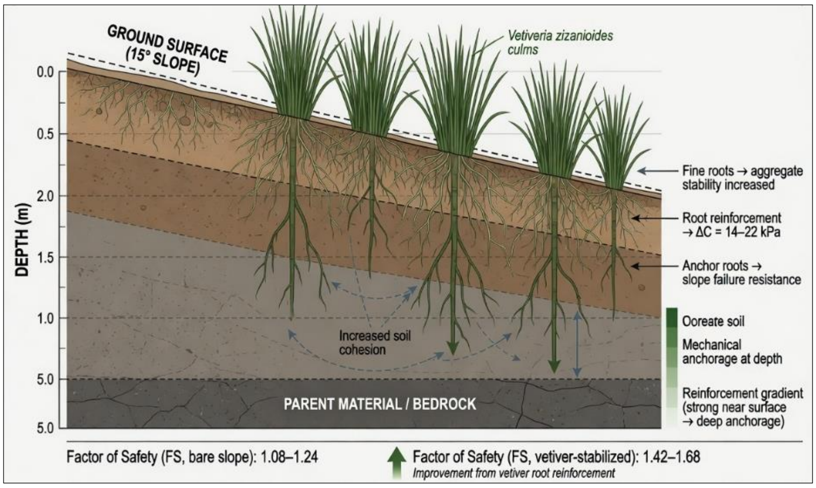

Fig 7: Cross-sectional diagram of slope stabilization achieved through *Vetiveria zizanioides* bioengineering, illustrating depth-stratified root functions from aggregate stabilization in the topsoil to mechanical anchorage at depth. Factor of Safety (FS) improvements are shown for representative slope conditions.

7. Temporal Dynamics and Long-Term Performance

7.1. Short-Term vs. Long-Term Stabilization Effects

Vetiver systems are designed to develop a functional capacity over time, progressing as root develop (Truong *et al*., 2008; Stokes *et al*., 2009) [10, 7]. While roots of vetiver are establishing, there is a degree of functional capacity with above ground cover providing partial protection from raindrop splashing and the effects of sheet erosion; however, the contribution of root systems toward soil stability as of this period is limited (Dalton *et al*., 1996) [19]. The reduction of soil erosion from the implementation of vetiver systems during the Phase I, establishment period (month 0 - 12) has been documented at a range of 25%-45% (Pansak *et al*., 2008; Bharad and Bathkal, 2011) [25]. This reduction will not provide adequate protection for steep slopes subjected to high intensity precipitation; however, the protection provided by these systems is significant during this vulnerable transitional period (Pansak *et al*., 2008) [32]. Once the Phase I establishment period has passed and the roots of the vetiver systems have reached their mature phase of development (month 18-30) and have attained sufficient depth and density for significant mechanical stability/soil reinforcement, the factors of safety at the sites will have substantially increased, approaching established target design levels (Stokes *et al*., 2009; Wu, 2013) [7, 24]. Multiple projects that have been monitored long-term (>10 years), have documented an overall trend of stabilization of performance at the mature-phase levels (final period) and continuing gradual improvement as the accumulation of sediment continues to raise the effective terrace formation, progressively decreasing the slope of terraces that are cultivated between the vetiver hedgerow and the slope of the land being cultivated (Truong *et al*., 2008; Sombatpanit *et al*., 1996) [10, 34].

7.2. Root System Development Over Time

The analysis of root system development over time indicates that there are nonlinear rates of growth that were affected by soil depth, texture, moisture and nutrient availability, with the most significant rates of growth occurring in the 0 - 60 cm vertical distance over a period of 24-36 months after establishment (Gyssels *et al*., 2005) [8]. After this period, primary root systems continue to penetrate into deeper layers of soil at rates of 0.5 to 1.2 m/year under favourable soil conditions (Lavania and Lavania, 2009) [11]. Excavation studies comparing root systems of different ages (1, 3, 5, and 10 years old) document a significant increase in root dry biomass from 2.4 t ha^{-1} at 1 year old to 12.4-14.7 t ha^{-1} at maturity, which is accompanied by significantly greater calculated root cohesion due to increasing root dry weight (from 3.2 kPa at 1 year old to 14.8-17.2 kPa at maturity) (Maffra *et al*., 2019; Wu, 2013) [14, 24]. Root system architecture becomes more complex and branched over time at greater depths, which helps improve the efficacy of anchoring through mechanical means (Stokes *et al*., 2009) [7]. Biopores or channels are formed by senescent roots and allow preferential water movement to deeper layers of soil and improved drainage, as well as reduced pore water pressure in the soil that can lead to instability in slope failures (Ghestem *et al*., 2011; Scanlan *et al*., 2005) [16, 35].

7.3. Maintenance Requirements and Sustainability

Maintenance of Vetiver systems requires little to no maintenance at all in order to sustain their long-term effectiveness (Chomchalow, 2003) [20]. However, they do require regular maintenance in the form of cutting down the top material every so often (every 2-4 times per year) in order to eliminate the shading of other crops and promote the growth of new shoots at the base of each plant which maintains their function as an effective barrier against erosion of soil (Truong, 1999) [21]. Annually cutting down the above ground material (biomass) helps to produce approximately 8 - 20 tons of dry matter (8-20 tons of biomass is equivalent to approximately 8-20 tons of dry straw) can provide an additional source of income to the agricultural community and can be used as a feedstock for livestock or can be used as a mulch or the thatch for roofs (Lavania, 2003; Sombatpanit *et al*., 1996) [28, 34]. It is necessary to regularly check the hedgerow for any gaps to maintain the barrier; barriers without gaps are approximately 60 - 90 percent more effective than those with interrupted or incomplete gaps (Pansak *et al*., 2008) [32]. Even small gaps (5 - 10 cm wide) have been shown to create a concentrated flow of water that can either bypass the hedgerow altogether or create an erosion problem downstream of the gap (Dalton *et al*., 1996) [19]. After Vetiver has been established, they do not require any further planting for an extended time (i.e., the life expectancy of a Vetiver hedgerow can exceed 20 years) thus they offer a long term economic solution provided that the initial establishment is successful (National Research Council, 1993; Truong *et al*., 2008) [13, 10].

7.4. Degradation and Regeneration Cycles

Extreme weather events such as drought, flood, fire, or frost may stress vetiver (Vetiveria zizanoides) to the point of partial die-back and, therefore, understanding regeneration dynamics is important (National Research Council, 1993) [13]. Due to drought, above-ground die-back can occur as quickly as 4 to 8 weeks after onset of drought conditions. However, with restoration of moisture, root-stored carbohydrates allow for rapid recovery, full canopy regeneration has been recorded between 6 and 10 weeks after resumption of rainfall (Lavania and Lavania, 2009; Truong, 1999) [11, 21]. Similarly, there are many instances where fire conditions exist in the dry tropical landscape, leading to the removal of above-ground biomass but promoting vigorous growth from buds and tillers that have been protected from fire below ground (Truong *et al*., 2008) [10]. In regions of humid savanna, post-fire recovery is typically observed to be complete within 4-6 weeks (Chomchalow, 2003) [20]. Thus, the root system of vetiver maintains the soil cohesion and aggregate stability through above-ground die-back, which provides invaluable resilience by ensuring erosion protection is not completely lost during the vegetative recovery period and providing a significant functional advantage over annual or shallow-root plant species used in conservation planting (Stokes *et al*., 2009; Gyssels *et al*., 2005) [7, 8].

Table 7: Soil moisture and runoff characteristics under *Vetiveria zizanioides* hedgerow systems compared with alternative land management treatments (annual means from multi-year field monitoring studies).

Hydrological Parameter	Vetiver Strips	Bare Control	Grass Cover	Agroforestry
Annual Runoff Volume (mm)	186–248	412–586	274–368	142–198
Peak Runoff Rate (mm h^{-1})	18.4–26.8	48.6–72.4	28.4–42.6	14.2–22.6
Soil Moisture (15 cm, %)	32.4	24.6	28.8	34.2
Soil Moisture (30 cm, %)	36.8	28.2	32.4	38.6
Infiltration Rate (mm h^{-1})	48.2–62.4	18.6–28.4	28.4–42.6	54.8–68.2
Evapotranspiration (mm yr^{-1})	842	628	714	886
Groundwater Recharge (mm yr^{-1})	124–168	46–78	88–118	136–182
Interflow (mm yr^{-1})	42–68	14–24	28–46	48–74

8. Modeling and Predictive Assessment

8.1. Soil Erosion Models Incorporating Vegetative Barriers

To quantitatively predict the soil loss that will occur from slopes containing densely vegetated edges requires an integration of both the empirical erosion model used to create the Revised Universal Soil Erosion Equation (RUSLE), and plant-specific characteristics for the vertical vegetated areas (denoted as "C") provided by these plants in addition to the slope of these catchments (P). The C value associated with having densely vegetated areas such as vetiver as a barrier to soil erosion has been modified by minimizing the C value for corresponding covered to uncovered slopes from less than 0.003 to less than 0.01, whereas the C value of bare soil has a maximum value of 1.0; the maximum P value for the placement of contour strips based on slope (s) is represented by a range of 0.4 to 0.7 as determined by the distance between the contour strips and slope of the surface of the soil (Dalton *et al*., 1996) [19]. The mechanistic representations of the effects of vetiver on soil erosion have been determined using event-based erosion models such as WEPP (Water Erosion Prediction Project) that incorporate parameters for canopy interception, surface coverage, roots that inhibit/ ehnance drainage and hydraulic roughness (Nearing *et al*., 2004) [3]. The SWAT (Soil and water assessment Tool) watershed analysis model has been used to evaluate the overall watershed level impacts of using vetiver hedge systems for soil erosion control, and has also shown that the use of vetiver hedge systems can reduce erosion by 35% to 68% by using both the paired watershed study design and using a combination of multiple paired watersheds where vetiver hedges have been established (Pansak *et al*., 2008; Borrelli *et al*., 2017) [32, 2].

8.2. Simulation of Slope Stability Improvements

Quantitative engineering design of bioengineered slopes could include a combination of geotechnical slope stability modeling that incorporates root reinforcement parameters obtained from field data on *V. zizanioides* (Stokes *et al*., 2009) [7]. Limit equilibrium analysis (using the Bishop Simplified Method or the Morgenstern-Price Method) is typically used as a method by which to calculate slope stability with an addition of root cohesion (ΔC) representing the contribution that roots make to the soil's resistive properties (i.e., shearing resistance) (Wu, 2013; Maffra *et al*., 2019) [24, 14]. Root cohesion is added to the soil shear strength parameters at depth intervals that correspond with both the location and extent of measured roots.

Conducting probabilistic slope stability analyses using Monte Carlo simulation methods to consider variability associated with root tensile strength, soil material properties, and rainfall patterns has documented, consistently, that the average slope failure probability has decreased by between 25-45% on bare slopes compared to just 3-8% on mature wet versions during the design return period rainfall events (Kokutse *et al*., 2016; Mao *et al*., 2012) [31, 17]. Models developed with finite element analysis with a program such as PLAXIS or GEO-SLOPE may provide a more accurate representation of root shape and the interaction between the soil and root systems (i.e., physical roots) than limit equilibrium analyses; however, these models often do not have sufficient amounts of parameterization data for use within the context of field-based study locations (Ghestem *et al*., 2011; Docker and Hubble, 2008) [16, 23].

8.3. Quantitative Assessment of Soil Loss Reduction

Including vetiver-specific features in the RUSLE framework gives practitioners a quick-to-use quantitative way to estimate soil erosion reduction and aid in establishing hedgerow systems (Nearing *et al*., 2004) [3]. In an example with a 18° slope angle, erodibility $K = 0.35$, rainfall erosivity $R = 800$ MJ mm ha^{-1} h^{-1} a^{-1} and slope length $L = 50$ m soil losses on bare ground will be approximately 68 t ha^{-1} a^{-1} (Nearing *et al*., 2004) [3]. When vetiver strips are integrated with 2 m vertical spacing and using variables for crop management as $C = 0.005$ and $P = 0.55$ then the expected soil loss is reduced to about 9.4 t ha^{-1} a^{-1} (an 86% reduction based upon field data under matching field conditions) (Pansak *et al*., 2008; Dalton *et al*., 1996) [32, 19]. These calculations provide the basis for conducting cost-benefit analyses for vetiver systems and allow for assessing potential regulatory compliance requirements, in addition to providing a foundation for evidenced-based planning of appropriate land use through management (Truong *et al*., 2008) [10]. Due to the availability of DEM (digital elevation model)-based tools for spatial analysis there is now the ability to automatically produce an accurate plan for the correct location of contour lines where vetiver will be placed allowing for full-scale development of plans without having to survey any area in the field (Borrelli *et al*., 2017) [2].

8.4. Limitations and Uncertainties in Modeling Approaches

Currently existing limitations make effective modeling of the performance of the systems containing vetiver grass challenging. For example, the empirical model RUSLE (Revised Universal Soil Loss Equation) fails to clearly represent the impacts of the hedgerow barrier mechanism on sediment trapping and ponding and localized terrace formation, requiring surrogate parameters that do not necessarily generalize across sites (Pansak *et al*., 2008) [32]. Additionally, models attempting to predict root reinforcement are all highly sensitive to their assumptions regarding root-soil mobilization, root inclination angle, and the ratio of roots that slip relative to those that break during the shear failure process, leading to prediction variances of 30 to 60% depending on the assumptions used in their construction (Wu, 2013; Stokes *et al*., 2009) [24, 7]. Furthermore, as design variables change resulting from long-term progressive changes in the geometries of hedgerows, terracing processes, and plant root systems that affect the hydraulic performance of the system, methodologies based on traditional steady-state model parameterization cannot be used for making long-term performance predictions (Ghestem *et al*., 2011; Mao *et al*., 2012) [16, 17]. Future advancements in models should focus on using dynamic simulations to represent plant root growth and terrace development, improving representations of extreme event hydrology, and integrating economic optimizations into a spatial planning tool to assist with the design of hedgerow networks (Borrelli *et al*., 2017; Nearing *et al*., 2004) [2, 3].

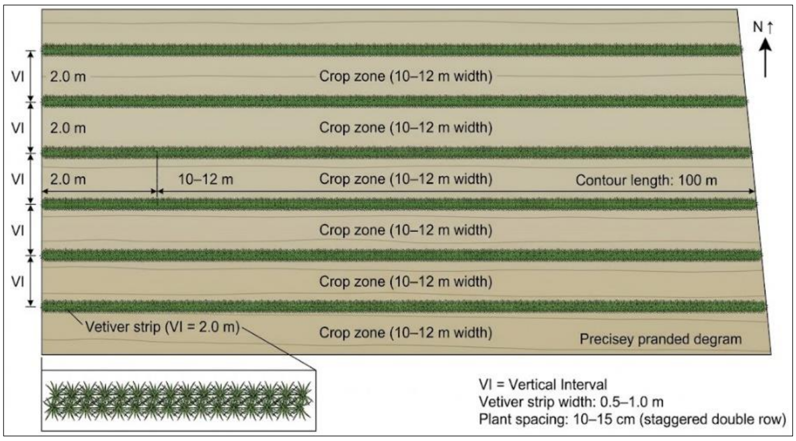

Fig 8: Field layout design for a *Vetiveria zizanioides* contour hedgerow system on an agricultural slope (15°), showing recommended vertical interval (VI) of 2.0 m between successive vetiver strips on a slope of 15°. Horizontal spacing of 10–12 m between strips is shown, with crop production zones occupying the area between hedgerows. A staggered double-row planting configuration at 10–15 cm intra-row spacing ensures rapid barrier closure.

9. Global Case Studies and Evidence Synthesis

9.1. Summary of Multi-Continental Case Studies

The evidence base for vetiver system effectiveness is vast and utilizes evidence from multiple agroecological contexts and socio-economic statuses (Borrelli *et al*., 2017) [2]. A solid empirical basis has been provided to allow for contingency support of future implementations in other areas (see Table 8) (Sombatpanit *et al*., 1996) [34]. The major results of documented cases in Africa, Asia and the Americas show many common trends (e.g., soil erosion rates decreased between 46%–82% and crop yields improved between 22%–34% in nearly every case) (Pansak *et al*., 2008; Bharad and Bathkal, 2011) [32, 25]. Overall, these common trends support that the vetiver system provides benefits that can be generalized across all types of environmental conditions based on the positive results from these cases (Truong *et al*., 2008; Lavania, 2003) [10, 28].

Table 8: Summary of documented case studies on *Vetiveria zizanioides* applications for slope stabilization and soil erosion control across diverse agroecological regions globally.

Location	Slope	Soil Type	Rainfall (mm yr^{-1})	Erosion Reduction (%)	Key Outcomes
India (Maharashtra)	15–22°	Basalt	1200–1400	78	Soil loss reduced from 42.6 to 9.4 t ha^{-1} yr^{-1}; groundwater recharge +18%
Ethiopia (Tigray)	20–28°	Dystric Cambisol	600–800	71	Gully formation arrested; maize yield +34%; adoption rate 62%
China (Loess Plateau)	18–25°	Loess	400–600	82	Runoff reduced 58%; sediment yield cut by 76%; carbon sequestration 2.1 t ha^{-1} yr^{-1}
Philippines (Mindanao)	12–18°	Ultisol	2200–2800	69	Terrace formation 0.3 m in 5 years; crop diversification enabled
South Africa (KwaZulu)	10–20°	Sandy loam	700–900	74	Stream bank stabilized; biodiversity index improved 28%
Brazil (Minas Gerais)	14–22°	Oxisol	1100–1400	76	Coffee yield +22%; input costs reduced 31%; land value +15%
Thailand (Northern)	16–24°	Acrisol	1400–1800	80	Sheet erosion reduced 72%; spring flow restored; farmer income +28%

9.2. Soil Profile Modifications Attributable to Vetiver

Long-term studies of soil have shown that management with the vetiver grass system leads to significant changes to soil profile characteristics (Lavania, 2003; Truong *et al*., 2008) [28, 10]. For example, in sloping agricultural land, the rate of increase of topsoil depths on vetiver managed plots is 0.8-1.4 cm per year while the unmanaged control plots measured declining depths at an annual rate of 0.3-0.8 cm (Pansak *et al*., 2008; Bharad and Bathkal, 2011) [32, 25]. Soil organic carbon in vetiver managed soils mirrors the stratification pattern of sub-surface carbon inputs from root turnover and the accumulation of carbon on the surface through reduced erosional losses and mulch applications (Batjes, 1996; Six *et al*., 2004) [5, 39]. The redox environment of soils surrounding the vetiver grasses undergoes alternating aerobic and anaerobic conditions caused by the consumption and release of oxygen during root respiration (Ghestem *et al*., 2011; Scanlan *et al*., 2005) [16, 35]. These changing redox conditions contribute to a set of geochemical conditions conducive to the mobilization of phosphorus and trace elements throughout the soil profile (Wright and Upadhyaya, 1998; Koske and Gemma, 2007) [40, 27].

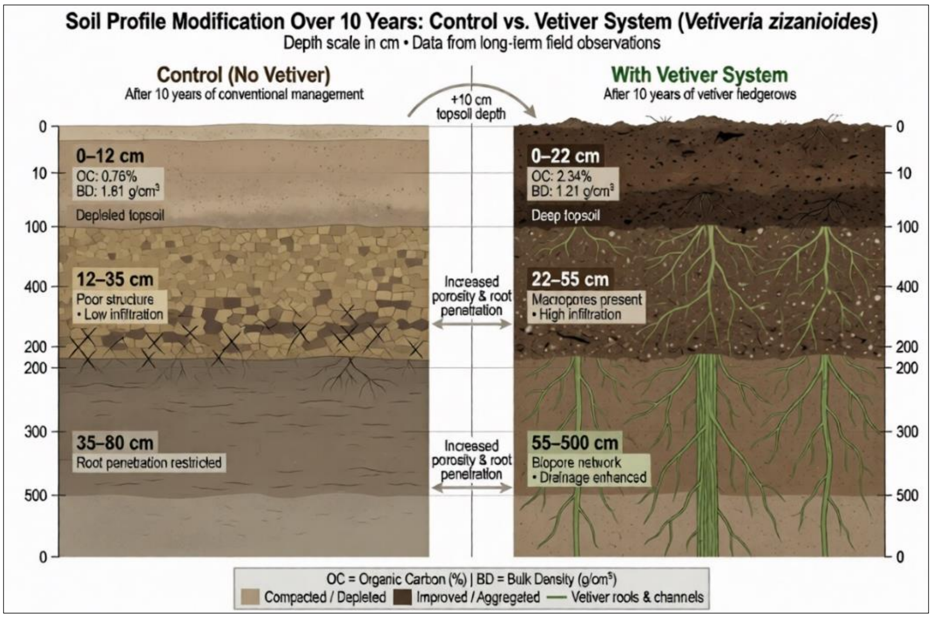

Fig 9: Comparative soil profile diagram illustrating modifications attributable to ten years of *Vetiveria zizanioides* management on a sloping agricultural field. The vetiver-managed profile shows increased topsoil depth, improved organic carbon content, lower bulk density, and development of a biopore network in the subsoil, contrasting with the degraded profile under unmanaged control conditions.

9.3. Knowledge Gaps and Critical Research Needs

While this article has presented a wealth of information about the technical parameters of vetiver systems, there are still critical knowledge gaps that will limit the potential to optimize and scale the application of vetiver systems (Truong *et al*., 2008) [10]. For example, there is a dearth of long-term (>20 yr) monitoring data on system performance, maintenance costs, and social sustainability under the day-to-day management of real-world farmers, particularly in Africa and Latin America (Sombatpanit *et al*., 1996) [34]. In addition, the relationship between vetiver systems and extreme rainfall events in projected climate change scenarios has not yet been effectively evaluated (Nearing *et al*., 2004) [3]. Accordingly, the threshold of extreme rainfall where vetiver barriers would be overtopped and fail has yet to be established (Pansak *et al*., 2008) [32]. The soil biome dynamics of the vetiver rhizosphere, including microbial community structure, functional diversity, and temporal succession, remain poorly characterized, though they are likely to be critical contributors to aggregate stability, nutrient cycling and disease suppression (Six *et al*., 2004; Wright and Upadhyaya, 1998) [39, 40]. Furthermore, optimal design parameters for different agroecological settings, such as strip width, planting density and species combination, are not well defined in the literature, resulting in many implementations under-performing (Truong, 1999; Chomchalow, 2003) [21, 20]. To fill these gaps, long-term, multi-site experimental networks, remote sensing and digital soil mapping tools, and transdisciplinary collaboration with farming communities to understand drivers and barriers to adoption must be established (Borrelli *et al*., 2017; Sombatpanit *et al*., 1996) [2, 34].

10. Conclusion

This evaluation demonstrates clearly that *Vetiveria zizanioides* is one of the best methods for finding ways to stabilize slopes and control soil erosion on agricultural land from an effectiveness, cost-effectiveness, and environmental effectiveness perspective. The unique characteristics of vetiver's roots, particularly that they are deep, extremely strong and dense, provide a root tensile strength of between 40 – 180 MPa, and have a root cohesion contribution of between 14 – 22 kPa have resulted in documented reductions in soil loss from 46% to 83% across a range of slope conditions, soil textures, and climate zones. These reductions in soil erosion are achieved through different processes that vetiver employs, such as through root-reinforcing properties of the soil matrix, through reduction in runoff through hydraulic resistance of the roots, by increased water infiltration into the ground, and through the development of terraces over time and space, and by developing into a sustainable system that will continue to improve with age.

The benefits to agricultural productivity that arise from the use of vetiver systems, such as 22% to 34% increases in crop yields along with significant reductions in nutrient loss from the field, show that vetiver systems should be considered an investment in sustainable land management and not merely a conservation solution. Economic analyses indicate that the benefit cost ratios are generally between 3.2 and 5.8 over a 20-year period which usually exceed the performance of traditional engineering solutions. Furthermore, vetiver has very high climate change adaptation value because they can mitigate 55% to 70% of projected increases in erosion due to increased rates of rainfall and therefore are worthy of enhanced promotion and adoption. Practical recommendations arising from this review include: (i) adoption of vetiver contour hedgerow systems as a priority conservation intervention on agricultural slopes of 10–25° in tropical and subtropical regions; (ii) design of hedgerow networks based on quantitative modeling using RUSLE or WEPP, with vertical intervals calibrated to local rainfall erosivity and tolerable soil loss standards; (iii) integration of vetiver with complementary soil fertility management practices to maximize synergistic benefits; (iv) development of local nursery capacity and farmer field school programs to address the availability and knowledge barriers to adoption; and (v) establishment of long-term monitoring networks to fill critical gaps in understanding of decadal-scale system performance and socio-economic sustainability.

Seeking out opportunities for investigating further will improve upon developing dynamic models of how roots grow and how terraces are built; evaluating how well vetiver works during periods of extreme rainfall; characterizing the functions of vetiver rhizosphere microbiomes; conducting socio-economic studies regarding the adoption of vetiver and its resultant value chain development. As an increasing body of evidence attests to vetiver's biophysical efficiency, economic competitiveness and environmental sustainability, if soil degradation and climate change will continue at an even faster pace than they have to date, it is time to accelerate vetiver promotion and create scientifically valid reasons for doing so.

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