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Performance Evaluation of Biological Soil and Water Conservation Grasses for Stabilization of Bench Terraces in Tigray, Ethiopia

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ABSTRACT

Soil erosion critically threatens agricultural sustainability in the Ethiopian highlands, particularly in Tigray. While bench terraces are widely implemented to combat this, their stability is compromised by vulnerable terrace risers. This study evaluated the performance of three grass species, namely, Rhodes (Chloris gayana), Vetiver (Chrysopogon zizanioides), and Wazwazo (Festuca roemeri) for biologically stabilizing bench terraces in Kola Tembien, Tigray, compared to a bare control. A Randomized Complete Block Design was used over two years (2019-2020) to assess growth parameters and soil loss. Results showed that Wazwazo had the highest tiller production, while Rhodes excelled in height, ground cover, root diameter, and biomass. Vetiver developed long roots comparable to Rhodes. Soil loss data revealed significant deposition under Rhodes (19.5 t/ha) and Vetiver (22.1 t/ha), stability with Wazwazo (0.0 t/ha), and significant erosion in the control (-16.9 t/ha). The study concludes that Rhodes grass is optimal for overall surface protection and fodder production, whereas Vetiver is best for deep structural reinforcement. Integrating suitable grasses significantly enhances terrace stability and reduces soil loss, offering a sustainable bioengineering solution for land management in erosion-prone landscapes.

Keywords: *Bench Terraces, Grass Species, Erosion Pins, Soil Loss.*

Introduction

Soil erosion is a major environmental challenge threatening agricultural productivity and food security in the highlands of Ethiopia [10]. The Tigray region, characterized by rugged topography, erratic rainfall, and centuries of intensive cultivation, is among the most severely affected areas. This land degradation manifests as the loss of fertile topsoil, a decline in crop yields, and the siltation of downstream water bodies, perpetuating a cycle of rural poverty and environmental instability.

To combat this pressing issue, the government of Ethiopia, in collaboration with local communities, has invested heavily in the widespread implementation of physical soil and water conservation (SWC) structures. Among these, bench terracing has been a cornerstone intervention on slope areas. Bench terraces function by breaking long slopes into a series of level steps, thereby reducing the velocity of surface runoff, enhancing water infiltration, and creating favorable conditions for agriculture [1]. The initial construction of these terraces has demonstrated significant potential in controlling soil loss and reclaiming degraded lands.

However, the long-term stability and effectiveness of these bench terraces are not guaranteed. The structural integrity of the terrace risers, the vertical or near-vertical faces between the level platforms, is highly vulnerable to erosive forces, particularly from concentrated flow and raindrop impact. Without adequate protection, these risers can experience collapsing, gully formation, and eventual collapse, rendering the entire terrace system ineffective and requiring costly maintenance [7]. This underscores a critical gap in the sustainability of purely structural SWC measures.

Integrating biological stabilization measures with physical structures is widely advocated as a sustainable solution.

The use of specific grass species on terrace risers provides a living protection that binds the soil with their dense root systems, dissipates the energy of rainfall, and reduces surface runoff velocity [13]. This bioengineering approach not only strengthens the terraces but also provides additional benefits such as fodder for livestock, which is crucial for the mixed crop-livestock farming systems prevalent in Tigray, and potentially improves the micro-environment. Farmers need cheap and easily implementable measures such as grass strips to manage their farm lands and maintain or restore the productivity of their soils in gentle slopes [4]. Grass strips are promoted as soil and water conservation measures because they demand less labor, do not bury the fertile topsoil and they can effectively reduce erosion on gentle slopes [14].

While the theoretical benefits of biological stabilization are well-established, the practical success hinges on the selection of appropriate grass species. Performance is highly site-specific, influenced by local agro-ecology, soil type, and management practices. Several grass species, including Elephant grass (*Pennisetum purpureum*), Vetiver grass (*Chrysopogon zizanioides*), Rhodes (*Chloris gayana*), and indigenous species like *Desho* grass (*Pennisetum pedicellatum*), have been promoted in various regions. A systematic evaluation of their establishment, growth rate, root system strength, drought resilience, and socio-economic acceptability within the specific context of Tigray's bench terraces is imperative.

Therefore, this study is designed to fill this knowledge gap by conducting a comparative performance evaluation of selected biological SWC grasses for the stabilization of bench terraces in the Tigray region. The findings will provide evidence-based recommendations to farmers, development agents, and policymakers, contributing to more resilient and sustainable land management practices in this erosion-prone landscape.

Materials and Methods

Study Area Location

Geographically, the study area is found in Kola Tembien district, which is located at *ca.*125 km away from Mekelle, the capital city of Tigray to the west. It is lies at 13^0, 38', 06” to 13^0, 38', 13.32”N and 38^0, 55', 06” to 38^0, 55', 21.39”E with an altitude ranging from 1734 to 1769 m a.s.l. This study was specifically conducted at Chechah bench terrace site covering an area of 9.48 ha (Figure 1). The study area with bench terrace was purposely selected from the district to conduct the intended study.

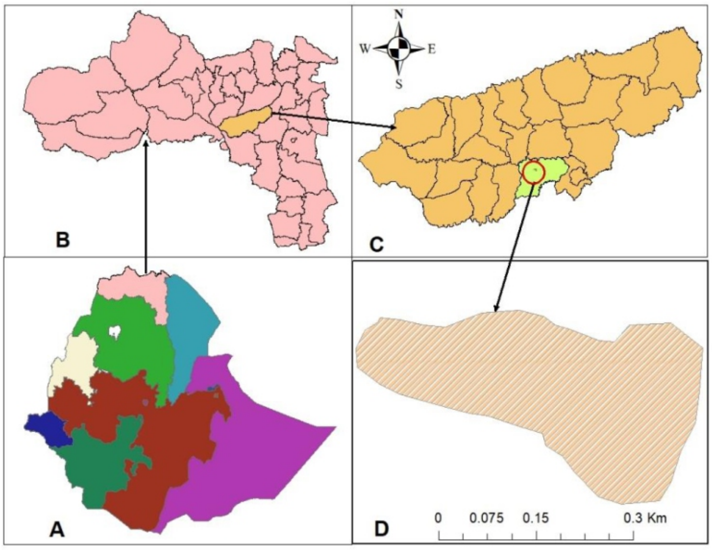

Figure 1. Location of the study area A) in Ethiopia B) in Tigray C) Kola Tembien district D) Chechah bench terrace site

The study area is characterized by a semi-arid agro-climatic zone with average yearly rainfall of 680 mm, varying from 500 to 860 mm, with unimodal distribution and monthly average temperatures ranging from 13.3 °C (min) to 29.8 °C (max) and 137 mm average potential evapotranspiration [3].

Experimental Design and Treatment

Randomized Complete Block Design (RCBD) with three replications was applied to each treatment in the block with plot size of 5 m by 1 m. Four treatments out of which the three were grass strips and one control (without grass) were applied. The three grass types used in this study were Rhodes (Chloris gayana), Vetiver grass (Chrysopogon zizanioides) and Wazwazo (Festuca roemeri). The grasses were planted on a five-year-old bench terraces on the beginning of the rainy season. The grasses were established with a spacing of 15 cm between grasses and 30 cm between rows in 4 rows on the top of the 5 m bench terrace. The erosion pins used were made of iron and were 1 m long, and they were installed between the central rows of the aforementioned treatment and distributed in 1 row, with 5 pins in each treatment. The installation depth of the erosion pins was 50 cm, leaving 50 cm above the surface. It is worth noting that smaller values are also commonly used by other authors [8, 11].

Method of Data Collection

At the beginning of the study (2019), initial measurements such as initial bench terrace height, the above-ground pin height and initial number of planted tillers for each grass was recorded randomly. During the two years study period (2019-2020), the parameters such as increased number of tiller, grass height, diameter covered by each grass and above-surface pin height were recorded at three-month interval.

Whereas, the root length, root diameter, grass biomass and bench terrace height were measured at the end of the study period (2020). Height measurement was done using a tape meter.

Determination of Soil Loss

The following equations were used to calculate the amount of soil loss from each treatments using the [9] equation.

For each pin (i), the change in height (ΔH_i) over time is measured as:

ΔH_i = H initial – H final ………………………... (1)

$\Delta H\_avg = (\Sigma \Delta H_i) / n$ …………………………… (2)

Where:

$\Sigma \Delta H_i$ = the sum of the height changes for all *n* pins.

n = the total number of pins.

- A negative ΔH indicates erosion (soil loss).
- A positive ΔH indicates deposition (soil gain). This is because in this study height measurement was taken from the above-ground pin. For example, if the final above-ground pin height becomes greater than the initial pin height, the difference will become negative which indicates the soil is eroded.

Volume = ΔH_avg (m) * plot area (m^2) …………………….. (3)

Then volume was converted into mass using the equation below;

Mass of the soil (Mg) = Volume (m^3) * Bulk density (Mg/m^3).. (4)

Recommended bulk density value is 1.35 Mg/m^3 where, Mg = Mega gram = 1 metric ton

Soil loss (ton/ha) = Mass of the soil (Mg) * 10000 ………….. (5)

Here, 10000 is used to convert 1 m^2 to hectare.

Method of Data Analysis

Analysis of variance (ANOVA) was carried out using SPSS version 29 statistical software program was used for data analysis. Statistically significant difference between and among treatment means was assessed using Tukey Post Hoc test at 5% level of significance.

Results and Discussion

Growth Performance of Biological Soil and Water Conservation Grasses

The distinct comparative performance patterns among the three grass species (Rhodes (Chloris gayana), Vetiver (Chrysopogon zizanioides), and Wazwazo (Festuca roemeri)) is presented in table (1).

Table 1: Mean and standard error (SE) for the collected key parameters of each grass

Treatment	Planted No of Tiller	Survived Number of Tiller	Increased Number of Tiller	Grass Height (m)	Diameter Covered by Each Grass (m)	Root Length (m)	Root Diameter (m)	Grass Biomass Kg/m2
Rhodes	3	1.67	80.33^{ab} (±5.4)	1.47^{a} (±0.09)	0.93^{a} (±0.08)	0.40^{a} (±0.03)	0.65^{a} (±0.02)	5.13^{a} (±0.15)
Vetiver	3	1.5	60^{bc} (±2.7)	0.82^{b} (±0.06)	0.55^{bc} (±0.01)	0.41^{a} (±0.02)	0.46^{bc} (±0.03)	3.73^{bc} (±0.29)
Wazwazo	3	1	93^{a} (±7.1)	1.39^{a} (±0.05)	0.64^{b} (±0.04)	0.27^{b} (±0.01)	0.50^{b} (±0.01)	4.10^{b} (±0.06)

All three grasses were initially planted with three tillers. Rhodes grass had the highest survival rate (1.67), followed by Vetiver (1.5), and Wazwazo (1.0). These initially planted grasses were gradually increased their tiller number during the two study years (2019-2020). Wazwazo demonstrated the highest tiller number, with a mean increase of 93 tillers, which was significantly higher than the others. Rhodes grass also showed strong tiller increment (80.33), while Vetiver had the lowest increase (60 tillers). With regard to vegetative growth and ground coverage, Rhodes (1.47 m) and Wazwazo (1.39 m) achieved significantly greater heights than Vetiver (0.82 m). Similarly, Rhodes grass provided the most extensive ground cover per plant (0.93 m), which was significantly greater than both Wazwazo (0.64 m) and Vetiver (0.55 m). In contrast of root length, Rhodes and Vetiver grasses developed similarly long roots (0.40 m and 0.41 m, respectively), both significantly longer than the roots of Wazwazo (0.27 m). While in the root diameter, Rhodes grass had the thickest roots (0.65 m), followed by Wazwazo (0.50 m), with Vetiver having the thinnest roots (0.46 m). The highest above-ground biomass was observed in the Rhodes grass produced a biomass of 5.13 Kg/m², which was significantly greater than the biomass from Wazwazo (4.10 Kg/m²) and Vetiver (3.73 Kg/m²).

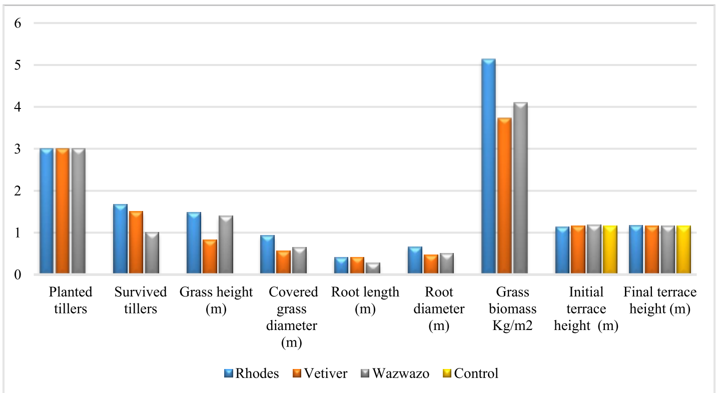

Figure 2: Shows the measured average values the testing parameters

Overall, Rhodes grass emerged as the most well-rounded performer with its excellent tiller capacity (second only to Wazwazo), combined with the tallest height and the most extensive ground coverage, which suggests it is highly effective at forming a dense vegetative barrier. This barrier is crucial for reducing water runoff velocity, minimizing raindrop impact on the soil, and trapping sediment. Furthermore, Rhodes grass developed a robust root system with the thickest roots and great length, which is a key trait for binding soil particles and reinforcing the terrace structure against slumping and slippage. Its highest biomass production further confirms its vigorous growth and potential for providing fodder, an important secondary benefit for local communities.

Vetiver grass, while often ranked as the premier soil conservation species globally, showed a more modest above-ground performance in this study. It had the lowest values for tiller increase, height, cover, and biomass. However, its key strength lies below ground. Vetiver developed roots as long as those of Rhodes grass (0.41 m), and its tendency to form dense, vertical root masses is renowned for creating a powerful anchor to the soil deeply. Vetiver's roots can grow very deep (2-3 meters) and are remarkably strong, acting like a "living nail" that reinforces the soil and provides exceptional structural integrity to terrace risers [6]. This is particularly valuable on very steep risers. When planted in dense hedges along the contour of the riser, it forms a very effective barrier that slows down runoff, traps sediment, and promotes water infiltration [12]. Therefore, while it may not provide the quickest ground cover or most biomass, its primary value is in deep structural stabilization of the terrace risers, making it exceptionally resistant to shear failure.

Wazwazo grass displayed a unique profile, being the most creative in tiller production (93). This indicates an excellent capacity for rapid colonization and forming a dense pasture, which is vital for quickly protecting newly constructed terraces from erosion. However, this strength is counterbalanced by a significant weakness: it developed the shortest root system (0.27 m). A shallower root system provides less anchorage and is less effective at stabilizing the deeper soil layers of a terrace. Consequently, Wazwazo may be excellent for surface protection and controlling sheet erosion, but may be less reliable for preventing the structural failure of steep terrace banks compared to Rhodes or Vetiver.

Bench Terrace Stabilization and Erosion Status

The analyzed results for initial and final heights of both terraces and pins for the different treatments and the calculated soil loss is summarized below in table (2). Statistically, no significant difference was observed in between the four treatments and within the treatments (the initial and final heights of both terrace and pins). Whereas a considerable significant difference was observed in soil loss across all treatments. In all treatments, including the control, showed remarkable change over the two year study period, indicating that under the specific conditions of this experiment, soil erosion and deposition was observed. However, a smaller but critical difference in the terrace and pin heights data suggests the grasses were indeed performing their protective function. All treatments started with very similar initial terrace heights (between 1.13m and 1.18m). The final heights for all treatments remained almost identical to their initial heights. The changes are very small (e.g., Rhodes: +0.03m, Vetiver: 0.00m, Wazwazo: -0.01m, Control: -0.01m).

Table 2: Initial and final height for the bench terrace and erosion pin

Treatment	Initial terrace height (m)	Final terrace height (m)	Initial pin height (cm)	Final pin Height (cm)	Soil loss (t/ha)
Rhodes	1.13^{a} (±0.02)	1.16^{a} (±0.02)	50^{a}	49.85^{a} (±0.03)	19.5^{a} (±0.01)
Vetiver	1.15^{a} (±0.00)	1.15^{a} (±0.00)	50^{a}	49.83^{a} (±0.16)	22.1^{b} (±0.02)
Wazwazo	1.18^{a} (±0.01)	1.17^{a} (±0.00)	50^{a}	50^{a} (±0.08)	0.0^{c} (±0.00)
Control	1.15^{a} (±0.00)	1.14^{a} (±0.00)	50^{a}	50.13^{a} (±0.30)	-16.9^{d} (±0.01)

Initial and Final Comparison	Treatment			
	Rhodes	Vetiver	Wazwazo	Control
Initial pin height (cm)	50^{a}	50^{a}	50^{a}	50^{a}
Final pin Height (cm)	49.85^{a}	49.83^{a}	50^{a}	50.13^{a}
Initial terrace height (m)	1.13^{a}	1.15^{a}	1.18^{a}	1.15^{a}
Final terrace height (m)	1.16^{a}	1.15^{a}	1.17^{a}	1.14^{a}

The fact that bench height did not change significantly high indicates that during the study period, no major structural failures, such as collapse of the terrace risers, occurred in any of the plots. This applies even to the control plot. This could be due to the short duration of the study or the inherent initial stability of the constructed terraces. Therefore, this parameter alone is insufficient to judge the long-term stabilizing effect of the grasses on the terrace structure itself. The small increase in terrace height in the three grass treatments is a strong indicator of grass function as a sediment trap. The grass barrier effectively filtered and trapped fine sediments from runoff water, causing net deposition and a build-up of the terrace level [5]. This is a key function for maintaining and even building soil on agricultural terraces. Therefore, the terrace height data provides a broader view of stability, integrating both erosion and deposition processes behind the pin.

The two grass species (Rhodes and Vetiver) showed a decrease in final pin height (49.85 cm and 49.83 cm respectively) with no change in the Wazwazo grass. This indicates that a remarkable amount of net sediment deposition occurred on the riser surface or bench terrace surface of the Rhodes and Vetiver cover. The Control showed an increase in final pin height (50.13cm). This indicates a small amount of soil detachment or erosion on the riser surface. The terrace height reflects the overall stability of the terrace structure, balancing erosion at the pin and potential deposition behind it.

In contrast, both the Rhodes (19.5 t/ha) and Vetiver (22.1 t/ha) treatments exhibited substantial and statistically significant soil deposition, with Vetiver showing the highest deposition rate among the cover treatments. The Wazwazo grass didn't show any change in its pin height resulting in a net soil loss of 0.0 t/ha, indicating soil stability for the measured period. In contrast, the control plot with no grass cover significantly showed a soil loss value of -16.9 t/ha. In the context of this study, the negative value indicates a net soil loss of sediment or surface level erosion. This is because, the measured value of above ground pin was greater (pin height increased) than the fixed initial measurement (50 cm).

The results reveal a clear and systematically logical story about the role of grasses in soil stabilization and the processes of erosion and deposition on terraces. Terraces stabilized with grasses like Vetiver show significantly lower runoff coefficients and soil loss compared to un-stabilized terraces [1]. Even though the change in the pin height is very small, a consistent soil loss accumulation was observed in grassed plots comparing to the control plot, as shown by the pin data. Their dense root systems bind the soil, and their surface cover absorbs the impact of raindrops and slows surface runoff. This reduction in flow velocity minimizes the water's ability to detach and transport soil particles [16]. The grasses contributed to stabilization the bench terrace through their root systems increasing the soil's shear strength, making it more resistant to being washed away and increased water infiltration and acted as physical filters, trapping suspended sediments [13]. Biological soil and water conservation grasses are excellent at trapping sediment and building up the terrace level, which is a valuable characteristic for combating soil loss in erosion-prone areas [15]. The consensus from research in Ethiopia is that the biological stabilization of bench terraces using appropriate grass species is a highly effective and sustainable practice [2].

Conclusion

In conclusion, the choice of grass for bench terrace stabilization in Tigray should be guided by the specific primary objective. For a balanced approach providing excellent surface cover, soil binding, and high biomass for fodder, Rhodes grass is the superior choice. For deep structural reinforcement of steep or vulnerable terrace risers where soil anchorage is the priority, Vetiver grass remains a specialized and valuable option. Despite the lack of statistical significance in the pin height, the clear trends demonstrate that all grass treatments were vastly superior to the control in preventing surface erosion. Vetiver grass provided the most balanced stability with better sediment accumulation, while Rhodes grass was the second effective at trapping sediment and building soil on the terrace. The use of vegetation is confirmed as a critical, living engineering tool for sustainable terrace management. The success of these interventions, however, depends on proper management, including controlled grazing and regular maintenance of the grass strips.

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