

Potential Grass Species for Soil Conservation and Fodder Production in the Nilgiri Hills of the Western Ghats

K. Kannan^{1,3*} | C. Babu² | P. Sundarambal³ | K. Rajan³ | P. Raja³

¹ICAR- Sugarcane Breeding Institute, Coimbatore 641007, India

²Department of Forage Crops, CPBG, Tamil Nadu Agricultural University, Coimbatore 641003, India

³ICAR- Indian Institute of Soil and Water Conservation, Udhamandalam 643004, India

*Corresponding Author:

E-mail: kannan_wtcer@yahoo.com

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ABSTRACT

Soil erosion and fodder shortages on sloping terrains in the Nilgiri Hills have intensified due to grassland conversion to agriculture. While bench terracing is recommended for slopes exceeding 16%, high costs limit farmer adoption. This two-year field experiment (2019–21) at ICAR-IISWC, Udhamandalam, evaluated eight grass species—four fodder grasses (Guinea grass, Congo signal, Cumbu Napier hybrid CO(CN) 4, Bajra Napier CO(BN) 5 and four native grasses (Weeping love grass, Guatemala grass, Vetiver, Lemon grass)—for soil conservation efficiency, biomass yield, and ecosystem services. Results showed that Bajra Napier CO(BN) 5 and Cumbu Napier CO(CN) 4 provided superior soil conservation through extensive foliage spread (150 and 146 cm), higher root mass density (1.26 and 1.20 g cc⁻¹), and greater soil binding capacity (195,613 and 180,867 cc), while delivering maximum biomass yields (310 and 262 t ha⁻¹ yr⁻¹) and superior crude protein content (14%). Vetiver and Congo signal grasses enhanced soil organic carbon stocks most effectively (38.7 and 31.7 t ha⁻¹ gain), with vetiver exhibiting greatest CO₂ sequestration (85.17 t ha⁻¹ yr⁻¹) despite higher soil respiration. Hybrid Napier grasses proved ideal for dual purposes—erosion control and fodder production—while vetiver excelled in carbon storage. Integrating complementary grasses offers a sustainable, low-cost alternative to mechanical bench terracing in fragile hill ecosystems.

1 | INTRODUCTION

Although the issues of runoff, soil erosion, and soil degradation have long been recognized, their intensity has escalated in recent years due to mounting pressure on natural resources. The conversion of grasslands into agricultural fields has not only resulted in acute fodder shortages but has also exacerbated soil erosion and degradation, particularly on sloping terrains in hilly regions (Sun *et al.*, 2018). In the Nilgiri Hills of the Western Ghats, vegetable cultivation is practiced on slopes ranging from 5% to 40%, leading to alarming soil losses of up to 40 t ha⁻¹ year⁻¹. Bench terracing is recommended for slopes exceeding 16% (Sahoo *et al.*, 2015). Yet, farmers are often reluctant to adopt it due to the high initial investment (Sudha *et al.*, 2016) and the risk of reduced crop yields from subsoil exposure during the cut-and-fill process. This practice also negatively impacts soil fertility in the early years (Mesfin *et al.*, 2018). An alternative approach—natural formation of low-cost bench terraces using vegetative barriers such as medicinal plants, known as the Puerto Rican type, which was previously documented by Muralitharan *et al.* (2008). Many studies globally and within India demonstrate that grasses and vegetation barriers are practical tools for

controlling soil erosion and enhancing carbon sequestration. For instance, Sudhishri *et al.* (2008) showed that vegetative barriers (including grasses) significantly reduced soil loss and improved soil moisture and nutrient retention under hill slopes in Orissa, India. Azis and Islam (2023) reported that vetiver grass (*Chrysopogon and zizanioides*) effectively reduced soil loss by up to 97% and runoff by over 20% under high-intensity rainfall, demonstrating its strong potential for erosion control even on steep tropical slopes with erodible soils. Do *et al.* (2023) reported that agroforestry systems integrating fruit trees, contour grass strips, and annual crops on sloping land in northwest Vietnam reduced soil, carbon, and nutrient losses by 27–84% through natural terrace formation, demonstrating the soil-conservation potential of grass-based agroforestry practices. Donjadee and Tingsanchali (2013) demonstrated that vetiver hedgerow systems reduced runoff by 31–69% and soil loss by 62–86% on steep slopes under simulated rainfall, confirming their strong effectiveness in minimizing erosion and providing reliable predictive equations for soil loss estimation.

Previous work in the region broadly examined

vegetative barriers/bench-terrace formation in isolation. It did not compare multiple grasses side-by-side for surface protection, root-mediated soil binding, SOC change/ CO_2 flux, and fodder yield and quality. Evaluating ecosystem services has become an essential area of study, highlighting the vital benefits that natural environments provide to human societies (Kumar et al., 2024). Our study fills this gap by simultaneously quantifying all four dimensions in one research field experiment (plus farmer validation), providing a trait-based, species-specific basis for recommending grasses that jointly maximize fodder, erosion control, and carbon benefits in hill ecosystems with the hypothesis that improved fodder grasses such as Napier hybrids would outperform native species in erosion control and biomass production. In contrast, deep-rooted native grasses like vetiver would contribute more significantly to carbon sequestration. We selected eight grasses to reflect both farmer-used, widely available fodder types (Guinea, Congo signal, CO (CN) 4, CO (BN) 5) and native/deep-rooted species (Weeping love, Guatemala, vetiver, lemon grass) that offer contrasting functional traits relevant to hill slopes—canopy cover for ground protection, root depth/lateral spread for soil binding, and fodder quality for on-farm value. The present study was undertaken to evaluate selected fodder and native grass species for their efficiency in soil and water conservation under the sloping terrains of the Nilgiri hills, to assess their biomass yield and nutritive value for identifying high-yielding and quality fodder options suitable for hill farming systems, and to quantify the contribution of different grass species to soil organic carbon enhancement and carbon sequestration potential as an indicator of ecosystem services.

2 | MATERIALS AND METHODS

2.1 | Study Location

A field experiment was carried out during 2019–20 to 2020–21 at the ICAR–Indian Institute of Soil and Water Conservation, Research Centre, Udahagamandalam, located in The Nilgiris, Tamil Nadu, India ($11^{\circ}24' \text{N}$ latitude, $76^{\circ}41' \text{E}$ longitude, 2218 m above mean sea level). The experimental site featured lateritic red soil of moderate to considerable depth, relatively fertile, with an acidic reaction (pH 5.0) and a medium to high organic carbon content (1.2%). The available nitrogen, phosphorus, and potassium levels were 276, 45, and 344 kg ha^{-1} , respectively. The region receives an average annual rainfall of approximately 1200 mm, with 53% occurring during the southwest monsoon (June to September) and 30% during the northeast monsoon (October to December). The mean maximum and minimum temperatures recorded were 19.3°C and 11.8°C , respectively.

2.2 | Field Experiment

The field experiment followed a Randomized Block Design (RBD) with three replications to control spatial heterogeneity. Within each block, the eight grass species were randomly allocated to plots, ensuring that each block had one plot per species. Each plot measured $10.0 \text{ m} \times 5.0 \text{ m}$, with a 1.0 m buffer between plots and guard rows along plot

HIGHLIGHTS

- Bajra Napier CO (BN)5 and Napier CO (CN) 4 provide extensive foliage spread, higher root mass density, and exceptional biomass yields.
- Vetiver grass emerged as the champion for carbon sequestration despite higher soil CO_2 emissions,
- Rapid micro-terrace formation using Bajra Napier CO (BN)5 contour hedgerows, providing evidence for scalable, low-cost biological alternatives to expensive bench terracing.

perimeters to minimize edge effects. Treatments were kept on the same physical plots across years to capture temporal responses; analyses were conducted by year and pooled. Eight grass species—comprising four fodder grasses and four native grasses—were planted in a randomized block design with three replications. The fodder grasses included Guinea grass (*Megathyrsus maximus*), Congo signal grass (*Brachiaria and ruziziensis*), Cumbu Napier hybrid CO (CN) 4, and Bajra Napier CO (BN) 5. The native grasses consisted of Weeping love grass (*Eragrostis curvula*), Guatemala grass (*Tripsacum and laxum*), Vetiver grass (*Chrysopogon and zizanioides*), and Lemon grass (*Cymbopogon citratus*). Grass slips were spaced at $50 \text{ cm} \times 50 \text{ cm}$ intervals. Plant height and canopy spread were measured with a tape measure. Month-wise yield was recorded and expressed in t ha^{-1} .

2.3 | Soil Properties

Soil organic carbon (OC) was estimated by the Walkley and Black (1934) method. Crude protein content in the biomass was estimated by the Kjeldahl method. The total nitrogen obtained was multiplied by 6.25 to express crude protein percentage on a dry matter basis. Soil organic carbon stock was computed using the method of Lal et al. (2001), based on soil organic carbon content, bulk density, and soil depth.

The SOC stock was calculated using the equation:

$$\text{SOC stock (t ha}^{-1}\text{)} = \text{SOC (\%)} \times \text{Bulk density (t m}^{-3}\text{)} \times \text{Soil depth (m)} \times 10$$

where SOC is the percentage of soil organic carbon, bulk density is expressed in t m^{-3} , and soil depth is the thickness of the sampled layer (m). The changes in SOC storage were calculated using the initial SOC storage values before the experiment and the final SOC storage values after 2 years (cumulative).

Soil conservation efficiency was calculated using the approach outlined by Manivanan et al. (2017), as follows: Net assimilation of carbon was measured using infrared gas analyzers (IRGAs), and soil carbon emission was measured using the EGM-5 Soil CO_2 Analyzer.

2.4 | Measurements of the Conservation efficiency of grasses

The height of the grass was measured vertically up the main stem from the ground level with a measuring tape. The

foliage lateral spread was measured at two directions perpendicular to each other as diameters with measuring tape, and the average value was calculated as follows:

$$FLS = (y1 + y2) \div 2$$

Where, FLS = average foliage lateral spread

y1, y2 = foliage lateral spread in 2 directions perpendicular to each other, passing through the main stem as a vertical central axis.

The rooting depth was measured vertically from ground level after uprooting it by digging. The lateral spread of the roots was measured in 3 directions from the main stem (central) of the grasses as radii, and the average value was calculated as follows.

$$RLS = (x1 + x2 + x3) \div 3$$

Where, RLS = average root lateral spread

x1, x2, x3 = root lateral spread in three directions from the main stem (central)

The root volume was measured by the water-displacement method (inserting the entire root into a measuring cylinder and measuring the increase in volume). Root mass density was calculated by dividing root dry weight by soil volume and expressed in grams/cc of soil volume.

2.5 | Volume of Soil Bound by the Fibrous Roots

Grasses are shallow-rooted, and it is assumed that fibrous roots bind the soil in a cylindrical shape. It is because the greater lateral spread of the roots provides an umbrella for the soil beneath, extending up to the maximum rooting depth. So, the formula for the volume of a cylinder is used as follows:

$$\text{General formula for the cylinder volume} = \pi r^2 h$$

And the adopted formula for the volume of soil bound by roots = $\pi (RLS)^2 (RD)$

Where RLS = root lateral spread (radial form from the main stand of grass) ; And RD = rooting depth of grass

2.6 | Ground Surface Area Protected by Grass Foliage against Direct Raindrop Effect

The ground surface area protected by grass foliage against direct raindrop effect is calculated using the formula to calculate the area of a circle ($A = \pi d^2/4$) as follows:

$$\text{Protected ground surface area} = \pi (FLS)^2/4$$

Where FLS is foliage lateral spread (taking as the diameter passing through the main stand of the grass) and d is the diameter.

2.7 | Statistical Analysis

To compare the treatments, the yield data were pooled, and an analysis of variance (ANOVA) was carried out using a randomized block design. The treatment effects were evaluated using analysis of variance (ANOVA), and significance was tested using the F-test at the 5% level in R.

3.0 | RESULTS AND DISCUSSION

3.1 | Soil Conservation Efficiency (SCE) and Ecosystem Services

Plant height, number of tillers per plant, foliage spread, and

the surface area protected by grasses against raindrop impact differed significantly (Table 1). The tallest plants were recorded in Guatemala grass, followed by Bajra Napier CO (BN) 5 and Cumbu Napier hybrid CO (CN) 4. Weeping love grass produced the most tillers; however, its soil conservation efficiency was lower than that of hybrid Napier grasses and Guatemala grass due to its limited lateral foliage spread. BN CO (BN) 5 recorded 150.4 cm foliage spread, which was 5.4–40.2% greater than other species, and provided a 15.3–64.0% higher protected surface area, indicating its significantly superior canopy development and ground-cover efficiency for soil and water conservation. Cumbu Napier Co(CN) 4 produced foliage spread of 146.2 cm, which was on par with Bajra Napier Co(BN) 5. The lowest value was recorded in the Congo signal grass due to its poor foliage spread. According to Kafle et al. (2008), the lateral spread of foliage determines the extent of ground surface protection from direct raindrop impact. Both Cumbu Napier Co(CN) 4 and Bajra Napier Co(BN) 5 have significantly higher values on surface area protected by the grass (17662 and 16733 cm²) compared to other grasses. Thus, hybrid Napier grasses, with their wider foliage spread, provide the maximum protection by covering a larger ground surface area.

The highest root depth was recorded in vetiver grass (47 cm), which was on par with Cumbu Napier hybrid CO (CN) 4 (43.1 cm) and Bajra Napier CO (BN) 5 (43.8 cm). In contrast, root lateral spread was significantly higher in Bajra Napier CO (BN) 5 (37.8 cm), followed by Cumbu Napier hybrid CO (CN) 4 (36.6 cm), Congo signal grass (36.6 cm), and weeping love grass (35.2 cm). Both Bajra Napier CO (BN) 5 and Cumbu Napier hybrid CO (CN) 4 produced significantly greater root volume (65.3 cc and 60.6 cc, respectively) and root mass density (1.26 g/cc and 1.20 g/cc), which were on par with vetiver grass (Table 2).

The grass species significantly influenced the volume of soil bound by the roots. The highest value (195613 cc) was recorded in Bajra Napier CO (BN) 5, and on par with Cumbu Napier hybrid CO (CN) 4, and it was followed by Congo signal grass (160677 cc), and vetiver grass (154923 cc). Since the volume of soil bound by roots is a function of root depth and root lateral spread, the higher values observed in hybrid Napier and Congo signal grass can be attributed to their greater root lateral spread (combined with higher root depth in hybrid Napier). Vetiver exhibited the deepest roots (47.0 cm;) but a smaller lateral spread than BN hybrids, resulting in significantly lower ($P < 0.05$) estimated soil volume bound by roots than BN CO (BN) 5. Wang and Zhang (2017) reported that plant root systems reduced soil detachment capacity by 53.6%, of which 41.4% and 12.2% were attributed to root binding and bonding effects, respectively. However, the two-year duration likely captures early canopy and root responses but may underestimate later-phase root lateral spread/mass density and SOC accrual typical of perennial grasses; multi-year monitoring is recommended.

TABLE 1 Surface area protected by various grasses against rain

Grass	Plant height (cm)	Tillers/ Plant	Foliage Lateral Spread (cm)	Surface area protected by the grass (cm ²)
Cumbu Napier hybrid CO (CN) 4	137.6 ^a	68.3 ^c	146.2 ^a	16733 ^a
Bajra Napier CO (BN) 5	145.5 ^a	75.4 ^b	150.4 ^a	17662 ^a
Guinea grass	128.6 ^a	54.0 ^a	126.2 ^b	12462 ^c
Weeping love grass	64.8 ^c	115.6 ^a	138.8 ^a	14950 ^b
Guatemala grass	148.6 ^a	46.4 ^c	142.6 ^a	15828 ^b
Vetiver	125.6 ^b	66.6 ^c	120.4 ^b	11304 ^d
Lemon grass	110.0 ^c	81.4 ^b	130.2 ^b	13266 ^c
Congo signal grass	98.6 ^d	58.3 ^d	90.2 ^c	6358 ^e
SEm±	5.2	4.25	7.93	492
CD p≤ 0.05	14.4	11.8	22.0	1365

Means with the same alphabet are not significantly different ($P \leq 0.05$).

TABLE 2 Root character and volume of soil bound by root

Grass	Root depth (cm)	Root lateral spread (RLS) (cm)	Root volume (cc)	Root mass density (gm/cc)	Volume of soil bound by roots (cc)
Cumbu Napier hybrid CO (CN) 4	43.1 ^a	36.6 ^a	60.6 ^a	1.20 ^a	180867 ^a
Bajra Napier CO (BN) 5	43.8 ^a	37.8 ^a	65.3 ^a	1.26 ^a	195613 ^a
Guinea grass	38.2 ^b	31.6 ^a	40.4 ^c	0.82 ^c	119775 ^d
Weeping love grass	30.0 ^c	35.2 ^a	25.0 ^d	0.74 ^d	116717 ^d
Guatemala grass	41.9 ^a	32.4 ^b	52.3 ^b	0.88 ^b	138112 ^c
Vetiver	47.0 ^a	32.4 ^b	55.0 ^b	1.24 ^a	154923 ^b
Lemon grass	40.2 ^b	30.6 ^b	30.0 ^d	0.66 ^d	118194 ^d
Congo signal grass	38.2 ^b	36.6 ^a	55.8 ^b	0.91 ^b	160677 ^b
SEm±	1.3	1.0	2.60	0.03	5335
CD (p≤ 0.05)	3.6	2.6	7.2	0.07	14810

Means with the same alphabet are not significantly different ($P \leq 0.05$).

3.2 | Soil Ecosystem Function

The increase in soil organic carbon stock over the initial value was the highest under vetiver grass (38.7 t ha⁻¹), which was significantly ($P \leq 0.05$) superior to all other grasses (Fig. 1). It was followed by Cumbu Napier Co(CN) 4 (33.7 t ha⁻¹), and was statistically on par with Bajra Napier Co(BN) 5 (32.3 t ha⁻¹), Weeping love grass (32.7 t ha⁻¹), and Congo signal grass (31.7 t ha⁻¹). Although Congo signal grass contributed relatively little to surface area protection against raindrops, its wider lateral root spread and dense root mats led to higher soil organic carbon accumulation. Similar findings were reported by Anup *et al.* (2019), who observed higher soil organic carbon stock under Congo signal grass and hybrid Napier grasses in the Tripura hills.

Soil CO₂ emission (Fig. 2) varied significantly among the grasses. The highest emission was recorded in soils under vetiver grass (34.73 t ha⁻¹ yr⁻¹), followed by soils under Guatemala grass (32.34 t ha⁻¹ yr⁻¹). In contrast, soils under Cumbu Napier hybrid CO (CN) 4 released the least amount of CO₂ (18.55 t ha⁻¹ yr⁻¹), as estimated using the

EGM-5 Soil CO₂ Analyzer. With respect to sequestration (Fig. 2), vetiver grass absorbed the most significant amount of atmospheric CO₂ (85.17 t ha⁻¹ yr⁻¹), followed by lemon grass (78.35 t ha⁻¹ yr⁻¹) and CO 5 (68.24 t ha⁻¹ yr⁻¹). These results clearly indicate that all the grasses studied acted as strong sinks for atmospheric CO₂, except Cumbu Napier hybrid CO (CN) 4, which had comparatively lower sequestration potential. The observed higher CO₂ emission under vetiver and Guatemala grasses aligns with earlier reports that deep-rooted perennial grasses enhance microbial activity and root respiration, thereby increasing CO₂ efflux (Singh *et al.*, 2009). However, these species also exhibited strong carbon sequestration potential, consistent with the findings of Conant *et al.* (2017), who reported that perennial grasses are effective atmospheric CO₂ sinks.

3.3 | Biomass Yield and Fodder Quality

Biomass yield and fodder quality (Fig. 3) varied considerably among the grasses studied. Bajra Napier hybrid CO (BN) 5. Month-wise analysis indicated that biomass production was generally higher during the rainy

season, while in winter, Bajra Napier CO (BN) 5 maintained superior yield due to its greater tolerance to frost (Fig. 4). In terms of nutritive value, hybrid Napier exhibited the highest crude protein content (14%), followed by Cumbu Napier CO 4, whereas native grasses recorded relatively lower protein levels. These findings are in line with the report by Gupta et al. (2019), who observed that hybrid Napier grass produced significantly higher biomass than native grasses under the humid tropical conditions of Eastern India. Similarly, studies by Pathan *et al.* (2012) and Kumar *et al.* (2023) have highlighted that improved Napier hybrids not only yield higher biomass but also have higher crude protein and digestibility than traditional grasses, making them highly suitable for fodder production under intensive livestock systems. Napier (Napier–bajra hybrids) provides a threefold benefit: fodder value, soil conservation effectiveness, and carbon sequestration that aligns with national and international research. Multi-location fodder

evaluations in India report that hybrid Napier consistently delivers higher biomass and superior forage quality than many competing grasses (Gupta et al., 2019). On sloping land, Napier hedgerows and grass strips serve as effective vegetative barriers, reducing runoff and soil erosion while promoting terrace formation—a process observed across Asia and Africa and measured under simulated storms (Kafle & Balla, 2008; Do et al., 2023). Beyond controlling erosion, perennial grass systems—including those with Napier-based strips—build soil organic carbon (SOC) through continuous root inputs and litter, functioning as net carbon sinks when managed with minimal disturbance (Conant et al., 2017; Do et al., 2023; Singh & Sharma, 2019). Together, these studies reinforce our Nilgiris findings that Napier hybrids simultaneously maximize fodder yield, stabilize slopes, and enhance SOC, making them a scalable, nature-based solution for hill farming systems.

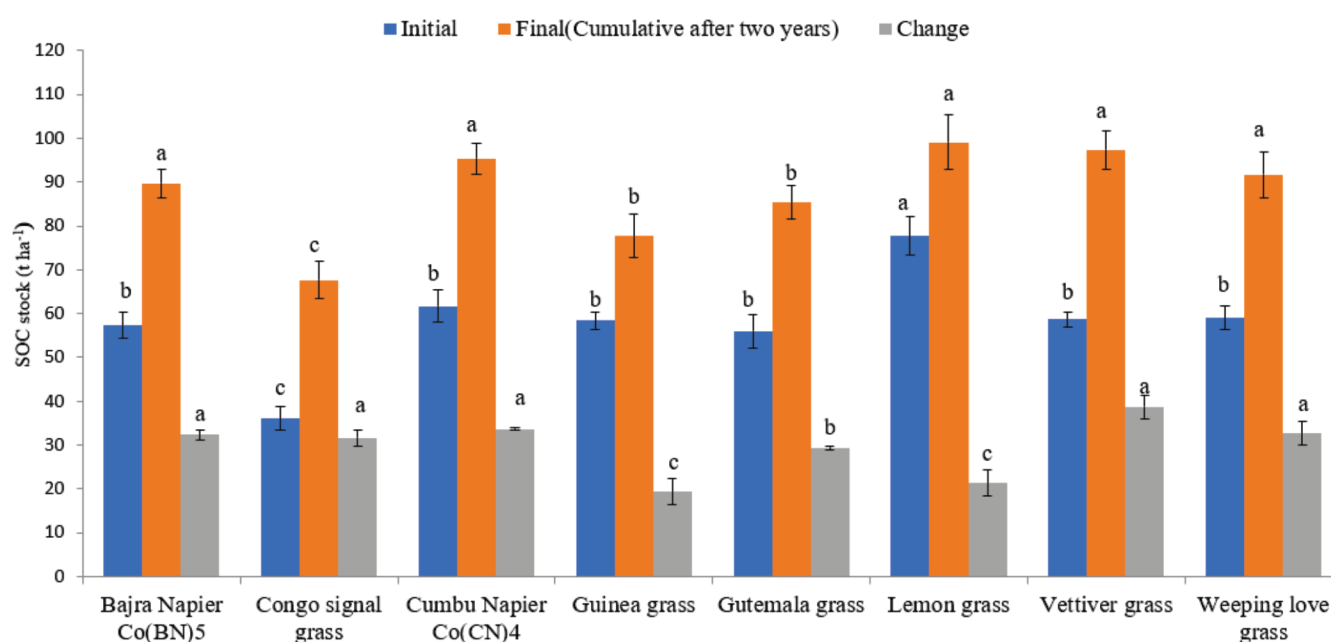


FIGURE 1 Effect of perennial grass species on soil organic Carbon (SOC) stock (t ha^{-1}) over two years. Error bars represent SEM ($n=3$). Columns followed by different letters differ significantly at $P \leq 0.05$ (DMRT)

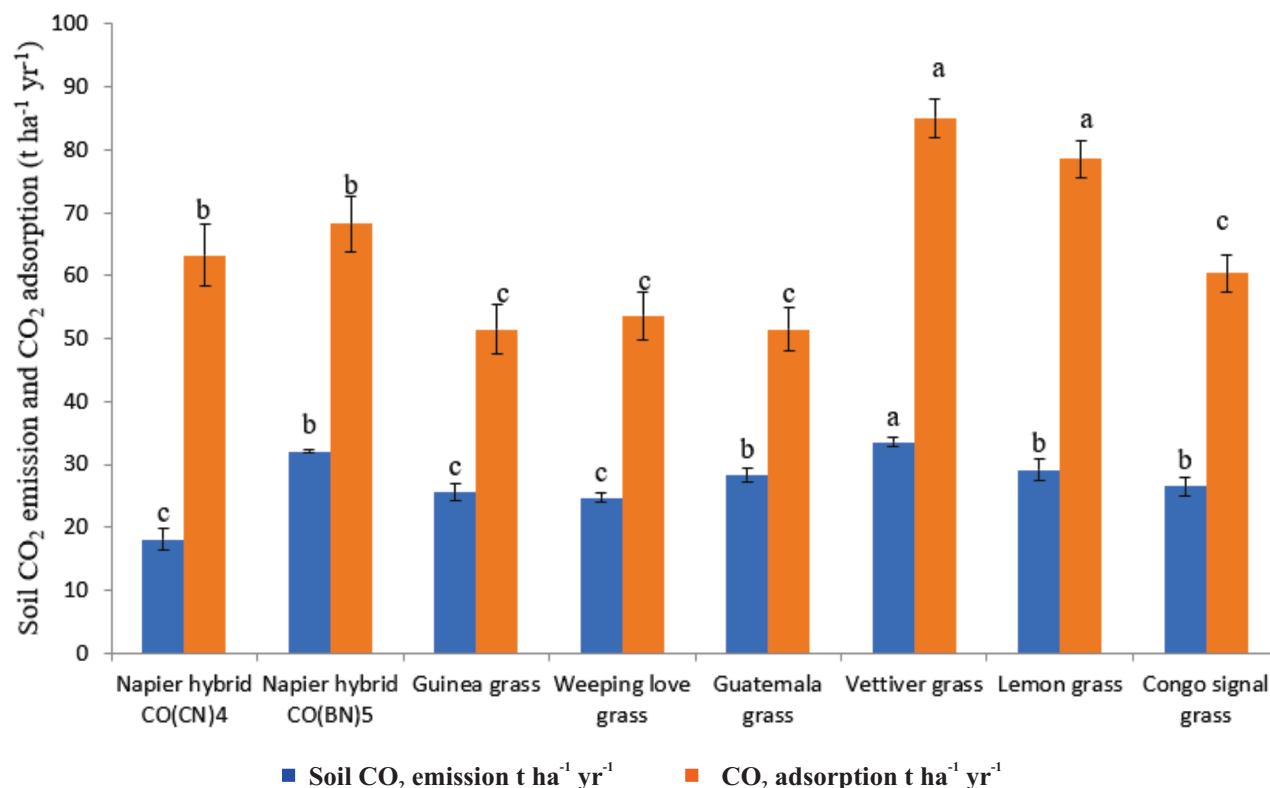


FIGURE 2 Soil CO₂ emission and atmospheric CO₂ adsorption (t ha⁻¹ yr⁻¹) under different perennial grasses. Errors bars represent mean $\pm$ SEM ($n = 3$). Bars followed by different letters differ significantly at $P \leq 0.05$ according to DMRT

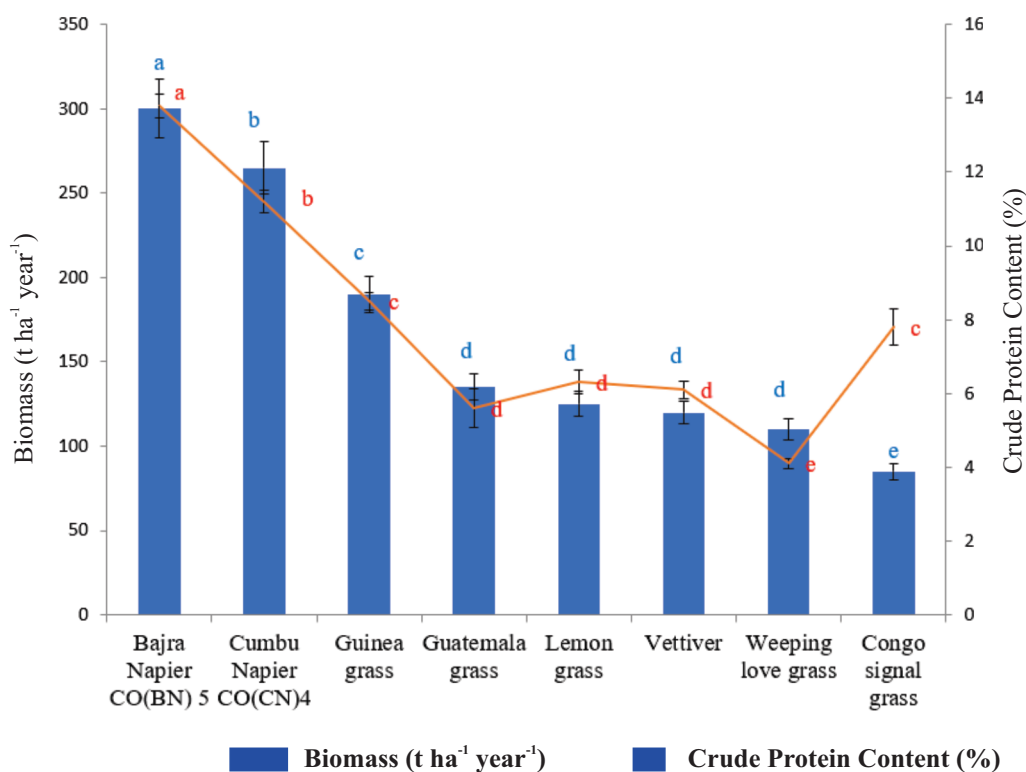


FIGURE 3 Biomass yield and crude protein content of various perennial grasses (mean $\pm$ SEM, $n = 3$).

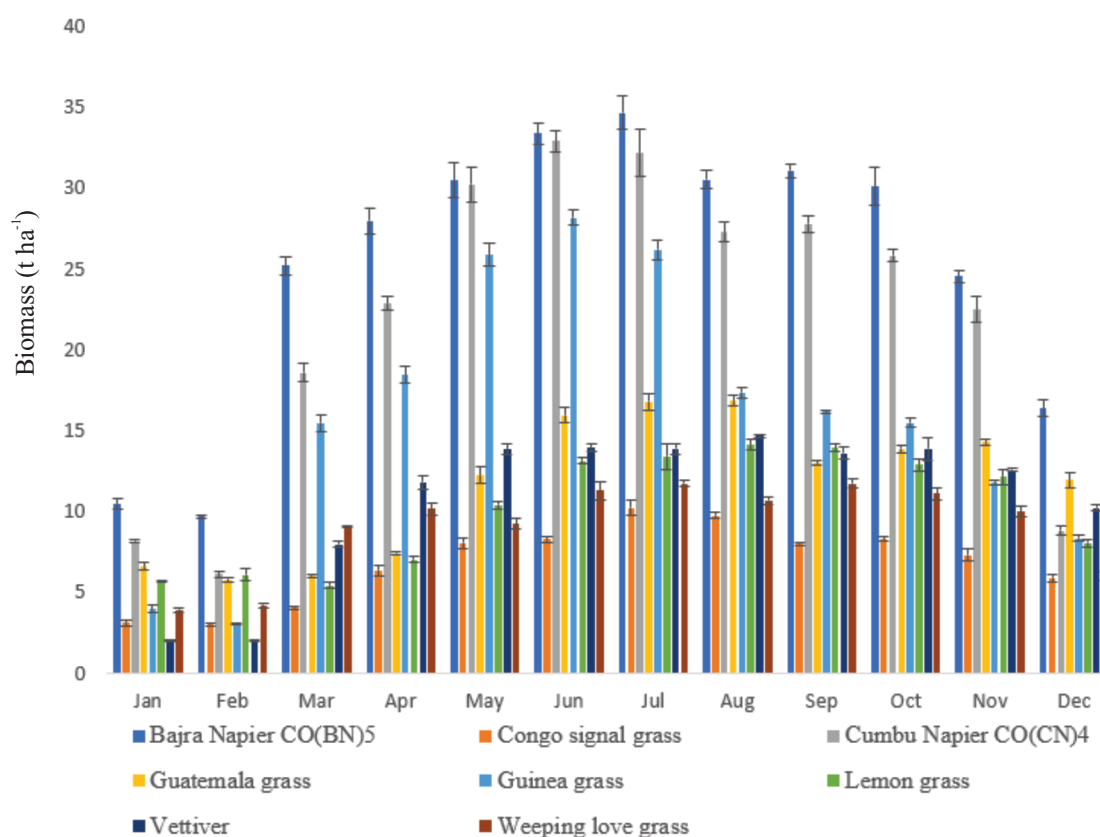


FIGURE 4 Monthly biomass production of various perennial grasses (mean $\pm$ SEM, $n = 3$).

4.0 | CONCLUSIONS

This study demonstrates that grass species differ significantly in soil conservation efficiency, biomass production, and ecosystem services, offering distinct functional advantages for hill agriculture. Bajra Napier CO (BN) 5 and Cumbu Napier CO (CN) 4 emerged as optimal dual-purpose species, excelling in both erosion control—through wider foliage spread, higher root mass density, and greater soil volume bound by roots—and fodder production, delivering superior biomass yields and nutritive quality. In contrast, vetiver and Congo signal grasses contributed more substantially to soil organic carbon accumulation and sequestration, with vetiver achieving the highest atmospheric CO₂ uptake (85.17 t ha⁻¹ yr⁻¹) despite elevated soil respiration rates.

These findings support a species-specific integration strategy: combining high-yielding Napier hybrids for immediate fodder and surface protection with deep-rooted grasses like vetiver for long-term carbon storage provides a comprehensive solution to soil erosion, fodder scarcity, and climate mitigation in sloping terrains. Such vegetative barrier systems represent a sustainable, economically viable alternative to conventional bench terracing, particularly suitable for smallholder farmers in

the Nilgiri hills and similar fragile ecosystems.

However, the two-year study duration may underestimate longer-term root system development and soil organic carbon accrual typical of perennial grasses. Future research should include multi-year monitoring across diverse sites and slopes, with direct measurement of runoff and sediment yield under natural and simulated rainfall events. Additionally, optimizing fodder harvest intervals to balance biomass production with continuous ground cover for erosion control warrants investigation. Integration of these grasses into watershed development programs, supported by performance-linked incentives and monitoring frameworks for carbon and soil credits, could enhance adoption and remunerate farmers for verified environmental benefits.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

All data supporting the findings of this study are available from the corresponding author upon reasonable request. Summary datasets generated or analyzed during the current study are included in the article.

AUTHOR'S CONTRIBUTION

KK: Project execution, biometric observations, soil conservation efficiency estimation, and manuscript preparation; CB: Species selection, cultivation practice standardization, protein analysis, and result interpretation; PS: Field demonstrations, farmer training, and result interpretation; KR: Soil physical and chemical analysis, soil organic carbon stock estimation, and data interpretation; PR: Measurement of soil CO₂ flux, atmospheric carbon absorption by grasses, and data interpretation.

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