

Article

Sustainable Intensification of Napier Grass: Intercropping with Legumes and Reduced Nitrogen Fertilization for Yield Maintenance and Carbon Sequestration

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Abstract

Driven by global climate change and Taiwan's Net-Zero initiatives, high-input livestock farming faces urgent pressures to transform. *Pennisetum purpureum*, a primary forage and bioenergy crop, traditionally relies on heavy chemical nitrogen inputs, thereby exacerbating its carbon footprint. This study evaluated a sustainable cultivation model integrating legume intercropping with reduced fertilization. A field trial in central Taiwan utilizing a Completely Randomized Design (CRD) compared four treatments: conventional full nitrogen (800 kg N/ha), sunn hemp (*Crotalaria juncea*) intercropping with half nitrogen, sunn hemp intercropping only, and organic compost. We monitored biomass, forage chemistry, and soil organic carbon (SOC) dynamics. The sunn hemp plus half-nitrogen treatment achieved dry matter yields (30–35 Mg/ha) and crude protein levels (7.1–7.4%) statistically equivalent to the full-nitrogen control, significantly surpassing other groups. While short-term SOC stocks (72–81 Mg C/ha) showed no significant differences, trends indicated carbon accumulation in deep soil (30–50 cm). Consequently, substituting 50% of chemical nitrogen through biological fixation proves a viable strategy to maintain yield while reducing inputs. This model sustains productivity and mitigates greenhouse gas emissions, offering an economically feasible, potential carbon-negative solution for tropical forage systems.

Keywords: *Pennisetum purpureum*; *Crotalaria juncea*; intercropping; soil organic carbon; nitrogen use efficiency; net-zero agriculture



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1. Introduction

Napier grass (*Pennisetum purpureum*) has emerged as a pivotal crop supporting the dairy industry and bioenergy development in tropical and subtropical regions worldwide, owing to its superior biomass production, rapid growth rate, and broad environmental adaptability [1,2]. In the context of global climate change, soil carbon sequestration is regarded as a critical strategy for mitigating the greenhouse effect. Perennial forage systems play a key role in this process; their extensive root biomass and reduced soil disturbance render them high-potential terrestrial carbon sinks [3,4]. However, to exploit the high photosynthetic potential of this C4 species and maintain high productivity, conventional farming practices typically rely on intensive chemical nitrogen fertilization [5]. While this high-input model ensures food and feed security, it exerts significant environmental pressure.

The manufacture and field application of chemical fertilizers constitute the primary source of greenhouse gas (GHG) emissions in Napier grass production systems, accounting for over 60% of the total carbon footprint [6]. Long-term excessive application may lead to soil acidification, reduced microbial diversity, and the eutrophication of water bodies [6]. Rahman et al. [7] highlighted that excessive nitrogen application not only violates the Law of Diminishing Returns in terms of yield but also inflicts long-term detrimental impacts on soil health, thereby weakening ecosystem resilience. Consequently, developing a sustainable cultivation model that balances “maintaining high productivity” with “mitigating carbon emissions” has become a pressing priority for agricultural scientists and policymakers [8].

Grass–legume intercropping is considered one of the most promising solutions to these challenges. Legumes facilitate biological nitrogen fixation (BNF) through symbiosis with rhizobia, converting atmospheric nitrogen into plant-available forms and providing a natural, slow-release nitrogen source [9]. A recent study highlights that Napier grass-based intercropping with legume cover crops significantly enhances overall land productivity through spatial and temporal complementarity, as evidenced by improved Land Equivalent Ratios (LERs) [10]. Specifically, long-term studies in Thailand and recent evaluations of nitrogen dynamics have demonstrated that Sunn hemp (*Crotalaria juncea*), as a fast-growing green manure crop, outperforms other legumes in biomass accumulation and effectively synchronizes nutrient release with the peak demand of companion crops [11,12].

Regarding carbon sequestration, appropriate intercropping combined with reduced fertilization not only sustains yields but also enhances the sequestration potential of soil organic carbon (SOC). The integration of diverse root architectures and specific root exudates in these mixed systems has been shown to alter soil microbiological attributes, which facilitates the stabilization of soil organic matter [13]. These optimized nutrient cycling and increased belowground biomass inputs are particularly critical for maintaining long-term soil health in perennial forage systems [3,4] and have been shown to offset greenhouse gas emissions (such as N_2O and CO_2) in tropical pasture management [8,14].

However, there remains a paucity of site-specific assessments regarding the carbon sequestration benefits and production efficiency of “Napier grass intercropped with Sunn hemp combined with reduced fertilization” under the specific climatic and edaphic conditions of Taiwan. This study aims to bridge this knowledge gap by testing the following hypothesis: that the incorporation of intercropped Sunn hemp can substitute for 50% of chemical nitrogen inputs without significantly compromising the yield and quality of Napier grass, while simultaneously maintaining or enhancing soil carbon stocks, thereby establishing a carbon-negative forage production system.

2. Materials and Methods

2.1. Study Site and Experimental Design

The field experiment was conducted at the Fuxing experimental site in Changhua County, central Taiwan (TWD97 coordinates: $X = 196,691$, $Y = 2,658,664$). The region is characterized by a typical subtropical monsoon climate, featuring hot, humid summers and mild, relatively dry winters. The experimental site is located on the Changhua coastal alluvial plain at an elevation of approximately 20–25 m above sea level. Prior to the establishment of the experiment, the field had been managed under a rice–green manure–short-season vegetable rotation system for more than 10 years, representing a typical cropping system in the region, and had remained fallow for approximately six months. According to the Taiwan Soil Survey Geographic Database (TSSURGO), the soil belongs to the Fuhsin Series, which is classified as Typic Endoaquents (Endoaquents, Aquents, Entisols)

under the USDA Soil Taxonomy system [15]. The soil was developed from recent alluvial deposits derived mainly from the Choshui River, consisting of mixed sand, silt, and clay sediments. The surface soil exhibits a sandy loam texture and is poorly to somewhat poorly drained. Baseline analysis indicated that the surface soil (0–30 cm) had a pH of 6.82 ± 0.11 (1:1 soil/water) and an organic carbon content of $2.07 \pm 0.13\%$.

The climatic conditions of the experimental site are highly conducive to the growth dynamics of the selected crops. As illustrated in Figure 1 (data sourced from the adjacent Taichung Weather Station), the primary precipitation period extends from April to October, accompanied by high average summer temperatures ranging from 28 to 30 °C between June and September. This hot and humid environment provides an optimal meteorological setting for the rapid biomass accumulation of C4 tropical forage species, such as Napier grass (*Pennisetum purpureum*), and tropical leguminous green manure crops, such as Sunn hemp (*Crotalaria juncea*). Consequently, the distinct climatic characteristics of this location make it an exceptionally suitable environment for evaluating the agronomic performance of this specific intercropping system.

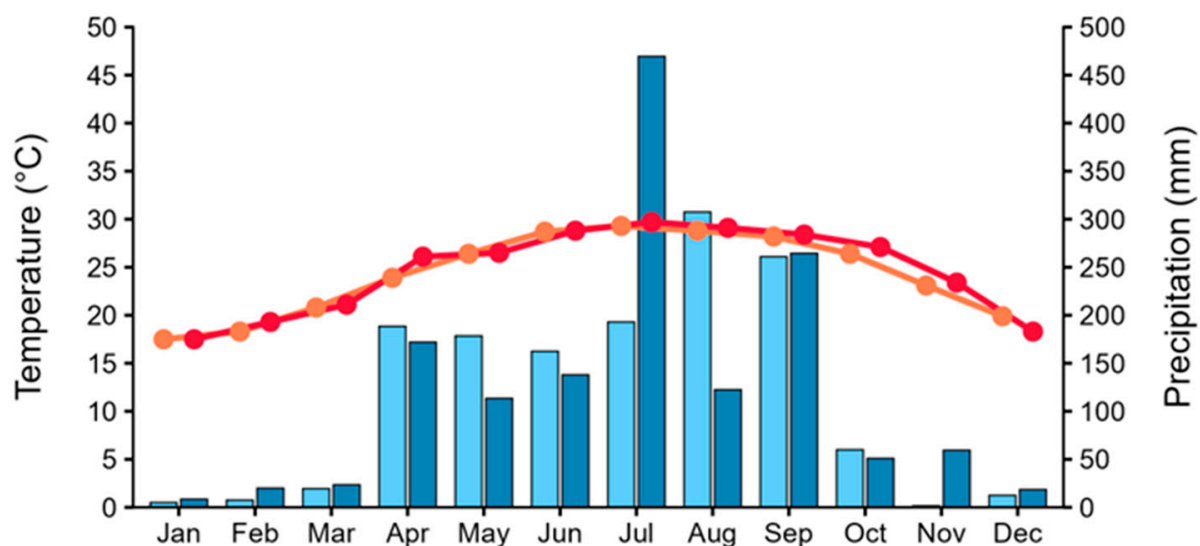


Figure 1. Interannual variations in monthly average temperature and total precipitation during the field experiment (2023–2024). Lines with solid markers illustrate the monthly average temperature (°C, left y-axis), with the light orange line representing 2023 and the dark red line representing 2024. The corresponding dodged bars denote the monthly total precipitation (mm, right y-axis), with the light blue bars indicating 2023 and the dark blue bars indicating 2024. Meteorological data were obtained from the Taichung Weather Station, Central Weather Administration.

The experiment was arranged in a Completely Randomized Design (CRD) comprising four cultivation treatments. A CRD was deliberately selected and justified based on the rigorous assessment of the experimental site's initial homogeneity: the completely flat topography engineered for paddy systems, the highly homogenized soil conditions resulting from historical puddling, and the statistically narrow variance of the pre-experiment baseline soil properties (e.g., pH 6.82 ± 0.11 and SOC $2.07 \pm 0.13\%$ across the site), which provided strong empirical evidence of spatial uniformity and effectively minimized external environmental variability. Each treatment was replicated three times. Individual plots measured 10 m × 10 m, with adequate buffer zones established to minimize interference between treatments. The specific treatment combinations applied in the Fuxing trial were as follows:

Conventional (T1): Chemical nitrogen fertilizer was applied at the recommended rate (800 kg N/ha/yr) in accordance with the guidelines of the Livestock Research Institute, Ministry of Agriculture (Taiwan) [12], serving as the standard control.

Intercropping + 50% N (T2): Sunn hemp was intercropped following the forage harvest, combined with a 50% reduction in chemical nitrogen fertilizer application, to assess the feasibility of a reduced fertilization strategy.

Intercropping (T3): This treatment relied solely on nitrogen fixation from green manure for nutrient supply, with the complete exclusion of chemical nitrogen fertilizer, to evaluate the maximum potential contribution of the green manure.

Compost (T4): Livestock and poultry manure compost (35 t/ha/yr) was applied to serve as a fully organic management control. The application was split into basal fertilizer (applied at stand establishment or the beginning of each year) and top dressing (applied after each forage harvest), distributed evenly between the rows of Napier grass.

2.2. Crop Management and Data Collection

The experimental material used was Napier grass cv. Taishiu No. 8 (*Pennisetum purpureum* cv. Taishiu No. 8), a high-quality cultivar characterized by vigorous tillering, tender foliage, excellent relative feed value (RFV), delayed senescence, and high yield potential [16]. Commercial green manure seeds of sunn hemp (*Crotalaria juncea* L.), imported from India, were purchased from Ming Feng Seed Co., Ltd. (Taichung, Taiwan) and utilized for all intercropping treatments. For the intercropping treatments, sunn hemp was sown in the inter-row spaces of the Napier grass immediately following the forage harvest at a seeding rate of 20 kg/ha. Approximately 6–8 weeks after sowing, when sunn hemp had reached a height of 100 cm but before stem lignification, the plants were incorporated into the soil with a rotary cultivator. This precise timing ensured that the green manure maintained a low carbon-to-nitrogen (C/N) ratio (typically < 20:1) and prevented stem lignification, thereby facilitating rapid decomposition and nutrient release in synchrony, a dynamic well documented in previous evaluations of *Crotalaria juncea* incorporation [17]. Following the incorporation of green manure, the Napier grass was allowed to regrow.

Data collection spanned 2023 and 2024. Napier grass was harvested approximately every 12–16 weeks, which corresponds to the recommended harvest interval for optimal forage production. Specifically, two forage harvests were conducted per year. The exact harvest dates were 29 April and 24 July in 2023 and 9 April and 14 October in 2024. At each harvest, a representative 1 m² quadrat was randomly selected within each plot and cut to determine the total fresh matter yield. From this harvested biomass, the plant material was thoroughly mixed, and a representative subsample of approximately 2 kg was immediately collected. This subsample was weighed fresh, oven-dried at 70 °C for 48 h, and reweighed to determine the dry matter (DM) percentage. The total dry matter yield (DMY) was subsequently calculated by multiplying the fresh matter yield by the corresponding DM percentage. Following the methodology described by Li et al. [16], the dried samples were ground to pass through a 1 mm sieve to determine the contents of crude protein (CP), acid detergent fiber (ADF), and neutral detergent fiber (NDF) to evaluate forage quality.

2.3. Soil Sampling and Carbon Stock Analysis

Soil sampling was conducted 1–2 weeks after each forage harvest to track temporal SOC dynamics and determine soil bulk density (BD), coarse fragment content, and soil organic carbon (SOC) concentration. Stratified soil sampling was performed using a soil auger at three distinct depth intervals: the topsoil layer (0–10 cm), the dense root zone (10–30 cm), and the deep soil layer (30–50 cm). At each depth, three soil cores were randomly collected within each experimental plot, resulting in a total of nine samples per plot.

Soil samples collected at the same depth within each plot were thoroughly composited and homogenized to obtain a single representative sample for laboratory analysis. Each treatment was performed in triplicate.

Undisturbed soil cores were collected using a fixed-volume soil core sampler for bulk density determination. The samples were oven-dried at 105 °C and weighed, enabling the calculation of the soil bulk density from their fresh and dry weights.

Soil samples designated for chemical analysis were air-dried at room temperature, gently crushed, and passed through a 10-mesh sieve (<2 mm). Material retained on the sieve (>2 mm) was classified as coarse fragments, and its dry weight was recorded to determine the coarse fragment content. The fine-earth fraction (<2 mm) was subsequently ground and passed through a 30-mesh sieve (<0.6 mm). The resulting homogenized soil samples were used to determine SOC concentration using a total organic carbon analyzer (Model OIA_1030D, OI Analytical, TX, USA; supplied by SYSTEMATIC Instruments Co., Ltd., New Taipei City, Taiwan). The soil carbon stock for each soil layer was estimated using the following equation:

$$SOC\ Stock = \sum_{i=1}^n [C_i \times BDi \times Di \times (1 - Si)] \quad (1)$$

where C_i represents the soil organic carbon concentration of the i -th layer (%), BDi is the bulk density (g/cm^3), Di denotes the thickness of the soil layer (cm), and Si is the rock fragment content.

2.4. Statistical Analysis

Data regarding agronomic traits, biomass yield, and forage quality (CP, ADF, NDF) were analyzed using a standard Analysis of Variance (ANOVA). In this model, cultivation treatments (T1–T4) and harvest years (2023, 2024) were designated as fixed factors to evaluate their main effects and interactions.

Conversely, to strictly control for potential spatial heterogeneity in soil parameters inherent to the CRD, an Analysis of Covariance (ANCOVA) was employed specifically for the soil organic carbon (SOC) stock data. To explicitly account for any underlying soil fertility gradients, the pre-experiment baseline SOC stock for each plot was included as a continuous covariate. This approach statistically adjusted the post-treatment SOC outcomes into Estimated Marginal Means (EMMs), significantly minimizing experimental error. All data processing, graphical visualizations (including the climograph generated via the ggplot2 package), and statistical analyses were conducted using the R statistical software environment (version 4.5.2; R Core Team, Vienna, Austria). When main effects or interactions were deemed statistically significant ($p < 0.05$), mean separations were performed using Fisher's Least Significant Difference (LSD) test.

3. Results

3.1. Biomass Yield

The results presented in Table 1 indicate that the different cultivation practices significantly affected the agronomic traits and yield performance of Napier grass. The complete analysis of variance (ANOVA), detailing the degrees of freedom, mean squares, and F -values for all main effects and interactions regarding agronomic traits, is provided in Supplementary Table S1. Over the harvest cycles in both 2023 and 2024, the “Conventional (T1)” and “Intercropping + 50% N (T2)” treatments consistently outperformed the other treatments. Although T1 was slightly superior to T2 in plant height and tiller number, no significant differences were observed between the two.

Table 1. Variations in Agronomic Traits and Yield Under Different Farming Systems Between 2023 and 2024.

Year and Treatment	Agronomic Traits			
	Plant Height (cm)	Number of Tillers (no/plant)	Fresh Matter Yield (Mg/ha)	Dry Matter Yield (Mg/ha)
2023				
T1	203.1 ± 5.4 Aa	32.0 ± 2.0 Ba	176.45 ± 17.6 Aa	35.29 ± 3.5 Aa
T2	188.9 ± 4.1 Ab	24.3 ± 3.1 Bb	151.43 ± 11.5 Aab	30.29 ± 2.3 Aa
T3	191.3 ± 1.1 Ab	22.3 ± 0.6 Ab	148.49 ± 10.5 Ab	29.70 ± 2.1 Aa
T4	187.7 ± 4.5 Ab	20.0 ± 1.7 Bb	147.62 ± 12.1 Ab	29.52 ± 6.2 Aa
Mean	192.8 ± 3.2 A	24.7 ± 1.8 B	156.00 ± 6.7 A	31.20 ± 1.8 A
2024				
T1	198.7 ± 4.8 Aa	41.0 ± 1.3 Aa	69.82 ± 2.13 Ba	15.57 ± 1.00 Ba
T2	183.9 ± 5.5 Ab	34.5 ± 1.3 Ab	65.44 ± 4.56 Ba	15.25 ± 0.38 Ba
T3	161.7 ± 4.0 Ac	26.2 ± 1.2 Ac	47.66 ± 4.79 Bb	9.33 ± 2.25 Bb
T4	164.8 ± 3.8 Bc	30.5 ± 1.8 Ad	54.91 ± 4.58 Bb	11.72 ± 0.59 Bb
Mean	177.3 ± 4.6 B	33.1 ± 1.7 A	59.46 ± 2.80 B	12.97 ± 0.85 B
Overall Treatment Mean				
T1	200.9 ± 3.5 a	36.5 ± 2.2 a	123.14 ± 22.5 a	25.43 ± 4.3 a
T2	186.4 ± 3.3 b	29.4 ± 2.3 b	108.44 ± 18.2 ab	22.77 ± 3.2 a
T3	176.5 ± 6.4 b	24.3 ± 1.0 c	98.08 ± 21.0 b	19.52 ± 4.3 a
T4	176.3 ± 5.0 b	25.3 ± 2.2 bc	101.27 ± 20.0 b	20.62 ± 4.0 a

Treatments: T1, conventional farming with full nitrogen fertilizer; T2, intercropping with *Crotalaria juncea* plus 50% nitrogen fertilizer; T3, intercropping with *C. juncea*; T4, compost application. Data are expressed as mean ± SE. Means followed by different uppercase letters between years for the same treatment are significantly different ($p < 0.05$); means followed by different lowercase letters within the same column and year are significantly different ($p < 0.05$) according to Fisher's LSD test. The explicit Fisher's Protected $LSD_{0.05}$ values for comparing treatments within a year are 15.0 cm for plant height, 6.0 no/plant for number of tillers, 27.1 Mg/ha for fresh matter yield, and 9.0 Mg/ha for dry matter yield. Main effect $LSD_{0.05}$ values (treatment overall) are 10.6 cm, 4.2 no/plant, 19.2 Mg/ha, and 6.4 Mg/ha, respectively.

Further analysis of the year effect revealed that yield performance across all treatments was significantly lower in 2024 than in 2023. For instance, in treatment T2, the dry matter yield (DMY) reached 30.29 ± 2.3 Mg/ha in 2023, which was comparable to the 35.29 ± 3.5 Mg/ha observed in T1. However, by 2024, yields across all treatments showed a substantial decline, with the DMYs of T2 and T1 dropping to 15.25 Mg/ha and 15.57 Mg/ha, respectively. Notably, despite the significant decline in yield in 2024, the tiller numbers in treatments T1 and T2 showed a significant increasing trend between years. For example, the tiller number in T1 increased from 32.0 in 2023 to 41.0 in 2024, while in T2, it increased from 24.3 to 34.5.

In contrast, the agronomic traits and yields of the “Intercropping (T3)” and “Compost (T4)” treatments were significantly lower than those of T1 and T2 in both years. Specifically, in 2024, the DMY of T3 fell to only 9.33 Mg/ha, which was significantly lower than the other treatments.

3.2. Forage Quality

Experimental results demonstrated that the impact of different cultivation models on CP content exhibited a consistent trend across both years. The full ANOVA results for forage quality parameters are detailed in Supplementary Table S2. In 2024, the CP contents for the “Conventional (T1)” and “Intercropping + 50% N (T2)” treatments were both 7.25%, which was significantly higher than the 6.55% in “Intercropping (T3)” and 6.80% in “Compost (T4)” (Table 2).

Table 2. Variations in Crude Protein and Fiber Contents Under Different Farming Systems Between 2023 and 2024.

Year and Treatment	CP (%)	ADF (%)	NDF (%)
2023			
T1	6.95 ± 0.2 Aab	34.20 ± 1.8 Aa	61.35 ± 1.3 Ab
T2	7.10 ± 0.2 Aa	33.20 ± 1.2 Aa	61.70 ± 1.1 Ab
T3	6.55 ± 0.2 Ac	32.80 ± 1.7 Aa	63.55 ± 1.9 Aa
T4	6.90 ± 0.3 Ab	31.95 ± 1.4 Aa	61.05 ± 1.5 Ab
Mean	6.88 ± 0.12 A	33.04 ± 0.72 A	61.91 ± 0.73 A
2024			
T1	7.25 ± 0.1 Aa	33.15 ± 1.2 Aa	62.80 ± 1.2 Aa
T2	7.25 ± 0.2 Aa	32.80 ± 1.2 Aa	61.30 ± 1.3 Aa
T3	6.55 ± 0.3 Ab	33.25 ± 2.1 Aa	61.80 ± 1.5 Aa
T4	6.80 ± 0.3 Ab	32.70 ± 1.6 Aa	60.60 ± 1.6 Aa
Mean	6.96 ± 0.14 A	32.98 ± 0.70 A	61.63 ± 0.68 A
Overall Treatment Mean			
T1	7.10 ± 0.12 a	33.68 ± 1.02 a	62.08 ± 0.88 a
T2	7.18 ± 0.12 a	33.00 ± 0.80 a	61.50 ± 0.80 a
T3	6.55 ± 0.16 b	33.03 ± 1.28 a	62.68 ± 1.18 a
T4	6.85 ± 0.18 ab	32.33 ± 1.00 a	60.83 ± 1.02 a

Treatments: T1, conventional farming with full nitrogen fertilizer; T2, intercropping with *Crotalaria juncea* plus 50% nitrogen fertilizer; T3, intercropping with *C. juncea*; T4, compost application. Data are expressed as mean ± SE. Means followed by different lowercase letters within the same column and year are significantly different ($p < 0.05$); means followed by different uppercase letters between years for the same treatment are significantly different ($p < 0.05$) according to Fisher's LSD test. The explicit Fisher's Protected $LSD_{0.05}$ values are 0.60% for CP, 4.50% for ADF, and 4.50% for NDF. Main effect $LSD_{0.05}$ values (treatment overall) are 0.42% for CP, 3.18% for ADF, and 3.18% for NDF.

Regarding interannual variations, the data in Table 2 revealed no significant differences in CP, ADF, and NDF contents across all treatments between the two years. For example, in the T2 treatment, the CP content slightly increased from $7.10 \pm 0.2\%$ in 2023 to $7.25 \pm 0.2\%$ in 2024, while ADF and NDF values remained stable. In terms of fiber components, aside from the significantly higher NDF content observed in T3 during 2023, the ADF and NDF contents across the remaining treatments showed no significant differences in either year.

3.3. Soil Organic Carbon Stock

The results presented in Table 3 indicate that the soil carbon stocks in the primary root zone (0–30 cm layer) across all treatment groups ranged approximately from 72.2 to 81.2 Mg C/ha. To strictly control for initial field micro-heterogeneity, an ANCOVA was performed, and the full statistical report is available in Supplementary Table S3. The carbon stocks for all treatments in this soil layer exhibited no significant differences when compared either to the pre-experiment baseline values or among the treatments themselves.

Table 3. Soil organic carbon (SOC) stocks (Mg C/ha) at different depths under various intercropping and fertilization treatments in 2023 and 2024.

Treatment	Pre-Experiment Site	T1	T2	T3	T4	Depth Mean
Year/Soil Depth		(Mg C/ha)				
2023						
0–30 cm	80.6 ± 6.4	79.0 ± 5.6 Aa	76.8 ± 13.2 Aa	79.1 ± 6.4 Aa	81.2 ± 2.7 Aa	79.0 ± 3.8 A
30–50 cm	39.3 ± 5.5	49.3 ± 4.7 Ab	48.6 ± 8.1 Ab	52.4 ± 8.2 Ab	50.1 ± 3.8 Ab	50.1 ± 3.1 A
0–50 cm	119.9 ± 5.8	128.2 ± 10.0 Ac	125.3 ± 21.0 Ac	131.5 ± 13.4 Ac	131.3 ± 5.3 Ac	129.1 ± 6.1 A
2024						
0–30 cm	—	80.1 ± 6.7 Aa	75.4 ± 7.6 Aa	78.9 ± 11.0 Aa	72.2 ± 11.0 Aa	76.7 ± 4.4 A
30–50 cm	—	50.7 ± 4.3 Ab	47.0 ± 5.9 Ab	49.6 ± 5.4 Ab	44.5 ± 9.2 Ab	48.0 ± 3.2 A
0–50 cm	—	130.8 ± 4.5 Ac	122.3 ± 7.6 Ac	128.6 ± 15.1 Ac	116.7 ± 8.7 Ac	124.6 ± 5.2 A

Table 3. Cont.

Treatment	Pre-Experiment Site	T1	T2	T3	T4	Depth Mean
Year/Soil Depth		(Mg C/ha)				
Overall Treatment Mean (0–50 cm)		129.5 ± 5.3 a	123.8 ± 10.3 a	130.1 ± 9.5 a	124.0 ± 6.2 a	

Treatments: T1, conventional farming with full nitrogen fertilizer; T2, intercropping with *Crotalaria juncea* plus 50% nitrogen fertilizer; T3, intercropping with *C. juncea*; T4, compost application. Data are expressed as mean ± SE. Means followed by different lowercase letters within the same column and year are significantly different ($p < 0.05$); means followed by different uppercase letters between years for the same treatment are significantly different ($p < 0.05$) according to Fisher's LSD test. The ANCOVA-adjusted Fisher's Protected $LSD_{0.05}$ values for treatment comparisons within the same year are 19.1 Mg C/ha (0–30 cm), 16.0 Mg C/ha (30–50 cm), and 27.5 Mg C/ha (0–50 cm). Main effect $LSD_{0.05}$ for overall treatment comparison (0–50 cm) is 19.4 Mg C/ha.

However, analysis of the 30–50 cm subsoil layer revealed that, although statistically non-significant, the carbon stocks of all treatment groups displayed an upward trend compared to the pre-experiment baseline (39.3 ± 5.5 Mg C/ha). Notably, in 2023, the values for T2 and T3 increased to 48.6 and 52.4 Mg C/ha, respectively.

Further analysis of interannual variations showed that the total soil carbon stocks in the 0–50 cm soil profile for T1, T2, and T3 remained stable, with no significant differences observed between 2023 and 2024. In contrast, T4 alone exhibited a significant downward trend, with its carbon stock dropping substantially from 131.3 ± 5.3 Mg C/ha in 2023 to 116.7 ± 8.7 Mg C/ha in 2024. Moreover, while the total profile carbon stock of T4 in 2024 (116.7 Mg C/ha) was numerically lower than those of T2 (122.3 Mg C/ha) and T3 (128.6 Mg C/ha), no statistically significant differences were detected among T2, T3, and T4; however, T4 was significantly lower than the conventional full-nitrogen T1 treatment (130.8 Mg C/ha).

4. Discussion

The non-significant differences in plant height and tiller number between T1 and T2 suggest that a management strategy integrating green manure with a moderate application of chemical nitrogen fertilizer has the potential to replace full-rate chemical fertilization. The yield of 30 Mg DM/ha observed in the T2 treatment of this study is comparable to the tropical Napier grass yields reported in previous studies [1,2]. This demonstrates that the organic nitrogen source provided by legume green manure can effectively compensate for the nutrient deficit resulting from a 50% reduction in chemical nitrogen fertilizer. This compensatory effect can be attributed to several factors: the highly efficient biological nitrogen fixation of Sunn hemp, which achieves nutrient release synchrony with the peak nutrient demand of Napier grass [12]; the enhancement of overall resource use efficiency within the grass–legume intercropping system [18]; and the higher productivity per unit area generated by the intercropping system compared to monoculture through spatial and temporal complementarity [10]. Furthermore, the return of legume residues is crucial for maintaining long-term soil fertility in continuous Napier grass cropping systems, thereby preventing soil exhaustion [19]. In terms of forage quality, this study confirms that despite a 50% reduction in chemical nitrogen application, the T2 treatment successfully maintained a protein nutritional value equivalent to that of full fertilization, facilitated by the supplementary green manure (Sunn hemp) [20]. The conclusions of the present study are highly consistent with these previous findings. Conversely, the poor performance of T3 and T4 confirms that, in the absence of supplemental readily available nitrogen fertilizer, relying solely on biological nitrogen fixation from Sunn hemp or the slow-release nutrients from compost is insufficient to meet the massive nitrogen demands of high-biomass crops like Napier grass during their rapid growth phase, thereby limiting their yield potential.

The drastic interannual yield decline from 2023 to 2024 highlights that climatic conditions or the effects of continuous cropping exert a strong influence on biomass, over-

riding the observed increase in plant tiller numbers. This phenomenon indicates that while the tillering capacity of Napier grass strengthened in the second year, the ultimate total biomass yield did not increase in tandem with tiller number, likely due to insufficient biomass accumulation per plant under environmental stress. Interestingly, under environmental stress or low-input management, Napier grass tended to maintain internal metabolic homeostasis to ensure plant tissue quality (as seen in stable CP and fiber contents), rather than merely prioritizing biomass accumulation. This suggests that the chemical composition of Napier grass is relatively unaffected by interannual climatic or environmental fluctuations, thereby exhibiting a high degree of quality stability, and implies that alterations in fertilization models did not exacerbate forage lignification.

Regarding SOC, the absence of significant differences in the 0–30 cm layer reflects the considerable buffering capacity and spatial variability of the topsoil carbon pool, suggesting that short-term alterations in agricultural management are unlikely to induce drastic fluctuations at the surface. Although the short-term increase in soil carbon sequestration did not reach statistical significance, this is highly consistent with the hysteresis in soil carbon dynamics following land-use change [21] and aligns with previous findings that the intensification of pasture systems has little short-term effect on topsoil carbon stocks [22]. In high-temperature and high-humidity environments, vigorous microbial activity accelerates the mineralization of organic matter, making rapid carbon accumulation challenging. For instance, recent evaluations of transitional agro-ecosystems in the Brazilian Cerrado—a region with climatic constraints similar to those of our study site—have demonstrated that short-term shifts in agricultural management rarely yield immediate, statistically detectable changes in topsoil carbon stocks [23]. This context effectively justifies our observation of non-significant SOC stock variations within the two-year trial framework in central Taiwan. Furthermore, the carbon stocks measured in this study are comparable to the baseline for healthy agricultural soil carbon pools (60–110 Mg C/ha) reported in analogous continuous forage systems, indicating that the current management model has not led to soil carbon loss.

The hypothesized reason for the SOC discrepancy in the T4 treatment relates to the mineralization rate of organic matter: although compost provides a carbon source, it decomposes rapidly in high-temperature and high-humidity environments. Without continuous and sufficient replenishment, its efficacy in enhancing the soil carbon pool may not be as stable as anticipated. Conversely, the higher crop biomass in T1 and T2 likely maintained a more stable soil carbon pool through the continuous return of robust root residues. Given that Napier grass possesses an extensive deep root system capable of sequestering carbon in subsoil layers [24], and that root exudates can alter soil microbial community structures to promote the Microbial Carbon Pump effect [13], the upward trend in deep soil carbon (30–50 cm) is highly indicative and directly attributed to the deep-rooted characteristics of both Sunn hemp and Napier grass. Therefore, continuous monitoring of deep carbon pool dynamics remains essential [25].

Evaluated from a “Net Carbon Benefit” perspective, this model is highly advantageous; reducing nitrogen fertilizer use directly mitigates substantial “upstream” carbon emissions [6]. Moreover, bioenergy crops managed under low-input regimes exhibit a superior net energy ratio [4]. More importantly, cover crops can regulate the soil nitrogen cycle, further offsetting soil N₂O emissions. Because the global warming potential of N₂O is nearly 300 times that of CO₂, reducing its emissions is critical to addressing climate change [8]. This makes the T2 treatment a genuine “low-carbon production” model, achieving emission reductions in the livestock sector through optimized forage management [14] while concurrently sustaining forage quality and carbon stocks.

5. Conclusions

In this study, we validate a transitional Napier grass production framework—integrating *Crotalaria juncea* intercropping with a 50% reduction in synthetic nitrogen—that successfully circumvents the yield penalties inherent in fully organic systems while mitigating the severe ecological footprint of conventional intensification. Our findings demonstrate that this agroecological strategy significantly curtails at-source carbon emissions without compromising biomass productivity or forage quality. Crucially, it stabilizes short-term soil organic carbon dynamics and reveals substantial potential for subsoil carbon sequestration, presenting a highly viable paradigm for the sustainable transition of tropical agriculture. We urge the integration of such high-yielding, climate-smart agricultural models into future agro-environmental policy frameworks. Moving forward, longitudinal soil monitoring remains imperative to elucidate the long-term mechanistic contributions of this regime to climate mitigation, thereby facilitating its scalability across global tropical forage systems.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/agronomy16151491/s1>: Table S1. Analysis of variance (ANOVA) for agronomic traits and yield; Table S2. Analysis of variance (ANOVA) for crude protein and fiber contents; Table S3. Analysis of covariance (ANCOVA) for soil organic carbon (SOC) stocks.

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Abbreviations

BD	Bulk density
BNF	Biological nitrogen fixation
C/N	Carbon-to-nitrogen ratio
CRD	Completely randomized design
GHG	Greenhouse gas
SOC	Soil organic carbon
DMY	Dry matter yield
FMY	Fresh matter yield
CP	Crude protein
ADF	Acid detergent fiber
NDF	Neutral detergent fiber

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