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Global Change Biology Bioenergy
BIOPRODUCTS FOR A SUSTAINABLE BIOECONOMY

RESEARCH ARTICLE OPEN ACCESS

Long-Term Cultivation of Perennial Energy Crops Enhance Ecosystem Multifunctionality on Marginal Red Soil Without Trade-Offs

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Received: 1 February 2026 | **Revised:** 14 May 2026 | **Accepted:** 3 June 2026

Keywords: ecosystem multifunctionality | ecosystem services | marginal land | *Miscanthus* | switchgrass

ABSTRACT

Perennial energy crops (PECs) are increasingly being recommended for cultivation on marginal lands to support the bioeconomy and promote soil restoration, owing to their low input requirements and large potential for soil organic carbon sequestration. However, the effects of the cultivation of PECs on the trade-offs or synergies among soil functions, and consequently on ecosystem multifunctionality (EMF), remain unclear, hindering large-scale adoption. We conducted our measurements in a long-term field experiment that was established a decade ago, where *Miscanthus* and switchgrass were cultivated alongside a native C_3 grass mixture (*Cyperus rotundus* L. and *Setaria viridis* L.) as reference to assess the effects of PECs on soil multifunctionality. We assessed 10 ecosystem functions grouped into provisioning, supporting, and regulating services. The results demonstrate that *Miscanthus* and switchgrass cultivation elevated the overall EMF by an average of 5.29-fold over the C_3 native grass control, with supporting, regulating, and provisioning services increasing by 2.08, 7.27, and 43.98-fold, respectively. Specifically, the two PECs improved all 10 measured soil functions, with the exception of abiotic stress regulation under switchgrass cultivation. *Miscanthus* outperformed switchgrass by 41.54% in supporting services and 81.09% in provisioning services, resulting in higher EMF. Moreover, strong positive relationships were observed among the three service categories, indicating that the cultivation of PECs improves EMF consistently without significant trade-offs. These findings suggest that cultivating PECs on marginal land can simultaneously provide sustainable biomass feedstock and enhance soil health, supporting the feasibility for larger-scale deployment.

1 | Introduction

Global challenges concerning population growth, climate change, and stagnation of yields are driving global demand for cropland expansion. Marginal lands, characterized by low productivity and ecological fragility resulting from adverse soil, hydrological, or topographic conditions, are increasingly viewed as a potential resource for such expansion (Cao et al. 2021). China's "storing grain in the land" strategy represents a significant theoretical and practical engagement aiming to address this issue (The Central Committee of the Communist Party of China and The State Council of the

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People's Republic of China 2018). For example, the development of salt-tolerant rice varieties has enabled the agricultural use of coastal saline-alkali soils, substantially expanding the rice cultivation area (Quan et al. 2024). The cultivation of stress-resistant varieties allows marginal and stressed lands to be converted to arable use, increasing the total cultivated area within a relatively short period. Nevertheless, breeding alone is often insufficient to address severe or intensified environmental stresses. In such cases, exploiting these lands first requires reducing environmental constraints through soil improvement. Moreover, rehabilitation of marginal soils aligns closely with the principles of sustainable agriculture.

Among various remediation approaches, phytoremediation stands out as a cost-effective, straightforward, and environmentally sustainable alternative (Salt et al. 1998). Its effectiveness, however, depends strongly on species-specific plant traits. Perennial energy crops (PECs) such as miscanthus (*Miscanthus* spp.) and switchgrass (*Panicum virgatum* L.) are particularly suitable due to their deep rooting systems, stress tolerance, low input requirements, and high biomass yield potential (Wang et al. 2023). These attributes help improve soil structure, increase soil organic matter (SOM) (Mi et al. 2014; Clifton-Brown et al. 2007), enhance water retention, and improve nutrient availability (Kane et al. 2023). PECs maintain stable growth under adverse conditions, thereby lowering both remediation costs and associated risks (Xue et al. 2016). Furthermore, the resulting biomass can be used for bioenergy and high value biorefinery products, generating synergistic ecological and economic benefits on marginal lands (Fu, Xu, Li, et al. 2022; Wang et al. 2022; Liu et al. 2024).

Current assessments of potential phytoremediation rely heavily on improvements in soil texture, fertility, and physicochemical properties. For example, long-term cultivation of PECs has been recognized to significantly increase soil organic carbon (SOC) across various marginal land types, including red soils, saline-alkali lands, and abandoned farmland (Xu et al. 2022; Fu, Xu, Hou, et al. 2022; Martani et al. 2021; Ameen et al. 2019). Moreover, these crops can improve soil physical properties by reducing bulk density and increasing porosity and permeability. Also, their rooting systems can help prevent erosion by stabilizing the soil (Das et al. 2016; Zhao et al. 2022; Martani et al. 2021; Evers et al. 2013). In addition, cultivation of PECs can alleviate soil acidity by elevating chelated iron and aluminum oxides, regulate salinity, and improve nutrient cycling (Hou et al. 2023). PECs can also enhance soil fertility by modifying the structure of nutrient-related microbial communities. For instance, *Miscanthus* cultivation has been reported to increase the abundance of nitrogen-fixing and nutrient-solubilizing microorganisms (e.g., phosphate- and potassium-solubilizers), thus boosting soil nutrient availability (Li et al. 2022; Liu and Ludewig 2019).

However, as an ecological restoration technique, evaluating phytoremediation based solely on soil-related indicators provides an incomplete picture. This is particularly evident for PECs, where there is a critical lack of research on their impacts on ecosystem multifunctionality (EMF), including synergies and trade-offs among individual functions. This knowledge gap hinders the optimized application of PECs across diverse types of marginal land. To address this issue, we conducted a 10-year field experiment to assess the effects of *Miscanthus* and switchgrass on EMF in a representative poor-quality red soil. Our objectives were to: (1) quantify the impacts of PECs cultivating on provisioning, supporting, and regulating ecosystem services; (2) identify synergies and trade-offs among these services; and (3) compare the effectiveness of *Miscanthus* and switchgrass in enhancing EMF and its stability. This work represents the first long-term, comprehensive study of ecosystem services on acidic red soil marginal land. Moreover, this research provides direct evidence for the synergistic ecological benefits of PECs, supports strategies for marginal land improvement, and informs crop selection and management to promote bioeconomic development and ecological security within the "*dual carbon* (carbon peak and neutrality)" framework (Xi 2020).

2 | Materials and Methods

Ecosystem multifunctionality (EMF) was calculated on 27 variables measured in a 10-year field experiment involving two perennial energy crops, *Miscanthus* and switchgrass, grown on degraded acidic red soil. These variables were categorized into 10 ecosystem functions (Figure 1): productivity, product quality, soil stability, carbon stocks, nutrient cycling, organic matter decomposition, abiotic stress regulation, microbial diversity, water regulation, and pollution control. These functions were further grouped into four ecosystem goods: feedstock production, soil health, biodiversity, and climate regulation. Corresponding to these goods, three categories of ecosystem services—supporting, regulating, and provisioning—were identified.

2.1 | Experimental Design

A long-term field experiment was established in 2011 at Liuyang Experimental Station (28°11′ N, 113°06′ E; 128.5 m a.s.l.) in Hunan Province, China. The site is characterized by a marginal loamy acidic red soil (pH = 5.12) with low soil organic carbon (SOC = 5.2 g kg^{-1}). The experiment followed a randomized block design with three replicates per treatment, each plot measuring 5 × 7.5 m. Treatments included two PECs: a diploid hybrid of miscanthus (*M. lutarioriparia* ♂ × *M. sinensis* ♀) and switchgrass (cv. Alamo), along with a control plot planted with a native C_3 grass mixture (*Cyperus rotundus* L. and *Setaria viridis* L.) that established naturally without human disturbance. Both PECs were planted at 1 m distance between rows and plants. Aboveground biomass was harvested annually (in December), and no additional management (i.e., fertilizatio, irrigation, weed control, and pest management) were applied throughout the entirety of the study period.

2.2 | Sampling and Measurement Strategies

Soil and root samples were collected from 0 to 20 cm depth in January 2021, after 10 years of cultivation. In plots cultivated with *Miscanthus* or switchgrass, four random plants were selected, and soil cores (4 cm diameter) were taken 10 cm and 50 cm from the center of each plant in each of the cardinal directions. These cores were combined to form one composite sample per plot. In nonplanted control areas, where the ground was fully covered by dense grassland, the soil collected was essentially rhizosphere

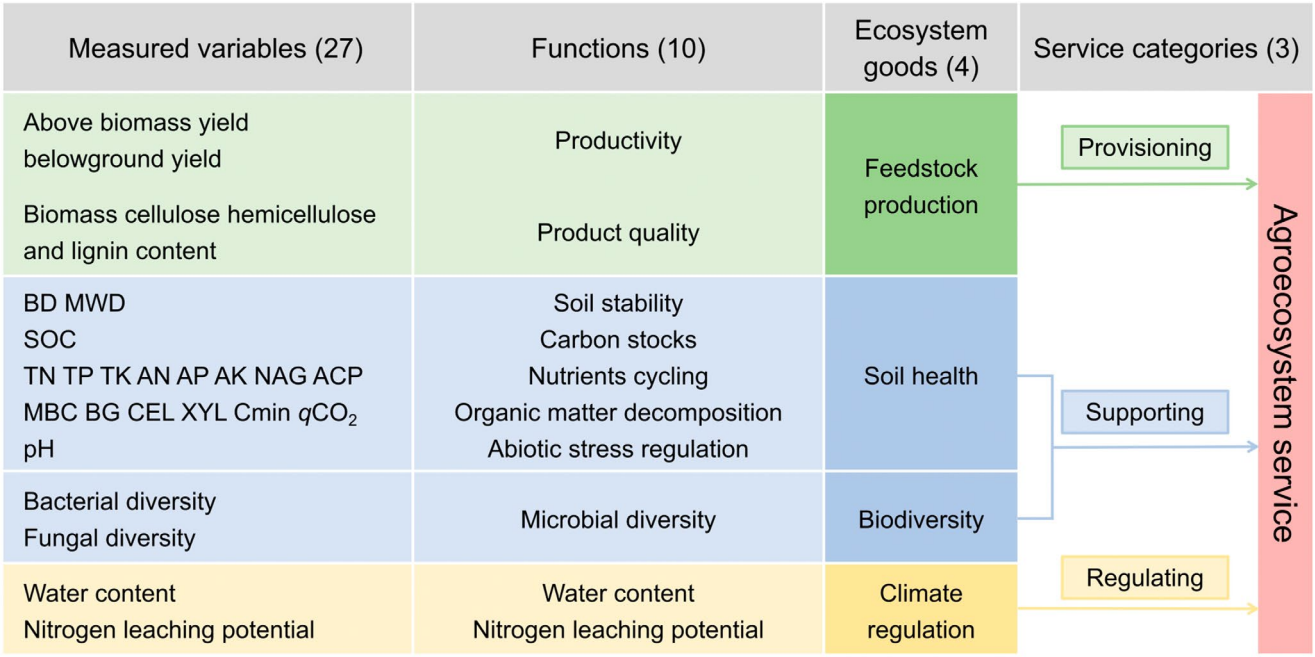


FIGURE 1 | Conceptual model for analysis of multiple ecosystem services in a long-term perennial energy crops cultivation experiment. ACP: Acid phosphatase; AK: Available potassium; AN: Available nitrogen; AP: Available phosphorus; BD: Bulk density; BG: β-glucosidase; C_{min}: Soil organic carbon mineralization; CEL: β-D-cellobiosidase; MBC: Microbial biomass carbon; MWD: Mean weight diameter; NAG: *N*-acetyl-*β*-glucosaminidase; qCO_2: Metabolic quotient; SOC: Soil organic carbon; TN: Total nitrogen; TP: Total phosphorus; TK: Total potassium; XYL: β-xylosidase enzyme activity.

soil. Composite samples were obtained by mixing soil cores from 10 random locations along an "S"-shaped sampling route. Furthermore, to assess nitrate nitrogen (NO_3^--N) accumulation across soil depths, a total of 12 soil profiles (three depths with four replicates) were established per treatment. Soil samples were collected from depths of 0–20, 20–40, and 40–60 cm. Root biomass was quantified by excavating a 1×1 m area to a depth of 20 cm. Aboveground biomass was determined by harvesting three randomly selected 1×1 m quadrats. The contents of cellulose and hemicellulose in the collected plant samples (aboveground and root) were determined using sulfuric acid hydrolysis, with subsequent quantification obtained by high-performance liquid chromatography (National Energy Administration 2017). The lignin content was calculated from the sum of acid-soluble and acid-insoluble lignin (National Energy Administration 2017).

The collected soil samplings were passed through a 2 mm mesh sieve and then divided into three subsamples. One subsample was air-dried for the test of soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), total potassium (TK), available nitrogen (AN), available phosphorus (AP), and available potassium (AK). A second subsample was stored at 4°C for the determination of microbial biomass carbon (MBC), NH_4^+-N, NO_3^--N and soil enzyme activity occurring over 1 week. The third subsample was used for aggregates fractionation by dry sieving into large macroaggregates (> 2 mm), small macroaggregates (0.25–2 mm), and microaggregates (< 0.25 mm) (Hou et al. 2023). Mean weight diameter (MWD) was calculated as a weighted average. The remaining portion was reserved for DNA extraction, performed using a three-step procedure: extraction, PCR amplification, and Illumina MiSeq sequencing. Detailed protocols of this procedure can be found in Wu et al. (2021).

Soil water content was determined by oven-drying at 105°C for 48 h. Dichromate oxidation was employed to measure SOC, while semimicro Kjeldahl, molybdenum-antimony anti-colorimetric, and flame photometry methods were used for TN, TP, and TK, respectively. Analysis of AN, AP, and AK was conducted using alkali-hydrolyzed diffusion, molybdenum-blue colorimetry, and flame photometry, respectively (Bao 2000). Additionally, the chloroform fumigation extraction method was applied to determine MBC (Brookes, Landman, et al. 1985). The NH_4^+-N and NO_3^--N were analyzed using a TOC analyzer (TOC-L CPN, Shimadzu, Japan) (Brookes, Kragt, et al. 1985) and a microplate spectrophotometer (Thermo1510, MULTISKAN GO, Thermo Fisher Scientific, USA). SOC mineralization (C_{min}) was calculated from cumulative CO_2 after incubating 30 g of soil at 25°C for 60 days (Xu et al. 2021). The metabolic quotient (qCO_2) was calculated as the ratio of the CO_2 emission rate to microbial biomass (Anderson and Domsch 1993).

Potential activities of six hydrolytic enzymes, including *β*-glucosidase (BG), *β*-D-cellobiosidase (CEL), *β*-xylosidase (XYL), *N*-acetyl-*β*-glucosaminidase (NAG), and acid phosphatase (ACP), were measured. Briefly, 1 g of fresh soil was suspended in 50 mL of sterile water. Then, 50 μL of the soil suspension was pipetted into a 96-well microplate and mixed with 50 μL of buffer and 100 μL of the corresponding substrates. Fluorometric measurements were taken at 0, 30, 60, and 120 min after substrate addition using an excitation/emission wavelength of 355/460 nm (Thermo Fisher Scientific, USA).

2.3 | Ecosystem Services Calculation

A total of 27 variables were used to quantify ecosystem services in accordance with the Millennium Ecosystem Assessment and

the UK National Ecosystem Assessment frameworks (MEA 2005; UKNEA 2011). All variables were adjusted to reflect positive contributions to ecosystem services. Variables with inherently negative effects, namely lignin content (in root samples), bulk density, nitrogen leaching potential, C_{min}, and qCO_2, were multiplied by a factor of −1 to convert them into positive indicators. Each variable was standardized using the min–max normalization method (Delgado-Baquerizo et al. 2020). These standardized variables were then categorized into 10 ecosystem functions as illustrated in Figure 1. The ecosystem multifunctionality was evaluated by arithmetically averaging standardized scores of these 10 functions. These functions were further grouped into four broader ecosystem goods (feedstock production, soil health, biodiversity, and climate regulation). These goods further correspond to three key service categories of provisioning, supporting, and regulating services. Each service category was computed as the average of its constituent functions. Finally, a multiservice index was derived by averaging the three ecosystem service categories.

2.4 | Statistical Analysis

All statistical analyzes were performed in R (version 4.5.1). Normality and homogeneity of variance were assessed using the Shapiro–Wilk and Levene's tests, respectively. For variables showing significant overall differences among treatments, one-way ANOVA was applied, followed by Duncan's multiple comparison test to identify pairwise differences ($p \leqq 0.05$). Principal component analysis (PCA) was applied to visualize trade-offs and synergies among ecosystem goods and functions across treatments. Functional stability was quantified using a multithreshold approach implemented in the *MULTIFUNC* package (Byrnes et al. 2014), which evaluates the proportion of functions maintained above thresholds (0–100%). Dissimilarity in ecosystem services provision among treatments was measured using the beta diversity index, computed with the *BETAPART* package. Relationships among multiple ecosystem functions were assessed using *Pearson* correlation analysis (Baselga and Orme 2012).

3 | Results

3.1 | Effects of PECs Cultivation on Ecosystem Services, Goods and Functions of Marginal Red Soil

Long-term cultivation of PECs on marginal red soil significantly enhanced its ecosystem service, goods and functions compared to the native C_3 grass (i.e., the control) dominated land (Figures 2 and 3). Specifically, both *Miscanthus* and switchgrass significantly ($p < 0.05$) improved supporting, regulating and provisioning services relative to the control, with increases ranging from 1.55- to 2.61-fold, 6.66- to 7.87-fold and 31.00- to

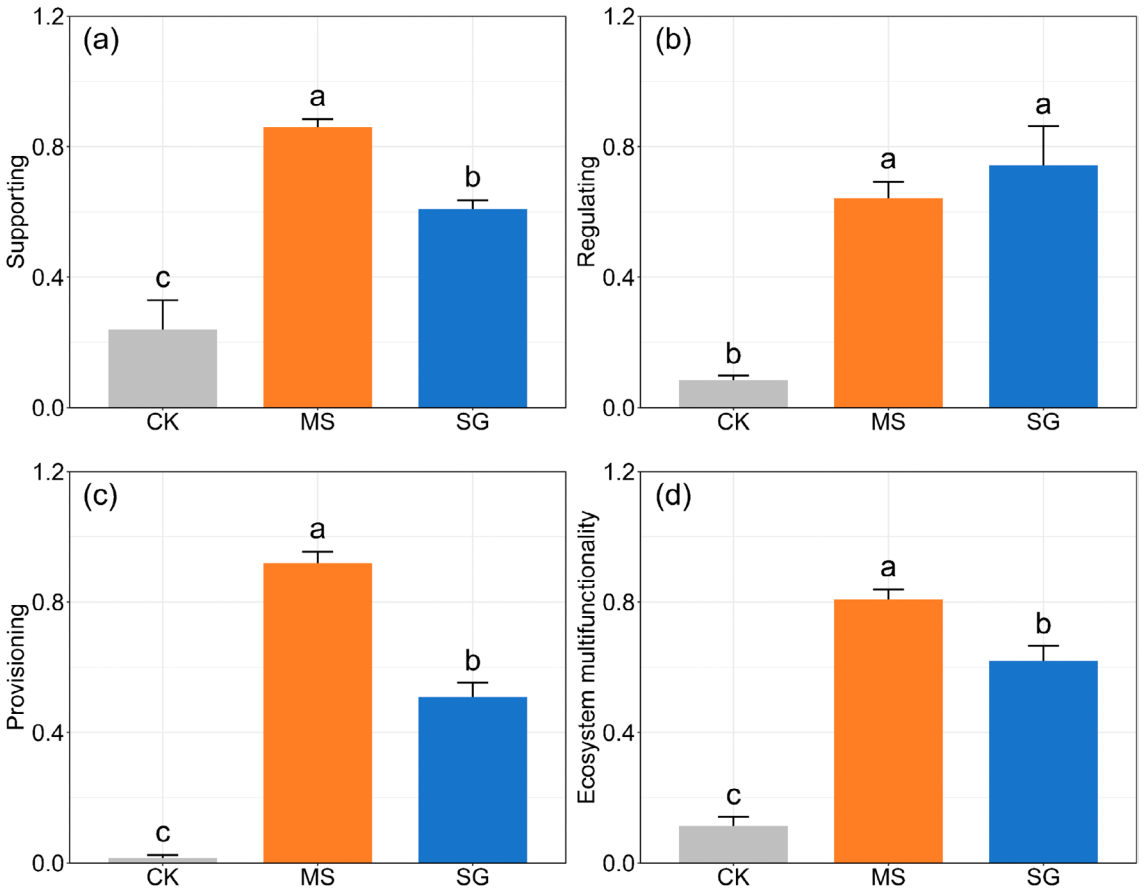


FIGURE 2 | Ecosystem services of the three cropping systems. Supporting (a), regulating (b), provisioning (c), and multifunctionality (d). CK: Native grass; MS: *Miscanthus*; SG: Switchgrass. Different lowercase letters represent significant differences between the three cropping systems ($p < 0.05$).

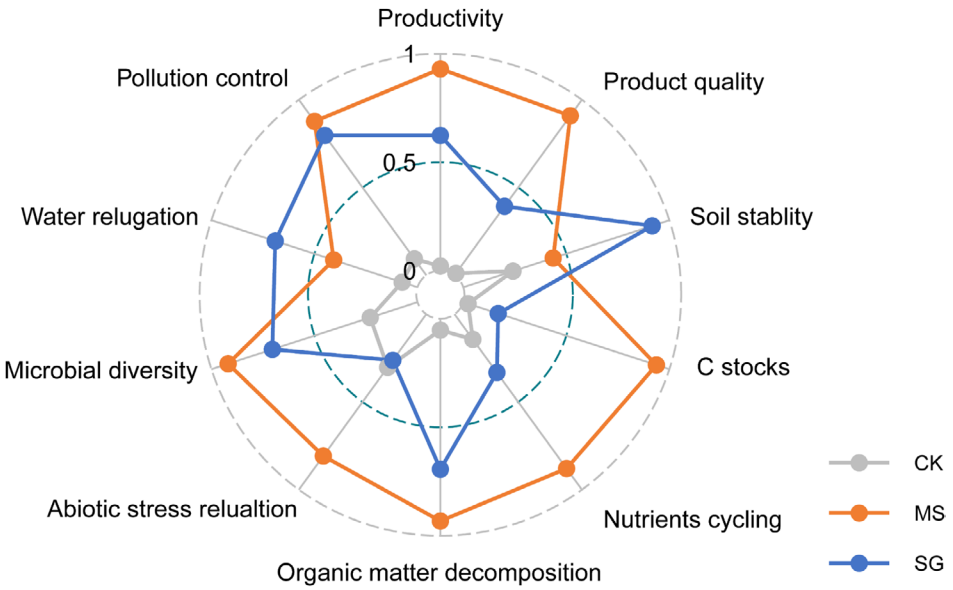


FIGURE 3 | Ecosystem functions of three cropping systems. CK: Native grass; MS: *Miscanthus*; SG: Switchgrass.

56.95-fold, respectively (Figure 2a–c). Notably, *Miscanthus* outperformed switchgrass in supporting and provisioning services ($p < 0.05$), achieving 41.54% and 81.09% greater improvements, respectively. Although switchgrass showed a 15.90% higher regulating service (Figure 2b) than *Miscanthus*, the difference was not statistically significant ($p > 0.05$).

The ecosystem multifunctionality (EMF), calculated as the average of the three service categories, was significantly ($p < 0.05$) influenced by *Miscanthus* and switchgrass cultivation (Figure 2d). *Miscanthus* treatment achieved the highest EMF (0.81), followed by switchgrass treatment (0.62), both significantly ($p < 0.05$) exceeding the control (0.11). In comparison to the control, *Miscanthus* and switchgrass improved EMF by 6.11- and 4.46-fold, respectively, with *Miscanthus* also surpassing switchgrass by 30.22%.

Results from the spider web analysis (Figure 3) further demonstrated that both *Miscanthus* and switchgrass treatments enhanced most of the key ecosystem functions (90%) compared to the control, with the exception of abiotic stress regulation under switchgrass. It is important to note that the control itself showed only a marginal advantage over switchgrass for this particular function. *Miscanthus* consistently showed superior performance across a majority of functions, including productivity, product quality, carbon stocks, nutrient cycling, organic matter decomposition, abiotic stress regulation, and microbial diversity. However, the enhancement in pollution control over switchgrass was limited. In contrast, switchgrass cultivation showed a distinct advantage in water regulation and soil stability compared to *Miscanthus* treatment and control (Figure 3).

3.2 | Synergies and Trade-Offs Among Multiple Ecosystem Services

We identified synergistic relationships among supporting, regulating, and provisioning services under *Miscanthus* and switchgrass cultivation. The significant positive correlations (Figure 4a–c) were observed between supporting and regulating ($R^2 = 0.63$, $p = 0.011$), regulating and provisioning ($R^2 = 0.89$, $p < 0.001$), and supporting and provisioning ($R^2 = 0.56$, $p = 0.021$). This indicates that *Miscanthus* and switchgrass cultivation promotes co-benefits across service categories without significant trade-offs. Results from the PCA revealed that *Miscanthus* contributed most strongly to supporting and provisioning services, whereas switchgrass was more closely associated with regulating services (Figure 4d). At the functional level, positive correlations were observed among pollution control, microbial diversity, organic matter decomposition, productivity, product quality, nutrient cycling, carbon stocks, and abiotic stress regulation. Furthermore, soil stability was also positively linked with water regulation, pollution control, microbial diversity, organic matter decomposition, and productivity (Figure 4d).

3.3 | Effects of PECs Cultivation on the Stability of Ecosystem Multifunctionality

Using a multithreshold approach, the stability of EMF under *Miscanthus*, switchgrass and the C_3 grass control was examined. *Miscanthus* and switchgrass maintained a greater number of functions above all threshold levels compared to the control (Figure 5a). Notably, *Miscanthus* supported more functions than switchgrass at moderate to high thresholds (> 20%). The decline in number of functions was more gradual in *Miscanthus*, with a sharp drop occurring only above 60%–100% thresholds, whereas switchgrass declined more rapidly between 45% and 75%. The beta diversity analysis of EMF showed that compared to the control CK, both *Miscanthus* and switchgrass significantly reduced beta values by 65% (0.30 vs. 0.18) and 55% (0.30 vs. 0.19), respectively (Figure 5b). The beta values showed nonsignificant ($p > 0.05$) differences between *Miscanthus* (0.18) and switchgrass (0.19). This indicates that both *Miscanthus* and switchgrass cultivation on marginal red soil provide more stable and consistent delivery of multiple ecosystem functions compared to the native grass system.

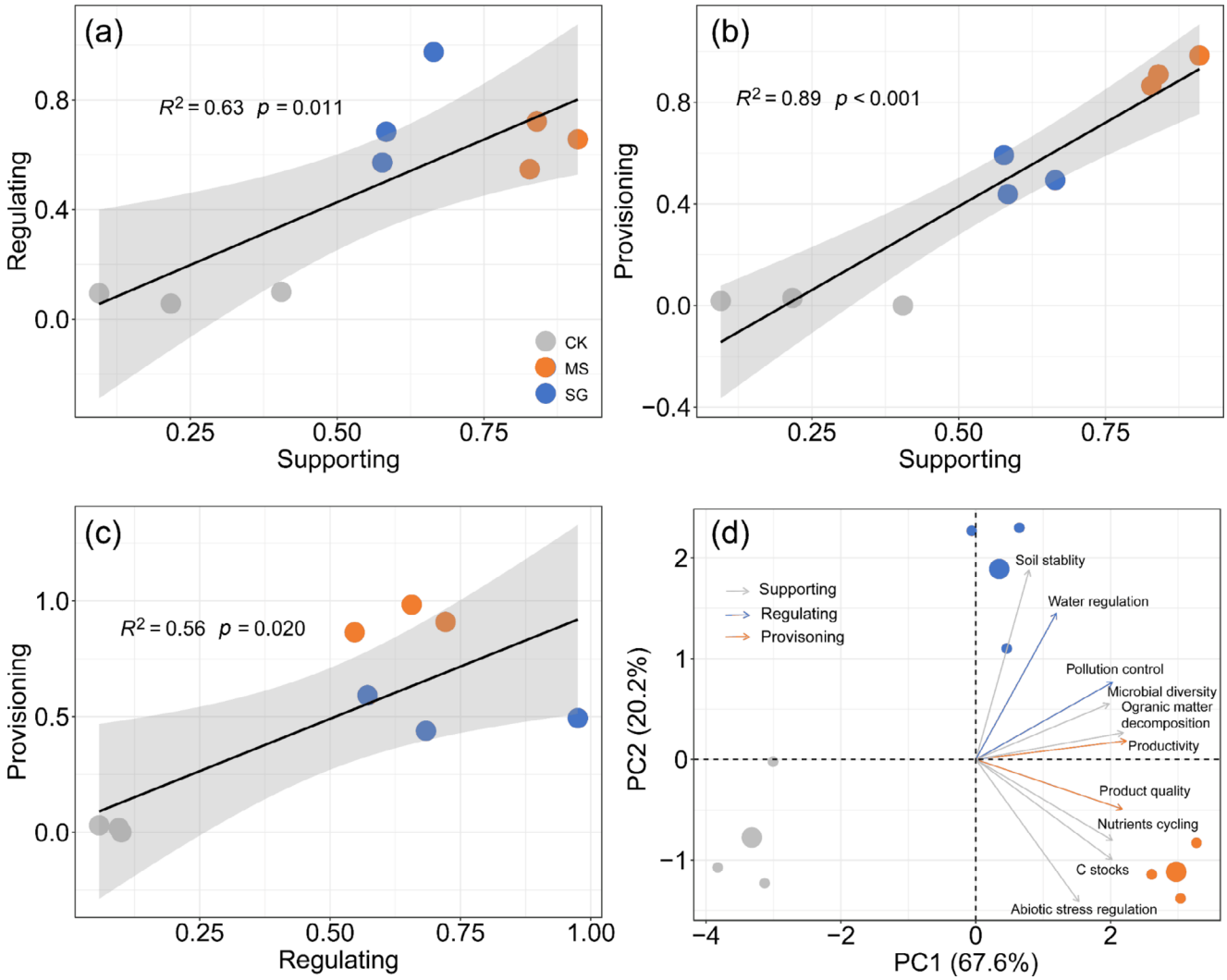


FIGURE 4 | Relationship between agroecosystem goods categories (supporting, regulating, provisioning) (a, b, c) and biplot illustrating the trade-offs and synergies between agroecosystem goods categories and functions of the three cropping systems (d). CK: Native grass; MS: *Miscanthus*; SG: Switchgrass.

4 | Discussion

4.1 | Synergistic Enhancement of Ecosystem Multifunctionality by PECs Cultivation

Meeting the growing global demand for food production requires intensified sustainable development and management of marginal lands (Von Cossel et al. 2019). However, its application hinges largely on maintaining ecosystem stability (Burland and von Cossel 2023). Our long-term study on acidic red soil demonstrates that the PECs cultivation both rehabilitates marginal land into arable land and synergistically improves EMF.

The key finding from our long-term experiment is the marked, synergistic improvement in EMF under *Miscanthus* and switchgrass cultivation. Crucially, this enhancement occurs without evident trade-offs among supporting, regulating, and provisioning services. This is in contrast to many intensive agricultural systems, where gains in production often impact other ecosystem functions (Zimmermann et al. 2021). For example, the enhancement of provisioning services in intensive agricultural systems often compromises services which are supporting or regulating (Yang et al. 2023). In contrast, under PECs cultivation, these services exhibited strong positive correlations. This co-benefit highlights the potential of PECs cultivation to concurrently advance biomass production, soil restoration, and climate mitigation on lands which are severely degraded. These results are in agreement with previous research on PECs in the bioenergy buffer zone (Ferrarini et al. 2017a).

In this study, our findings identify the substantial and sustained input of SOC by PECs as a central driver of this synergy (Tan et al. 2026). The deep and extensive rooting systems of *Miscanthus* and switchgrass, coupled with substantial litter production, act as continuous "*carbon pumps*," significantly increasing soil SOC levels (Dheri et al. 2022). Specifically, compared to annual crops, *Miscanthus* and switchgrass increased SOC in nonrhizosphere soil (0–20 cm) by 42% and 6.7%, respectively, corroborating global meta-analysis (Xu et al. 2024; Wu et al. 2024). This carbon influx initiates a cascade of positive feedback mechanisms. Notably, these positive feedback

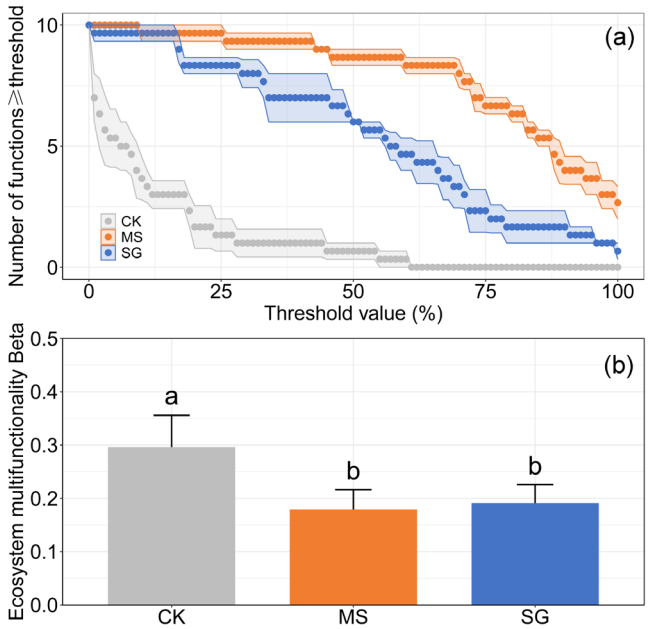


FIGURE 5 | Alpha and beta diversity of ecosystem multiple services under three cropping systems. The effects of the cropping system on the number of functions performed above a threshold (a). Beta-multifunctionality, calculated as the average dissimilarities of functions of the three cropping systems (b). The higher the value, the more specialized functions delivery (few functions at a higher level). CK: Native grass; MS: *Miscanthus*; SG: Switchgrass. Different lowercase letters represent significant differences between the three cropping systems ($p < 0.05$).

mechanisms increase soil aggregate structure, regulate water infiltration, create diverse microbial niches, and enrich soil microbial diversity. Furthermore, through microbially driven decomposition of SOM, this carbon influx activates nutrient turnover networks (e.g., N and P mineralization) and strengthens soil buffering capacity against stressors such as drought and salinization. These processes collectively promote plant growth, further increasing carbon inputs and establishing a virtuous "*plants-microorganisms-soil*" feedback cycle which holistically enhances soil ecosystem services (Martani et al. 2021; Totsche et al. 2018).

This mechanistic framework is further supported by the documented increases under PECs cultivation across numerous forms including nutrient cycling enzyme activities (Cattaneo et al. 2014), the abundance of N-transforming microbes (Mao et al. 2011), and arbuscular mycorrhizal fungi (Oates et al. 2016), as well as the microbial diversity (Herzberger et al. 2014). A deep root system with high nitrogen utilization efficiency also helps to facilitate deep-soil denitrification driven by root exudates (Ferrarini et al. 2017b), while shaping a stable denitrification community dominated by archaea (Mao et al. 2011). This significantly reduces N_2O emissions and enhances rhizospheric nitrogen fixation (Hargreaves and Hofmockel 2014), strengthening multidimensional soil ecosystem services, including nutrient cycling, pollution control, and water regulation. The strong positive correlations observed between carbon stocks and most all other measured functions provide robust support for this integrated mechanism.

4.2 | Functional Differentiation and Strategic Advantages of Different PECs

This study has presented distinct and advantageous functional profiles between the two PECs of *Miscanthus* and switchgrass, underpinned by their divergent ecological strategies. These differences are key to understanding their species-specific impacts on ecosystem services.

Regarding provisioning service, which concentrates on biomass yield and quality, compared with C_3 grasses, the provisioning service capacity of PECs has increased by a large extent. This is because the C_3 grass mixture shows a rather low biomass yield and quality levels (Xu et al. 2024). More importantly, *Miscanthus* outperformed switchgrass, producing higher biomass with greater fiber lignin content. This positive trait is primarily governed by its genetic makeup and morphological structure. Crucially, the yield and quality of both PECs were strongly dependent on underlying soil quality, including soil carbon pools and abiotic stress regulation, highlighting a positive feedstock mechanism which sustains provisioning services.

For supporting service, *Miscanthus* induced broad, multidimensional improvements, significantly enhancing carbon stocks, nutrient cycling, organic matter decomposition, abiotic stress regulation and microbial diversity. In contrast, switchgrass demonstrated a more pronounced advantage in promoting soil stability. The distinct impact of *Miscanthus* on the soil carbon cycle can be attributed to the "*high-biomass, low-quality*" characteristics of its root system, influenced by a high lignin-to-nitrogen ratio—a metric that was first established by Melillo et al. (1982) that, unlike the conventional C/N ratio, specifically isolates the most recalcitrant carbon fraction (lignin) relative to microbial nitrogen demand. This high ratio results in extremely slow root decomposition and limited microbial accessibility, thereby more accurately reflecting the low-quality nature of the root litter (Xu et al. 2024). This creates a dual effect: the substantial root biomass directly inputs a large amount of plant-derived carbon into the soil, while the chemical recalcitrance of this biomass (due to the carbon-nitrogen ratio imbalance) significantly inhibits microbial decomposition and mineralization rates (Xu et al. 2024; Villarino et al. 2021). Consequently, this dual mechanism reduces the decomposition loss of newly input carbon and promotes the effective accumulation of stable SOC. A global meta-analysis corroborates this examination, showing a more profound increase in SOC under *Miscanthus* cultivation (16%) compared to switchgrass (7%) (Xu et al. 2024).

Conversely, switchgrass develops a deep and high-quality root system characterized by a dense network of fine roots. This architecture increases the root-soil contact area, and when combined with efficient root turnover and exudation, delivers abundant, liable SOC inputs (An et al. 2022; Panchal et al. 2022). This process, synergizing with associated soil microbial communities, effectively promotes the formation of soil aggregates (Lee et al. 2024). This bio-chemical-microbial coupling effect strengthens the soil structure stability and optimizes the soil pore architecture. As a result, water infiltration and storage capacity is improved leading to superior water regulation (Lucas

et al. 2022). This study therefore confirms a strong positive correlation between soil stability and water regulation, explaining the superior performance of switchgrass in this specific function compared to *Miscanthus*.

The selection of PECs species should be strategically aligned with primary restoration objectives: *Miscanthus* is recommended for maximal carbon sequestration and biomass production on stable sites, whereas switchgrass is better suited for erosion control and water management on vulnerable slopes or severely degraded landscapes. Our finding that *Miscanthus* maintains a higher number of functions above moderate to high thresholds further underlines its robustness in delivering consistent multifunctionality.

4.3 | Enhanced EMF and Stability Under PECs Cultivation

Beyond the quantitative enhancement of EMF, our multithreshold analysis provides critical insights into the stability of delivering appropriate and efficient services. The *Miscanthus* system consistently maintained a greater number of functions above moderate to high thresholds (e.g., > 60% of maximum potential) compared to switchgrass and the control. This indicates that the *Miscanthus* system not only delivers a higher average level of EMF but also demonstrates greater resilience, effectively safeguarding a broader suite of functions against potential declines under environmental stress or perturbation. This improved resilience can likely be attributed to the larger and more stable SOC pool accumulated under *Miscanthus* cultivation, serving as a foundational reservoir sustaining diverse biological processes and physical properties (Hou et al. 2023). The significantly lower β-multifunctionality under both PECs indicates a more consistent and predictable delivery of multiple functions across replicates or potentially over time. This contrasts with the higher variability (indicative of specialization or instability) observed under the native grass system. Such functional stability is a paramount attribute for sustainable land management on marginal sites, which are inherently prone to environmental fluctuations.

4.4 | Implications and Future Perspectives

The synergistic relationships among ecosystem services under PECs, as demonstrated in our long-term study, carry profound practical implications for land-use policy and climate strategy. The large-scale deployment of PECs cultivation on marginal lands such as acidic red soils can be adopted as a *win-win-win* achieved by: (1) producing sustainable biomass for bioeconomy, reducing reliance on fossil materials and alleviating pressure on prime cropland; (2) restoring soil health and functionality (evidenced by increased SOC, improved soil structure, and enhanced biodiversity), to reverse land degradation trends; and (3) contributing significantly to climate change mitigation through substantial belowground carbon sequestration, as validated by our SOC data and low carbon mineralization rates.

Our results provide a robust scientific foundation for integrating PECs into national and regional strategies aimed at achieving "*Dual Carbon*" goals (carbon peak and neutrality) and ensuring food security while not impacting productive cropland (Xi 2020). To translate this potential into policy and practice, future research should focus on quantifying the regional-scale carbon sequestration potential and economic viability of PECs cultivation across vast marginal red soil resources. The identified species-specific functional profiles (*Miscanthus* for maximizing EMF/stability, switchgrass for soil/water regulation) offer an evidence-based framework for selecting appropriate PECs tailored to specific site conditions and restoration priorities.

While we have established SOC as a central driver, the specific microbial consortia and biochemical pathways governing carbon stabilization and nutrient cycling under different PECs remain to be fully elucidated. Future research using advanced tools like metagenomics and metatranscriptomics is essential to further explore these underlying mechanisms. Investigating root exudate profiles and their interactions with the soil microbiome will provide deeper mechanistic insights. Furthermore, multisite long-term trials across diverse marginal land types (e.g., saline-alkali, contaminated, semiarid) are crucial to validate the generality of the observed synergies and species differences, and to develop tailored remediation protocols. It is equally critical to assess PECs performance and EMF resilience under projected climate change scenarios (e.g., drought, extreme rainfall). Finally, developing integrated assessment frameworks which combine our EMF metrics with life cycle assessment (LCA), economic analysis (Kiefer et al. 2023), and landscape-level modeling will be indispensable for optimizing the ecological and socio-economic sustainability of PECs-based marginal land. Furthermore, this will be critical for guiding specific, strategic policy decisions. Particular attention should also be paid to subsoil (> 20 cm) processes (e.g., carbon dynamics, microbial communities, and water/nutrient cycling), as the deep rooting systems of PECs may play a vital yet under-explored role in long-term carbon storage and ecosystem stability.

5 | Conclusion

Our decade-long field study unequivocally demonstrates that *Miscanthus* and switchgrass cultivation on marginal acidic red soils induces a synergistic enhancement of EMF without significant trade-offs among key ecosystem service categories. The distinct functional strategies for each PECs offer a strategic, science-based framework for targeted land restoration. This study has shown that *Miscanthus* is the optimal candidate for maximizing EMF, carbon sequestration, and long-term stability, whereas switchgrass excels in scenarios prioritizing soil stabilization and enhanced water regulation. This research provides a robust scientific foundation for harnessing PECs to transform degraded marginal lands into productive, climate-smart ecosystems, contributing significantly to bioeconomy development and environmental sustainability goals.

Author Contributions

Yini Wu (伍旖旎): writing – original draft, formal analysis, visualization. **Yi Xu (许依):** investigation, data curation, formal analysis,

visualization, writing – review and editing. **Tongcheng Fu (傅童成)** and **Meng Li (李蒙):** writing – review and editing, resources. **Moritz von Cossel**, **Grant Campbell**, **Pete Smith**, and **Yasir Iqbal:** writing – review and editing. **Zili Yi (易自力):** writing – review and editing, conceptualization, supervision. **Shuai Xue (薛帅):** project administration, methodology, supervision, writing – review and editing. All authors have read, reviewed and edited the manuscript and agreed to its publication.

Acknowledgments

Shuai Xue thanked the support from China Scholarship Council for the visiting in University of Aberdeen. We sincerely thank all the people, especially Dr. Wei Hou, for their help in establishing the field experiment. During the preparation of this work the author(s) used DEEPSEEK in language checking. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Funding

This work was supported by the Yuelushan Laboratory Breeding Project (YLS-2025-ZY04075), the Hunan Provincial Natural Science Foundation (2024JJ7225), and the Research funding of Hunan Agricultural University (25KJ040 & 2024XKJC05).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data openly available in a public repository of Research Gate with the DOI of dataset is https://doi.org/10.13140/RG.2.2.32808.74248 and https://doi.org/10.13140/RG.2.2.22810.93128.

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