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Bioenergy Production From Sugarcane Straw: Implications for Soil-Related Ecosystem Services

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ABSTRACT

Sugarcane straw removal for bioenergy production—especially second-generation ethanol—is shown to be a promising pathway for decarbonization. However, indiscriminate straw removal can negatively affect soil-related ecosystem services (SES), compromising the sustainability of the associated bioenergy production. Here, a comprehensive literature review was conducted to select and quantify the changes in agronomic and environmental indicators affected by low (≤ 1/3), moderate (> 1/3 to ≤ 2/3), and high (> 2/3) straw removal levels and the consequential impacts on eight SES. A quali-quantitative approach was developed to generate an impact matrix that provides the direction of the effects (negative, neutral, or positive) and the associated confidence levels. Overall, the lowest impact on SES occurs under low straw removal with a neutral effect on C storage, nutrient cycling, weed control, greenhouse gas (GHG) mitigation, and provision of food and bioenergy. Water regulation, erosion control, and maintenance of soil biodiversity were the SES most negatively affected by straw removal. Moderate and high levels of straw removal negatively impact the maintenance of SES and compromise the sustainability of sugarcane cultivation areas, except for pest control and soil GHG emission mitigation. Finally, it was also discussed how the negative impacts of straw removal on SES could be mitigated or even reversed through the adoption of best management practices, such as cover crops, organic amendments, biological products (e.g., use of phosphate-solubilizing bacteria and mycorrhizal fungi), reduced tillage, and machinery traffic control. Ultimately, the results of this study can be useful to guide decision-making by farmers, investors, stakeholders, and policymakers toward sustainable bioenergy production that contributes to a low-carbon economy and climate change mitigation.

1 | Introduction

Soil is one of the most complex and essential components of the planet's ecosystems (Young and Crawford 2004). Its diversity and multifunctionality are decisive for overcoming the great challenges facing humanity in the 21st century, such as ensuring food, water, and energy security, biodiversity protection, and climate change mitigation and adaptation (Smith et al. 2019; Lal 2021; Kopittke et al. 2022). Hence, healthy soils are critical components in providing the benefits that people obtain from the ecosystem (i.e., ecosystem services; MEA 2005) and play vital roles in achieving several of the United Nations Sustainable Development Goals (SDGs) (Smith et al. 2021).

Faced with the challenging scenario imposed by climate change and its threat to biodiversity loss and reduction of terrestrial carbon (C) storage, increasing bioenergy production has been widely recognized as a potential pathway to achieving net-zero greenhouse gas (GHG) emissions (Reid et al. 2020; García-Freites et al. 2021; van Soest et al. 2021; Raimi et al. 2022; Cantarella et al. 2023; Weiskopf et al. 2024). In this scenario, Brazil stands out as the world's largest producer of sugarcane—accounting for 40% of world production—from which almost 28 billion liters of ethanol are produced (CONAB 2023). In the last decades, sugarcane cultivation has been conducted under a mechanized harvesting system, in which a significant amount of straw (ranging from 10 to 20 Mg ha^{-1}) is maintained on the soil surface (Menandro et al. 2017). Recently, there has been a growing interest in using some of this straw to produce bioenergy (electricity and second-generation (2G) ethanol), thus contributing to effective climate change mitigation (Carvalho et al. 2019), especially when used for 2G ethanol production (Bordonal et al. 2024).

Conversely, straw removal can affect several soil-related ecosystem services (SES). Identifying the key drivers and understanding how they change the delivery of soil ecosystem services is imperative for planning interventions to minimize negative impacts (Schröter et al. 2019). Studies have indicated that removing sugarcane straw from the field impairs soil health indicators (Cherubin et al. 2021a) and sugarcane yields (Carvalho et al. 2019). Field studies located across the Brazilian territory revealed that the maintenance of large amounts of straw on the soil surface contributes to the delivery of SES, including those associated with (i) regulation: C sequestration (Morais et al. 2020; Tenelli et al. 2021), water regulation (Santos et al. 2021), erosion control (Gallo et al. 2022), and weed control (Silva Jr et al. 2016); (ii) supporting: nutrient cycling (Cherubin et al. 2019) and habitat and food for organisms (Menandro et al. 2019; Morais et al. 2019); and (iii) provision: food and biofuel (i.e., stalk productivity; Carvalho et al. 2019). Conversely, the maintenance of large amounts of straw in the field can generate ecosystem drawbacks such as increased pest infestation (Castro et al. 2019) and increased GHG emissions (Gonzaga et al. 2018; Vasconcelos et al. 2018).

Therefore, the benefits and trade-offs associated with sugarcane straw management on SES delivery are documented in the literature. Nevertheless, most studies tend to evaluate only one indicator or a limited set of indicators, which makes robust interpretations of the relationship between soil properties and ecosystem services impracticable (Adhikari and Hartemink 2016). Furthermore, the intensity of effects on SES depends on the level of straw removal, edaphoclimatic conditions, and management practices, giving a range of uncertainties for the observed effects. Overcoming these challenges would require long-term field experiments in several regions and modeling studies, which require significant investments and infrastructure.

Given this scenario, compiling studies measuring agronomic and environmental parameters affected by sugarcane straw removal is critical to identifying the effects and uncertainties of this management practice on soil multifunctionality and SES. Such science-based information is the foundation for updating or formulating public policies while supporting decision-making for public and private investments in this sector in Brazil. Here, a systematic review was conducted with the overall objective of integrating different indicators into an impact matrix to evaluate the effect of sugarcane straw removal for bioenergy production on different SES using a quali-quantitative approach.

2 | Material and Methods

2.1 | Data Collection

To assess the impact of different levels of sugarcane straw removal on SES, data was obtained (up to December 2023) from the Scopus and Web of Science databases. The terms used in the search were ((“sugarcane” OR “sugar cane”) AND (“trash management” OR “trash removal” OR “residue management” OR “residue removal” OR “straw management” OR “straw removal”) AND (“Bra?il*”)). For this study, only papers published in peer-reviewed journals were considered, and review papers were excluded. The *revtools* package (Westgate 2019) in the R software was used to eliminate repetitions between the papers found in both databases, resulting in a total of 132 papers. Subsequently, the papers were analyzed, and only field studies (excluding greenhouse studies) evaluating the impact of different levels of straw removal were considered. After this filter, 50 papers were retained for data extraction and analysis.

2.2 | Soil-Related Ecosystem Services

This study included eight SES that are impacted by straw removal as follows: C storage (SES1); water regulation and erosion control (SES2); pest control (SES3); weed control (SES4); GHG emission mitigation (SES5); nutrient cycling (SES6); maintenance of soil biodiversity (SES7); and provision of food and biofuel (SES8). These SES were selected based on a literature review (Adhikari and Hartemink 2016; Smith et al. 2021; Kopittke et al. 2022) and the authors' expertise in previous studies (Oliveira et al. 2019; Silva-Olaya et al. 2022; Carvalho et al. 2022; Ferreira et al. 2024; Mello et al. 2024). The rationale and mechanisms by which straw removal affects the provision of SES were outlined according to Gasparatos et al. (2018) and are presented in Table 1. The indicators/proxies used to assess each SES are shown in Figure 1.

The geographical distribution of the experimental sites where indicators of each evaluated SES are shown in Figure 2.

In this study, straw removal was divided into three levels: low removal (≤ 1/3 removal), moderate removal (> 1/3 to ≤ 2/3 removal), and high removal (> 2/3 removal). The effect of different levels of straw removal on SES was divided into positive, neutral, or negative, and the confidence level of these effects was categorized as low, medium, high, and very high. A similar approach is used in the reports of the Intergovernmental Panel for Climate Change (IPCC 2023). However, there is still a lack of quantitative criteria for defining confidence levels (Holland et al. 2015; Sánchez et al. 2018).

Considering the papers in our database, a spreadsheet was created with the average values and the comparison test results between the treatments within each SES indicator (Figure 1). Each

TABLE 1 | Selected soil-related ecosystem services (SES), rationale, and mechanisms through which sugarcane straw removal affects SES.

SES	Rationale and mechanisms
SES 1–*C storage*	*Rationale*—Straw is a source of C; therefore, if the straw is left on the soil surface, it will be decomposed by soil biota, and part of the C will be incorporated into the soil organic matter, increasing soil C stocks over time. If the straw is removed for bioenergy production, soil C inputs will be reduced, depleting soil C stocks over time. *Mechanism*—Straw removal reduces soil C inputs, which may significantly decrease soil C storage over time.
SES 2–*Water regulation and erosion control*	*Rationale*—Straw covers the soil, protecting against the impact of raindrops and reducing susceptibility to soil erosion. Straw cover directly regulates soil temperature and reduces water loss through evaporation. In addition, straw increases soil C and enhances soil structure, promoting higher water infiltration and retention in the soil. *Mechanism* – Straw removal may negatively affect the soil's capacity to regulate water flow and reduce its ability to resist erosion.
SES 3–*Pest control*	*Rationale*—The straw layer creates a favorable microclimate (i.e., high moisture and lower temperature variation) in the soil-straw interface. It acts as a shelter (refuge) and food source for soil organisms, providing suitable conditions to proliferate some soil pests in the sugarcane field. *Mechanism*—Straw removal leads to habitat loss and depletion of food supply for soil biota, making the soil less favorable to the proliferation of organisms, some of which are considered pests for sugarcane crop.
SES 4–*Weed control*	*Rationale*—Straw cover intercepts solar radiation (light incidence) and reduces soil temperature, negatively affecting the germination of weed seeds. In addition, the straw layer acts as a physical barrier, impairing weed seedling growth and survival. *Mechanism*—Straw removal increases weed infestation, requiring more herbicide applications for weed control.
SES 5–*Greenhouse gas emission mitigation*	*Rationale*—Straw is a source of C, and favors greater soil humidity which can create conditions that stimulate the production and emission of nitrous oxide (N_2O). *Mechanism*—Straw removal increase the activities of microbial groups responsible for N_2O emissions.
SES 6–*Nutrient cycling*	*Rationale*—Straw is composed of C, H, O, and nutrients (macro and micronutrients); therefore, as the straw is decomposed, the nutrients are released into the soil, increasing nutrient availability to plants and soil organisms. *Mechanism*—Straw removal reduces nutrient cycling and the soil's ability to supply nutrients for plant growth, requiring greater fertilizer application.
SES 7–*Maintenance of soil biodiversity*	*Rationale*—Straw creates a favorable soil microclimate (i.e., high moisture and lower temperature variation) and acts as a shelter (refuge) and food source for soil organisms (biota), supporting higher soil biodiversity. *Mechanism*—Straw removal can reduce shelter and food supply for soil biota, reducing the soil's ability to provide habitat and sustain high biodiversity.
SES 8–*Provision of food and biofuel*	*Rationale*—Straw is a feedstock for cellulosic bioethanol and bioelectricity production, but in the field, straw plays a critical role in sustaining key soil functions and plant growth. Therefore, straw removal became an opportunity to increase the provision of biofuel/electricity while it may impair sugarcane yields, reducing the provision of food (sugar), biofuel, and other biomaterials. *Mechanism*—Straw removal provides feedstock to directly increase biofuel or bioelectricity production, but it may also indirectly reduce crop yield and, thus, the provision of food (sugar) and biofuel.

level of straw removal (low, moderate, and high) was compared with the treatment with no removal (pairwise comparisons). When the effect of straw removal was not significant ($p > 0.05$), a neutral effect was assigned. Conversely, when the reported effect was significant ($p < 0.05$), a positive or negative effect was assigned according to each SES. For SES with more than one

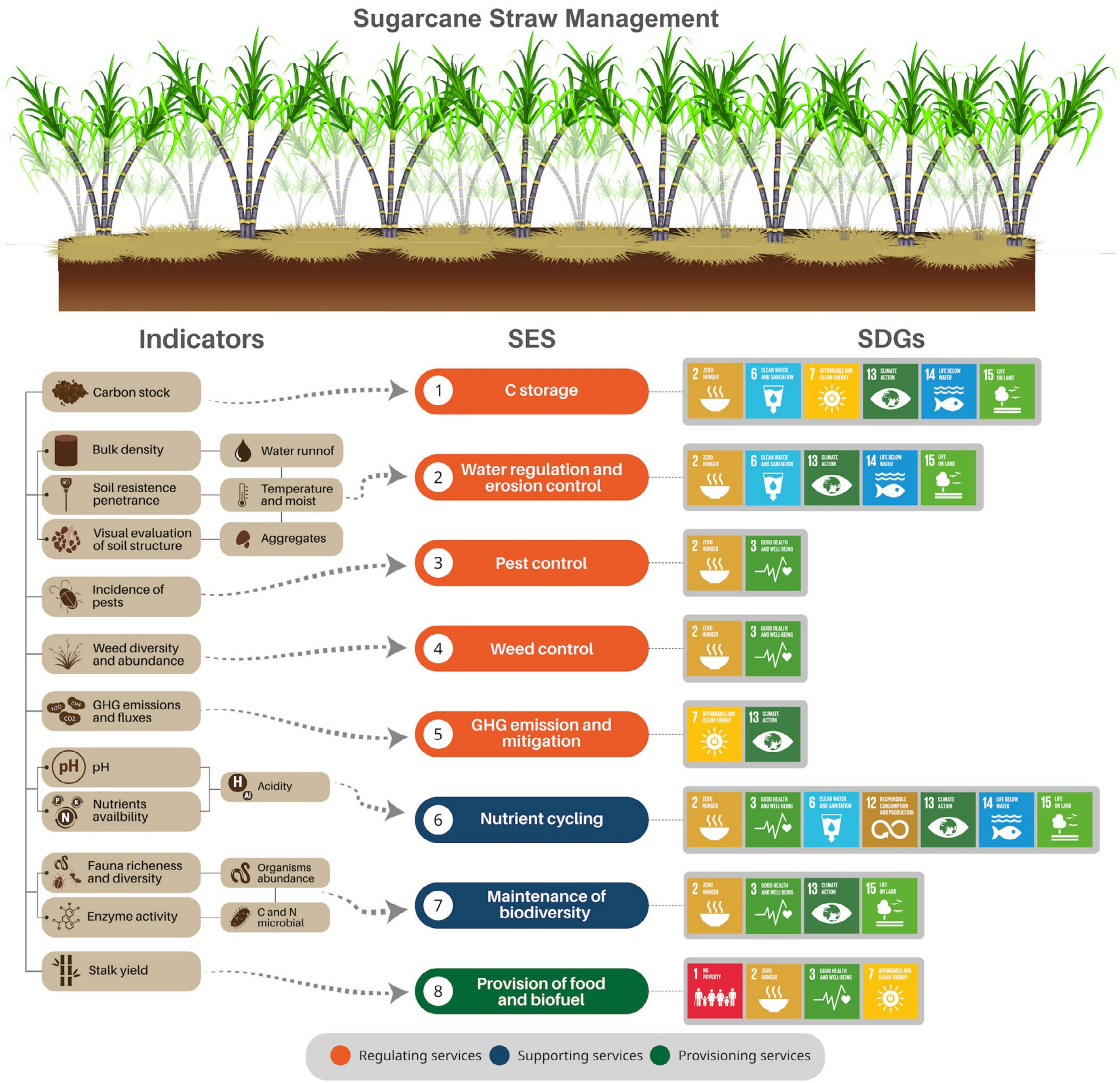

FIGURE 1 | Indicators/proxies used to assess the SES affected by straw management and their relationship with the Sustainable Development Goals (SDGs). The relationship between ecosystem services and the Sustainable Development Goals was based on Kopittke et al. (2022) and Smith et al. (2021).

indicator, if at least one indicator showed a significant difference in the mean comparison test, the positive or negative effect was accounted for.

The percentage of neutral, positive, and negative effects was calculated from the total pairwise comparisons to establish the confidence level. Thus, the following criteria were proposed: (i) for the neutral effect, confidence will be low, medium, high, and very high when the percentage of pairwise comparisons with a neutral effect is 90%–92%, 92%–94%, 94%–96%, and > 96%; (ii) for the positive and negative effects, confidence will be low, medium, high, and very high when the percentage of pairwise comparisons with these effects is 10%–25%, 25%–50%, 50%–75%, and > 75%, respectively. For services with less than 10 pairwise comparisons, low confidence was assigned. Finally, a total of 1024 pairwise comparisons were assessed to determine the effect (negative, neutral, or positive) and its confidence level (low, medium, high, and very high) of three levels of sugarcane straw removal (low, moderate, and high) on eight SES.

3 | Results and Discussion

Our results highlighted that the lowest negative impact occurs under low straw removal, showing a neutral effect in most of the SES evaluated (Figure 3). Water regulation and erosion control, as well as maintenance of soil biodiversity, were the SES most

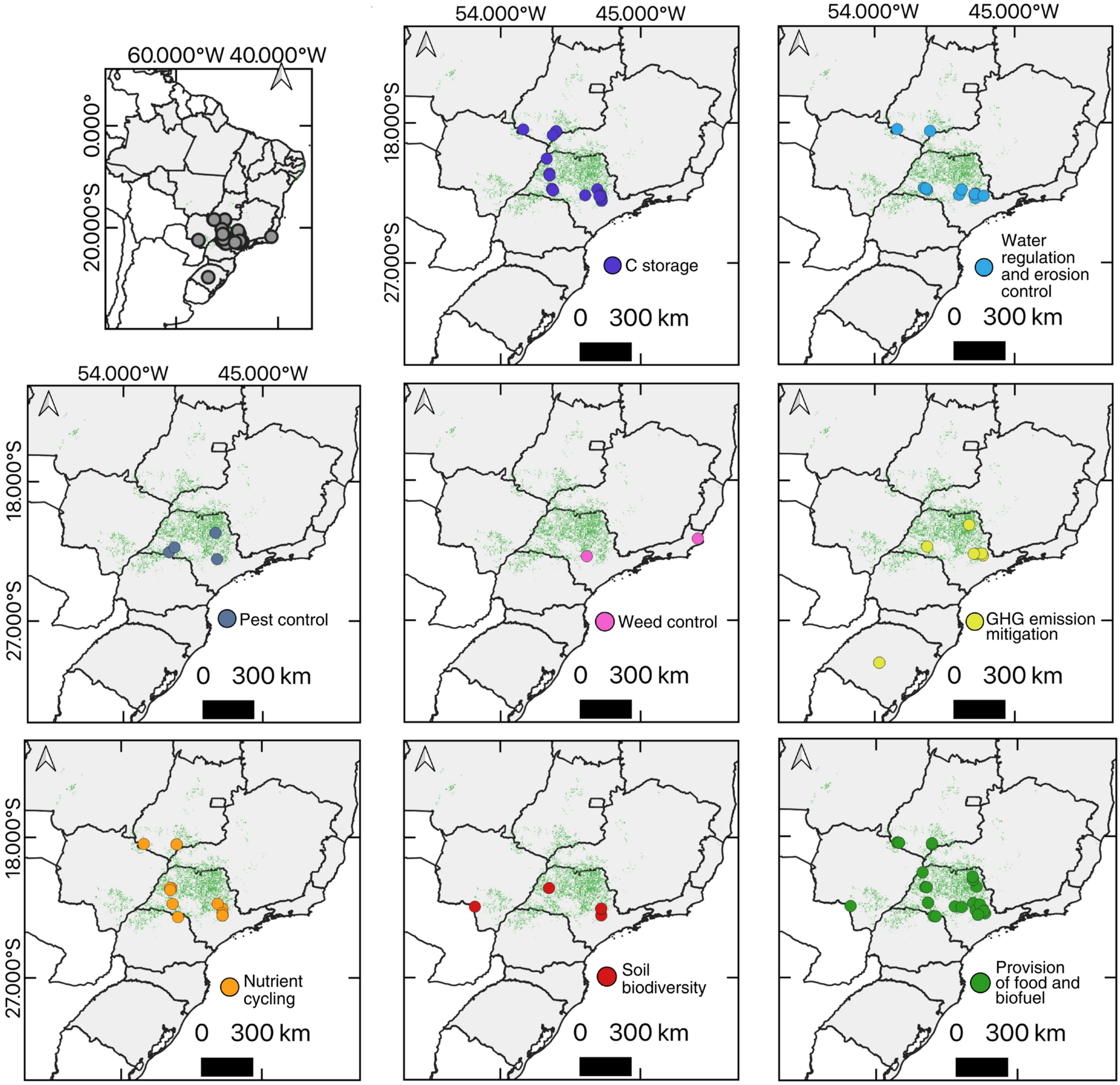

FIGURE 2 | Geographical distribution of the study sites where the indicators for the different soil-related ecosystem services were evaluated in sugarcane cultivation areas (green areas).

negatively affected by straw removal. Overall, moderate and high levels of straw removal harm the delivery of SES, except for pest control and soil GHG emission mitigation, which showed a positive effect at these removal levels.

3.1 | Impact of Sugarcane Straw Removal on Regulating SES

3.1.1 | Soil C Storage

Given the role of straw as a primary soil C source in sugarcane areas (Carvalho et al. 2017), its indiscriminate removal often affects soil C storage (Tenelli et al. 2021). Our findings showed that low straw removal had a neutral effect on soil C storage with very high confidence (Figure 3). Regardless of edaphoclimatic conditions, this level of removal did not reduce soil C stock. However, it is important to stress that our database includes only short-term evaluations (≤ 4 years), and long-term studies are required to better account for this effect. On the other hand, the effect for the moderate and high removal was negative, with a low and medium confidence levels, respectively.

Soil C stock depletion induced by moderate and high removal occurs more intensively in sandy soils, as reported by the multi-site study conducted by Tenelli et al. (2021). However, those effects were only observed after 4 years of straw removal. This result corroborates those found by Sousa Junior et al. (2018), who concluded that short-term (2 years) straw removal was insufficient

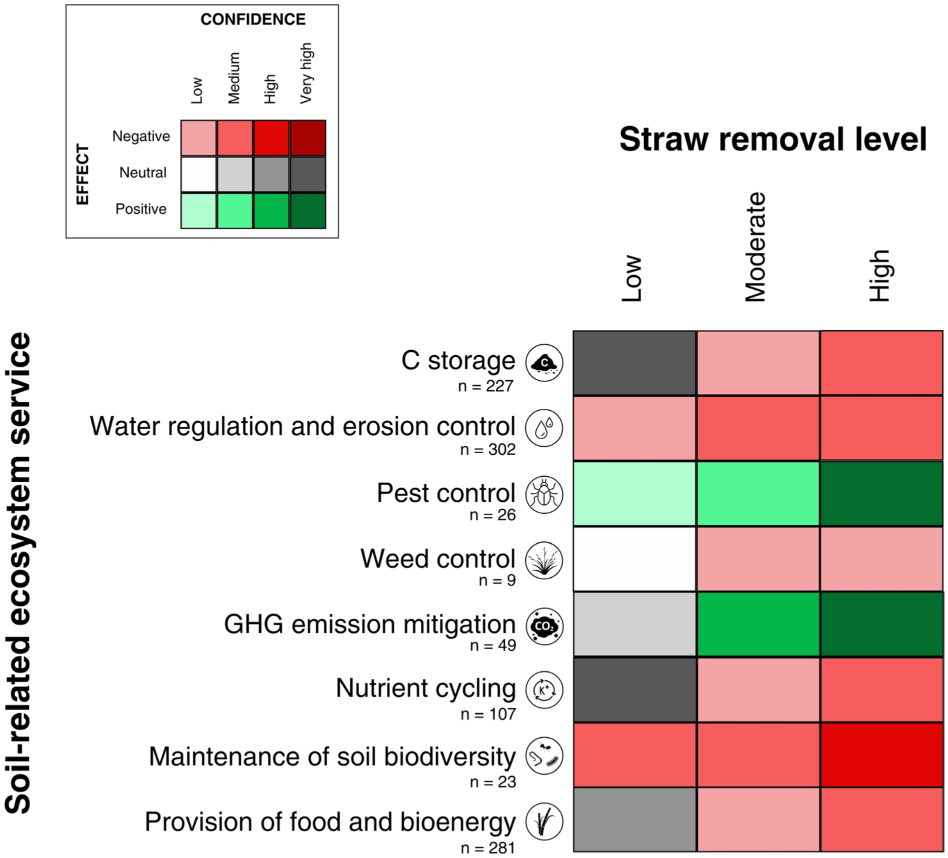

FIGURE 3 | Matrix of effect and its confidence level of the three sugarcane straw removal levels [low (≤ 1/3 removal), moderate (> 1/3 to ≤ 2/3 removal), and high (> 2/3 removal)] on soil-related ecosystem services. n means the number of pairwise comparisons for each soil-related ecosystem service.

to significantly reduce C stock in sandy soils. The authors associated this result with the low C retention capacity of sandy soils due to the low C stabilization capacity via organo-mineral interactions and physical protection within soil aggregates, which does not promote C increases even with complete straw maintenance (Cerri et al. 2011).

For clayey soils, the reduction in soil C stocks was observed predominantly in the surface layer under high levels of straw removal. It agrees with the results of Tenelli et al. (2019), who observed C depletion only in the 0–10 cm layer. These findings may be related to the greater C stabilization capacity in clayey soils, where the conversion rate was 95 kg C ha^{-1} for each Mg of straw left in the field, while for sandy soils, it was only 55 kg C ha^{-1} (Tenelli et al. 2019). In a pioneering study of the impact of straw removal on soil health, Cherubin et al. (2021a) concluded that sandy soils were functioning at 41%–56% and 67%–86% of their full potential, respectively. The authors reported that the greatest sensitivity to soil health degradation in sandy soils was mainly caused by soil C loss and recommended that straw removal in these soils should be avoided.

Our results showed soil C depletion due to the high removal of sugarcane straw in Brazil, which is in accordance with studies conducted on different crops and climate conditions (Alvarez 2024). Likewise, through a worldwide meta-analysis, Xu et al. (2019) showed that corn stover removal reduced soil C stocks by 8% in the top 30 cm of soil. In North China, results showed that adding straw to mineral fertilizer treatments significantly increased soil C stocks, highlighting the importance of stoichiometric demand for N to incorporate straw into the soil C pool (Berhane et al. 2020). In Europe, Searle and Bitnere (2017) showed that it is necessary to maintain at least 4 Mg ha^{-1} annually to avoid soil C depletion due to straw removal. Their findings also showed that only a residue input of more than 10 Mg ha^{-1} would result in greater soil C accumulation. Powlson et al. (2008) emphasized that the primary rationale for crop residue management should be maintaining soil C levels, which directly affects soil quality and functioning, beyond the primary aim of soil C sequestration for climate change mitigation. Therefore, before utilizing crop residues for bioenergy production, it is crucial to evaluate whether such practices can maintain neutral or positive effects over soil C storage, as well as other SES closely linked to soil C, such as nutrient cycling, water regulation, biodiversity, and crop yield (Smith et al. 2019).

3.1.2 | Water Regulation and Erosion Control

Sugarcane straw plays a pivotal role in maintaining soil physical quality—the main challenge in sugarcane areas—and its removal may negatively affect the soil's capacity to regulate water flow and mitigate the erosion of soils and sediments. Our results showed that straw removal negatively affected water regulation and erosion control service at all levels of straw removal, with low confidence for low removal and medium confidence for both moderate and high removal (Figure 3). Due to the ability of sugarcane straw to buffer part of the compressive stress applied to the soil surface (Cherubin et al. 2021c), the negative impact on the water regulation and erosion control service can be observed even under low levels of straw removal. Castioni et al. (2018) observed that straw removal increased soil bulk density and soil penetration resistance in sandy and clayey soils, thus highlighting the risk of soil compaction with increased straw removal regardless of soil texture.

Regarding soil porosity and structure—the main drivers of water infiltration and storage—the effect of straw removal appears to vary according to soil texture. For example, Castioni et al. (2018) concluded that straw removal reduced the macroporosity of clayey soils, while sandy soils were more sensitive to reduced microporosity. In addition, straw removal also had a greater impact on reducing the mean weight diameter of soil aggregates in sandy soils. In such soils, the predominance of macropores combined with low aggregation and poor structural stability further intensifies their low water storage capacity (Rabot et al. 2018). The reduction in water content occurs more significantly in sandy soils, although straw removal has a more significant effect on the temperature amplitude of clayey soils (Santos et al. 2021; Corrêa et al. 2019). It increases the sensitivity of sandy soils with low productive potential.

Erosion control is a critical service, particularly in tropical regions, which are more susceptible to high levels of soil erosion (Borrelli et al. 2017). Therefore, straw cover protects the soil against the direct impact of raindrops that cause surface sealing and increase water runoff and soil erosion (Wang et al. 2022). In this context, our evidence synthesis revealed that moderate and high straw removal raises concerns about erosion control (Figure 3), especially in the early stages of sugarcane growth, where low soil cover (both by the straw and the crop canopy) intensifies erosion, one of the main agents of soil degradation in sugarcane cultivated areas in Brazil (Thomaz et al. 2022). In a laboratory study, Silva et al. (2019) concluded that 7 Mg ha^{-1} of sugarcane straw is required for complete soil cover, making the soil less susceptible to erosion. These findings corroborate the results of Vaz et al. (2021), where maintaining an amount of straw of 7 Mg ha^{-1} was enough to drastically reduce water runoff compared to total removal. Considering the average annual straw production of 14 Mg ha^{-1} (Menandro et al. 2017), removing 50% (moderate level) would ensure soil cover and protection against erosion. Despite that, it is worth mentioning that soil tillage in the sugarcane renovation (planting) is still the major driver of soil degradation by erosion in Brazil (Hartemink 2008). However, straw maintenance contributes to preventing further soil degradation in sugarcane fields.

3.1.3 | Pest Control

Maintaining sugarcane straw in the field provides a favorable microclimate for the proliferation of soil pests (Dinardo-Miranda and Fracasso 2013). However, the effect of straw removal on the pest control service is poorly reported in the literature. Castro et al. (2019) are the only study that shows positive effects for all levels of straw removal, with low, medium, and very high confidence for low, moderate, and high removal, respectively (Figure 3). This study revealed that straw removal reduced root spittlebug (*Mahanarva fimbriolata*) infestation, regardless of soil texture and climatic conditions. Despite the positive effect on reducing root spittlebug infestation, straw removal did not affect the sphenophorus (*Sphenophorus levis*) population. However, the level of damage was higher in the areas that maintained a higher amount of straw, as the activity of the sphenophorus larvae was favored by the higher soil moisture in these treatments.

One interesting piece of information is that Castro et al. (2019) evaluated only the first two sugarcane ratoon cycles. Therefore, further studies with longer evaluation periods are important to assess the best response of pest populations to sugarcane straw removal. Our results show an increase in the confidence of the effect of increased straw removal on pest control; however, high straw removal harms several other SES, thus suggesting that moderate straw removal combined with integrated pest control is likely a more sustainable alternative. Given the importance of soil pests in the sugarcane production system, straw removal appears to be an important management practice to control these pests and reduce insecticide loads in the field.

3.1.4 | Weed Control

Straw mulch is a physical barrier (solar radiation interception), reducing weed germination and emergence. Our data revealed that moderate and high straw removal has a negative effect on weed control, while low removal did not induce any changes (Figure 3). More than a few studies reported that under high straw removal, additional herbicide application was needed to reduce weed infestation (Oliveira and Freitas 2009; Silva Jr et al. 2016; Castro et al. 2024). Therefore, considering the perspective of this SES, maintaining straw may contribute to reducing the use of herbicides and increasing the sustainability of sugarcane plantations.

3.1.5 | GHG Emission Mitigation

Crop residues are recognized worldwide as an important driver of GHG emissions (Carmo et al. 2013; Kravchenko et al. 2017). Our findings agree with this statement and show that straw removal led to GHG emission mitigation, particularly under moderate and high removal levels (high and very high confidence) (Figure 3). Several studies have shown that maintaining large amounts of straw in the field increases GHG emissions, particularly N_2O (Carmo et al. 2013; Sousa et al. 2017; Varanda et al. 2018; Popin et al. 2020). In a pioneering study, Carmo et al. (2013) observed that higher N_2O emissions were associated with maintaining a greater amount of straw on the soil surface. Similar results were obtained by Vasconcelos et al. (2018), in which total straw removal resulted in a 45% reduction in N_2O emissions. Our review also found inconclusive results for CH_4 emissions due to the high variability of daily flows (Gonzaga et al. 2018; Popin et al. 2020; Vasconcelos et al. 2018, 2022). According to the literature, CH_4 emissions in tropical upland soils are negligible, and frequently, very low emissions or CH_4 consumption are observed (Blazewicz et al. 2012; Paredes et al. 2015; Gonzaga et al. 2018).

The high C:N ratio (about 100) of sugarcane straw results in a low straw decomposition rate and slow release of organic N to the soil (Carvalho et al. 2017). Nevertheless, maintaining high levels of straw in the field increases soil humidity and C inputs, which, combined with the application of N fertilizers (synthetic and organic), contributes to increased N_2O production throughout nitrification and denitrification processes (Carmo et al. 2013; Oliveira et al. 2023). Several studies have indicated that sugarcane straw by itself is not an important source of N_2O emissions, but when combined with N fertilizer and/or vinasse boosts N_2O emissions (Gonzaga et al. 2019; Vasconcelos et al. 2022; Gabetto et al. 2024). Higher N_2O emissions in straw amendment soils can be associated with adding organic residues, which provide easily degradable C to the soil and may have favored N_2O formation (Vargas et al. 2019; Lourenço et al. 2022). According to Kravchenko et al. (2017), crop residues act as a hotspot for N_2O emissions by retaining water and providing N and labile C to soil microorganisms responsible for N_2O production.

3.2 | Impact of Sugarcane Straw Removal on Supporting SES

3.2.1 | Nutrient Cycling

Sugarcane straw represents an important source of nutrients for the sugarcane crop (Trivelin et al. 2013), and this nutrient supply can be altered if the straw is not removed in a sustainable manner. Our results indicate that low removal had a neutral effect with high confidence for the nutrient cycling service (Figure 3). However, the effect was negative for moderate and high removal, with low and medium confidence, respectively. The main nutrients affected by straw removal were potassium (K) and phosphorus (P). The moderate level of straw removal mainly reduced the availability of K, while the reduction in P occurred predominantly under high straw removal. This effect is likely related to the amount of these nutrients in the straw, as the K content is approximately 13 times higher than the P content (Cherubin et al. 2019), making K more sensitive to a moderate level of removal.

According to Soltangheisi et al. (2021), maintaining an amount of 5 Mg ha^{-1} (high removal) was sufficient to ensure efficient P cycling and reduce the use of inorganic P fertilizers in sugarcane fields. Nevertheless, Cherubin et al. (2019) highlight that although the P content in sugarcane straw is low, this amount can become substantial along the sugarcane cycle (5–7 years). In the same study, the authors concluded that the potential nutrient removal by straw removal can reach as much as 69, 7, 92, 45, 16, and 14 kg ha^{-1} for N, P, K, Ca, Mg, and S, respectively, impacting the short- and long-term demand for fertilizers and consequently increasing the production costs with fertilizers. Similar results were also reported in experiments with corn stover removal in the USA (Karlen et al. 2015), showing that stover removal resulted in additional costs with synthetic fertilizers.

3.2.2 | Maintenance of Soil Biodiversity

The maintenance of soil biodiversity service was negatively impacted at all levels of straw removal. The confidence level was medium for low and moderate removal and high for high removal rates (Figure 3). Straw removal reduces food abundance and habitat for soil organisms due to the effect of straw in lowering the temperature range and preserving soil moisture (Corrêa et al. 2019). Menandro et al. (2019) observed a reduction in the richness and diversity of macrofauna induced by straw removal in clayey soils. No changes were observed in the sandy soils; however, the values were low even with no removal due to a less favorable habitat for macrofauna in such soils (low water storage capacity and lower nutrient availability). Yet, a drastic reduction in earthworm abundance was found with increasing straw removal, especially in the rainy season. However, no individuals were observed under high removals in the dry season. These findings corroborate the results of Castioni et al. (2018), who observed a reduction in earthworm abundance due to straw removal.

In addition to the impact on soil macrofauna, straw removal also affects microorganisms' activity. Vieira et al. (2021) observed that straw removal reduced C and N in the microbial biomass and β-glucosidase activity. In addition, Morais et al. (2019) showed reductions in microbial biomass C and in the abundance of bacteria, archaea, and fungi at high straw removal rates in sandy soil. Similarly, high straw removal also affects the soil microbial community, thereby increasing the number of negative interactions (Pimentel et al. 2019).

Based on the results, it was observed that soil biodiversity is highly sensitive to straw removal, which is one of the main challenges to the sustainability of sugarcane areas. The importance of maintaining soil biodiversity occurs directly and indirectly in several key processes such as soil aggregation (Lehmann et al. 2017; Arai et al. 2018), creation of biopores (Pagenkemper et al. 2015), and decomposition and incorporation of organic matter into the soil (Cotrufo et al. 2015), contributing to other ecosystem services such as nutrient cycling, water regulation and erosion control, and C storage.

3.3 | Impact of Sugarcane Straw Removal on Provisioning SES

3.3.1 | Provision of Food and Bioenergy

Sugarcane straw is a flexible raw material that can be used for several purposes, like improving soil health indicators, increasing biomass yields, and consequently increasing the production of food (sugar) and bioenergy (Carvalho et al. 2019). Our findings indicate that moderate and high removal rates negatively affect sugarcane stalk yield, while low removal has no impact (neutral—high confidence) (Figure 3). Sugarcane yield was reduced with increasing intensity of straw removal, which is highly associated with soil health degradation (Cherubin et al. 2021a), particularly in the soil's physical aspects, as a result of the impact on soil compaction, high-temperature amplitude, and low water retention (Castioni et al. 2018; Corrêa et al. 2019; Santos et al. 2021).

Sugarcane yield response to straw removal is closely associated with soil texture. Our results observed a sugarcane yield of 71 Mg stalk ha^{-1} for sandy soils (< 15% clay), 91 Mg stalk ha^{-1} for loamy soils (≥ 15% to < 35% clay), and 109 Mg stalk ha^{-1} for clayey soils (≥ 35% clay). However, in a multilocation study involving 67 sites/years in south-central Brazil, Carvalho et al. (2019) highlighted that the sugarcane yield response to straw removal depends on a complex interaction between weather conditions, soil type, harvest season, and crop age. This study showed that younger ratoons were more responsive to straw removal since they present higher productive potential due to the better conditions for plant growth (e.g., high plant stand, high soil fertility, low pest and weed infestation, and low soil compaction). However, the adoption of a set of good agricultural practices to ensure high stalk yields throughout the crop cycle is fundamental to providing high straw production and reducing the negative impacts of straw removal.

3.4 | Management Recommendations to Mitigate or Reverse Trade-Offs Associated With Straw Removal

Our study provides a robust synthesis of evidence of the effects of straw removal on different SES. However, in addition to showing the impacts of straw removal on SES, it is important to highlight the best management practices that can be used to mitigate or even partially reverse the negative impacts of straw removal (Table 2). Producing bioenergy with lower negative externalities is a critical agenda. More detailed discussion about the possible impacts of the adoption of best management practices in the sugarcane production system can be found in Bordonal et al. (2018), Cherubin et al. (2021b); Cherubin et al. (2024), and Rossetto et al. (2022).

Implementing cover crops in the renovation period offers an effective solution to mitigate the adverse impacts of straw removal on several SES in sugarcane-cultivated areas. The use of cover crops is widely recognized as one of the most viable practices to increase soil C input and storage (Poeplau and Don 2015; Ruis and Blanco-Canqui 2017; Jian et al. 2020), thus attenuating the adverse impact of straw removal. Furthermore, cover crops play a crucial role in reducing soil compaction, penetration resistance, and erosion by improving soil cover, as well as soil structure and porosity (Koudahe et al. 2022). Additionally, their decomposition releases nutrients into the soil, enhancing nutrient availability and soil N and C cycling (Crusciol et al. 2015; Canisares et al. 2021; Souza et al. 2024). C inputs of different cover crops have shown the potential to enhance species richness and overall diversity, both in the soil macrofauna and microbiome (Brussaard et al. 2007; Aquino et al. 2008; Elhakeem et al. 2019; Kim et al. 2020; Fiorini et al. 2022). Cover crops are an effective strategy for weed control and suppress weed germination and establishment, leading to a significant reduction in the need for herbicides (Schappert et al. 2018).

The abundant sugarcane agroindustry residues present a high potential for bioenergy production, but can also be used for biochar production. Biochar represents a stable C form that can be used to support soil health and several SES. Due to its high stability, biochar application has proven to be an important strategy for increasing soil C storage in sugarcane fields (Lefebvre et al. 2020; Gabetto et al. 2024). Moreover, the impact of biochar extends beyond C sequestration, influencing soil biological activity and health by promoting microbial diversity, enhancing nutrient cycling, and mitigating soil contamination (Bolan et al. 2024). However, biochar is little used in sugarcane fields, and more studies evaluating the influence of biochar addition in areas of straw removal are needed.

Sugarcane fields commonly utilize organic amendments due to the production of vinasse and filter cake during ethanol production. These byproducts contain a substantial amount of C and other nutrients in organic form, effectively enhancing soil C stock (Silva-Olaya et al. 2017; Zani et al. 2018). Thus, this practice can mitigate the soil C depletion induced by straw removal. Furthermore, vinasse application has notable effects on microbial biomass C, leading to an increase in nitrogen concentration (Pinto et al. 2022) and improving soil health (Luz et al. 2024). Due to the considerable concentration of nutrients in the vinasse, especially potassium (Christofoletti et al. 2013), its application is an effective alternative for increasing nutrient cycling and reducing the need for synthetic fertilizers (Laime et al. 2011). This further highlights the potential of organic amendments like vinasse to positively influence soil health and agricultural productivity through enhanced nutrient cycling and soil biodiversity. Therefore, applying organic amendments increases nutrient availability and sugarcane stalk yield, contributing to the sustainable supply of food and bioenergy (Rossetto et al. 2018).

In Brazil, the growing interest of farmers in using biological products led to initiatives like RenovAgro and the National Bioproduct Program (Vidal et al. 2021), aiming to increase the production and adoption of management practices utilizing these products. Biological products are an important alternative to reduce the high demand for fertilizers to improve nutrient cycling. In this context, the inoculation of arbuscular mycorrhizal fungi and phosphate-solubilizing bacteria has been considered an effective and economical strategy to improve the bioavailability of nutrients in soils (Sundara et al. 2002; Etesami et al. 2021), thus increasing nutrient cycling and sugarcane production while promoting sustainable agriculture (Silva et al. 2010).

The intense mechanization of all stages of production in the sugarcane cultivation areas is the main driver of soil compaction (Cherubin et al. 2016), and the greatest threat to the water regulation and erosion control service, as well as causing loss of biodiversity and crop yield. Due to the restrictions on plant growth, conventional tillage is widely adopted in sugarcane cultivation areas to reduce the effects of soil compaction. However, soil disturbance causes intense soil C loss and increased GHG emissions (La Scala Jr et al. 2006; Silva-Olaya et al. 2013). Recent studies conducted by Luz et al. (2022, 2023) have shown that the implementation of machinery traffic control is a key approach for alleviating soil physical constraints, enabling the adoption of reduced tillage systems, and subsequently leading to a decrease in C losses and GHG emissions (La Scala Jr et al. 2006; Silva-Olaya et al. 2013). Furthermore, the adoption of machinery traffic control ensures better development of sugarcane roots and increases stalk yield (Souza et al. 2014). Another important strategy for reducing soil compaction risk is adopting an integrated harvesting system (Lisboa et al. 2017). Currently, the most common way of harvesting straw is by raking, baling, and

TABLE 2 | A summary of the best management practices to mitigate/reverse the negative impacts of straw removal on soil-related ecosystem services.

Management practices	SES	Justification
Cover crops	SES 1—*Soil C storage*; SES 2—*Water regulation and erosion control*; SES 4—*Weed control*; SES 6—*Nutrient cycling*; SES 7—*Maintenance of soil biodiversity*	The use of cover crops increases the input and sequestration of C in the soil. Cover crops can alleviate soil compaction and enhance water infiltration by forming biopores (Koudahe et al. 2022). C inputs and soil cover also improve soil aggregation, protect the soil against direct raindrop impact, and increase soil rugosity, reducing runoff and erosion (Carvalho et al. 2022). Furthermore, cover crops are a source of food for organisms (biota), increasing soil biodiversity (Kim et al. 2020) and nutrient cycling, enhancing soil fertility (Canisares et al. 2021; Souza et al. 2024). Cover crops are also a physical barrier to weed germination, particularly relevant during the sugarcane replanting period (Schappert et al. 2018).
Organic amendments	SES 1—*Soil C storage*; SES 6—*Nutrient cycling*; SES 7—*Maintenance of soil biodiversity*; SES 8—*Provision of food and biofuel*	Vinasse and filter cake are sources of C and nutrients (Christofoletti et al. 2013). Organic amendments increases soil C stocks, nutrient cycling, and stalk yield (Silva-Olaya et al. 2017; Rossetto et al. 2018; Zani et al. 2018; Luz et al. 2024). Adding organic residues in sugarcane fields has contrasting effects on bacterial and fungal communities, with bacterial diversity increasing while fungal diversity decreases (Lourenço et al. 2023). Biochar is a promising alternative to increase soil C stocks by adding a highly stable C source (Lefebvre et al. 2020; Gabetto et al. 2024).
Biological products	SES 6—*Nutrient cycling*; SES 8—*Provision of food and biofuel*	The use of phosphate-solubilizing bacteria, mycorrhizal fungi, and N-fixing organisms increases nutrient availability and absorption (Etesami et al. 2021), and sugarcane stalk yields (Silva et al. 2010).
Reduced tillage	SES 1—*Soil C storage*; SES 2—*Water regulation and erosion control*; SES 5—*Greenhouse gas emission mitigation*	Adopting reduced tillage during crop renewal reduces soil disturbance and aggregate breakdown, which in turn improves water infiltration and percolation, and reduces soil C losses and GHG emissions (Silva-Olaya et al. 2013; Rabot et al. 2018; Tenelli et al. 2019; Luz et al. 2022).
Machine traffic control	SES 2—*Water regulation and erosion control*; SES 8—*Provision of food and biofuel*	Controlling machinery traffic reduces the risk of soil physical degradation caused by disordered soil compaction in the field. It sustains traffic-free seedbed zones, that favor water infiltration and availability to plants, soil aeration, and plant growth (Luz et al. 2022, 2023), increasing stalk yields and crop longevity. Furthermore, sugarcane crop established in physically healthy soils are less vulnerable to abiotic stresses (i.e., drought) (Souza et al. 2014).

transporting the residue after harvesting stalks. Thus, the integral harvesting system (stalk plus straw) reduces the number of mechanized operations, the risk of soil physical degradation, and the effective cost of harvesting (Cardoso et al. 2013).

Ultimately, by integrating these management practices (e.g., cover crops, biochar, organic amendments, bio-products, machinery traffic control, and reduced tillage), farmers can mitigate some of the negative impacts of straw removal and promote more efficient and sustainable sugarcane production systems.

4 | Perspectives and Final Remarks

Our comprehensive review study provided a matrix with novel evidence synthesis of sugarcane straw removal's effects (and confidence level) for bioenergy production on multiple SES. Overall, low straw removal levels had neutral or low negative impacts on SES (C storage, nutrient cycling, weed control, GHG mitigation, and provision of food and bioenergy) and seem to be a more viable alternative for the long-term sustainability of sugarcane bioenergy production. Water regulation and erosion control, as well as maintenance of soil biodiversity, were the most sensitive SES, being negatively affected at all levels of straw removal. Moderate and high levels of straw removal negatively impact most SES, except for pest control and soil GHG emission mitigation.

Considering the urgent need to accelerate the energy transition agenda, a set of best management practices that would mitigate or reverse the impact of straw removal on SES was outlined. These practices include (i) use of cover crops during planting renovation to increase C input and storage, improve soil physical quality and surface cover (water regulation and erosion control), as well as being a source of food for soil organisms, contributing to the maintenance of biodiversity and nutrient cycling; (ii) use of biological products such as growing-promoting, nitrogen-fixing, and phosphate-solubilizing bacteria and mycorrhizal fungi to increase nutrient cycling and their absorption by plants, and consequently an increase in crop yield; (iii) application of sugarcane by-products (filter cake, vinasse, biochar) as organic amendments to contribute to increased C storage, nutrient cycling, and crop yield; and (iv) reduced tillage and machine traffic control to reduce the risk of soil physical degradation, especially soil compaction, which favors plant growth and increases crop yield.

Lastly, the impact matrix of effect associated with sugarcane straw removal developed in this study will be useful in guiding decision-making by farmers, investors, stakeholders, and policymakers, aiming to promote progress toward sustainable bioenergy production that contributes to a low-carbon economy and climate change mitigation.

Author Contributions

Carlos Roberto Pinheiro Junior: conceptualization, data curation, methodology, visualization, writing – original draft, writing – review and editing. **João Luís Nunes Carvalho:** conceptualization, visualization, writing – original draft, writing – review and editing. **Lucas Pecci Canisares:** formal analysis, methodology, visualization, writing – original draft, writing – review and editing. **Ricardo de Oliveira Bordonal:** visualization, writing – original draft, writing – review and editing. **Carlos Eduardo Pellegrino Cerri:** conceptualization, writing – original draft, writing – review and editing. **Maurício Roberto Cherubin:** conceptualization, funding acquisition, supervision, visualization, writing – original draft, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data supporting this study's findings are openly available in Zenodo at https://doi.org/10.5281/zenodo.15056860.

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