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Environmental Impacts of Sugarcane Cultivation: Soil Degradation and Erosion Dynamics

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Abstract As an important sugar crop, sugarcane is widely planted in tropical and subtropical regions worldwide. However, its cultivation process may have adverse effects on soil structure, nutrients, and ecological balance. Soil degradation and erosion, as important environmental issues, not only threaten the sustainability of agricultural production, but also pose challenges to the stability of ecosystems. This study delves into the specific impacts of sugarcane cultivation activities on soil environment, particularly the dynamic changes in soil degradation and erosion. By revealing the potential link between sugarcane cultivation and soil degradation and erosion, research has found that unreasonable planting methods and management measures, such as excessive tillage, unreasonable fertilization, and irrigation, may accelerate the process of soil degradation and erosion. At the same time, corresponding prevention and control strategies and management suggestions were proposed, aiming to reduce the negative impact of sugarcane cultivation on the soil environment, promote sustainable agricultural development, and have important significance for protecting soil resources, maintaining ecological balance, and promoting sustainable agricultural development.

Keywords Sugarcane (*Saccharum officinarum*); Soil degradation; Soil erosion; Environmental impact; Sustainable agricultural development

Sugarcane (*Saccharum officinarum*) cultivation is a globally significant agricultural activity, not only for its role in providing sugar but also as a source of bioethanol, a renewable energy resource. The crop's importance is underscored by its extensive cultivation in tropical and subtropical regions worldwide, with Brazil being a major producer. The expansion of sugarcane production has been driven by the increasing demand for bioenergy, which aims to reduce dependency on crude oil and mitigate climate change (Bordonal et al., 2018).

However, the intensification and expansion of sugarcane cultivation raise concerns about the environmental impacts, particularly soil degradation and erosion. Soil degradation refers to the decline in soil quality and productivity, which can result from various factors, including compaction, loss of soil structure, nutrient depletion, and increased salinity. Erosion, a related process, involves the removal of the topsoil by water, wind, or tillage, leading to further degradation and reduced agricultural productivity (Bengtson et al., 2006; Cherubin et al., 2016; Gallo et al., 2022).

The link between sugarcane cultivation and soil degradation is multifaceted. The conversion of native ecosystems or degraded pastures to sugarcane fields can lead to increased soil compaction, reduced porosity, and diminished water infiltration, which in turn can exacerbate erosion risks (Cherubin et al., 2016). Moreover, the removal of sugarcane residue, which could otherwise protect the soil surface, has been associated with increased soil erosion, as the protective organic layer is diminished, leaving the soil more vulnerable to water and wind forces (Bengtson et al., 2006; Gallo et al., 2022).

The impact of these processes on the environment and agricultural production is profound. Soil degradation and erosion can lead to a decline in crop yields, loss of soil biodiversity, and reduced water quality due to sedimentation and nutrient runoff. These changes not only threaten the sustainability of sugarcane production but also have broader implications for ecosystem services and food security (Bengtson et al., 2006; Bordonal et al., 2018; Gallo et al., 2022). In light of these challenges, there is a pressing need to understand the dynamics of soil degradation and erosion in sugarcane cultivation and to develop sustainable management practices. Such practices may include the adoption of minimum tillage, the maintenance of crop residues on the field, and the implementation of soil conservation measures to enhance organic matter content and improve soil structure (Bengtson et al., 2006; Cherubin et al., 2016; Bordonal et al., 2018; Gallo et al., 2022).

This study aims to explore the potential relationship between sugarcane cultivation and soil degradation and erosion, analyze the impact mechanism of sugarcane cultivation on soil environment, and propose corresponding prevention and control measures and management strategies. This is of great significance for protecting soil resources, maintaining ecological balance, and promoting sustainable agricultural development. At the same time, it can also provide reference and inspiration for the cultivation of other sugar crops and crops.

1 The Relationship Between Sugarcane Cultivation and Soil Degradation

1.1 Effects of sugarcane cultivation on soil physical properties

Sugarcane cultivation has been identified as a significant factor influencing soil physical properties, with various studies highlighting the detrimental effects on soil structure and function. The expansion of sugarcane for biofuel feedstock production, particularly in Brazil, has led to land-use changes that have impacted soil physical quality. Intensive mechanization associated with sugarcane production has been shown to increase soil compaction, which in turn reduces macroporosity, microporosity, and total porosity, leading to decreased aeration porosity and water hydraulic conductivity. These changes create an unbalanced ratio between water- and air-filled pore space, which can compromise the soil's capacity to perform its physical functions (Cherubin et al., 2016).

Long-term sugarcane cultivation has also been reported to result in higher bulk density and lower structural stability, particularly in fine-textured soils. This can lead to the formation of a dense compacted layer, which further exacerbates the reduction in the number of macropores and structural stability, indicating a significant alteration in soil physical properties due to prolonged cultivation (Barzegar et al., 2005).

The shift from traditional practices of burning sugarcane fields before harvest to mechanized harvesting has also been studied. While this change aims to reduce environmental concerns related to emissions during burning, it has been observed that different sugarcane management systems can influence the potential production of greenhouse gases in the soil, which indirectly suggests changes in soil physical conditions (Tavares et al., 2018). Moreover, the use of sugarcane byproducts, such as vinasse, has been scrutinized for its environmental implications. The application of vinasse to soils can alter their physical-chemical properties, potentially leading to soil degradation if not managed properly (Christofoletti et al., 2013).

1.2 Effects of sugarcane cultivation on soil chemical properties

Sugarcane cultivation has been identified as a significant factor influencing soil chemical properties, with various management practices leading to different outcomes. The shift from traditional burning to mechanized harvesting of sugarcane has been shown to affect soil greenhouse gas (GHG) production, with a noted impact on the potential production of carbon dioxide (CO_2) in the soil (Tavares et al., 2018). This change in practice has implications for soil organic matter content, as the presence of sugarcane residue on the soil surface can alter CO_2 emission patterns (Tavares et al., 2018).

The use of sugarcane vinasse, a by-product of ethanol production, as a soil amendment has been reported to alter the chemical composition of soils. Its application can lead to soil acidification, changes in electrical conductivity, and the presence of chemical elements that may affect soil nutrient levels (Christofoletti et al., 2013). Moreover, the substitution of chemical fertilizers with industrial wastes like vinasse and filter cake from ethanol production has been explored as a means to improve the environmental performance of ethanol. This practice can influence soil nutrient dynamics, potentially reducing soil nutrient loss and mitigating some negative environmental impacts (Moore et al., 2017).

The comparison between burned and unburned sugarcane harvesting systems has revealed that unburned systems, which leave high amounts of crop residues, can stabilize soil carbon and reduce GHG emissions, particularly CO_2. This suggests a potential decrease in soil organic matter degradation compared to burned systems (Motinho et al., 2021).

Motinhod et al. (2021) found that compared to burning sugarcane, unburned (managed) sugarcane residues can increase soil carbon storage and reduce soil CO_2 emissions. This is because unburned sugarcane residues can improve the physical, chemical, and biological properties of soil, promote the decomposition of organic matter, and fix carbon. In addition, sugarcane residues can improve soil structure, increase soil porosity and water holding capacity, which is beneficial for soil nutrient retention and crop growth. This study emphasizes that improving agricultural management practices, such as using unburned sugarcane residues, can effectively reduce carbon emissions in agricultural activities, promote soil carbon storage, and make a positive contribution to addressing global climate change.

Additionally, different sugarcane management regimes have been found to impact soil bacterial communities, which are closely related to the dynamics of soil nutrients and may indirectly influence soil chemical properties (Rachid et al., 2012).

Land use change (LUC) from native vegetation to sugarcane cultivation has been associated with soil acidification and a decrease in soil chemical quality, as indicated by lower levels of available phosphorus (P), sulfur (S), calcium (Ca), magnesium (Mg), and boron (B). However, the subsequent conversion from pasture to sugarcane can increase soil nutrient levels and reduce soil acidity due to lime and fertilizer applications (Cherubin et al., 2015).

1.3 Effects of sugarcane cultivation on soil biological activity

Sugarcane cultivation has been identified as a significant factor influencing soil biological activity, with various management practices impacting the quantity and quality of soil microorganisms, soil enzyme activity, and the overall ecological balance of the soil. The transition from traditional pre-harvest burning to mechanized harvesting in sugarcane fields has been shown to affect greenhouse gas production potential in the soil, with implications for soil microbial processes (Tavares et al., 2018). Specifically, the management systems of sugarcane cultivation, including the duration of green sugarcane management, have been observed to impact the potential production of CO_2, N_2O, and CH_4 in the soil, which are key indicators of microbial activity and soil health (Tavares et al., 2018).

Furthermore, the application of nitrogen fertilizers and crop residue retention in sugarcane production has been associated with significant nitrous oxide (N_2O) emissions, a potent greenhouse gas that reflects changes in the soil microbial community responsible for nitrogen cycling (Yang et al., 2020). The increase in N_2O emissions has been found to correlate with the rate of nitrogen fertilizer application, suggesting that conventional sugarcane cultivation practices may disrupt the balance of soil nitrogen transformations carried out by soil microorganisms (Yang et al., 2020).

The physical and chemical alterations in soil due to sugarcane cultivation, such as changes in soil compaction and nutrient content, have been shown to influence the biological attributes of the soil, including microbial biomass and activity (Cherubin et al., 2016).The spatial variation in environmental impacts of sugarcane expansion, including soil erosion and biodiversity, further highlights the complex interactions between sugarcane cultivation and soil biological activity (Vera et al., 2020).

2 Soil Erosion Dynamics Caused by Sugarcane Cultivation

Soil erosion is a significant environmental concern associated with sugarcane cultivation. The dynamics of soil erosion involve various types and mechanisms, each contributing to the degradation of soil quality and the potential reduction in crop yield and quality.

2.1 Types and mechanisms of soil erosion

Soil erosion can occur through different mechanisms, including hydraulic erosion, wind erosion, and gravity erosion. Hydraulic erosion is the removal of soil by water runoff, which can be exacerbated by the intensive mechanization of sugarcane production, leading to soil compaction and reduced water infiltration (Cherubin et al., 2016). Wind erosion refers to the transport of soil particles by wind, which can be significant in areas with reduced vegetation cover due to sugarcane fields. Gravity erosion, or mass wasting, involves the downward movement of soil and rock under the influence of gravity, which can occur on sloped lands where sugarcane is cultivated.

2.2 Factors that exacerbate soil erosion during sugarcane cultivation

Several factors contribute to the exacerbation of soil erosion in sugarcane cultivation. Cultivation methods, such as the intensive mechanization mentioned earlier, can lead to soil compaction and structural degradation, increasing the risk of erosion (Cherubin et al., 2016). The frequency of tillage operations, especially during replanting, can have a short-term positive effect on soil physical quality but may decrease the resistance to erosion over time (Cherubin et al., 2016). Reduced vegetation cover, particularly when sugarcane residue is removed or burned, leaves the soil surface exposed and more susceptible to erosion (Bengtson et al., 2006). Rainfall intensity and frequency also play a critical role, as heavy and frequent rains can lead to increased runoff and soil loss (Gallo et al., 2022).

The factors that exacerbate soil erosion during sugarcane cultivation mainly include cultivation activities, rainfall erosion rate, and the properties of the soil itself. Gallo et al. (2022) analyzed multi temporal satellite images from 2008 to 2017 and the SYSI dataset, and found that different tillage management strategies (such as planting, harvesting, and straw treatment) and straw coverage (0%~100%) significantly affected soil erosion rate. Especially the frequent rainfall during the rainy season and the bare soil period during sugarcane cultivation are more likely to lead to intensified soil erosion. Through soil sampling and radar data collection, researchers further quantified the impact of these factors on soil erosion losses and explored restoration and remediation strategies to reduce soil erosion and adapt to the impacts of climate change.

2.3 Impact of soil erosion on sugarcane yield and quality

Soil erosion has direct and indirect impacts on sugarcane yield and quality. Poor root development can occur due to the loss of the upper soil layer, which is often the most fertile and rich in organic matter (Bordonal et al., 2018). Hindered nutrient absorption is another consequence, as essential nutrients are washed away with the eroded soil (Bengtson et al., 2006). An insufficient water supply can result from reduced soil water storage capacity and hydraulic conductivity, leading to drought stress in the sugarcane plants (Cherubin et al., 2016). These factors collectively contribute to a decrease in both the quantity and quality of the sugarcane yield.

3 Prevention and control strategies for soil degradation and erosion in sugarcane cultivation

3.1 Rotation and fallow system

The rotation and fallow system in sugarcane cultivation plays a critical role in maintaining soil fertility and structure. Crop rotation, involving the alternation of sugarcane with other crops, and the implementation of fallow periods, where land is left unplanted, can significantly impact soil health. The length and purpose of the fallow period are tailored to allow for the recovery of soil properties and to disrupt pest and disease cycles. Studies have shown that land-use change from native vegetation to pasture and subsequently to sugarcane can lead to soil compaction, reduced aeration porosity, and decreased water hydraulic conductivity, ultimately resulting in an unbalanced ratio between water- and air-filled pore space in the soil (Cherubin et al., 2016). Therefore, incorporating rotation and fallow periods can mitigate these effects by enhancing soil organic matter and minimizing compaction, thus preventing further soil physical quality degradation (Cherubin et al., 2016).

3.2 Soil management measures

Improvement of cultivation methods is essential for the sustainable management of sugarcane soils. The adoption of non-burning sugarcane harvesting techniques has been identified as a win-win strategy due to its agronomic and environmental benefits, including the preservation of soil organic matter (Bordonal et al., 2018).

The maintenance and restoration of vegetation cover are also crucial for preventing soil erosion. Studies have indicated that the conversion of pastureland to sugarcane can lead to increased runoff and soil loss, particularly in the first year after planting. However, as sugarcane residue mulch ground cover increases, these levels decrease, highlighting the importance of maintaining adequate ground cover to reduce erosion (Youlton et al., 2016).

Optimization of irrigation and drainage systems is another vital soil management measure. Proper irrigation practices can help maintain soil structure and reduce the risk of erosion. Additionally, the management of sugarcane straw is a critical factor; while straw removal can be beneficial for bioenergy production, excessive removal rates can deplete soil organic matter, leading to soil health degradation. Therefore, moderate straw removal is recommended to balance the release of straw-carbon to the soil through decomposition, without compromising soil carbon stocks (Morais et al., 2020).

3.3 Fertilizer application strategies

The intensification of sugarcane cultivation has raised concerns about soil degradation and the need for sustainable management practices. Research indicates that soil compaction, acidification, and loss of organic matter are common issues associated with intensive sugarcane cultivation (Hartemink, 2008). To address these challenges, a combination of organic and inorganic fertilizers is recommended. Organic fertilizers can help increase soil organic matter levels, which in turn improves soil structure, water retention, and cation exchange capacity. The timing and measurement of fertilizer application are critical to minimize environmental impacts such as leaching and eutrophication of water bodies (Hartemink, 2008). Precision farming principles and improved crop husbandry can enhance the effectiveness of fertilizing practices, ensuring nutrients are supplied at the right time and in the right amounts to meet the crop's needs while minimizing losses to the environment (Hartemink, 2008).

3.4 Biological control technology

Biological control technology offers a promising alternative to chemical inputs for managing soil health in sugarcane cultivation. The application of microbial agents can enhance soil biological activity and contribute to the breakdown of organic matter, thereby improving soil structure and fertility (Cherubin et al., 2021). The use of plant extracts and other bioactive substances can also play a role in controlling pests and diseases while minimizing the impact on non-target organisms and the environment (Racines et al., 2022). Studies have shown that the presence of sugarcane waste on the soil surface can increase the time required for the initiation of surface runoff, thus reducing soil and water loss and increasing the infiltration rate (Valim et al., 2016). This suggests that sustainable residue management, such as the use of sugarcane waste as mulch, can be an effective strategy for controlling interrill erosion and improving soil health (Valim et al., 2016). Additionally, the impact of biological control on soil biological activity is significant, as it can lead to a more favorable biological environment and reduce the need for chemical inputs.

4 Construction of a Sustainable Sugarcane Cultivation System

4.1 Concept and characteristics of sustainable planting systems

Sustainable sugarcane cultivation systems are designed to balance the need for biofuel production with environmental conservation and soil health. The concept of sustainability in sugarcane cultivation encompasses a range of practices aimed at maintaining soil quality, reducing erosion, and minimizing negative environmental impacts.

Research has shown that land-use change (LUC) for sugarcane expansion, particularly in Brazil, has led to soil compaction, decreased soil porosity, and reduced water hydraulic conductivity, which are indicative of soil physical quality degradation (Cherubin et al., 2016). The transition from native vegetation or pasture to sugarcane fields has been associated with a decrease in the soil's capacity to perform its physical functions, highlighting the need for sustainable management practices (Cherubin et al., 2016).

In conclusion, constructing a sustainable sugarcane cultivation system requires a multifaceted approach that addresses soil physical and chemical quality, residue management, and erosion control. By integrating these practices, it is possible to enhance the environmental and economic sustainability of sugarcane ethanol production.

4.2 Components of sustainable sugarcane cultivation system

A high-quality soil environment is fundamental to sustainable sugarcane cultivation. Soil physical quality is a critical factor, as it influences the soil's capacity to perform its functions, such as supporting plant growth, storing and filtering water, and cycling nutrients. Research has shown that land-use change from native vegetation to sugarcane cultivation can lead to soil compaction, reduced porosity, and decreased water hydraulic conductivity, which are indicators of soil degradation (Cherubin et al., 2016). To maintain a high-quality soil environment, practices such as minimizing soil compaction, increasing soil organic matter, and avoiding excessive tillage are essential (Cherubin et al., 2016).

A reasonable planting structure refers to the strategic arrangement of crops to optimize yields while minimizing environmental impacts. This includes considerations such as crop rotation, intercropping, and the appropriate use of crop residues. Studies have indicated that the management of sugarcane residues can significantly impact soil erosion, with the presence of waste on the soil surface increasing the time required for the initiation of surface runoff and reducing soil and water loss (Valim et al., 2016). Additionally, the management of sugarcane residues can influence greenhouse gas emissions from the soil (Tavares et al., 2018).

Scientific management measures involve the application of knowledge and technology to improve the sustainability of sugarcane cultivation. This includes the use of precision agriculture techniques, optimized fertilizer and pesticide application, and the adoption of mechanized harvesting where appropriate. Such measures can help to reduce the environmental impacts of sugarcane cultivation, such as greenhouse gas emissions, soil degradation, and water resource depletion (Tavares et al., 2015; Prasara and Gheewala, 2016). Moreover, the implementation of best management practices can improve the socio-economic sustainability of sugarcane cultivation by increasing yields, reducing production costs, and improving labor conditions (Prasara and Gheewala, 2016).

4.3 Practical cases of sustainable sugarcane cultivation systems

The expansion of sugarcane cultivation, particularly for biofuel production, has necessitated the development of sustainable agricultural practices to mitigate negative environmental impacts. In Brazil, the transition from degraded pastures to sugarcane plantations has been associated with soil compaction, reduced aeration porosity, and decreased water hydraulic conductivity, leading to an imbalance between water- and air-filled pore space in the soil (Cherubin et al., 2016). To address these issues, soil management practices that increase soil organic matter and minimize compaction are essential for preventing further soil physical quality degradation and improving the economic and environmental sustainability of sugarcane ethanol production (Cherubin et al., 2016).

In North-eastern Thailand, the environmental and socio-economic impacts of sugarcane cultivation were assessed, with recommendations including optimal fertilizer and pesticide application, and zoning agricultural crops to improve sustainability (Prasara and Gheewala, 2016).

The challenges faced in sustainable sugarcane cultivation include soil degradation, water resources contamination, competition between food and fuel production, and labor conditions (Goldemberg et al., 2008). Solutions to these challenges involve a multifaceted approach, including the management of sugarcane residues to reduce soil greenhouse gas emissions (Tavares et al., 2018), and the implementation of sustainable crop management practices such as crop rotation, intercropping, and precision agriculture (Putra et al., 2020). These practices not only aim to mitigate environmental impacts but also to enhance the socio-economic benefits for workers and local communities (Prasara and Gheewala, 2016; Putra et al., 2020).

5 Outlook

The expansion of sugarcane cultivation, particularly for biofuel production, has led to land-use changes with significant impacts on soil physical quality. In Brazil, the conversion from native vegetation or degraded pastures to sugarcane fields has resulted in increased soil compaction, decreased aeration porosity, and reduced water hydraulic conductivity, leading to an imbalance between water- and air-filled pore space in the soil (Cherubin et al., 2016). While tillage operations during sugarcane replanting have a short-term positive effect on soil physical quality, they can decrease resistance to erosion and structural degradation over time (Cherubin et al., 2016).

Sustainable sugarcane cultivation practices in Thailand suggest that managing fertilizer and agro-chemical applications, increasing yields, and zoning agricultural crops could improve sustainability (Prasara and Gheewala, 2016). However, mechanized harvesting, while reducing production costs, is associated with increased environmental impacts and reduced employment (Prasara and Gheewala, 2016).

The future of sustainable sugarcane cultivation lies in the adoption of best management practices that mitigate negative environmental impacts. This includes conservation tillage, sustainable crop residue management, rational fertilization, and recycling by-products (Cherubin et al., 2021). The transition from low-productivity pastures to sugarcane cultivation can enhance soil health and carbon sequestration, although challenges such as soil compaction, biodiversity loss, and erosion remain (Cherubin et al., 2021).

Spatial variation in environmental impacts due to sugarcane expansion in Brazil indicates that strategies should be developed to mitigate negative effects and enhance positive ones for future expansion (Vera et al., 2020). Additionally, the impact of climate change on sugarcane production must be considered, with strategies proposed to mitigate negative impacts and improve sustainability and profitability (Zhao and Li, 2015).

Future research should focus on the long-term effects of land-use change on soil properties and the development of sustainable management practices that can maintain or improve soil quality (Cherubin et al., 2016). Studies on the socio-economic impacts of sugarcane cultivation, such as employment generation, worker income, wages, and working conditions, are also crucial (Prasara and Gheewala, 2016).

Research on the impact of sugarcane cultivation on greenhouse gas emissions is necessary, with a focus on different management systems such as pre-harvest burn and mechanical, unburnt harvest (Rachid et al., 2012; Tavares et al., 2018). Additionally, the role of sugarcane-derived bioenergy in mitigating global warming and climate change should be further explored, considering the potential for large-scale land-use change and its effects on the environment and socio-economic factors (Cherubin et al., 2021).

Lastly, system dynamics models could be used to estimate the environmental effects of irrigation, pest, and weed control in both traditional and organic sugarcane crops, providing insights into the depletion of water resources and soil contamination (Racines et al., 2022). This approach could support decision-making by considering additional aspects that affect crop yield, profit margin, and volatility (Racines et al., 2022).

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Conflict of Interest Disclosure

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