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CARBON BALANCE IN SOYBEAN AND INTERCROPPED MAIZE PRODUCTION SYSTEMS IN A LONG-TERM EXPERIMENT

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To my beloved family, whose unwavering support
and encouragement have been my rock throughout this
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I dedicate

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"But how could you live and have no story to tell?"

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ABSTRACT

Human CO_2 emissions play a pivotal role in global warming. Since soil serves as a significant reservoir of carbon (C), depending on how it is managed, it can either release or sequester atmospheric C. Agricultural production systems, like no-till and intercropping, offer essential alternatives from both environmental and agronomic perspectives. This study examined the long-term impact (15 years) of no-till and soil cover on C dynamics in the soil and atmosphere. The treatments involved different cropping systems, with various plants intercropped with maize in a soybean-maize succession: (1) maize without intercropping (fallow); (2) Ruzigrass (intercropped with *Urochloa ruziziensis*); (3) Sunn hemp (intercropped with *Crotalaria spectabilis*); and (4) Sunn hemp+ruzigrass. Intercropped systems, particularly those with ruzigrass, exhibited an increase in dry matter, nitrogen, and C input both above and below the ground. Due to the substantial input, ruzigrass in intercropping achieved a positive C balance (~0.7 Mg ha^{-1}), whereas when alone (2) and combined with sunn hemp (4), the balance was less negative. Ruzigrass intercropped system (2) resulted in an increase of around 30% in C stock (0-1 m depth) compared to fallow. Grain yield and relative emissions (kg of C-CO_2 per kg of grains) were notably enhanced with the introduction of ruzigrass into the systems. The results emphasize the importance of intercropping with ruzigrass in tropical conditions, showcasing how cover crops are valuable amidst global climate changes and the imperative to increase food production.

Keywords: carbon dioxide emissions; carbon sequestration; conservationist systems.

RESUMO

Emissões antrópicas de CO_2 desempenham um papel fundamental no aquecimento global. O solo atua como um reservatório significativo de carbono (C) e a depender de como é manejado, pode emitir ou sequestrar C atmosférico. Sistemas conservacionistas de produção agrícola, incluindo semeadura direta e introdução de culturas de cobertura, oferecem alternativas essenciais tanto na perspectiva ambiental quanto agronômica. Este estudo examinou o efeito de longa duração (15 anos) de semeadura direta e diferentes culturas de cobertura na dinâmica do C no solo e na atmosfera. Os tratamentos envolveram diferentes sistemas de cultivo, com diferentes culturas de cobertura em consórcio como o milho em sistemas de sucessão soja-milho: (1) milho sem consórcio (pousio); (2*) Urochloa ruziziensis* (consorciado com braquiária); (3) *Crotalaria spectabilis* (milho consorciado com crotalária); e (4) Crotalária + braquiária. Sistemas consorciados, especialmente aqueles consorciados com braquiária, mostraram um aumento na matéria seca, nitrogênio e aporte de C tanto na parte aérea quanto nas raízes. Devido ao maior aporte de C, o sistema com braquiária (2) alcançou um saldo de C positivo (~0,7 Mg ha^{-1}), enquanto crotalária + braquiária (4), o saldo foi menos negativo. O sistema consorciado com braquiária (2) resultou em um aumento de aproximadamente 30% no estoque de C (0-1 m de profundidade) em comparação ao pousio. A produtividade de grãos e as emissões relativas (kg de C-CO_2 por kg de grãos) melhoraram significativamente com a introdução de braquiária nos sistemas. Os resultados destacam a importância do consórcio com braquiária em condições tropicais, demonstrando como as culturas de cobertura são valiosas diante das mudanças climáticas globais e da necessidade premente de aumentar a produção de alimentos.

Palavras-chave: emissões de dióxido de carbono; sequestro de carbono; sistemas conservacionistas.

LIST OF ILLUSTRATIONS

ABBREVIATIONS AND ACRONYMS LIST

Al	Aluminum
BS	Base saturation
C	Carbon
C	Calcium
CC	Cover crops
CE	Carbon stocks
CEC	Cation exchange capacity
CO_2	Carbon dioxide
Cu	Copper
DAS	Days after sowing
DAS	Days after sowing
F	Fallow
Fe	Iron
GHG	Greenhouse gases
GY	Grain yield
IPCC	The Intergovernmental Panel on Climate Change
IRGA	Infra red gas analyzer
K	Potassium
LOM	Living organic matter
Mg	Magnesium
Mn	Manganes
N	Nitrogen
NLOM	Non-living organic matter
NTS	No-tillage system
P	Phosphorus
RE	Relative emissions
RG	Ruzigrass
S	Sulfur
SCCI	Soil carbon conservation index
SH	Sunn hemp
SOC	Soil organic carbon
SOM	Soil organic matter
Zn	Zinc

SUMMARY

1 INTRODUCTION

Global climate change, resulting from greenhouse gas (GHG) emissions, including CO_2, is manifested through extreme heatwaves, storms, hurricanes, and widespread drought (Lee *et al.,* 2023; Zapparoli *et al.,* 2018). Agriculture contributes to 20-25% of global CO_2 emissions (Masson-Delmotte *et al.,* 2021). The soil is crucial for mitigating CO_2 emissions (Abbas *et al.,* 2020) as it is the Earth's second-largest carbon (C) reservoir with a stock of 2,500 Pg (1 Pg = 10^9 tons) (Lal; Negassa; Lorenz, 2015). Conservationist agricultural practices, in alignment with UN Sustainable Development Goals 13 and 15, target reduced soil GHG emissions, increased atmospheric C sequestration, biodiversity, and improved ecosystem health, fostering global sustainability.

The soybean/maize succession is prevalent in Brazil, particularly in no-tillage systems (NTS). Together, they contribute to 86% of the country's grain production, covering 78% of the cultivated area. Soybean is exclusively grown in the summer, while about 79% of maize is produced in the autumn-winter season (Conab, 2023). NTS, acknowledged for enhancing soil aggregate stability, play a crucial role in protecting C by reducing CO_2 emissions from soil organic matter (SOM) decomposition (Conceição; Dieckow; Bayer, 2013; Neto *et al.,* 2021). Thus, conservationist practices like NTS with cover crops (CC), significantly increase C incorporation in Cerrado ecosystems (Tivet *et al.,* 2013). The increase in soil C storage depends on the balance between cumulative C-CO_2 emissions and C inputs from plant residues and the formation of stable compounds in the soil (Rigon; Calonego, 2020). C addition to soil under NTS compared to conventional tillage, contributed up to 30 Mg ha^{-1} of C in the 0-1 m depth (Corazza *et al.,* 1999). Intercropping involving grass (Rosolem; Li; Garcia, 2016) and/or legumes (Rigon; Calonego, 2020) elevate C input, sequestration, and yield (Das *et al.,* 2014; Rosolem; Li; Garcia, 2016), what is desired considering the rapidly increasing world population, necessitating greater food production (Lutz; Sanderson; Scherbov, 2008).

Increasing yield per unit area holds significant potential for reducing the emission of C-CO_2 per kg of grain produced. However, in Central Brazil's grain-producing regions, maintaining crop residue and soil cover is challenging due to scarce fall-winter rainfall and high temperatures hastening residue degradation (Assunção *et al.,* 2019). Additionally, there is a shortage of information on the C balance benefits of intercropping, encompassing inputs from crop residues and roots, as well as C-CO_2 outputs. Moreover, there is insufficient data concerning the introduction of other species into intercropping systems, particularly legumes in both simple intercropping with maize and triple intercropping systems (maize/forage grass/legume).

We posited the following hypotheses: I - Intercropped systems involving *Crotalaria spectabilis* and/or *Urochloa ruziziensis* augment soil C stocks through increased C input both above and below ground; II – Intercropped systems would yield higher, leading to reduced kg of C-CO_2 per kg of grains; and, III - The final C balance in intercropped systems is either neutral or positive, with conservationist systems facilitating agricultural production while maintaining neutral net C emissions to the environment. This study aimed to assess the C balance and soil C stock in a long-term experiment involving soybean cultivation during the spring-summer season and maize in succession during the autumn-winter season. The intercropping configurations included *Urochloa ruziziensis*, *Crotalaria spectabilis*, *U. ruziziensis+C. spectabilis*, and a non-intercropped system.

6 CONCLUSIONS

This study highlights the significant impact of intercropping, particularly with ruzigrass, on enduring changes in no-till crop production systems. Key findings underscore the crucial role of intercropping in enhancing C stock, grain yield, and mitigating C-CO_2 emissions. Introducing ruzigrass resulted in substantial increases in dry matter, N, and C inputs, above and belowground, extending to a soil depth of 1 m. Ruzigrass played a pivotal role in achieving a positive C balance, increasing soil C stock, and reducing relative emissions. Notably, isolated sunn hemp intercropping proved less effective for C balance and soil stock compared to systems with ruzigrass. These insights are relevant for soil management practices, particularly in mitigating C-CO_2 emissions in tropical agriculture. The positive influence of intercropping extends across the entire system, promoting enhanced plant development and improved yield. In essence, this study underscores the crucial role of ruzigrass intercropping in shaping sustainable no-till crop production systems under challenging agroecological conditions.

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