University of São Paulo
"Luiz de Queiroz" College of Agriculture

Sugarcane straw removal for bioenergy production: implications on plant and soil responses

Izaias Pinheiro Lisboa

Thesis presented to obtain the degree of Doctor in Science. Area: Bioenergy

Piracicaba
2018

Izaias Pinheiro Lisboa
Agronomist

Sugarcane straw removal for bioenergy production: implications on plant and soil responses

versão revisada de acordo com a resolução CoPGr 6018 de 2011

Advisor:
Prof. Dr. **CARLOS EDUARDO PELLEGRINO CERRI**

Thesis presented to obtain the degree of Doctor in Science: Area: Bioenergy

Piracicaba
2018

Dados Internacionais de Catalogação na Publicação
DIVISÃO DE BIBLIOTECA – DIBD/ESALQ/USP

Lisboa, Izaias Pinheiro

Sugarcane straw removal for bioenergy production: implications on plant and soil responses / Izaias Pinheiro Lisboa. - - versão revisada de acordo com a resolução CoPGr 6018 de 2011. - - Piracicaba, 2018.

127 p.

Tese (Doutorado) - - USP / Escola Superior de Agricultura "Luiz de Queiroz". Universidade Estadual de Campinas. Universidade Estadual Paulista " Julio de Mesquita Filho"

1. Crescimento da cana-de-açúcar 2. Palha de cana-de-açúcar 3. Qualidade do solo 4. SMAF I. Título

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to the following people and institutions who made a valuable contribution for the conclusion of this thesis:

- God for the countless blessings on my life.
- University of São Paulo - "Luiz de Queiroz" College of Agriculture (USP-ESALQ), São Paulo State University – "Júlio de Mesquita Filho" (UNESP), University of Campinas (Unicamp) and the Graduate Program Bioenergy for the opportunity and strong supporting for I obtain my Ph.D in Science.
- My advisers Prof. Dr. Carlos E. P. Cerri and Prof. Carlos C. Cerri (*in memoriam*) for the trust in my work, teachings, support and strong guidance throughout this journey. I will be always very grateful for the opportunity, thank very much!
- Prof. Dr. Maurício R. Cherubin for the several suggestions, helping and countless insights during the development of the manuscripts and my thesis, thank so much, my friend! Also, I want to thank Prof. Dr. Brigitte J. Feigl for the friendship and availability to help me whenever required.
- Prof. Dr. Ciro A. Rosolem for the first teachings on science.
- The United States Department of Agriculture - Agricultural Research Service (USDA-ARS), Agroecosystem Management Research (NE) and Grassland Soil and Water Research Laboratory (TX) units for providing infrastructural support during my internship.
- Dr. Brian J. Wienhold for the supervision during the internship and accepting me as a visiting scholar in you research team. I really appreciate your patience, friendship, hospitality and mentorship.
- Dr. Marty Schmer and Dr.Virginia L. Jin for the hospitality, friendship, helping and valuable suggestions on my research. I am very thankful for your helping and supporting for I visit the Grassland Soil and Water Research Laboratory unit, Texas. Also, I want to thank the staffs at the Agroecosystem Management Research, especially Paul Koerner, Gary Maixner and Susan Siragusa-Ortman.
- Dr. Serge Edme for friendship and countless helping.
- Dr. James R. Kiniry and Dr. Laurie Kiniry for the friendship and warm hospitality at your house, in Texas, many thanks!

- Dr. James R. Kiniry, Dr. Manyowa Meki and Mrs. Amber Williams for your patience, friendship and hospitality during my visiting in Tample. I am also very thankful for your mentorship on Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC).
- My professors of the Graduate Program in Bioenergy for the teachings and knowledge.
- My graduate colleagues for the friendship: Michel A.A. Colmanet and Elizio F.F. Júnior, especially to Renato P. Lima for your very useful helping in adjusting the models and for the funny and relaxing time.
- Friends of the Environmental Biogeochemistry Laboratory (LBA) - Center for Nuclear Energy in Agriculture: Marcos S. Neto, Adraina M. S. Olaya, Naissa M. S. Dias, Tatiana R. Diniz, André M. Mazzeto; Caio F. Zani, Ingrid K. S. Santana and Bruna G.O. Carvalho, especially to all components of the Thematic Project: "Tecnologia para o aproveitamento de palha da cana-de-açúcar no tripé geração de energia, produção de etanol de segunda geração e produtividade da cultura canavieira."
- The LBA's staffs: Ralf V. de Araújo, Lilian A.C. Duarte, Sandra M.G. Nicolete, Dagmar G.M. Vasca, Admilson R. Margato and José V. de Souto for the valuable help during my doctorate course.
- Professors and staffs at the Soil Science Department, especially Eleusa C. Basse for the helping with samples processing.
- The Brazilians Federal agencies: The Coordination for the Improvement of Higher Education Personnel (CAPES) and The National Council for Scientific and Technological Development (CNPq) for providing the scholarships granted during my doctorate in Brazil (CNPq, process #141459/2015-8) and internship abroad (CAPES, process #88881.134605/2016-01 and CNPq, process: #201207/2017-6).
- The Brazilian Development Bank, Raízen Company, and Delta CO_2 for the essential support on the experimental activities and data collection.
- The internships and friends: Willian, Guilherme, Paulo and Gean for the several hours dedicated to processing and analyzing my samples.
- My friends: Hugo Villalba, Júnior Damian, Leonardo Inforsato, Acácio Mira, Leandro, Pedro Garcia, Aijânio Silva, Marcos Antonio, Henrique Góia, Adjailton, Larissa Noel, Adriano Santos, Adriano Violante, Anderson, José Lucas, Lucas Satiro, Rogério Nóia, Pedro, Arthur Prudêncio, Antônio Leite, Dener Oliveira, Fábio Coutinho and José Paulo. Thank you so much for the enjoyable moments shared with you during my doctorate in Piracicaba.

- My friends, Denny, Roy and Nirosh for accepting me in your house as a member of your family in Lincoln, USA.
- My parents Antonio L. Sobrinho and Terezinha M. Lisboa, my uncle Antonio B. Leal and aunt Dalcy C. Leal for the essential and strong supporting during my academic life. I would not reach this point without your loving, supporting and encouraging me several times, thank you so much!
- My brothers: Daniel P. Lisboa, Eliseu N. Lisboa, Evangelio P. Lisboa, Isaac L. Sobrinho, Vandilson S. Lisboa and Bento L. Sobrinho; my sisters-in-law: Maura, Fernanda, Juliana, Iede and Gercimara; my nephew Cauã and nices: Daniele, Bruna, Lara, Isadora and Maria Eduarda. Thank you very much for the helping, supporting and lovely moments, which gave me strength during my academic life.

Thank you all!

CONTENTS

RESUMO

Remoção da palha de cana-de-açúcar para bioenergia: implicações na planta e respostas do solo

O uso de resíduos culturais, dentre outros tipos de biomassa lignocelulósica, tem sido considerado uma alternativa promissora para produção de bioenergia (etanol de segunda geração e bioeletricidade). Com a implementação da colheita mecanizada da cana-de-açúcar no Brasil, em média 15 Mg ha^{-1} palha são deixadas no campo anualmente. A utilização de parte deste resíduo para produção de bioenergia tem se tornado uma prática comum, enquanto a manutenção de parte da palha no campo viabiliza vários benefícios ao sistema solo-planta. Esforços têm sido feitos a fim de estabelecer a melhor rota para remoção da palha do campo e definir a quantidade que atenda ambas demandas. Assim, os objetivos deste estudo foram: i) estabelecer um guia que viabilize a remoção de diferentes taxas de palha; ii) determinar as implicações oriundas da remoção de taxas de palha no crescimento, produtividade e qualidade tecnológica de colmos; iii) avaliar a eficácia do enleiramento da camada de palha sobre o crescimento e produtividade da cultura e, iv) utilizar *Soil Management Assessment Framework* (SMAF) como ferramenta para avaliar de modo integrado os efeitos da remoção de diferentes taxas de remoção de palha sobre a qualidade do solo (QS). Para tanto, foram conduzidos quatro ensaios, sendo um na estação seca e outro na estação úmida em dois locais: Capivarí e Valparaíso, SP; locais com diferentes condições edafoclimáticas. Crescentes rotações no extrator primário da colhedora viabilizaram a deposição e remoção de taxas de palha proporcionais a 0, 25, 50, 75 e 100%. Após dois anos, análises de parâmetros associados aos atributos químicos [(P, K, pH), físicos (densidade) e biológicos (carbono da biomassa microbiana – MBC e SOC)] do solo foram realizadas nas profundidades 0-5, 5-10, 10-20 e 20-30 cm. Em condições climática mais fria, a remoção de crescentes quantidades de palha melhora o perfilhamento da cultura; entretanto, o crescimento e produtividade de colmo são pouco afetadas pelo manejo da palha. A qualidade tecnológica de colmos colhidos na época seca é superior aos colhidos na época úmida, entretanto, este parâmetro não é afetado pela remoção de crescentes quantidades de palha. Sobre condições climática mais fria, o perfilhamento é beneficiado pelo enleiramento da palha, ao passo que tanto o crescimento quanto a produtividade são insensíveis à essa prática. A retenção da palha aumenta o conteúdo de P no tecido vegetal, especialmente em solo naturalmente pouco fértil. A SMAF foi capaz de detectar alterações na QS em função da remoção de taxas de palha; sendo o Latossolo Vermelho distrófico típico o mais afetado pela remoção da palha em relação ao Argissolo Vermelho-Amarelo distrófico típico em curto prazo. A remoção total da palha promoveu degradação física do primeiro tipo de solo; dentre os atributos do solo avaliados, o atributo físico na profundidade 0-10 cm está correlacionado com a produtividade da cultura. A remoção parcial da palha de cana-de-açúcar para produção de bioenergia promove otimização no uso da biomassa da cultura. Entretanto, a taxa de palha a ser removida é intrínseca para cada local e variou de 4-9 Mg ha^{-1} neste estudo. A produtividade é insensível ao enleiramento da palha. O monitoramento nos teores de carbono do solo, a adoção do controle de tráfego de máquinas e a aplicação de resíduos da agroindústria canavieira podem ser estratégias adotadas para melhorar a QS e, por consequência, a sustentabilidade de cultivo da cana-de-açúcar.

Palavras-chave: Cana-de-açúcar; Crescimento de planta; Enleiramento da palha; Qualidade do solo; SMAF

ABSTRACT

Sugarcane straw removal for bioenergy production: implications on plant and soil responses

The usage of crop residues, among other lignocellulosic biomass, has being considered a promising alternative feedstock for bioenergy (*i.e.*, second generation ethanol – ethanol 2G and bioelectricity) production. With the adoption of sugarcane-mechanical harvesting in Brazil, in average 15 Mg ha^{-1} of straw are left on the field annually. Partial straw removal for bioenergy production has become a common practice, while partial straw retention on the field ensures several benefits for the soil-plant system. Efforts have being done in order to establish the best route to straw recovery from the field and defining the amount which meeting both needs. Thus, the aims of this study were: i) to establish a step-by-step guidelines to straw recovery from the field; ii) to determine the implications of increasing rates of straw removal on plant growth, stalk yield and stalk industrial quality; iii) to evaluate the effectiveness of straw-blanket raking practice on plant growth and yield, and iv) to use Soil Management Assessment Framework (SMAF) as a tool to perform an integrated approach of soil quality (SQ) under different rates of straw removal. To achieve the proposed goals, a 2-years experiment was set up within the dry and wet seasons at Valparaíso and Capivari, São Paulo, locations with different edaphoclimatic conditions. Increases of primary extractor fan's velocity on the harvester lead to placement and removal of straw rates proportionally to 0, 25, 50, 75 e 100%. After two years, parameters associated to the soil- chemical [(Phosphorus-P, Potassium-K and pH), physical-(bulk density) and biological-(microbial biomass carbon-MBC and SOC)] attributes were analyzed within the 0-5, 5-10, 10-20 and 20-30 cm. Under colder climatic condition, plant tillering improved by the increasing rates of straw removal, however plant growth and stalk yield are slightly affected by the straw management. Stalk harvested in the dry season presented higher industrial quality than those harvested within the wet season but this parameter is unaffected by straw removal. Further, under colder climatic condition, to rake the straw blanket enhanced plant tillering while plant growth and stalk yield were not influenced by raking the straw blanket. No straw removal increases P content on plant tissue, regardless of blanket management, especially under the poorest inherent soil condition. The SMAF tool was able to detect changes on soil quality under different rates of straw removal and Oxisol responds faster to straw removal management than Ultisol in the short term. Total straw removal leaded to Oxisoil physical quality degradation; among the soil attributes, soil-physical attribute within the 0-10 cm is correlated with stalk yield. The partial straw removal for bioenergy production leads to the optimization on sugarcane biomass usage. However, the appropriate rate of straw to be removed is site specific and ranged 4-9 Mg ha^{-1} under the conditions in which this study was performed. The stalk yield was unaffected by raking the straw blanket. The monitoring of SOC, adoption of traffic controller and application of subproducts from the sugarcane industry are strategies to increase soil quality and, consequently, the sustainability of the crop cultivation.

Keywords: Sugarcane; Plant growth; Straw-raking; Soil Quality; SMAF

1. GENERAL INTRODUCTION

Fossil fuels consumption is pointed out as the main cause of climate change (Hanaki and Portugal-Pereira, 2018), while ethanol is considered the most eco-ecofriendly option to fossil fuels (Zabed et al., 2016), thus it is estimated a wide national and international demand for ethanol in the upcoming years (Goldemberg et al., 2014; FAO, 2017). As most of the feedstock for bioethanol production are edible sources (Aditiya et al., 2016) (sugars and starch) (Zabed et al., 2016) and use the same natural resource such as water (Mathioudakis et al., 2017), a wide discussion has been raised up around the usage of edible source for first generation ethanol production and food security. In this sense, lignocellulosic biomass conversion into fermentable sugars for ethanol 2G production has been considered a promising alternative to meet global demand for ethanol (Santos et al., 2012; Zabed et al., 2016; Aditiya et al., 2016; Mitchell et al., 2016), due to its low cost and high availability (Bhatia et al., 2012).

Crop residues are considered an attractive and abundant lignocellulosic feedstock for ethanol 2G production (Gupta & Verma, 2014; Saini et al., 2014). Since sugarcane mechanical harvesting adoption in Brazil, around 10 to 20 Mg ha^{-1} of straw [*i.e.*, straw consisting of shredded leaves (dry and green) plus small pieces of stalk] is left on sugarcane field annually, and thus crop residue has become a viable and economically feedstock for bioenergy production (Carvalho et al., 2017). Moreover, sugarcane straw along with bagasse is an important feedstock for bioelectricity cogeneration, which is pointed out as a sustainable and alternative electricity source to supply the national energy demand (Trombeta and Filho, 2017). The usage of sugarcane straw as a feedstock for bioethanol leads to the increasing of this biofuel per area (Rosseto et al., 2013; Pereira et al., 2014).

Conversely, various agronomic benefits for the soil-plant system are also associated to the retention of sugarcane straw on soil surface (Carvalho et al., 2017; Cherubin et al., 2018), such as: decreasing on soil compaction (Satiro et al., 2017), reduction of soil erosion process, protection the soil against excessive evapotranspiration and solar radiation, leading to higher soil-water infiltration and availability (Ronquim, 2010; Anjos et al., 2017). In addition, because of straw retention on the soil surface, there is an increase of biological activity (Rosseto et al., 2008; Paredes Jr. et al., 2015),soil carbon stocks (Bordonal et al., 2018; Sousa Jr et al., 2018; Leite et al., 2018), soil-macroaggregate formation (Guimarães et al., 2018) and nutrients cycling (Fortes et al., 2013; Almeida et al. 2015).

Besides defining the proper quantities of straw that can be sustainably removed as feedstock for bioenergy production and the amount necessary to maintaining or improving soil

functions, sugarcane industry also has faced another challenge, which is to define the best route to sugarcane straw recovery and transportation from the field to the refineries. Two routes were tested: i) after sugarcane-harvesting operation, the straw is baled and thereafter recovered and ii) the straw is transported to the mill along with chopped stalk and thereafter separated from this last plant component in a cleaning station. The latter was considered the most cost-effective route (Cardoso et al., 2013). In this sense, the aim of the **first chapter** was to establish a guidelines to set up a combination of angular velocity on sugarcane harvester's extractors *(i.e.*, primary and secondary) to remove different rates of straw along with chopped stalk. Since the guidelines enabled us to achieve increasing rates of straw removal, the objective of the **second chapter** was to determine the implications of these rates of straw removal on plant growth, stalk yield and industrial quality under two seasons and edaphoclimatic conditions.

Although the effects of straw blanket on plant growth is unclear, plant tillering and stalk yield may be decreased by straw blanket on the soil surface, especially within Brazilian colder regions (Campos et al., 2010). Based on this fact, the majority of farmers and mills have adopted straw raking management to move out the straw from above rows to inter-row positions to overcome the effects of straw on plant. However, the effectiveness of this practice remain unclear (Carvalho et al., 2017) and has not widely addressed within the main Brazilian sugarcane producer (*i.e.*, center-south region). Therefore, the effectiveness of this straw management on plant growth, nutritional status and stalk yield was the aim of the **third chapter**.

Similar to other agroecosystems, most inferences about soil quality under straw removal in sugarcane fields are made by performing determination of soil-quality indicators (*e.g.*, SOC, microbial activities and bulk density) individually. Despite this fact, there are in the literature various tools/methods to make integrated approaches on soil quality under different management (Acton and Gregorich, 1995; Andrews at al., 2004; Idowu et al., 2008 and Moebius-Clune et al., 2016). The soil management assessment framework (SMAF) is a globally-known tool and widely used to evaluate soil quality under different managements. Thus, the objective of the **fourth chapter** was to make an integrated approach of soil quality under sugarcane straw removal. In addition, since SMAF indicated which soil attribute (*i.e.*, chemical, physical and biological) is most impacted by a given management, stalk and straw yields were correlated with the soil attributes and overall soil quality index.

The principal findings obtained in this thesis resulted in the following scientific manuscripts:

Lisboa, I.P., Cherubin, M.R., Cerri, C.C., Cerri, D.G. and Cerri, C.E., 2017. Guidelines for the recovery of sugarcane straw from the field during harvesting. *Biomass and Bioenergy*, 96, pp.69-74.

Lisboa, I.P., Cherubin, M.R., Lima, R.P., Cerri, C.C., Satiro, L.S., Wienhold, B.J., Schmer, M.R., Jin, V.L. and Cerri, C.E., 2018. Sugarcane straw removal effects on plant growth and stalk yield. *Industrial Crops and Products*, 111, pp.794-806.

Lisboa, I.P., Cherubin, M.R., Lima, R.P., Gmach, M.R., Wienhold, B.J., Schmer, M.R., Jin, V.L., Frade Jr., E.F.F., Guerra, H.P., Cerri, C.C. and Cerri, C.E.P., 2018. Sugarcane straw blanket management impacts plant growth, but not stalk yield in southeastern Brazil, *Crop Science* (*submitted*).

Lisboa, I.P., Satiro, L.S., Cherubin, M.R., Siqueira Neto, M., Lima, R.P., Wienhold, B.J., Schmer, M.R., Jin, V.L., Cerri, C.C. and Cerri, C.E.P., 2018. Short-term sugarcane straw removal and soil quality changes evaluation using Soil quality Assessment Framework (SMAF), *Industrial Crops and Products*, (*submitted*).

REFERENCES

Acton, D.F., and Gregorich, L.J., 1995. The Health of Our Soils: toward Sustainable Agriculture in Canada. Centre for Land and Biological Resources Research, Research Branch, Agriculture and Agri-Food Canada, Ottawa, Ont xiv + 138 pp.

Aditiya, H.B., Mahlia, T.M.I., Chong, W.T., Nur, H. and Sebayang, A.H., 2016. Second generation bioethanol production: A critical review. Renewable and sustainable energy reviews, 66, pp.631-653.

Almeida, H.J., Cruz, F.J.R., Pancelli, M.A., Flores, R.A., Vasconcelos, R.D.L. and de Mello Prado, R., 2015. Decreased potassium fertilization in sugarcane ratoons grown under straw in different soils. Australian Journal of Crop Science, 9(7), p.596.

Andrews, S.S., Karlen, D.L. and Cambardella, C.A., 2004. The soil management assessment framework. Soil Science Society of America Journal, 68(6), pp.1945-1962.

Anjos, J.C.R.D., Andrade Júnior, A.S.D., Bastos, E.A., Noleto, D.H., Melo, F.D.B. and Brito, R.R.D., 2017. Water storage in a Plinthaqualf cultivated with sugarcane under straw levels. Pesquisa Agropecuária Brasileira, 52(6), pp.464-473.

Bhatia, L., Johri, S. and Ahmad, R., 2012. An economic and ecological perspective of ethanol production from renewable agro waste: a review. Amb Express, 2(1), p.65.

Bordonal, R.O., Menandro, L.M.S., Barbosa, L.C., Lal, R., Milori, D.M.B.P., Kolln, O.T., Franco, H.C.J. and Carvalho, J.L.N., 2018. Sugarcane yield and soil carbon response to straw removal in south-central Brazil. Geoderma, 328, pp.79-90.

Campos, L.H.F., Pinto de Carvalho, S.J., Christoffoleti, P.J., Fortes, C. and Sahade da Silva, J., 2010. Sistemas de manejo da palhada influenciam acúmulo de biomassa e produtividade da cana-de-açúcar (var. RB855453). Acta Scientiarum. Agronomy, 32(2), p. 345-350.

Cardoso, T.D.F., Cavalett, O., Chagas, M.F., Morais, E.R.D., Carvalho, J.L.N., Franco, H.C.J., Galdos, M.V., Scarpare, F.V., Braunbeck, O.A., Cortez, L.A.B. and Bonomi, A., 2013. Technical and economic assessment of trash recovery in the sugarcane bioenergy production system. Scientia Agricola, 70(5), pp.353-360.

Carvalho, J.L.N., Nogueirol, R.C., Menandro, L.M.S., Bordonal, R.D.O., Borges, C.D., Cantarella, H. and Franco, H.C.J., 2017. Agronomic and environmental implications of sugarcane straw removal: a major review. GCB Bioenergy, 9(7), pp.1181-1195.

Cherubin, M.R., Oliveira, D.M.D.S., Feigl, B.J., Pimentel, L.G., Lisboa, I.P., Gmach, M.R., Varanda, L.L., Morais, M.C., Satiro, L.S., Popin, G.V. and Paiva, S.R.D., 2018. Crop residue harvest for bioenergy production and its implications on soil functioning and plant growth: A review. Scientia Agricola, 75(3), pp.255-272.

Fortes, C., Vitti, A.C., Otto, R., Ferreira, D.A., Franco, H.C.J. and Trivelin, P.C.O., 2013. Contribution of nitrogen from sugarcane harvest residues and urea for crop nutrition. Scientia Agricola, 70(5), pp.313-320.

Goldemberg, J., Mello, F.F., Cerri, C.E., Davies, C.A. and Cerri, C.C., 2014. Meeting the global demand for biofuels in 2021 through sustainable land use change policy. Energy Policy, 69, pp.14-18.

Guimarães, M.D.F., Oliveira, J.F., Telles, T.S., Machado, W., Barbosa, G. and Tavares Filho, J., 2018. Soil aggregation and carbon stabilization in burn and no-burn sugarcane management systems. Anais da Academia Brasileira de Ciências. 9p.

Gupta, A. and Verma, J.P., 2015. Sustainable bio-ethanol production from agro-residues: a review. Renewable and Sustainable Energy Reviews, 41, pp.550-567.

Hanaki K., Portugal-Pereira, J., 2018. The Effect of Biofuel Production on Greenhouse Gas Emission Reductions. In: Takeuchi K., Shiroyama H., Saito O., Matsuura M. (eds) Biofuels and Sustainability. Science for Sustainable Societies. Springer, Tokyo.

Idowu, O.J., van Es, H.M., Abawi, G.S., Wolfe, D.W., Ball, J.I., Gugino, B.K., Moebius, B.N., Schindelbeck, R.R. and Bilgili, A.V., 2008. Farmer-oriented assessment of soil quality using field, laboratory, and VNIR spectroscopy methods. Plant and Soil, 307(1-2), pp.243-253.

Leite, L.F.C., Sagrilo, E., de Araújo, A.S.F. and de Souza, H.A., 2018. Short-Term Effect of Sugarcane Straw on Soil Organic Carbon Pools. Journal of Agricultural Science, 10(8), p.405.

Mathioudakis, V., Gerbens-Leenes, P.W., Van der Meer, T.H. and Hoekstra, A.Y., 2017. The water footprint of second-generation bioenergy: a comparison of biomass feedstocks and conversion techniques. Journal of cleaner production, 148, pp.571-582.

Mitchell, R.B., Schmer, M.R., Anderson, W.F., Jin, V., Balkcom, K.S., Kiniry, J., Coffin, A. and White, P., 2016. Dedicated energy crops and crop residues for bioenergy feedstocks in the central and eastern USA. BioEnergy Research, 9(2), pp.384-398.

Moebius-Clune, B.N., Moebius-Clune, D.J., Gugino, B.K., Idowu, O.J., Schindelbeck, R.R., Ristow, A.J., Van Es, H.M., Thies, J.E., Shayler, H.A., McBride, M.B., Wolfe, D.W., and Abawi, G.S., 2016. Comprehensive Assessment of Soil Health. The Cornell framework manual. Third ed. Cornell University, Geneva, NY.

OECD/FAO, 2017, OECD-FAO Agricultural Outlook 2017-2026, OECD Publishing, Paris.

Paredes, F.P.Jr., Portilho, I.I.R. and Mercante, F.M., 2015. Microbiological attributes of the soil under cultivation of sugar cane with and without burning straw. Semina: Ciências Agrárias, 36(1), pp.151-164.

Pereira, L.G., Dias, M.O., Junqueira, T.L., Pavanello, L.G., Chagas, M.F., Cavalett, O., Maciel Filho, R. and Bonomi, A., 2014. Butanol production in a sugarcane biorefinery using ethanol as feedstock. Part II: Integration to a second generation sugarcane distillery. Chemical Engineering Research and Design, 92(8), pp.1452-1462.

Ronquim, C.C., 2010. Queimadas na colheita da cana-de-açúcar: impactos ambientais, sociais e econômicos. Embrapa Monitoramento por Satélite. Documentos 77. 48p.

Rossetto, R., Vitti, A.C., Gava, G.J.C., Mellis, E.V., Vargas, V.P., Cantarella, H., PRADO, H.D., Dias, F.L.F., Landell, M.G.A., Brancalião, S.R. and Garcia, J.C., 2008. Cana-de-açúcar: cultivo com sustentabilidade. Informações Agronômicas, (124), pp.8-13.

Saini, J.K., Saini, R. and Tewari, L., 2015. Lignocellulosic agriculture wastes as biomass feedstocks for second-generation bioethanol production: concepts and recent developments. 3 Biotech, 5(4), pp.337-353.

Santos, F.A., Queiróz, J.D., Colodette, J.L., Fernandes, S.A., Guimarães, V.M. and Rezende, S.T., 2012. Potencial da palha de cana-de-açúcar para produção de etanol. Química Nova, 35(5), pp.1004-1010.

Satiro, L.S., Cherubin, M.R., Safanelli, J.L., Lisboa, I.P., da Rocha Junior, P.R., Cerri, C.E.P. and Cerri, C.C., 2017. Sugarcane straw removal effects on Ultisols and Oxisols in south-central Brazil. Geoderma Regional, 11, pp.86-95.

Sousa Jr., J.G.A., Cherubin, M.R., Oliveira, B.G., Cerri, C.E., Cerri, C.C. and Feigl, B.J., 2018. Three-Year Soil Carbon and Nitrogen Responses to Sugarcane Straw Management. BioEnergy Research, pp.1-13.

Trombeta, N.D.C. and Caixeta Filho, J.V., 2017. Potencial e Disponibilidade de Biomassa de Cana-de-açúcar na Região Centro-Sul do Brasil: indicadores agroindustriais. Revista de Economia e Sociologia Rural, 55(3), pp.479-496.

Zabed, H., Sahu, J.N., Boyce, A.N. and Faruq, G., 2016. Fuel ethanol production from lignocellulosic biomass: an overview on feedstocks and technological approaches. Renewable and Sustainable Energy Reviews, 66, pp.751-774.

2. GUIDELINES FOR THE RECOVERY OF SUGARCANE STRAW FROM THE FIELD DURING HARVESTING

Abstract

Cellulosic ethanol derived from sugarcane straw may have a significant role to play in the projected increase of Brazilian biofuel production for next years. However, some practical challenges, such as, defining how much and how to recover straw from the field still need to be overcome. Integrated sugarcane harvesting (*i.e.* stalks plus straw) with straw separation at the processing site has shown greater cost-effectiveness. However, there is no published procedure to quantify the yield of sugarcane straw, to set up the harvester to collect only a specific portion of this straw or to verify the quantity of straw left in the field. We conducted four field trials in the southeast of Brazil to develop systematic field guidelines that describe how to estimate the yield of sugarcane straw, the harvester setup to vary the amount of straw left in the field and how to evaluate the overall performance of the operation. The results showed that these guidelines were efficient ($r^2 \geq 0.97$, $p < 0.01$) and, therefore, can be incorporated into a standard protocol to help the sugarcane industry improve the efficiency of the sugarcane straw harvesting process for bioelectricity cogeneration and cellulosic ethanol production.

Keywords: Straw recovery route; Sugarcane harvester setup; Extractor fans; Bioelectricity cogeneration; 2-G ethanol

2.1 Introduction

Brazil is the largest sugarcane producer in the world, with 9.1 Mha cultivated and an estimated production of about 691 million tons of stalks and 30.5 billion liters of ethanol in the 2016-2017 season [1]. In spite of this significant production, increasing demands for biofuels and other types of bioenergy have been put upon internal and external markets [2], principally with respect to the sugarcane straw that is currently left in the field and could be used for bioelectricity cogeneration and cellulosic ethanol (*i.e.*, second generation or 2G ethanol) production.

Since early 2000s, sugarcane management has gradually changed from burning and manual harvesting to unburnt and mechanized harvesting system. The reasons for the elimination of burning and changing the sugarcane harvesting system are primary associated to increasing incidence of respiratory diseases caused by air pollution and environmental impact, such as the emission of greenhouse gases [3-6]. Thus, using mechanized sugarcane harvesting, large amounts of straw (~15 Mg ha-1 dry mass [7, 8]) have been left in the field annually. Sugarcane straw left on the soil surface plays a key role in sustaining and enhancing the soil functions, such as increasing organic carbon accumulation [9], nutrient cycling [10], water storage and infiltration

[11,12], increased resistance to erosion [12] and biological activity [13]. Consequently, healthier soils can provide suitable conditions for sugarcane growth, leading to higher biomass yields [14].

On the other hand, straw presents a high energetic potential, representing 1/3 the total energetic potential of sugarcane [15]. Thus, the sugarcane industry have started investing in the use of sugarcane straw as a feedstock to produce 2G-ethanol and cogenerate bioelectricity [16, 17]. However, some technical challenges, such as how to most efficiently collect the straw, how much to leave in the field to protect soil health, and how to most efficiently transport the straw to refineries still need to be overcome [8, 16, 18]. Although clear criteria have not yet been established to define the amount of straw that can be collected in a sustainable manner without deleterious impacts on long-term sugarcane production, numerous studies have been conducted to evaluate collection strategies (routes) for the transportation of sugarcane straw from the field (*e.g.*, [7, 19, 20]).

The two main sugarcane straw collection strategies that have been tested to date are: i) chopped cane harvesting and ii) "integrated" harvesting. In the first, chopped cane is transported to the sugarcane mill and the straw is baled using different techniques and devices. In the second, a portion of the straw is left on the ground, while the remaining part is transported to the mill along with the sugarcane stalks. At the mill stalks and straw are separated at the dry cleaning station [18].

Studies have shown that integrated harvesting is more cost-effective [7, 18, 19] although it can present some restrictions, when there are large distances between the field and the refinery, because when straw is transported together with stalks the load density is reduced [20]. However, even if the baling system reduces the cost over long distances [20], it could include disadvantages such as high concentrations of mineral impurities (soil) and the short period between harvest and baling. In addition, baling involves machinery, which causes soil compaction and consequent damages to the sugarcane root system due to heavy traffic of machines [21].

An integrated harvest system has great potential if implemented on a large scale in Brazil over the coming years. However, to our knowledge there is no published guidelines (step-by-step) to quantify the yield of sugarcane straw, to set up the harvester to collect only a specific portion of the straw and to verify amount of straw left in the field. Thus, we conducted four field trials to develop guidelines that could be used to create a standard protocol to guide producers and researchers during the harvesting of sugarcane straw.

2.2 Material and Methods

2.2.1 Site descriptions

The field trials were carried out at two experimental sites located in southeast of Brazil and represent typical areas for commercial sugarcane production. These areas are located in São Paulo state, near to Capivari at the Bom Retiro mill (Lat.: 22°59'42" S; Long.: 47°30'34" W) and near Valparaiso at the Univalem mill (Lat.: 21°14'48" S; Long.: 50°47'04" W) (Fig. 1).

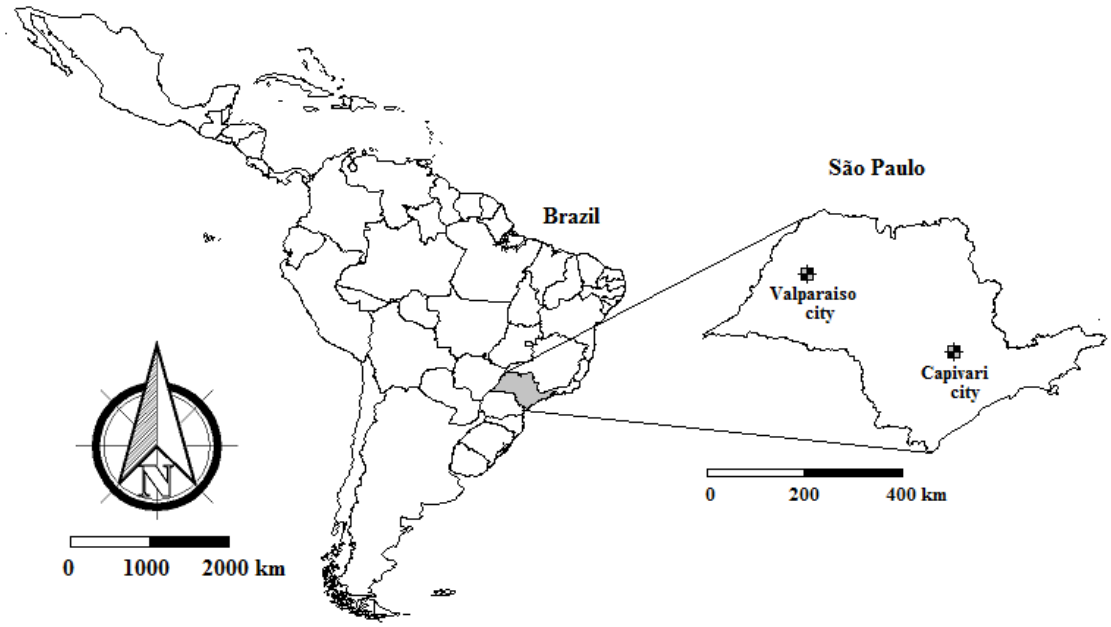

Fig. 1. Geographic location of the study areas.

In each study site, two field trials were performed, one in the dry season (August 2014) and another in the rainy season (October 2014). Thus, enabling us to contrast different edaphic and climatic conditions in this study, giving a stalk yield from 80 to 130 Mg ha^{-1} (*i.e.,* variation of 62%) and straw yield from 9.7 to 17.9 Mg ha^{-1} (*i.e.*, variation of 85%). Sugarcane planting occurred in February 2013 using alternate double row spacing, 0.9 m (SR2) and 1.5 m (SR1), in the same area (Fig. 2). The crop varieties were CTC 14 and the RB867515 in the field trials conducted at the Bom Retiro and Univalem mills, respectively.

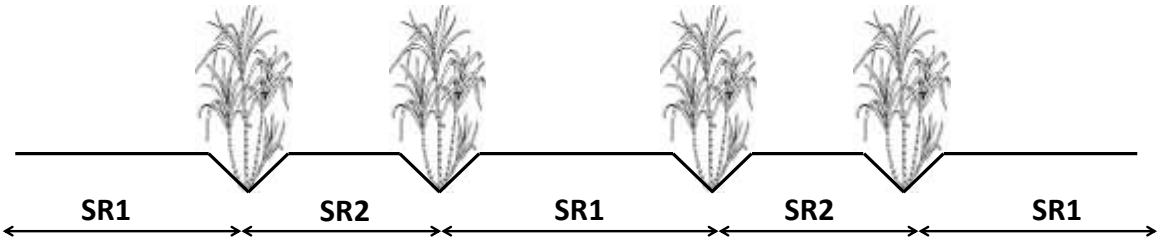

Fig. 2. Scheme of sugarcane planting using alternated double row spacing. SR1: 1.5 m and SR2: 0.9 m.

Mechanized sugarcane harvesting begins by cutting top leaves using the topper, then compilation and alignment of the plants by the crop divider, tumbling of stalks carried by the knockdown rollers and finally the plants are sequentially cut from the base upwards and transported into harvester. During that last step, part of the impurities (especially soil) that are collected together with plants is separated and discarded. Afterwards, stalks and straw are chopped, part of straw is separated using the primary extractor fan, after transportation by a conveyer belt the remaining straw is removed by secondary extractor fan, and chopped stalks are deposited into a wagon [22]. The harvester design is illustrated in Fig. 3.

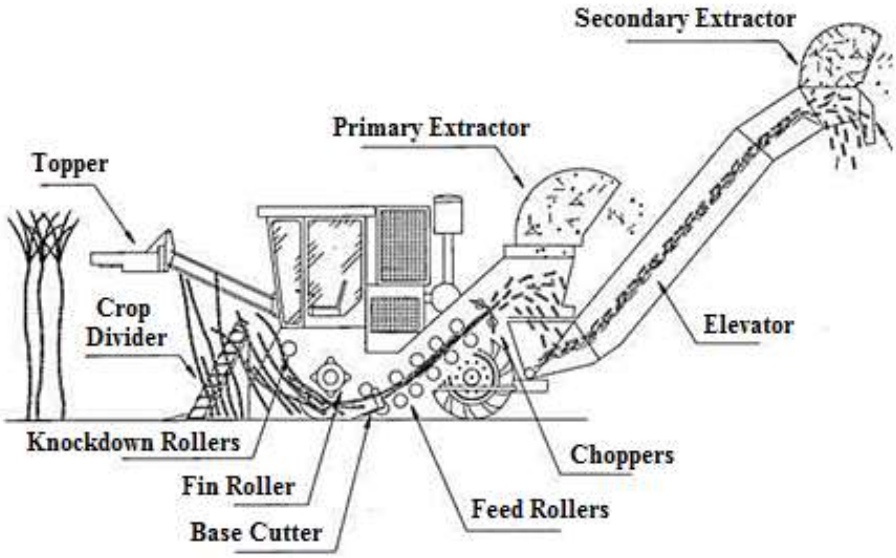

Fig. 3. Sugarcane harvester, highlighting the principal components and the position of primary and secondary extractor fans. Source: Price et al. [13].

2.2.2 Quantification of the yield of sugarcane straw

In each field trial, all the sugarcane straw left on the ground after harvest was quantified. In the control, 100% of straw remains in the field, to achieve this the primary extractor fan of the harvester was set at maximum power (*i.e.* 1100 rpm) and the secondary extractor fan was turned

on. In order to leave different quantities of straw in the field, combinations of different primary fan rotations with the secondary extractor fan switched on or off were tested (Table 1). The harvester was regulated to leave approximately 0, 25, 50, 75 and 100% of the sugarcane straw in the field after harvest (*i.e.*, straw removal of approximately 100, 75, 50, 25 and 0%).

Table 1. Setup of the sugarcane harvester for achieving desired (theoretical) rate of sugarcane straw kept on the soil.

Setup of the sugarcane harvester			Theoretical rate of sugarcane straw kept on the soil (%)
Primary extractor fan		Secundary extractor fan	
Status	Angular velocity (rpm)	Status	
off	0	off	0
on	500	off	25
on	700	on	50
on	900	on	75
on	1100	on	100

It is worth highlighting that a considerable amount of straw is naturally deposited on the ground throughout of sugarcane cycle due to leaf senescence. Thus, even when the harvester was set to remove 100% of the straw (*i.e.*, two extractor fans off) so that no straw was deposited on the plastic sheeting, from 18 to 25% (*i.e.*, 3.4 to 4.8 Mg ha^{-1} of dry mass) of the total straw produced was found on the ground. This amount of straw is variable according to edaphic and climatic conditions under which sugarcane was grown during its cycle as well as the characteristics of sugarcane cultivar. As the senescent leaves were not deposited during harvesting, this value was subtracted from the final amount of straw deposited onto the ground. In addition, a small proportion of the straw that is still attached to the stalks is transferred into the wagons even when the extractor fans are turned on at maximum power.

2.2.3 Harvester calibration

Harvester calibration was performed to verify if the regulation/setup used (primary and secondary extractor fans) resulted in leaving the desired amounts of straw on the ground as described in Table 1. This procedure included the regulation of angular velocity of the primary extractor fan using the harvester's control panel and the elevator was placed above the wagon so

that the primary and secondary extractor fan exits allowed the discharge of the straw behind the harvester. This procedure is currently being used during harvesting in commercial fields.

Before harvesting started, 4 m² of plastic sheeting were on the ground 10 and 20 m in front of harvester, approximately 1 meter apart of the row of sugarcane to collect all the deposited straw (Fig. 4). Afterwards, the straw that was deposited with the chopped stalks was separated and weighed. This initial test was used as a parameter for guiding the necessary changes in the harvester setup to produce the desired result. Thus, the straw on the plastic sheeting was not used to adjust the harvester set up, because the intensity and direction of wind during harvesting as well as the variation of the moisture content of the biomass through the day are factors that influence the amount of straw deposited onto the plastic sheeting.

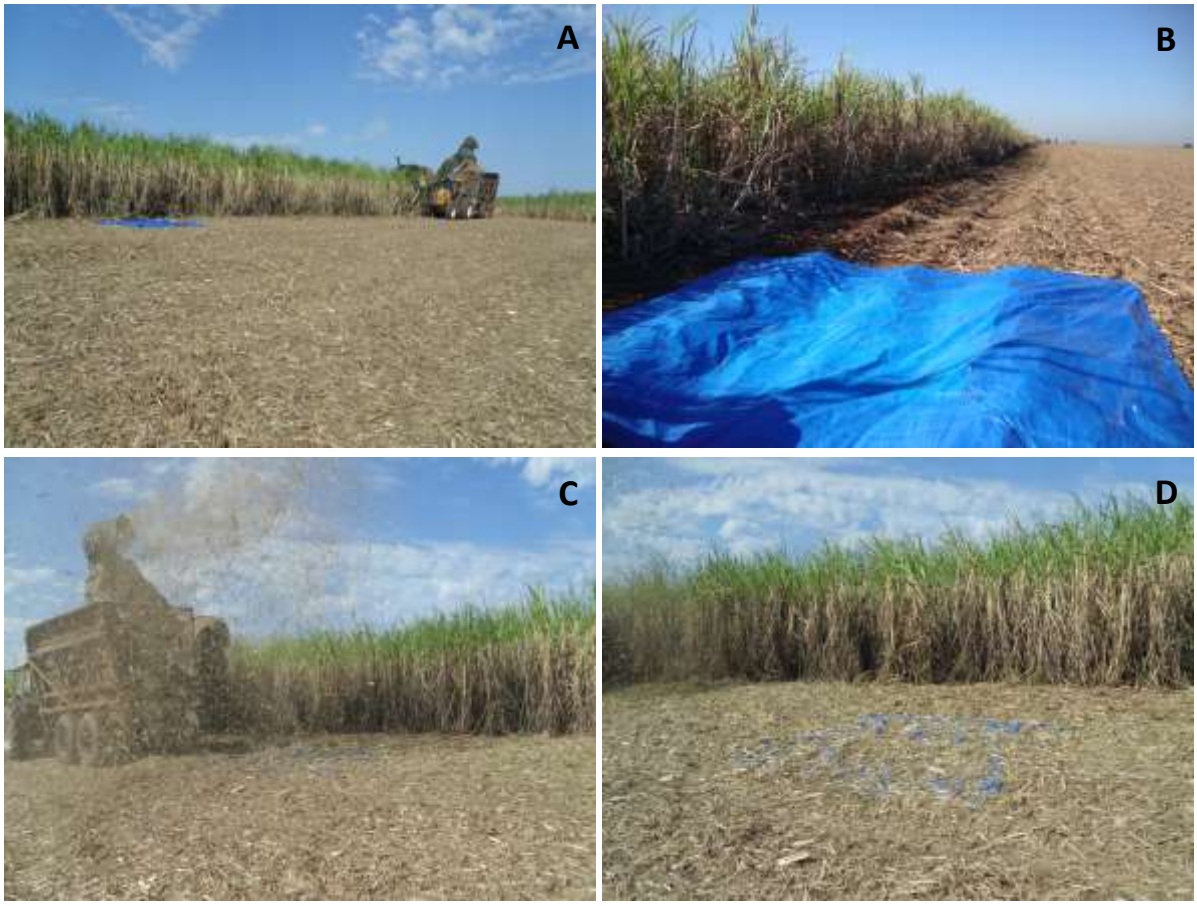

Fig. 4. Location of the plastic sheeting in relation to the harvester (A) and the planting row (B), biomass expelled by the extractor fans (C), plastic sheeting partly covered by biomass after harvesting (D).

2.2.4 Performance checking procedure

In order to check the efficiency of harvester setup to maintain the desired amount of straw in the field, we weighed the sugarcane straw deposited on the ground in randomly

positioned 1m² metal squares. All the straw within this area was separated from the chopped stalks and weighed. This procedure was performed three times (repetitions) for each treatment. We repeated this quantification in a side-by-side perpendicular to the planted row, in order to avoid potential heterogeneous straw deposition causeded by the variation in row spacing (Fig. 2).

2.3 Results and discussion

Both the harvester setup and performance checking procedure were efficient. Linear equations performed between the predicted (theoretical) amounts of straw and the measured ones presented $r^2 > 0.98$ at Bom Retiro and $r^2 = 0.97$ at Univalen (Fig. 5). These results validated the proposed procedure, which starts with the determination of the maximum amount of straw left on the ground after harvesting (baseline, 100%). Thereafter, in order to deposit different rates of the maximum amount of straw on the ground (e.g., ~ 0, 25, 50 and 75%), other settings between the primary and secondary extractor fans were tested. Finally, the straw amount that effectively remained on the ground was weighed to determine the efficiency of the procedure.

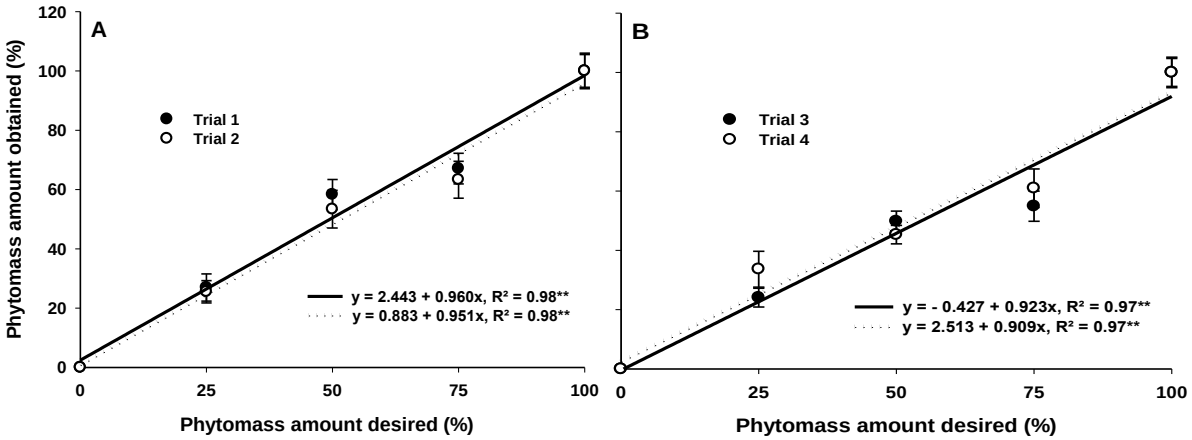

Fig. 5. Relation between the predicted (theoretical) and measured sugarcane straw amount left on the ground after harvesting on field trials conducted at Bom Retiro (A) and Univalem (B) areas as function of different setup of the primary and secondary extractor fans; **significant by F's test (p<0.01).

A team of five people, plus the operators of the harvester and the tractor, carried out all the fieldwork. This activity required around 6 hours and the number of staff can vary according to the labor availability. It is worth mentioning that the execution of these activities with a reduced number of people (e.g., 2 or 3) will be time consuming and consequently, will increased operational costs, since the harvester will stay on standby longer, reducing its operational efficiency.

The main difficulties found during the execution of the field trials were: i) crop lodging where fallen plants increase harvest losses, therefore, part of this fallen plants remains on the ground and is partially incorporated into the soil during harvester tracking. This can cause a small underestimation in the amount of straw remaining in the field, since soil-incorporated straw was not quantified during the performance checking procedure; ii) meteorological variations throughout the day, such as alterations in wind intensity that affects the uniformity of straw deposition onto the field, air temperature and humidity changes modify the straw moisture content, making it more difficult to standardize the straw amounts deposited throughout the day; iii) numbers of wagons pulled by tractor, where it is recommended to use just one wagon per tractor in field trials procedures. The use of two wagons is commonly practiced by mills, which can underestimate the straw amount expelled by the extractor fans, since part of the straw will fall into the second wagon, reducing the amount actually deposited onto the soil/plastic sheeting; iv) different makes/models and age of harvester show variations in extractor fan setup (e.g., a wider range of angular velocity) and in the degree of wear on mechanical components. Therefore, we suggest that the whole field trial is conducted with the same harvester in order to avoid variation in straw deposition. In this study, we had no intention to produce a long list of harvester setup specifications that could be applicable in every situation, but we describe the process as a whole; v) commercial sugarcane harvesters have limitations in the separation of straw and stalks [23]. Therefore, some of the straw always enters the wagons together with stalks, as vegetal impurities.

Although our aim was to setup sugarcane harvesters to remove different amounts of straw ranging from 0 to 100%, we recognize that it is a difficult task under field conditions, since too many factors, as described above, are acting simultaneously. Nevertheless, our findings showed that the systematic guidelines developed in this study enable the producers or researchers to achieve a very good approximation of the amount of straw that is removed. Partnerships between universities/research institutes and stakeholders (e.g., machinery industry) must be pursued towards improving or developing new mechanized devices (or systems) of sugarcane straw recovery, making the process more efficient and feasible.

2.4 Conclusions

Sugarcane straw is considered one of the main alternatives to meet increasing demands for bioenergies. Therefore, the elaboration of protocols for straw recovery and quantification of the amount left in the field are essential as guidelines for the sugarcane industry and the installation of new field experiments.

Based on assumption that the more cost-effective route for straw recovery is the integrated harvesting, in which stalks and straw are collected together and subsequently separated at the mill, this pioneer study describes a step-by-step field procedure, from harvester setup to vary the amount of straw left in the field, through the quantification of the yield of sugarcane straw, to performance checking. The results showed that these guidelines were efficient and could be adopted as a protocol to help the sugarcane industry improve the efficiency of the 2G-ethanol and bioelectricity cogeneration programs.

REFERENCES

[1] Companhia Nacional de Abastecimento – Conab. Acompanhamento da safra brasileira de cana-de-açúcar. v. 3 – Safra 2016/17, n. 1, Primeiro Levantamento, Brasília. 2016. Retrieved June 30, 2016 from: http://www.conab.gov.br/OlalaCMS/uploads/arquivos/16_04_18_14_27_15_boletim_cana_portugues_-_1o_lev_-_16.pdf

[2] J. Goldemberg, F.F.C. Mello, C.E.P. Cerri, C.A. Davies, C.C. Cerri, Meeting the global demand for biofuels in 2021 through sustainable land use change policy, Energ. Police 69 (2014) 14-18.

[3] J.E. Cançado, P.H. Saldiva, L.A.Pereira, L.B. Lara, P. Artaxo, L.A. Martinelli, M.A. Arbex, A. Zanobetti , A.L. Braga, The impact of sugar cane-burning emissions on the respiratory system of children and the elderly, Environ. Health Perspect. 114 (2006) 725-729.

[4] M. Galdos, O. Cavalett, J.E. Seabra, L.A.H. Nogueira, A. Bonomi, Trends in global warming and human health impacts related to Brazilian sugarcane ethanol production considering black carbon emissions, Appl. Energy 104 (2013) 576-582.

[5] R.S. Capaz, V.S.B. Carvalho, L.A.H. Nogueira, Impact of mechanization and previous burning reduction on GHG emissions of sugarcane harvesting operations in Brazil, Appl. Energy 102 (2013) 220-228.

[6] M.L.D.S. Paraiso, N. Gouveia, Health risks due to pre-harvesting sugarcane burning in São Paulo State, Brazil, Rev. Bras. Epidemiol. 18 (2015) 691-701.

[7] S.J. Hassuani, M.R.L.V. Leal, I.C. Macedo, Biomass power generation: sugarcane bagasse and trash. Piracicaba: PNUD-CTC (Série Caminhos para Sustentabilidade). 2005.

[8] M.G.A. Landell, M.S. Scarpari, M.A. Xavier, I.A Anjos, A.S. Baptista, C.L. Aguiar, et al., Residual biomass potential of commercial and pre-commercial sugarcane cultivars, Sci. Agric. 70 (2013) 299-304.

[9] C.C. Cerri, M.V. Galdos, S.M.F. Maia, M. Bernoux, B.J. Feigl, D. Powlson, C.E.P. Cerri, Effect of sugarcane harvesting systems on soil carbon stocks in Brazil: an examination of existing data. Eur. J. Soil Sci. 62 (2011) 23-28.

[10] C. Fortes, A.C. Vitti, R. Otto, D.A. Ferreira, H.C.J. Franco, P.C.O. Trivelin, 2013. Contribution of nitrogen from sugarcane harvest residues and urea for crop nutrition, Sci. Agric. 70 (2013) 313-320.

[11] J.G. Peres, C.F. Souza, N.A. Lavorenti, Avaliação dos efeitos da cobertura de palha de cana-de-açúcar na umidade e na perda de água do solo, Eng. Agric. 30 (2010) 875-886.

[12] W.C. Valim, E. Panachuki, D.S. Pavei, T.A. Sobrinho, W.S. Almeida, Effect of sugarcane waste in the control of interrill erosion, Semin: Cien. Agrar. 37 (2016) 1155-1164.

[13] F.P.P. Junior, I.I.R. Portilho, F.M. Mercante, 2015. Atributos microbiológicos de um latossolo sob cultivo de cana-de-açúcar com e sem queima da palhada, Semin: Cien. Agrar. 36 (2015) 151-164.

[14] G.S. de Aquino, C. de Conti Medina, A.L.P. Junior, L.O. Santos, A.C.B. Cunha, D.A.O. Kussaba, J.H. dos Santos Júnior, L.F. Almeida, A.D. Santiago, Sistema radicular e produtividade de soqueiras de cana-de-açúcar sob diferentes quantidades de palhada, Pesq. Agropec. Bras. 50 (2015) 1150-1159.

[15] F.A. Santos, J.H. Queiróz, J.L. Colodette, S.A. Dernandes, V.M. Guimarães, S.T. Rezende, Potencial da palha de cana-de-açúcar para produção de etanol, Quim. Nova 35 (2012) 1004-1010.

[16] H.C.J. Franco, M.T.B. Pimenta, J.L.N. Carvalho, P.S.G. Magalhães, C.E.V. Rossell, O.A. Braunbeck, et al., Assessment of sugarcane trash for agronomic and energy purposes in Brazil, Sci. Agric. 70 (2013) 305-312.

[17] D. Khatiwada, S. Leduc, S. Silveira, I. McCallum, Optimizing ethanol and bioelectricity production in sugarcane biorefineries in Brazil, Renew. Energy 85 (2016) 371-386.

[18] M.R.L.V. Leal, M.V. Galdos, F.V. Scarpare, J.E.A. Seabra, A. Walter, C.O.F. Oliveira, Sugarcane straw availability, quality, recovery and energy use: A literature review, Biomass Bioenerg 53 (2013) 11-19.

[19] M.B. Michelazzo, O. Braunbeck, Analysis of six systems of trash recovery in mechanical harvesting of sugarcane, Rev. Bras. Eng. Agric. Ambient. 12 (2008) 546-552.

[20] T.F. Cardoso, O. Cavalett, M.F. Chagas, E.R. Morais, J.L.N. Carvalho, H.C.J. Franco, et al., Technical and economic assessment of trash recovery in the sugarcane bioenergy production system, Sci. Agric. 70 (2013) 353-360.

[21] V. Seebaluck, M.R.L.V. Leal, Feedstock Supply Chains. In: Souza, G.M., Victoria, R., Joly, C., Verdade, L. (Eds.). Bioenergy & Sustainability: Bridging the gaps. Paris: SCOPE. 2015. 779p.

[22] G.C. Belardo, J.H.M. Rosa, P.S.G. Magalhães, Evolução da colheita mecanizada na cana-de-açúcar. In: G.C. Belardo, M.T. Cassia, R.P. da Silva, Processos agrícolas e mecanização da cana-de-açúcar. SBEA, 2015; p 335-356.

[23] P.S.G. Magalhães, O.A. Braunbeck, Sugarcane and straw harvesting for ethanol production, in: L.A.B. Cortez (Eds.). Sugarcane bioethanol - R&D for Productivity and Sustainability. São Paulo: Editora Edgard Blücher, 2014, p. 465. doi: 10.5151/BlucherOA-Sugarcane-SUGARCANEBIOETHANOL_43

[24] R. Price, J. Larsen, A. Peters, Development of an optical yield monitor for sugar cane harvesting. ASAE Annual International Meeting (2007). American Society of Agricultural and Biological Engineers, p. 1-27.

3. SUGARCANE STRAW REMOVAL EFFECTS ON PLANT GROWTH AND STALK YIELD

Abstract

There is growing interest in sugarcane straw removal from the field to use as raw material for bioenergy production. In contrast, sugarcane straw removal may have negative implications for many soil ecosystem services and subsequent plant growth. A two-year experiment was conducted at Bom Retiro and Univalem mills within the dry and wet seasons for assessing the impact of straw rates removal on plant production. The experimental design was randomized blocks with five treatments proportional to 0, 25, 50, 75 and 100% of straw removal. Plant parameters evaluated included: tillering, phytomass accumulation, stalk yield and stalk industrial quality. Straw removal increased plant tillering at Bom Retiro mill in both seasons and within dry season at Univalem mill, however the plant population at the end of each ratoon cycle was not affected by straw management. Phytomass yield across each ratoon cycle was fit to a sigmoidal model ($R^2 \geq 0.92$, $p < 0.05$). Time necessary for plant completes its lag-phase is higher at the treatments applied in the dry season, whereas there was no time-pattern for plants to complete the linear and stationary growth phases. Moderate amounts of straw: 4 to 9 Mg ha^{-1} (dry base) on soil surface enhanced stalk yield. Different rates of straw removal did not affect stalk industrial quality. Overall, partial straw removal, at least in the short-term, could be a win-win situation, sustaining sugarcane yields and providing feedstock for bioelectricity cogeneration and/or 2G-ethanol production.

Keywords: Crop residue management; Bioenergy production; Harvesting season; Plant responses, Sugarcane

3.1 Introduction

Brazil is the world's largest sugarcane producer, with 8.8 Mha cultivated and an estimated production of 648 million Mg of stalks and 26.4 billion L of ethanol in the 2017/2018 cropping season (Conab, 2017). During sugarcane mechanical harvest, an average of 15 Mg ha^{-1} dry mass of straw (*i.e.*, a mix of dry and green leaves) remains in the field (Landell et al., 2013). Sugarcane straw presents high heating value (Menandro et al., 2017) and accounts for about 30% of total energy potential of aboveground biomass of the crop (Santos et al., 2012). Therefore, sugarcane straw can be an important feedstock for bioenergy production (*i.e.,* bioelectricity and second-generation ethanol) (Khatiwada et al., 2016; Lisboa et al., 2017; Menandro et al., 2017). Consequently, there is growing interest within the sugarcane industry to remove straw from the field for other uses.

In contrast, sugarcane straw removal may have negative implications on many soil ecosystem services (Cantarella et al., 2013; Carvalho et al., 2016; Cherubin et al., 2017). Several studies have shown the benefits of straw retention including: carbon accumulation (Cerri et al., 2011, Galdos et al., 2017), nutrient cycling (Fortes et al., 2013; Galdos et al., 2017), water storage

and infiltration (Cheong and Teeluck, 2016; Valim et al., 2016; Nxumalo et al., 2017), protection against soil erosion (Valim et al., 2016) and biological activity (Paredes et al., 2015).

Based on available literature, Carvalho et al. (2016) suggested that at least 7 Mg ha^{-1} of sugarcane straw should remain in the field to avoid reducing sugarcane yield and increasing environmental degradation. According to Aquino et al. (2017), the maintenance of 10 Mg ha^{-1} of sugarcane straw was enough to sustain plant growth and yield in an Oxisol. In the same soil type, Oliveira et al. (2016) observed the highest stalk yields under 9.6 and 4.7 Mg ha^{-1} of straw retained for the cane-plant and first ratoon cycles, respectively. Variation in the minimum amount of sugarcane straw needed to sustain soil and plant yields likely depends on soil type, crop management, topography and climate conditions (Marin et al., 2014; Seebaluck and Leal, 2015; Carvalho et al., 2016; Cherubin et al., 2018, Galdos et al., 2017). Thus, the sustainable sugarcane straw retention rate still needs to be experimentally determined (Carvalho et al., 2017) over a range of conditions. Further studies are also necessary to better understand potential trade-offs between retaining sugarcane straw in the field to enhance soil quality or removing straw for use as a feedstock for meeting bioenergy demands (Menandro et al., 2017).

Recent studies have begun quantifying sugarcane straw removal effects on plant growth, yield (Aquino et al., 2017; Oliveira et al., 2017) and industrial quality (Aquino et al., 2016). Additional studies that encompass contrasting soil, growing season conditions, and harvesting seasons (*e.g.*, dry and wet season) are still necessary to better understand the agronomic impacts of straw removal on sugarcane yield. In this context, we conducted a two year experiment (two sites and two harvesting seasons) within the main sugarcane-producing region in Brazil (*i.e.*, central-southern) for assessing the impact of five rates of straw removal on plant tillering, growth, stalk yield and industrial quality of stalk. The hypothesis tested was that sugarcane straw can be partially or integrally removed for bioenergy production without impairing sugarcane yields. Moreover, the optimum straw removal rate is the same in both edaphoclimatic condition and harvesting season.

3.2 Materials and methods

3.2.1 Study sites and experimental design

The study sites were presented in the item 2.2.1.

Within each study site, treatments were applied during the dry and wet seasons and maintained for two years. At both sites, sugarcane was planted in February/2013 and the

treatments were applied after cane plant (first cycle) harvesting in 2014. The timeline of the experiments is shown in Fig. 1.

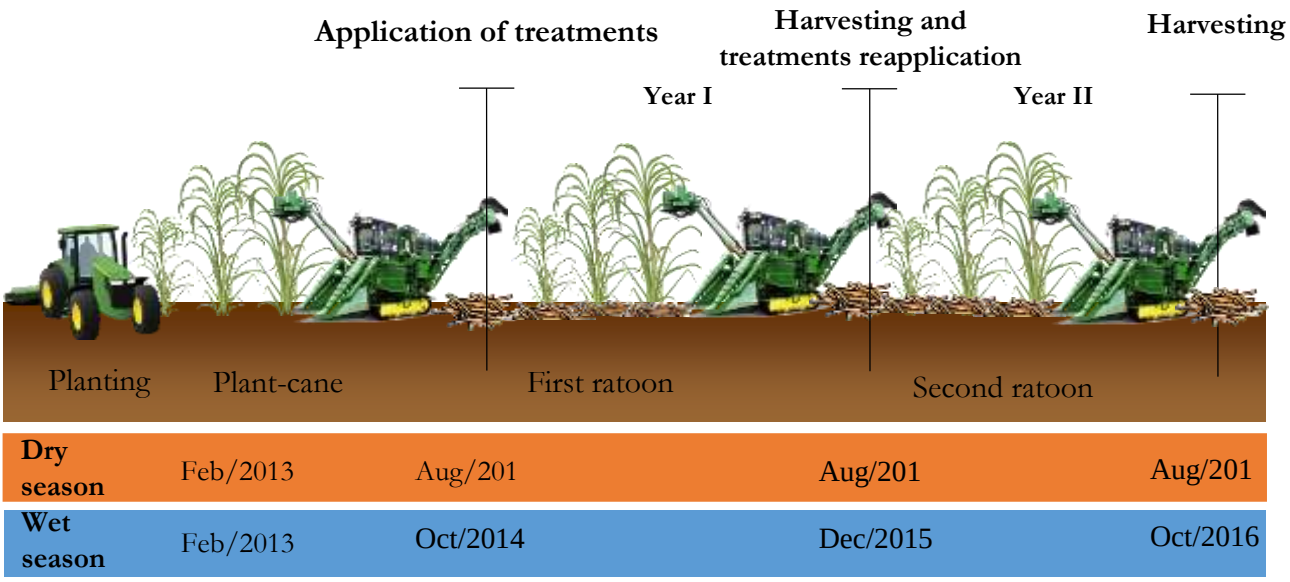

Fig. 1. Timeline for the treatments applied in dry and wet seasons and conducted over two years in southeast Brazil

Sugarcane varieties CTC 14 and RB 867515 were cultivated in Bom Retiro and Univalem mill, respectively. At both sites, sugarcane was planted using an alternating double row spacing of 1.5 and 0.9 m within the same area.

The regional climate for the Bom Retiro site is humid subtropical - Cwa type (Köppen classification) characterized by dry winter and hot summer, with a mean annual temperature of 21.8 °C and annual precipitation of 1,289 mm (Fig. 2A). At the Univalem site, the climate is tropical - Aw type, characterized by dry winter, with a mean annual temperature of 23.4 °C and annual precipitation of 1,241 mm (Fig. 2B). Rainfall at both sites is concentrated in the spring and summer (October to April), while the dry season is in the autumn and winter (May to September).

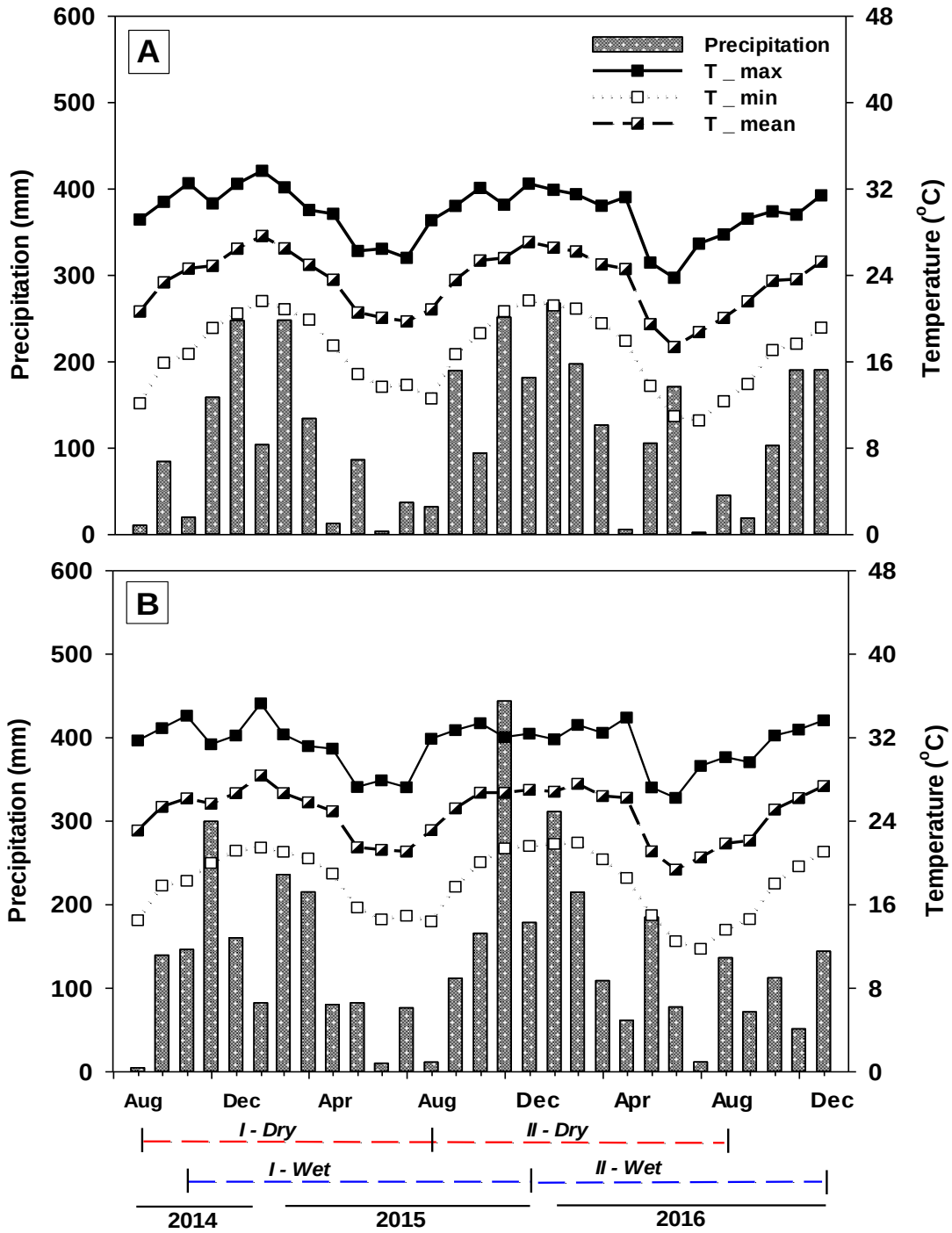

Fig. 2. Mean monthly temperature (maximum, mean and minimum) (°C) and monthly precipitation (mm) at the Bom Retiro mill (Capivari, SP) (A) and Univalem mill (Valparaiso, SP) (B). Red and blue dashed lines indicate the conduction period of the experiments installed in dry and wet seasons, respectively. I and II denotes the first and second ratoons. Sources: CEPAGRI (http://www.cpa.unicamp.br) and ESALQ (http://www.leb.esalq.usp.br/posto/).

In order to remove different rates of sugarcane straw from the field, we set up the harvester varying the angular velocity on the primary extractor fan and keep the secondary extractor fan off or on. Initially, our goal was to remove the amount of straw proportional to 0,

25, 50, 75 and 100% of the straw yield in each area. However, in the field conditions, we did not achieve the exact proportion, but the rates were very close to those intended (Table 1). More details about harvester set up and the efficiency of mechanical straw removal procedures were described in Lisboa et al. (2017). The experimental design was randomized blocks with five treatments (*i.e.*, straw removal rates), as presented in Table 1, and four replications (plots of ~50 x 25 m).

Table 1. Sugarcane straw amount left on soil surface in each treatment and year.

Sugarcane straw removal rate	Bom Retiro mill				Univalem mill			
	Dry season		Wet season		Dry season		Wet season	
	Year I	Year II	Year I	Year II	Year I	Year II	Year I	Year II
	Straw amount left on the soil surface (Mg ha^{-1})*							
100	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)
75	3.4 (±0.2)	3.2 (±0.4)	4.2 (±0.6)	2.4 (±0.1)	5.1 (±0.5)	4.1(±0.2)	4.0 (±0.5)	3.2 (±0.5)
50	7.8 (±0.6)	9.7 (±0.4)	8.7 (±0.9)	5.5 (±1.0)	8.4 (±0.7)	7.9 (±0.1)	10.2 (±0.9)	6.8 (±0.4)
25	13.0 (±0.7)	11.4 (±0.7)	15.1(±1.5)	10.5 (±0.1)	11.4 (±1.1)	9.6 (±0.1)	12.5 (±0.9)	11.6 (±0.5)
0	16.6 (±1.6)	14.7 (±0.8)	18.9 (±1.6)	13.6 (±2.0)	15.0 (±1.1)	12.4 (±0.8)	16.4 (±1.4)	13.7 (±1.1)

*dry mass; (I) and (II) denote the first and second sugarcane ratoon, respectively; the standard error associated to the mean (n = 12) is presented between brackets

At the installation of each experiment, a composed sample of sugarcane straw was collected for characterizing the initial carbon and macronutrients contents (Table 2). Carbon and nitrogen concentration in plant tissue were determined by an elemental analyzer (Leco© Truspec®, St. Joseph, Michigan). Phosphorus, K, Ca, Mg and S concentrations were determined following methods described by Malavolta et al. (1997).

Table 2. Carbon (C) and macronutrient (nitrogen – N, phosphors – P, potassium – K, calcium – Ca, magnesium – Mg, sulphur - S) contents in sugarcane straw used in each experiment

Sites	C	N	P	K	Ca	Mg	S	C:N
	----------g kg^{-1}----------							
Bom Retiro$^{(I - dry)}$	437 (±9)	3.68 (± 0.18)	0.36 (±0.02)	2.23 (±0.19)	2.83 (±0.06)	1.71 (±0.07)	0.93 (0.01)	119 (±5)
Bom Retiro$^{(I - wet)}$	467 (±4)	4.02 (±0.23)	0.38 (±0.02)	2.45 (±0.17)	2.44 (±0.11)	1.54 (±0.10)	0.74 (0.01)	116 (±7)
Bom Retiro$^{(II - dry)}$	470 (±4)	4.80 (±0.20)	0.79 (±0.03)	6.12 (±0.45)	4.99 (±0.16)	1.31(±0.04)	1.62 (±0.05)	98 (±5)
Bom Retiro$^{(II – wet)}$	422 (±8)	6.04 (±0.29)	0.58 (±0.03)	1.30 (±0.29)	8.55 (±0.68)	2.55 (±0.36)	0.95 (±0.04)	73 (±2)
Univalem$^{(I - dry)}$	476 (±2)	3.22 (±0.15)	0.38 (±0.02)	2.26 (±0.17)	2.39 (±0.08)	1.54 (±0.09)	0.74 (±0.04)	148 (±7)
Univalem$^{(I - wet)}$	479 (±3)	2.58 (±0.09)	0.39 (±0.02)	1.66 (±0.22)	1.96 (±0.10)	1.38 (±0.04)	0.45 (±0.02)	186 (±6)
Univalem$^{(II - dry)}$	474 (±4)	3.58 (±0.08)	0.54 (±0.01)	1.35 (±0.09)	4.22 (±0.18)	1.08 (±0.03)	0.71 (±0.03)	132 (±4)
Univalem$^{(II – wet)}$	470 (±4)	3.10 (±0.15)	0.34 (±0.01)	0.56 (±0.04)	4.22 (±0.29)	1.24 (±0.50)	0.35 (±0.02)	152 (±9)

Mean values (n = 12) of each chemical element content in straw tissue; the standard error associated with each mean is presented between brackets; $^{(I)}$ and $^{(II)}$ denote the first and second sugarcane ratoon, respectively.

3.2.2 Evaluation of sugarcane response to residue removal management

We evaluated sugarcane responses to straw removal in different phases of plant development over the annual crop cycle (Fig. 3) in the first and second ratoon. The evaluations started with the monitoring of tillering dynamics in the early phases, then biometric evaluations to follow the plant growth dynamic. Finally, crop yield (stalk and straw) and stalk industrial quality were evaluated in the late phase during harvesting.

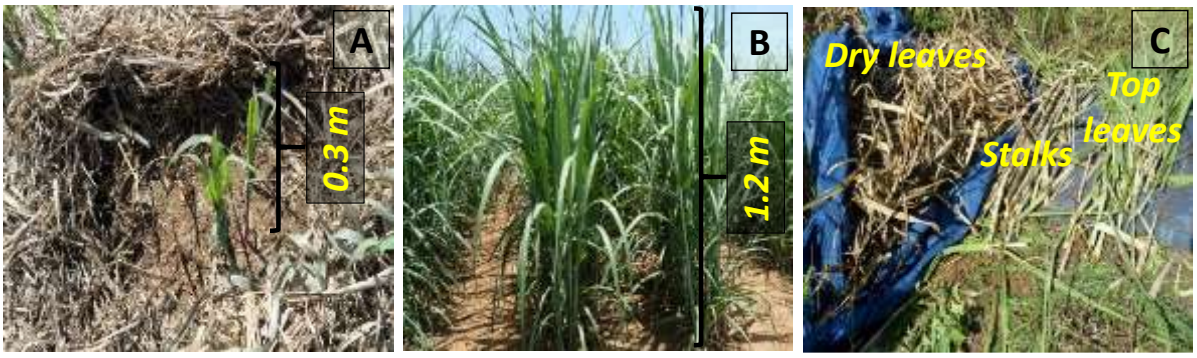

Fig. 3. Detail of sugarcane tillering (A), plant four months after harvesting (B) and plant divided in three components in the end of the cycle (C).

3.2.3 Plant tillering

Plant tillering evaluations consisted of counting the number of tillers within a 20-m per plot. Across the ratoon cycle, at each evaluation time, the tiller counts were performed in the same location within plots to reduce variability. Tillering was measured several times during the sugarcane growth cycle. For both sites (Bom Retiro and Univalem mills), in the treatments applied in the dry season, tillering evaluations occurred at 60, 90, 120 and 210 days after harvesting in the first year. For the treatments applied in the wet season, tillering evaluations were performed at 60, 90 and 135 days after harvesting in the first year. In the second year, treatments applied in the dry season, tillering evaluations were performed at 30, 60, 90, 120 and 360 days after harvesting, whereas for treatments applied in the wet season the same evaluations were performed at 30, 60, 90, 120, 180 and 360 days after harvesting.

3.2.4 Plant growth

The dynamics of sugarcane growth was measured through biometric evaluations. Biometric evaluations consisted on destructively sampling the aboveground phytomass within four meters at the crop row in each plot. Sugarcane plants were separated into dry leaves, green leaves and stalks (Fig. 3C). The fresh phytomass of each component was weighed using an

electronic scale and then, all fresh phytomass was ground in a forage grinder and subsampled. Thereafter, samples were oven-dried at 65 °C and weighed for dry mass determination. To estimate dry mass yield per hectare, it was considered the row-spacing 1.2 m and one hectare with 8,333 meters of rows.

In the first year, first biometric evaluations were performed when plants did not have dry leaves and stalks (Fig. 3B) yet. Therefore, instead of measuring separately phytomass yield of each component (*i.e.*, dry leaves, green leaves and stalks), all phytomass combined was weighted and sampled. This same procedure was also adopted at the second biometric evaluation at the wet season.

In the first year at Bom Retiro mill, plant biometric evaluation was performed at 120, 210, 290 and 360 days after harvesting in the dry season treatment, and at 90, 135, 230 and 370 days after harvesting in the wet season treatment. In the first year at the Univalem mill, biometric evaluations were performed at 120, 210, 270 and 360 days after harvesting in the dry season treatment and at 90, 135, 230 and 410 days after harvesting in the wet season treatment. In the second year, these evaluations were performed at 180 and 360 days for the treatments installed in the wet season and at 210 and 360 days for the treatment installed in the dry season, regardless of the site.

Although we had planned to evaluate plant growth on the same dates in all treatments, variation in plant growth among treatments prevented this. Overall, treatments applied in the wet season had more favorable conditions (*i.e.*, temperature and water availability) for plant growth after the beginning of each cycle. This resulted in faster phytomass accumulation, which lead us to perform evaluations on these treatments around three and five months after harvesting. Conversely, dry season treatments had favorable conditions for plant growth later in the cycle which delayed phytomass accumulation. Based on that, we decided to delay plant growth evaluations on dry season treatments compared to the evaluations done at wet season treatments. Usually, plant growth evaluations were performed according to the climatic conditions in each experiment and considering the different phases of plant growth (*i.e.*, lag, linear growth and stationary phase).

3.2.5 Leaf area index

Leaf area index (LAI) was adopted as an indirect parameter to evaluate plant growth. LAI evaluations were performed at 15 points randomly chosen in eight central rows of each plot. All readings were performed at a height of 0.6 m above the ground with a LAI-2200 Plant Canopy Analyzer (LI-COR), all evaluations were performed between 7 and 9 am. Regardless to the study

site, all treatments applied in the dry season and first year, LAI evaluations were done 170 and 210 days after harvesting. In the same year, at the treatments applied in the wet season, LAI evaluations occurred 90 and 135 days after harvesting. In the second year, across all treatments, LAI determinations were concentrated in the beginning of ratoon cycle, 90 and 120 days after harvesting.

3.2.6 Stalk yield

Stalk yield was quantified at the end of each ratoon cycle, approximately one year from previous harvesting. The stalk fresh mass mechanically harvested from the five central rows 500 m long (525 m^2) of each plot was weighed in the field using a wagon coupled with a scale and extrapolated to Mg ha^{-1}.

3.2.7 Industrial quality of sugarcane stalks

Before harvesting, ten plants per plot were harvested from the rows that were not used for stalk yield quantification. A composited stalk sample was sent for laboratory analysis to determinate parameters used to evaluate sugarcane industrial quality [fiber content (fiber), soluble solids content (Brix), apparent sucrose in the juice (Pol), apparent juice purity (purity), and reducing sugar (RS)]. The parameters used for determining sugarcane industrial quality were measured as described by Consecana (2006).

3.2.8 Data analysis and calculations

Analysis of variance (ANOVA) was used to test the effects of straw removal on plant tillering, LAI, and stalk yield within each season, year, and site. If the ANOVA results were significant ($p < 0.05$), then treatment means were compared using Tukey's test ($p<0.05$). ANOVA and Tukey's test were performed using R software (R Core Team, 2016).

A non-linear growth regression model (Equation 1) was fit to estimate the plant-growth curve (phytomass accumulation) for each treatment using R software based on the F-test ($p < 0.05$) of the regression model and coefficients.

$$Y = \frac{Y_{max}}{1+e^{-\frac{(DAH-A)}{B}}} \qquad \text{Eq. 1}$$

where: Y is the phytomass yield (Mg ha^{-1}), Y_{max} is the maximum phytomass yield (Mg ha^{-1}) over each ratoon cycle, DAH is day after harvesting, A and B are constants. Figures were created using SigmaPlot (SigmaPlot version 11.0; Systat Software, 2008).

3.3 Results and discussion

3.3.1 Straw removal effects on plant tillering dynamics

Large amounts of sugarcane straw on the soil surface negatively affected early plant tillering (*i.e.*, until 90 days after harvesting) for the treatments applied during the dry season at the Bom Retiro (Fig. 4 A and B) and Univalem (Fig. 4 E and F) sites. After this period, the number of tillers decreases and the straw no longer influenced plant tillering. A similar pattern of sugarcane tillering was observed for the treatments applied in the wet season at Bom Retiro mill (Fig. 4 C and D). However, in the wet season, the maintenance of straw on the soil surface negatively affected plant tillering for a longer period, at least until 180 days after harvesting. In contrast, plant tillering was not affected by increasing amount of straw on the soil surface in wet season treatments both years at the Univalem mill site (Fig. 4 G and H). Despite the negative effect of straw on plant tillering observed in the earliest ratoon stages in the majority of the treatments, plant population at the end of the cycle (*i.e.*, ~360 days after harvesting) was not affected by increasing amount of straw (Fig. 4).

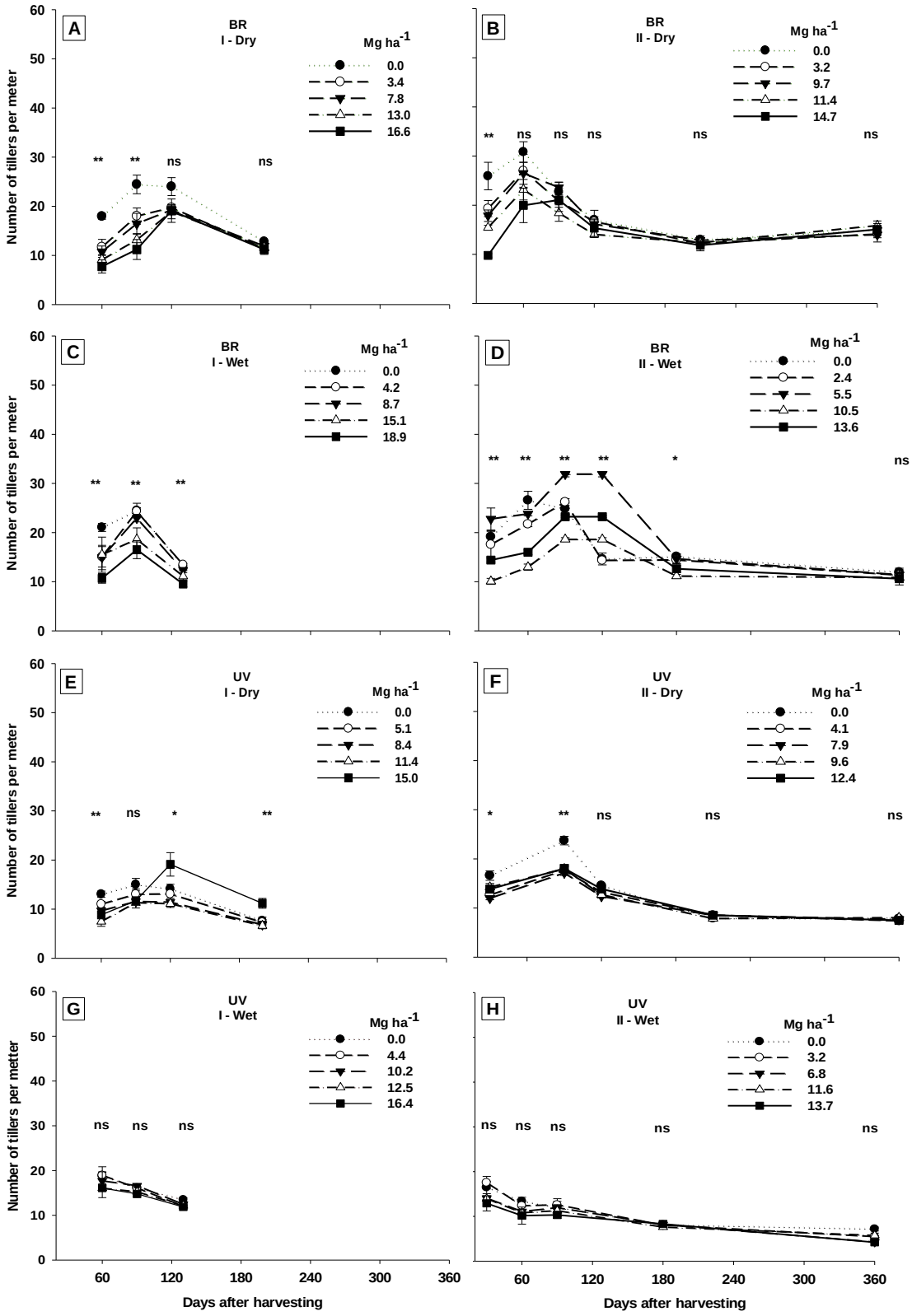

Fig. 4. Sugarcane tillering dynamics under increasing amount of straw left on the soil surface in treatments applied in the dry and wet seasons at the Bom Retiro - BR (A to D) and Univalem - UV (E to H) mill and conducted over two ratoons (I and II). ** and * denotes that means differ significantly by Tukey's test ($p < 0.01$) and ($p < 0.05$), respectively; ns: non-significant; error bars denote standard error of the mean

Higher rainfall and temperature favored plant tillering and growth in the wet season compared to dry season at the Univalem site (Fig. 2 B). These factors likely offset the negative implications of thick straw layer on plant tillering, explaining the absence of significant effects of increasing amount of straw on plant tillering observed in the wet season treatments across both years (Fig. 4 G and H). Studies conducted in Brazil have shown that even under tropical or subtropical conditions, the maintenance of a thicker straw layer on the soil surface decreases soil temperature (Awe et al., 2015), thus reducing sugarcane tillering in colder regions (Campos et al. 2010). In our studies, lower temperatures were observed at the Bom Retiro site, especially in the beginning of each ratoon cycle, compared to those temperatures recorded at the Univalem site (Fig. 2 and 2S). This resulted in increased straw amounts negatively affecting plant tillering at the Bom Retiro mill site in both treatments and years (Fig. 4 A to D *vs* E to H). Moreover, higher temperature at the Univalem mill site resulted in plant growth and canopy closure, which reduced straw amount effects on LAI (Fig. 1S A to D *vs* E to H).

The effects of sugarcane straw on plant tillering is controversial and temperature seems to be the abiotic factor influencing plant tillering. Even within the same thermal zone, previous studies have shown different results. For instance, in tropical conditions, some studies did not verify a significant effect of straw on plant tillering (Ball-Coelho et al., 1993; Tavares et al., 2010; Aquino et al., 2017), whereas other studies reported reduced plant tillering and final plant population when all straw remained on soil surface (Campos et al., 2008; Campos et al., 2010). In contrast to these studies, we verified negatives effects of sugarcane straw on plant tillering in the earliest ratoons stages (Fig. 4 A to F) which agrees with Nxumalo et al. (2017).

3.3.2 Plant growth and phytomass yield

Overall, the accumulation of phytomass of sugarcane was adjusted using the sigmoidal models. Non-linear equations performed between days after harvesting (*i.e.*, different periods across each ratoon cycle) and phytomass yield presented $r^2 > 0.92$ and $r^2 > 0.93$, respectively at Bom Retiro and Univalem mill (Table 3). The sigmoidal model is typical to describe sugarcane phytomass accumulation over the cycle, as also reported by Mariano et al. (2016) and Leite et al. (2016).

Phytomass accumulation over each ratoon cycle in each experiment occurred in three-phase model (Fig. 5), to date: i) lag-phase, characterized by a slow initial plant growth; ii) linear growth, in this phase occurs a faster phytomass accumulation; and finally, iii) stationary-phase, characterized by another slow phytomass accumulation when the values reach the plateau. The time required in each phase and the respective phytomass accumulation ranged according to the

treatment, season, year and site (Table 1S). In average, the lag-phase extended approximately from 0 to 108 days, representing ~17% of final phytomass yield (*i.e.*, relative to the maturity); then linear growth phase extended from 108 to 206 days, representing ~64% of final phytomass yield and finally, the stationary-phase, from 206 to 360 days accounted for ~19% of final phytomass yield.

Table 3. Adjusted models for phytomass yield as affected by increasing amount of straw (Mg ha^{-1}) left on soil surface over two ratoons

First year						Second year					
Dry season			Wet season			Dry season			Wet season		
Amount of straw	Model§	R^2	Amount of straw	Model	R^2	Amount of straw	Model	R^2	Amount of straw	Model	R^2
Bom Retiro mill											
0.0	$Y= 58.47/1+e^{(-(X-208.00)/26.42)}$	0.98**	**0.0**	$Y= 32.89/1+e^{(-(X-119.97)/23.86)}$	0.92*	**0.0**	$Y= 38.12/1+e^{(-(X-189.57)/38.15)}$	0.99**	**0.0**	$Y= 26.45/1+e^{(-(X-110.49)/23.64)}$	0.99**
3.4	$Y= 50.91/1+e^{(-(X-212.89)/48.36)}$	0.99**	**4.2**	$Y= 35.01/1+e^{(-(X-128.52)/31.06)}$	0.99**	**3.2**	$Y= 41.35/1+e^{(-(X-208.83)/54.93)}$	0.99**	**2.4**	$Y= 27.42/1+e^{(-(X-114.98)/28.36)}$	0.99**
7.8	$Y= 53.80/1+e^{(-(X-217.25)/49.70)}$	0.99**	**8.7**	$Y= 38.84/1+e^{(-(X-138.53)/24.36)}$	0.95*	**9.7**	$Y= 38.01/1+e^{(-(X-180.66)/35.72)}$	0.99**	**5.5**	$Y= 31.55/1+e^{(-(X-150.25)/38.47)}$	0.97*
13.0	$Y= 48.43/1+e^{(-(X-198.30)/29.71)}$	0.99**	**15.1**	$Y= 34.02/1+e^{-(-(X-136.11)/23.09)}$	0.97*	**11.4**	$Y= 37.53/1+e^{(-(X-186.67)/36.58)}$	0.99**	**10.5**	$Y= 30.57/1+e^{-(-(X-144.19)/29.66)}$	0.99**
16.6	$Y= 61.53/1+e^{(-(X-210.47)/29.50)}$	0.98**	**18.9**	$Y= 36.92/1+e^{(-(X-137.46)/22.54)}$	0.97*	**14.7**	$Y= 32.98/1+e^{(-(X-174.33)/32.74)}$	0.99**	**13.6**	$Y= 30.62/1+e^{(-(X-136.28)/27.28}$	0.99**
Univalem mill											
0.0	$Y= 35.13/1+e^{(-(X-190.05)/39.40)}$	0.99**	**0.0**	$Y= 29.38/1+e^{(-(X-152.20)/33.00)}$	0.99**	**0.0**	$Y= 25.06/1+e^{(-(X-154.03)/27.21)}$	0.99**	**0.0**	$Y= 18.51/1+e^{(-(X-177.05)/57.81)}$	0.96*
5.1	$Y= 26.74/1+e^{(-(X-174.70)/34.71)}$	0.94*	**4.0**	$Y= 25.49/1+e^{(-(X-132.45)/29.00)}$	0.99**	**4.1**	Not adjusted	---	**3.2**	$Y= 20.70/1+e^{(-(X-174.88)/59.19)}$	0.95*
8.4	$Y= 27.08/1+e^{(-(X-175.77)/38.31)}$	0.99**	**10.2**	$Y= 35.86/1+ e^{(-(X-178.78)/55.62)}$	0.99**	**7.9**	Not adjusted	---	**6.8**	$Y= 17.32/1+ e^{(-(X-135.65)/48.15)}$	0.98**
11.4	$Y= 30.75/1+e^{(-(X-181.40)/40.90)}$	0.99**	**12.5**	$Y= 25.16/1+ e^{(-(X-134.66)/33.84)}$	0.99**	**9.6**	$Y= 29.49/1+e^{(-(X-151.28)/21.21)}$	0.99**	**11.6**	$Y= 23.90/1+ e^{(-(X-203.87)/70.22)}$	0.94*
15.0	$Y= 29.61/1+e^{(-(X-166.90)/28.39)}$	0.96*	**16.4**	$Y= 26.38/1+e^{(-(X-134.31)/19.28)}$	0.98**	**12.4**	Not adjusted	---	**13.7**	$Y= 17.88/1+e^{(-(X-174.61)/25.88)}$	0.93*

§ The equations come from the model: $Y = \frac{Y_{max}}{1+e^{-\frac{(DAH-A)}{B}}}$ where: Y is the phytomass yield (Mg ha^{-1}), Ymax is the maximum phytomass yield (Mg ha^{-1}) over each ratoon cycle, DAH is day after harvesting, A and B are constants; **and * are respectively significant levels of 1 and 5% by F's test

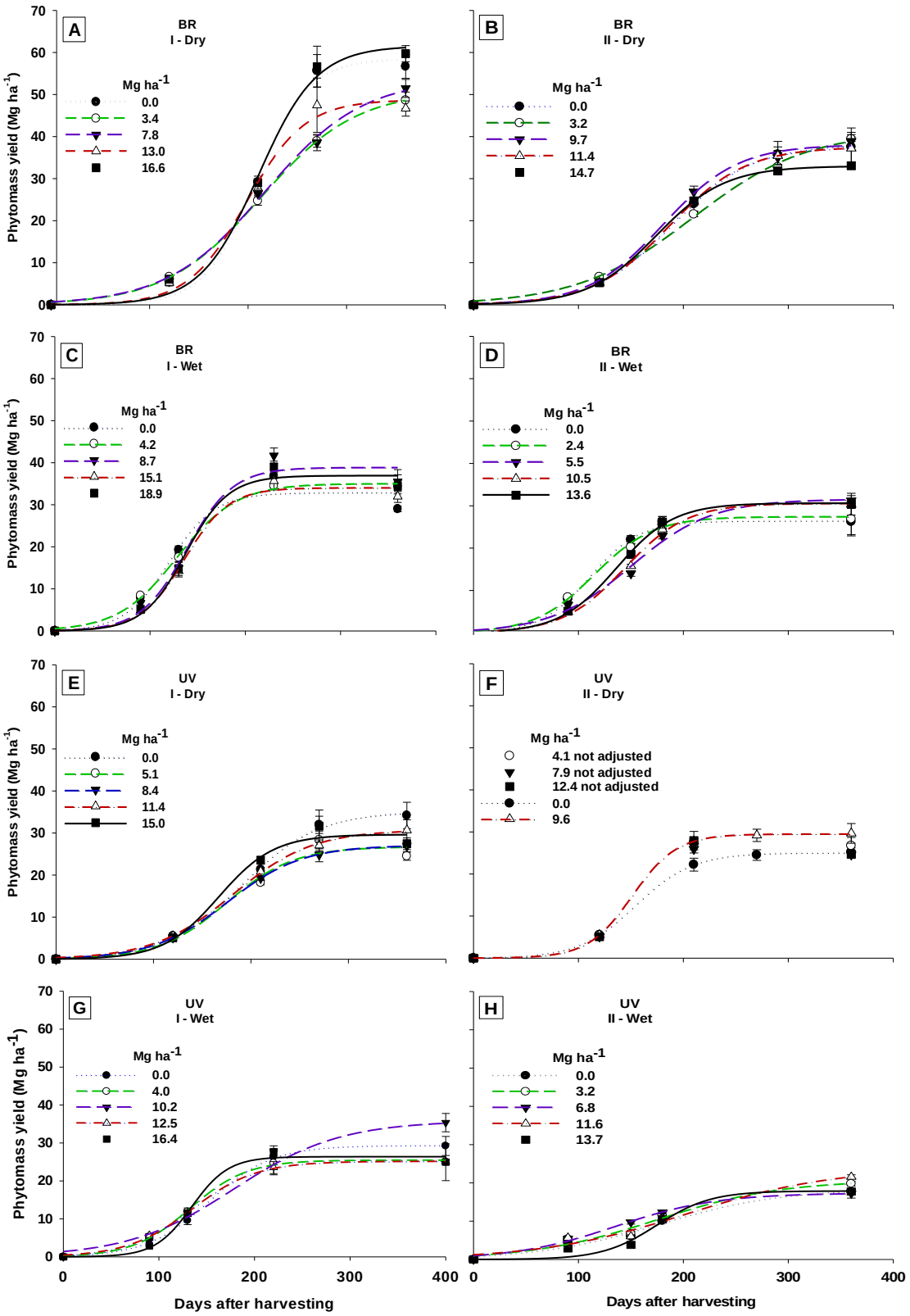

Fig. 5. Phytomass accumulation curves of sugarcane cultivated under increasing amount of straw left on soil surface in experiments installed in dry and wet season at Bom Retiro - BR (A to D) and Univalem - UV (E to H) mill and conducted over the first (I) and (II) ratoons.

Although, sugarcane growth curve presented similar overall shape (sigmoid) for all treatments, the straw removal and harvesting season affected differently specific phases of this curve in each ratoon cycle (Fig. 5). In general, the maintenance of straw reduces phytomass yield mainly during the earliest stages of ratoon cycle in wet season treatments. After this period, plant recover and phytomass yield is greater with covered soil than that observed with bare soil (*i.e.*, total straw removal) (Fig. 5 A and G).

High or total straw removal (bare soil) allows faster plant sprouts with higher number of tillers during earliest ratoon stages. However, competition for water and nutrients plus self-shading of the plant canopy favored senescence of leaves and decreasing phytomass yield. On the other hand, higher nutrients and water availability under increased straw amounts reduces plant senescence and could support higher plant population, which in turn increases phytomass yield later in the cycle. Residue-derived N has limited availablity to plants in the short-term (Ferreira et al., 2016; Trivellin et al., 2013). In contrast, K is readily released from residue to soil due to potassium's non-structural function in plants (Epstein and Bloom, 2006). Rapid release from residue makes the straw an important short-term source of K for plant growth (Carvalho et al., 2016). The capacity of plants to recover over the cycle from the negative effect of straw observed in the beginning of each ratoon cycle relates to the long cycle of the crop, around one year, and sugarcane's high efficiency in intercepting annual radiation (Inman-Bamber, 2013).

Phytomass yield at the end of each ratoon cycle is higher in dry season treatments (Fig. 6), regardless of site. In Bom Retiro, phytomass yield was ~37% (20 Mg ha^{-1}) and 24% (9 Mg ha^{-1}) higher in the first and second ratoon, respectively (Fig. 6 A) in the dry season than wet season treatments. Similar pattern was found in Univalem mill, where phytomass gains in dry season accounted for ~5% (2 Mg ha^{-1}) and 26 % (7 Mg ha^{-1}) in the first and second ratoon, respectively (Fig. 6 B).

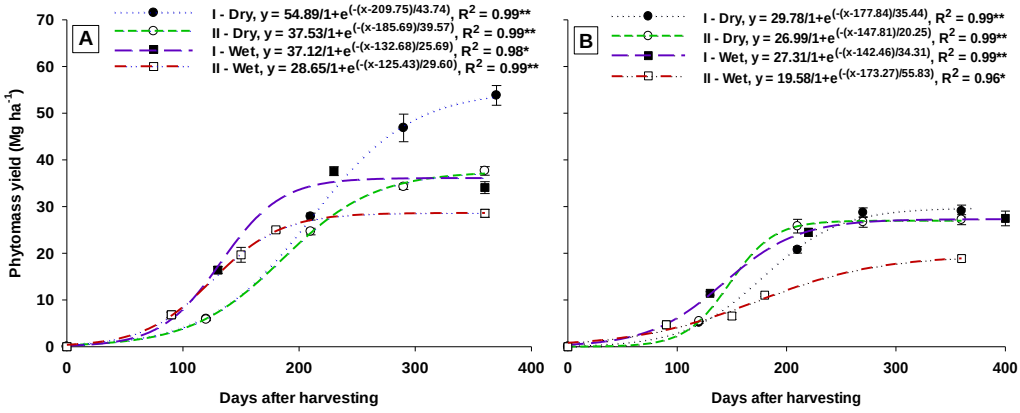

Fig. 6. Average of phytomass accumulation in dry- and wet-season experiments over each ratoon cycle at Bom Retiro (A) and Univalem (B) mill; first (I) and second (II) ratoon; ** and * significant by F's test ($p < 0.01$) and ($p < 0.05$), respectively

Although wet season treatments were installed when precipitations and temperature were favorable for plant growth (Fig. 2A), five months later, during the main growth phase, a significant reduction in temperature and precipitation (Fig. 2 and Fig. 2S) occurred. This fact likely impaired plant growth and, consequently, phytomass accumulation in these treatments.

We observed a significant reduction in phytomass accumulation from the first to the second ratoon (year) at both sites (Figs. 5 and 6). Overall, phytomass yield was ~23% (11 Mg ha^{-1}) in Bom Retiro and 21% (6 Mg ha^{-1}) in Univalem lower at the end of the second ratoon than in the first ratoon. The reduction in phytomass yield across the annual cycle is typically reported in sugarcane fields, being related to factors such as: i) mechanical damage to the root system during field operations (*i.e.*, harvesting and crop fertilization), which reduces plant vigor in the follow ratoon cycle and causes row gaps (failures) that may result in decreasing plant population and increasing weed infestations; ii) intensive machinery traffic induced soil compaction over each ratoon cycle (Cherubin et al., 2016) makes the soil conditions less favorable to root growth; iii) lower nutrient availability due to annual nutrient removal from the soil by stalk and straw removal (Trivelin et al., 2013; Menandro et al., 2017) if nutrient replenishment is not properly managed. These factors potentially contribute to the reduction in phytomass yield at the end of the second ratoon observed in our experiment.

3.3.3 Sugarcane straw removal vs stalk yield

The straw management affected significantly ($p < 0.01$) stalk yield only at first ratoon and yields accumulated over two ratoons at wet season experiment in Bom Retiro mill (Fig. 7B), a smooth trend of higher stalk yield under intermediate amount of straw left on soil surface was

also observed at dry-season experiments in this mill (Fig. 7 A and B). These intermediates amount of straw (dry base) were 8.7 and 7.1 Mg ha^{-1}, respectively at dry and wet season experiments (Fig. 7 A and B).

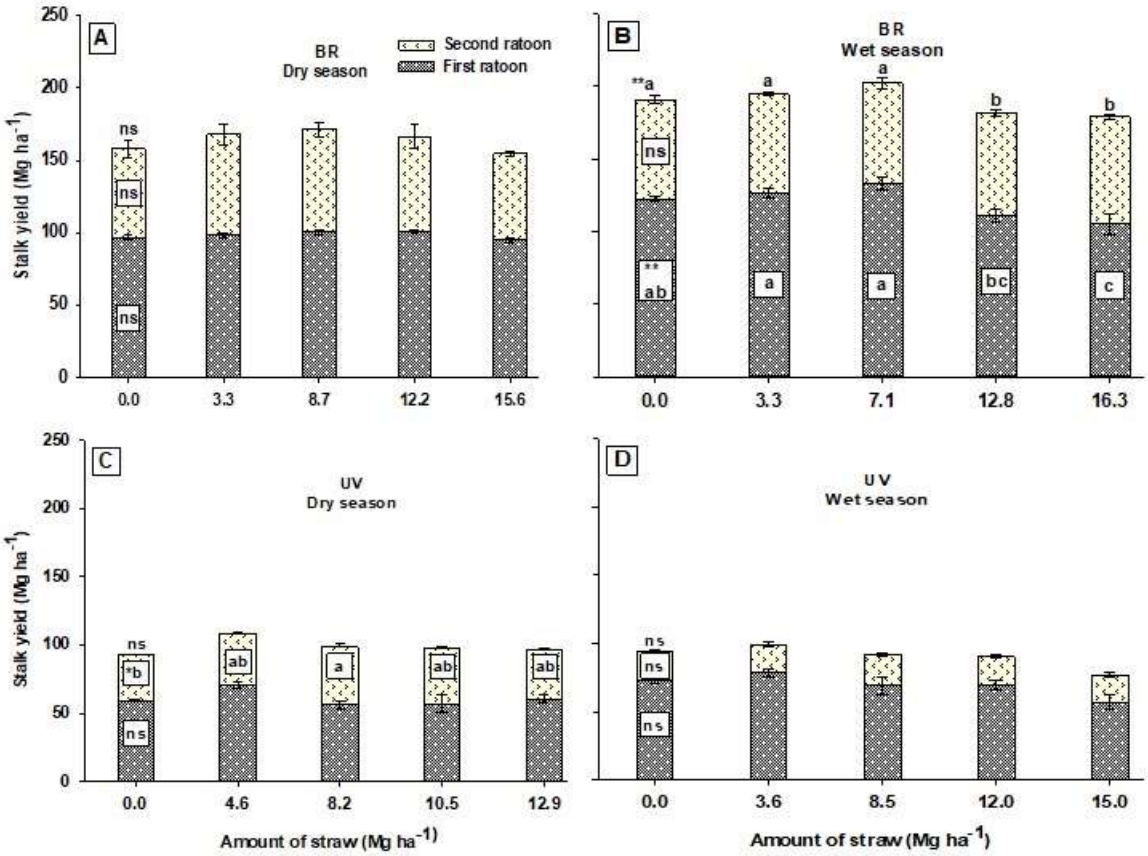

Fig. 7. Stalk yield of sugarcane cultivated under increasing amounts of straw (mean of both ratoon cycles) on soil surface in experiments installed in dry and wet season at Bom Retiro – BR (A and B) and Univalem (C and D) mills over two ratoons. ** and * significant by Tukey's test ($p < 0.01$) and ($p < 0.05$), respectively; ns: non-significant; error bars denote standard error of the mean

At the Bom Retiro mill the stalk yield over both ratoon cycles from intermediate amount of straw (*i.e.*, 8.7 Mg ha^{-1}) left on soil surface was ~8% (13 Mg ha^{-1}) and 10% (17 Mg ha^{-1}) higher than stalk yield for the 0 or 100% straw retained treatments in the dry season (Fig. 7 A). The same pattern was observed in the wet-season where stalk yield over both ratoons at the intermediate amount of straw (*i.e.*, 7.1 Mg ha^{-1}) was ~6% (12 Mg ha^{-1}) and 11% (23 Mg ha^{-1}) higher than stalk yield for the 0 or 100% straw retained treatments (Fig. 7 B), respectively.

At the Univalem mill, straw removal rates affected stalk yield only in the second ratoon of the dry season treatments (Fig. 7 C). At this site stalk yield accumuled over both ratoons under ~5 Mg ha^{-1} of straw on soil surface was around 15% (16 Mg ha^{-1}) and 11% (12 Mg ha^{-1}) higher than stalk yield in the 0 or 100% removal treatments, respectively. Although different levels of

straw removal did not affect stalk yield in the treatment established in the wet season at the Univalem mill, stalk yield in each ratoon cycle, as well stalk yields accumuled over both ratoons, under ~4 Mg ha^{-1} was around 5% (5 Mg ha^{-1}) and 22% (23 Mg ha^{-1}) higher than stalk yield determined in the 0 and 100% removal treatments, respectively (Fig. 7 D).

Our findings are consistent with recent studies also conducted in central-southern Brazil (Oliveira et al., 2016; Aquino et al., 2017). Oliveira et al. (2016) reported higher stalk yield under intermediate amount of straw (9.6 Mg ha^{-1}) in the first ratoon, however in the second year, 4.7 Mg ha^{-1} (~75 % of straw removal) was enough to sustain high yield. Aquino et al. (2017) reported that the maintenance of 10 Mg ha^{-1} (50% removed) of straw on the soil surface (*i.e.,* intermediate amount) enhanced plant growth and stalk yield. Aquino et al. (2017) also reported that stalk yield increased 29% under intermediate amount of straw compared to the stalk yield observed in the burned cane system.

The effect of straw removal on stalk yield was similar at both mills. Nevertheless, at the Univalem mill the highest stalk yield was obtained under smaller amounts of straw compared to the straw amount that induced the highest yields at the Bom Retiro mill. Moreover, the straw amount that enables highest stalk yields varies from one year to another in both sites. These results indicated that from first to second ratoon it is possible to use higher straw removal rates without impairing stalk yield in the following ratoon. Overall, intermediate amounts of residue enhanced stalk yield in both ratoons. Further studies are needed to better understand the effects of increasing rates of straw removal over ratoons cycles, residue placement effects (*e.g.* whole residue left within inter rows as currently practiced by most mills in Brazil) on nutrient extraction, soil quality and long-term plant growth.

3.3.4 Industrial quality of sugarcane stalks

Sugarcane straw removal rates did not affect the parameters of industrial quality of the sugarcane stalk (Table 4), as also reported by Aquino et al. (2016).

Table 4. Industrial quality of sugarcane stalk at the end of each experiment

	First year										Second year									
Parameters	**Dry season**					**Wet season**					**Dry season**					**Wet season**				
(%)	**Amount of straw (Mg ha^{-1})**																			
	0.0	**3.4**	**7.8**	**13.0**	**16.6**	**0.0**	**4.2**	**8.7**	**15.1**	**18.9**	**0.0**	**3.2**	**9.7**	**11.4**	**14.7**	**0.0**	**2.4**	**5.5**	**10.5**	**13.6**
	Bom Retiro mill																			
Brix	18.4^{ns} (±0.8)	17.8 (±0.4)	17.8 (±0.2)	15.8 (±0.4)	18.0 (±0.5)	18.4^{ns} (±0.1)	17.4 (±0.3)	18.0 (±0.2)	18.3 (±0.2)	17.7 (±0.3)	19.5^{ns} (±0.2)	19.4 (±0.2)	19.1 (±0.3)	19.6 (±0.3)	19.0 (±0.6)	16.1^{ns} (±0.2)	16.2 (±0.1)	16.1 (±0.4)	16.2 (±0.3)	15.7 (±0.2)
Pol	16.0^{ns} (±0.8)	15.6 (±0.4)	15.6 (±0.3)	13.2 (±0.5)	15.7 (±0.6)	16.3^{ns} (±0.0)	15.3 (±0.4)	16.0 (±0.2)	16.1 (±0.2)	15.5 (±0.4)	17.2^{ns} (±0.2)	16.9 (±0.3)	16.6 (±0.4)	17.3 (±0.2)	16.4 (±06)	13.4^{ns} (±0.2)	13.7 (±0.1)	13.4 (±0.4)	13.6 (±0.3)	13.0 (±0.2)
RS	0.65^{ns} (±0.03)	0.65 (±0.01)	0.67 (±0.02)	0.67 (±0.02)	0.62 (±0.03)	0.60^{ns} (±0.02)	0.63 (±0.02)	0.60 (±0.01)	0.62 (±0.02)	0.63 (±0.02)	0.61^{ns} (±0.01)	0.64 (±0.02)	0.66 (±0.04)	0.61 (±0.01)	0.68 (±0.01)	0.79^{ns} (±0.01)	0.74 (±0.01)	0.79 (±0.02)	0.78 (±0.02)	0.80 (±0.01)
Fiber	12.1^{ns} (±0.4)	12.4 (±0.2)	12.4 (±0.2)	11.6 (±0.2)	12.4 (±0.2)	12.4^{ns} (±0.1)	12.2 (±0.3)	12.3 (±0.1)	12.4 (±0.2)	12.7 (±0.3)	14.5^{ns} (±0.2)	14.6 (±0.1)	14.9 (±0.3)	14.1 (±0.0)	14.3 (±0.5)	13.8^{ns} (±0.2)	13.3 (±0.2)	13.8 (±0.3)	13.5 (±0.2)	13.4 (±0.3)
Purity	87.2^{ns} (±0.8)	87.5 (±0.2)	87.2 (±0.5)	86.8 (±0.7)	87.2 (±0.8)	88.6^{ns} (±0.5)	87.8 (±0.7)	88.8 (±0.3)	88.0 (±0.4)	87.7 (±0.5)	88.3^{ns} (±0.2)	87.4 (±0.7)	87.0 (±1.0)	88.2 (±0.2)	86.3 (±0.4)	83.3^{ns} (±0.4)	84.5 (±0.2)	83.1 (±0.5)	83.6 (±0.6)	82.7 (±0.4)
	Amount of straw (Mg ha^{-1})																			
	0.0	**5.1**	**8.4**	**11.4**	**15.0**	**0.0**	**4.0**	**10.2**	**12.5**	**16.4**	**0.0**	**4.1**	**7.9**	**9.6**	**12.4**	**0.0**	**3.2**	**6.8**	**11.6**	**13.7**
	Univalem mill																			
Brix	18.2^{ns} (±0.1)	18.5 (±0.1)	17.7 (±0.1)	18.1 (±0.1)	18.3 (±0.1)	18.8^{ns} (±0.2)	19.2 (±0.2)	18.4 (±0.4)	18.5 (±0.6)	18.0 (±0.4)	18.8^{ns} (±0.1)	18.9 (±0.1)	18.6 (±0.2)	18.7 (±0.3)	19.0 (±0.2)	14.9^{ns} (±0.2)	14.8 (±0.2)	14.6 (±0.4)	14.7 (±0.3)	15.0 (±0.2)
Pol	20.3^{ns} (±0.2)	20.6 (±0.2)	19.8 (±0.3)	20.0 (±0.3)	20.3 (±0.2)	16.7^{ns} (±0.2)	17.1 (±0.2)	16.4 (±0.4)	16.2 (±0.3)	15.9 (±0.4)	21.4^{ns} (±0.2)	21.3 (±0.1)	21.2 (±0.2)	21.1 (±0.2)	21.5 (±0.2)	17.4^{ns} (±0.3)	17.2 (±0.2)	17.2 (±0.4)	17.2 (±0.5)	17.4 (±0.3)
RS	0.41^{ns} (±0.01)	0.40 (±0.01)	0.43 (±0.01)	0.45 (±0.01)	0.43 (±0.01)	0.48^{ns} (±0.01)	0.47 (±0.01)	0.49 (±0.02)	0.54 (±0.03)	0.49 (±0.01)	0.46^{ns} (±0.01)	0.47 (±0.01)	0.46 (±0.01)	0.46 (±0.00)	0.49 (±0.00)	0.48^{ns} (±0.01)	0.48 (±0.01)	0.46 (±0.01)	0.48 (±0.02)	0.49 (±0.01)
Fiber	13.9^{ns} (±0.3)	14.0 (±0.2)	14.4 (±0.3)	13.9 (±0.2)	13.8 (±0.1)	13.1^{ns} (±0.1)	13.4 (±0.1)	12.9 (±0.2)	13.2 (±0.2)	13.2 (±0.2)	16.4^{ns} (±0.1)	15.9 (±0.2)	16.5 (±0.3)	16.1 (±0.2)	15.6 (±0.1)	19.0^{ns} (±0.4)	18.6 (±0.7)	19.2 (±0.7)	19.1 (±0.3)	18.7 (±0.6)
Purity	91.3^{ns} (±0.2)	91.1 (±0.2)	90.5 (±0.5)	90.6 (±0.5)	90.9 (±0.3)	89.2^{ns} (±0.1)	89.4 (±0.4)	89.0 (±0.4)	87.4 (±0.8)	88.5 (±0.5)	89.3^{ns} (±0.4)	88.9 (±0.3)	88.9 (±0.2)	89.1 (±0.2)	88.3 (±0.2)	87.4^{ns} (±0.3)	87.7 (±0.6)	88.0 (±0.8)	87.2 (±0.7)	87.3 (±0.4)

Brix: soluble solids content; Pol: apparent sucrose content; RS: reducing sugars; Fiber: fiber content; Purity: apparent juice purity; ns: within the same season, means are not significant by Tukey's test ($p < 0.05$); the standard error associated to each mean (n = 4) is presented between brackets

Sugarcane ripening (*i.e.*, sucrose accumulation on the stalks) is a natural process that can be affected by solar radiation, photoperiod, nitrogen content, and adverse environmental conditions such as reduction of temperature (van Heerden et al., 2013; Cardoso and Sentelhas, 2013) and soil water availability. However, in tropical conditions, decreasing air temperature and reduced soil water content are the most important drivers of the ripening process in sugarcane crop (Cardoso and Sentelhas, 2013). In our study, contrasting treatments such as no removal or total straw removal did not induced any significantly industrial quality changes in the sugarcane (Table 4). These results were contrary to our expectation. Considering that straw maintenance on the soil surface increases water content (Ball-Coelho et al., 1993; Tavares et al., 2010; Nxumalo et al., 2017), we expected that higher water content under management without straw removal would favor plant growth, which in turn could reduce Brix and Pol in the juice and consequently, increase the percentage of reducing sugar. However, that was not observed (Table 4). Higher soil nitrogen immobilization during straw decomposition (Sousa Jr. et al., 2017) and consequent lower soil nitrogen availability under no removal straw management probably was the most limiting factor for plant growth and, consequently, affects the indicators of industrial quality of sugarcane. Indeed, according to Rhein et al. (2016), nitrogen levels from 0 to 150 kg ha^{-1} (applied through drip irrigation using urea) enhanced industrial quality of sugarcane.

Although straw removal management did not affect the parameters of industrial quality of sugarcane, most of those parameters are reduced when harvesting was performed at the wet season (Table 2S). The stalks harvested in the wet season were experienced greater precipitation events at the ending of cycle (Fig. 3). Increased precipitation probably increased stalk hydration and reduces sucrose concentration, which lead to decreased Brix and Pol contents (Table 2S).

The increase in water availability and temperature when wet-season treatments were harvested (Fig. 2) may have stimulated new plant tissue formation (*i.e.*, sprouting) after a period of reduced growth. New tissue formation in sugarcane plants demands greater reducing sugar content to meet higher respiration demands. In our experiment, the percentage of reducing sugars increased in stalks from wet-season treatments in the first ratoon at Univalem and in the second ratoons at Bom Retiro mill (Table 2S). Regarding the lower juice purity observed at the wet season treatments, it might be associated with the presence and harvesting of tillers along with mature stalks at the end of cycle. Furthermore, high precipitation prior to harvesting (Fig. 2) leads to an increase in soil moisture which can increase plant lodging. Lodged plants are more difficult to harvest and leads to an increase in soil contamination of stalks taken to the mill.

3.4 Conclusions

Straw removal enhances plant tillering and phytomass accumulation in the early sugarcane growth phase, especially in colder regions. These effects are not observed after one year and have no effect on the final plant population and phytomass yield. Our findings suggest that 4 to 9 Mg ha^{-1} of straw (dry base) left on soil surface is needed to sustain stalk yield. The amount of straw retained varies according to the soil and climate conditions and sugarcane-harvesting season. The straw management did not affect the sugarcane phytomass yield losses verified from the first to second ratoon.

Sugarcane harvested in the wet season (October, November, December, January and February) decreases the suitable period (*i.e.*, higher temperature and rainy availability) for plant growth in the follow ratoon, which in turn decreases total phytomass yield. Furthermore, stalks harvested during wet season present lower industrial quality compared to those harvested in the dry season (April, May, June, July, August and September).

Over this two-year study, we concluded that even extreme straw management, such as no-removal or total straw removal (*i.e.*, bare soil) only slightly affected overall plant responses. Based on that, we suggest that partial straw removal, at least in the short-term, could be a win-win situation, sustaining sugarcane yields and providing feedstock for bioelectricity cogeneration and 2G ethanol production. However, further studies are necessary to understand potential effects of moderate amount of straw removal in protecting the soil against erosion process and soil carbon loss.

REFERENCES

Awe, G.O., Reichert, J.M., Wendroth, O.O., 2015. Temporal variability and covariance structures of soil temperature in a sugarcane field under different management practices in southern Brazil. Soil and Tillage Res. 150, 93-106.

Ball-Coelho, B., Tiessen, H., Stewart, J.W.B., Salcedo, I.H., Sampaio, E.V.S.B., 1993. Residue management effects on sugarcane yield and soil properties in Northeastern Brazil. Agron J. 85, 1004-1008.

Campos, L.H.F., Carvalho, S.J.P., Christoffoleti, P.J., Fortes, C., Silva, J.S., 2008. Crescimento e produtividade da cana-de-açúcar (Var. SP83-2847) submetida a três manejos da palhada. STAB. 26, 33-36.

Campos, L.H.F.D., Carvalho, S.J.P.D., Christoffoleti, P.J., Fortes, C., Silva, J.S.D., 2010. Straw management systems influence biomass accumulation and yield of sugarcane crop (var. RB855453). Acta Sci., Agron. 32, 345-350.

Cantarella, H., Cerri, C.E.P., Carvalho, J.L.N., Magalhães, P.S.G., 2013. How much sugarcane trash should be left on the soil? Sci. Agric. 70, 1-2.

Cardozo, N.P., Sentelhas, P.C., 2013. Climatic effects on sugarcane ripening under the influence of cultivars and crop age. Sci. Agric. 70, 449-456.

Carvalho, D.J., Veiga, J.P.S., Bizzo, W.A., 2017. Analysis of energy consumption in three systems for collecting sugarcane straw for use in power generation. Energy. 119, 178-187.

Carvalho, J.L.N., Nogueirol, R.C., Menandro, L.M.S., Bordonal, R.D.O., Borges, C.D., Cantarella, H., Franco, H.C.J., 2016. Agronomic and environmental implications of sugarcane straw removal: a major review. Glob Change Biol Bioenergy. 9, 1181-1195.

Cerri, C.C., Galdos, M.V., Maia, S.M.F., Bernoux, M., Feigl, B.J., Powlson, D., Cerri, C.E.P., 2011. Effect of sugarcane harvesting systems on soil carbon stocks in Brazil: an examination of existing data. Eur. J. of Soil Sci. 62, 23-28.

Cheong, L.N., Teeluck, M., 2016. The practice of green cane trash blanketing in the irrigated zone of Mauritius: effects on soil moisture and water use efficiency of sugarcane. Sugar Tech. 18, 124-133.

Cherubin, M.R, Oliveira, D.M.S., Feigl, B.J., Pimentel, L.G., Lisboa, I.P., Gmach, M.R., Varanda, L.L., Moraes, M.C., Satiro, L.S., Popin, G.V., de Paiva, S.R., dos Santos, A.K.B., de Vasconcelos, A.L.S., de Melo, P.L.A., Cerri, C.E.P., Cerri, C.C., 2018. Crop residue harvest for bioenergy production and its implications on soil functioning and plant growth. Sci. Agric. 75, 255-272.

Cherubin, M.R., Karlen, D.L., Franco, A.L., Tormena, C.A., Cerri, C.E., Davies, C.A., Cerri, C.C., 2016. Soil physical quality response to sugarcane expansion in Brazil. Geoderma. 267, 156-168.

Companhia Nacional de Abastecimento e Conab, Acompanhamento da safra brasileira de cana-de-açúcar. v. 4, Safra 2017/18, n. 1, Primeiro Levantamento, Brasília, 2017. Retrieved May 20, 2017 from, http://www.conab.gov.br/OlalaCMS/uploads/arquivos/17_04_19_11_27_36_boletim_cana_portugues_-_4o_lev_-_16-17.pdf

CONSECANA - Conselho dos Produtores de Cana-de-Açúcar, Açúcar e Álcool do Estado de São Paulo, 2006. Manual de Instruções. 5º ed. Piracicaba-SP, Consecana-SP. 112p.

de A. Sousa José G., Cherubin Maurício R., Cerri Carlos E. P., Cerri Carlos C., Feigl Brigitte J., 2017. Sugar cane straw left in the field during harvest: decomposition dynamics and composition changes. Soil Research

de Aquino, G.S., de Conti Medina, C., da Costa, D.C., Shahab, M., Santiago, A.D., 2017. Sugarcane straw management and its impact on production and development of ratoons. Ind Crops and Prod. 102, 58-64.

de Aquino, G.S., de Conti Medina, C., Junior, A.D.O.M., Pasini, A., Brito, O.R., Cunha, A.C.B., dos Santos Junior, J.H., Kussaba, D.A.O., Almeida, L.F., 2016. Impact of harvesting with burning and management of straw on the industrial quality and productivity of sugarcane. Afri. J. of Agric. Res. 11, 2462-2468.

de Oliveira, M.A., Zucareli, C., Neves, C.S.V.J., Domingues, A.R., de Conti Medina, C., de Assis Moraes, L.A., 2016. Agronomic performance of sugarcane cultivated under quantities of sugarcane straw on the soil surface. Semin: Cien. Agrar. 37, 3983-3996.

Epstein E, Bloom A.J. 2006. Mineral Nutrition of Plants: Principles and Perspectives, 2nd edn. Planta, Londrina, BR, pp. 251–286.

Ferreira, D.A., Franco, H.C., Otto, R., Vitti, A.C., Fortes, C., Faroni, C.E., Garside, A.L., Trivelin, P.C., 2015. Contribution of N from green harvest residues for sugarcane nutrition in Brazil. GBC Bioenergy. 8, 859-866.

Fortes, C., Vitti, A.C., Otto, R., Ferreira, D.A., Franco, H.C.J., Trivelin, P.C.O., 2013. Contribution of nitrogen from sugarcane harvest residues and urea for crop nutrition. Sci. Agric. 70, 313-320.

Galdos, M.V., Cantarella, H., Hastings, A., Hillier, J., Smith, P., 2017. Environmental Sustainability Aspects of Second Generation Ethanol Production from Sugarcane. In: Buckeridge, M.S., de Souza, A.P (Eds.), Advances of Basic Science for Second Generation Bioethanol from Sugarcane . Springer Nature, Cham, CH, pp. 177-195 (Chapter 10).

Inman-Bamber, G., 2013. Sugarcane Yields and Yield-Limiting Processes. In: Moore, P.H., Botha, F.C. (Eds.), Sugarcane: Physiology, Biochemistry, and Functional Biology. Wiley-Blackwell, Oxford, UK, pp. 579-600 (Chapter 21).

Junior, F.P.P., Portilho, I.I.R., Mercante, F.M., 2015. Microbiological attributes of the soil under cultivation of sugar cane with and without burning straw. Semin: Ciên. Agrar. 36, 151-164.

Khatiwada, D., Leduc, S., Silveira, S., McCallum, I., 2016. Optimizing ethanol and bioelectricity production in sugarcane biorefineries in Brazil. Renew. Energy. 85, 371-386.

Landell, M.G.D.A., Scarpari, M.S., Xavier, M.A., Anjos, I.A.D., Baptista, A.S., Aguiar, C.L.D., Silva, D.N.D., Bidóia, M.A.P., Brancalião, S.R., Bressiani, J.A., Campos, M.F.D., 2013. Residual biomass potential of commercial and pre-commercial sugarcane cultivars. Sci. Agric. 70, 299-304.

Leite, J.M, Ciampitti, I.A, Mariano, E., Vieira-Megda, M.X, Trivelin P.C.O, 2016. Nutrient Partitioning and Stoichiometry in Unburnt Sugarcane Ratoon at Varying Yield Levels. Front. Plant Sci. 466, 1-14.

Lisboa, I.P., Cherubin, M.R., Cerri, C.C., Cerri, D.G., Cerri, C.E., 2017. Guidelines for the recovery of sugarcane straw from the field during harvesting. Biomass and Bioenergy. 96, 69-74.

Malavolta, E., Vitti, G.C. de Oliveira, S.A.,1997. Avaliação do estado nutricional das plantas: princípios e aplicações. Potafos Piracicaba.

Mariano, E., Leite, J.M., Vieira-Megda, M.X., Ciampitti, I.A., Vitti, A.C., Faroni, C.E., Franco, H.C., Trivelin, P.C., 2016. Biomass and nutrient content by sugarcane as affected by fertilizer nitrogen sources. Crop Sci. 56, 1234-1244.

Marin, F.R., Thorburn, P.J., da Costa, L.G., Otto, R., 2014. Simulating long-term effects of trash management on sugarcane yield for Brazilian cropping systems. Sugar Tech. 16, 164-173.

Menandro, L.M.S., Cantarella, H., Franco, H.C.J., Kölln, O.T., Pimenta, M.T.B., Sanches, G.M., Rabelo, S.C., Carvalho, J.L.N., 2017. Comprehensive assessment of sugarcane straw: implications for biomass and bioenergy production. Biofuels, Bioprod. Biorefing. 11, 488-504.

Nxumalo, N., Ramburan, S., Steyn, J.M., 2017. Growth and yield responses of commercial sugarcane cultivars to mulching in the coastal rainfed region of South Africa. S Afr J Plant & Soil. 34, 9-18.

Paredes Junior, F.P., Portilho, I.I.R., Mercante, F.M., 2015. Atributos microbiológicos de um latossolo sob cultivo de cana-de- açúcar com e sem queima da palhada. Semina: Ciências Agrárias 36, 151–164.

R Core Team. R: A language and environment for statistical computing [internet]. Vienna, Austria: R Foundation for Statistical Computing; 2016 [accessed on: 07 Dec. 2016]. Available at: http://www.R-project.org/.

Rhein, A.F., Pincelli, R.P., Arantes, M.T., Dellabiglia, W.J., Kölln, O.T. and Silva, M.D.A., 2016. Technological quality and yield of sugarcane grown under nitrogen doses via subsurface drip fertigation. Rev. bras. eng. agríc. ambient. 20, 209-214.

Santos, F.A., Queiróz, J.D., Colodette, J.L., Fernandes, S.A., Guimarães, V.M., Rezende, S.T., 2012. Potencial da palha de cana-de-açúcar para produção de etanol. Quim Nova. 35, 1004-1010.

Seebaluck, V., Leal, M.R.L.V., 2015. Feedstock supply chains. In: Souza, M., G.M, Victoria, R.L., Joly, C.A., Verdade, L.M. Bioenergy & Sustainability: Bridging the Gaps. Scientific Committee on Problems of the Environment, Sao Paulo, SP. 348-372 (Chapter 11).

Systat Software. 2008. SigmaPlot version 11.0. Systat Software, San Jose, CA.

Sousa Jr., J.G.A., Cherubin Maurício, R., Cerri Carlos, E.P., Cerri Carlos, C., Feigl Brigitte, J., 2017. Sugar cane straw left in the field during harvest: decomposition dynamics and composition changes. 11:249. Soil Res.

Tavares, O.C.H., Lima, E., Zonta, E., 2010. Crescimento e produtividade da cana planta cultivada em diferentes sistemas de preparo do solo e de colheita. Acta Sci. Agron. 32, 61-68.

Trivelin, P.C.O., Franco, H.C.J., Otto, R., Ferreira, D.A., Vitti, A.C., Fortes, C., Faroni, C.E., Oliveira, E.C., Cantarella, H., 2013. Impact of sugarcane trash on fertilizer requirements for São Paulo, Brazil. Sci. Agric. 70, 345-352.

Valim, W.C., Panachuki, E., Pavei, D.S., Sobrinho, T.A., Almeida, W.S., 2016. Effect of sugarcane waste in the control of interrill erosion. Semin: Cien Agrar. 37, 1155-1164.

van Heerden, P.D., Eggleston, G., Donaldson, R.A., 2013. Ripening and postharvest deterioration. In: Moore, P.H., Botha, F.C. (Eds.), Sugarcane: Physiology, Biochemistry, and Functional Biology. Wiley-Blackwell, Oxford, UK, pp. 55-84 (Chapter 4).

Supplementary materials

Table 1S. Time required for phytomass accumulation in all trials across each ratoon cycle in both mills

First year						Second year					
Dry season			Wet season			Dry season			Wet season		
Bom Retiro mill											
Phases	Period (days)	Dry mass yield (%)	Phases	Period (days)	Dry mass yield (%)	Phases	Period (days)	Dry mass yield (%)	Phases	Period (days)	Dry mass yield (%)
Lag	0-144	19	Lag	0-92	16	Lag	0-125	18	Lag	17	0-79
Linear growth	144-273	64	Linear growth	92-174	64	Linear growth	125-240	62	Linear growth	63	79-167
Stationary	273-360	17	Stationary	174-390	20	Stationary	240-360	20	Stationary	19	167-360
Univalem mill											
Lag	0-114	14	Lag	0-90	17	Lag	0-111	12	Lag	21	0-98
Linear growth	114-227	71	Linear growth	90 -192	62	Linear growth	111-167	74	Linear growth	53	98-332
Stationary	227-360	15	Stationary	192- 410	21	Stationary	167-360	14	Stationary	26	232-360

Table 2S. Industrial quality of sugarcane stalk harvested from experiments installed in dry and wet season at the Bom Retiro e Univalem mill and conducted over two years

	First year				Second year			
	Straw management							
Parameter	Bare soil		Covered soil		Bare soil		Covered soil	
(%)	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season
	Bom Retiro mill							
Brix	18.4^{ns}	18.4	18.0^{ns}	17.6	19.5a**	16.1b	19.0a*	15.7b
Pol	16.0^{ns}	16.3	15.8^{ns}	15.5	17.2a**	13.4b	16.4a*	12.9b
RS	0.65^{ns}	0.60	0.64^{ns}	0.63	0.61b**	0.79a	0.68b**	0.80a
Fiber	12.1^{ns}	12.4	12.4^{ns}	12.7	14.5^{ns}	13.8	14.3 ^{ns}	13.4
Purity	87.2 ^{ns}	88.6	87.4^{ns}	87.7	88.3a**	83.3b	86.3a*	82.7b
	Univalem mill							
Brix	18.2^{ns}	18.7	18.3^{ns}	18.0	18.8 a**	14.9b	19.2 a**	15.0b
Pol	20.3a**	16.7b	20.3a**	16.0b	21.4 a**	17.4b	21.4 a**	17.4b
AR	0.41b*	0.48a	0.43b**	0.49a	0.45^{ns}	0.48	0.48 ^{ns}	0.48
Fiber	13.9^{ns}	13.1	13.8^{ns}	13.2	16.4b*	19.0a	15.6b*	18.7a
Purity	91.3a	89.2b	90.9 ^{ns}	88.5	89.3 ^{ns}	87.4	88.3 ^{ns}	87.3

Brix: soluble solids content; Pol: apparent sucrose content; RS: reducing sugars; Fiber: fiber content; Purity: apparent juice purity; Means values followed by the same letter within the same straw management system do not differ between themselves according to Tukey's test ($p < 0.01$)** and ($p < 0.05$)*; ns: non-significant

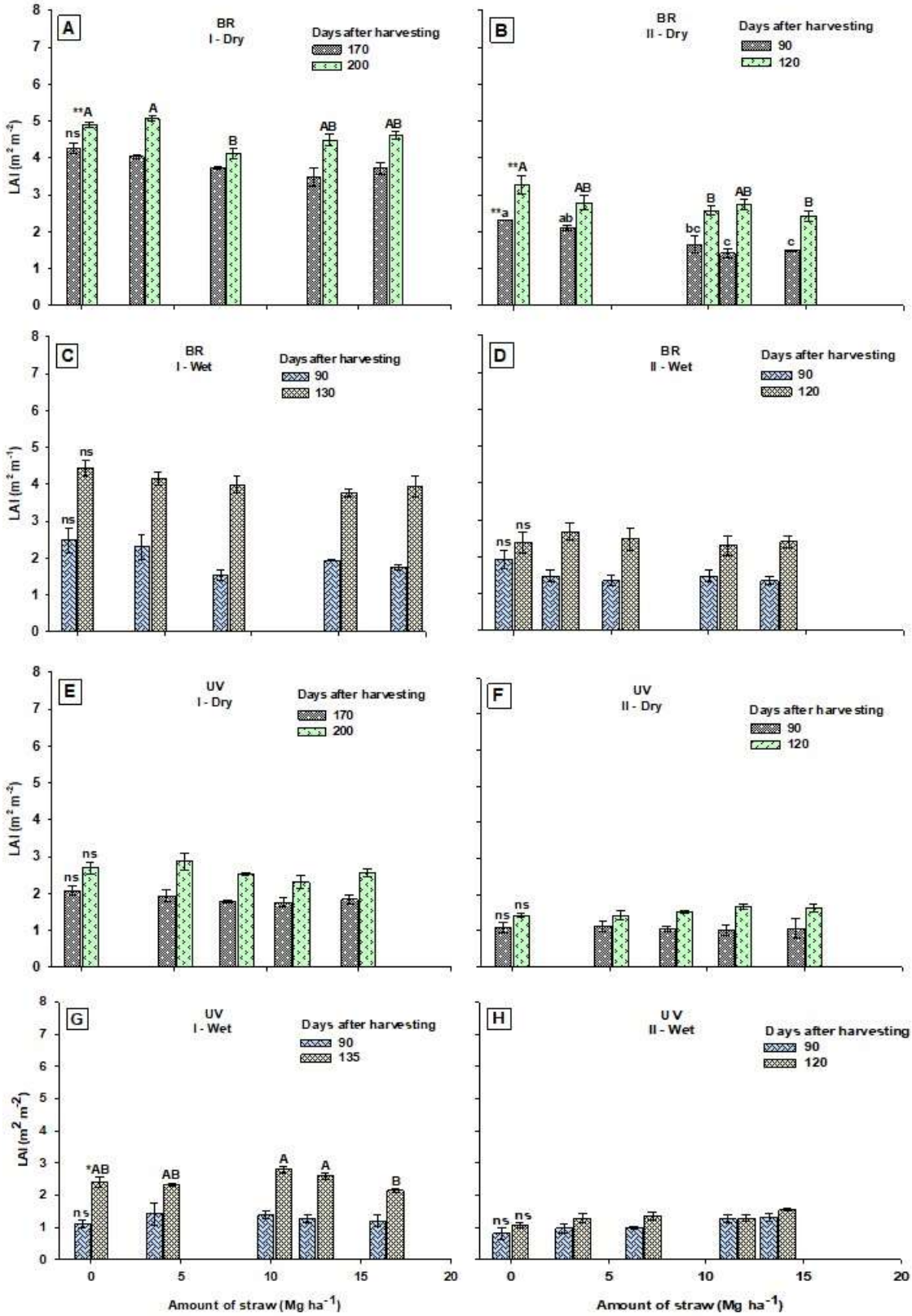

Fig. 1S. Leaf area index (LAI) of sugarcane cultivated under increasing amount of straw on soil surface in experiments installed in dry and wet season at Bom Retiro - BR (A to D) and Univalem - UV (E to H) mill and conducted over two ratoons (I and II). ** and * denotes that means differ significantly by Tukey's test ($p < 0.01$) and ($p < 0.05$), respectively; ns: non-significant; error bars denote standard error of the mean

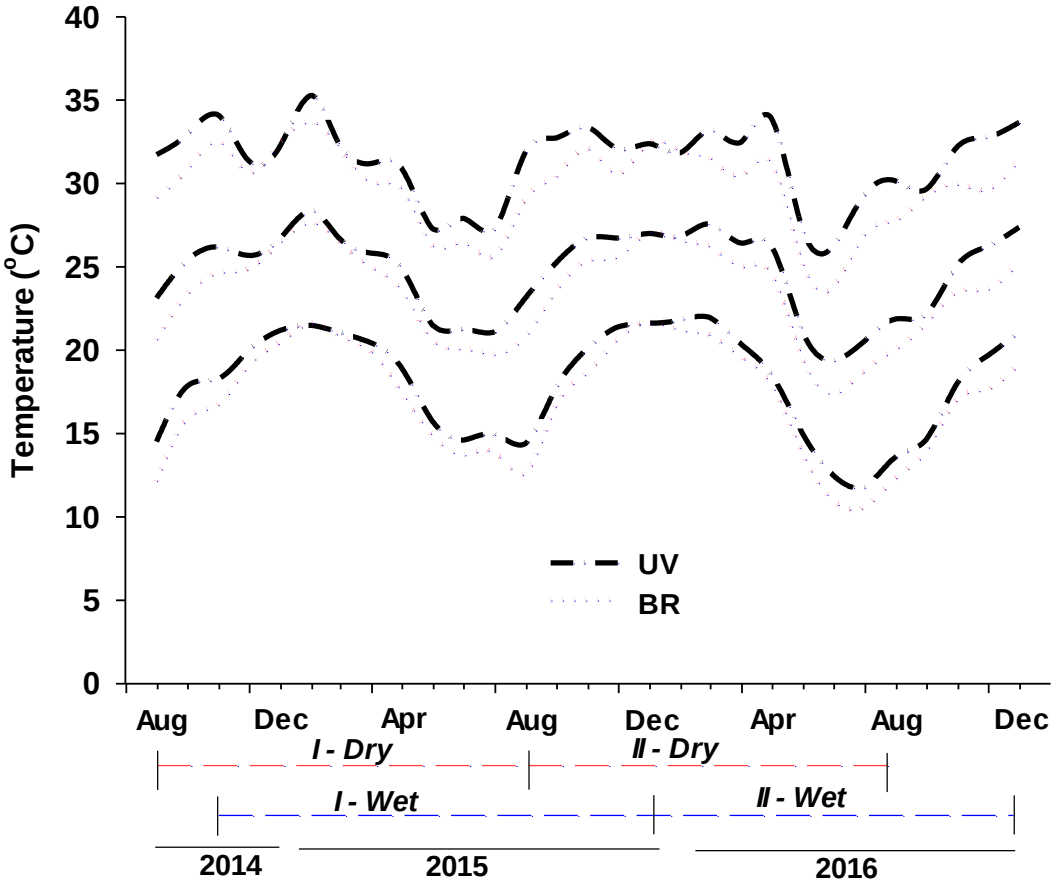

Fig. 2S. Comparison of mean monthly temperature (maximum, mean and minimum) in the two region studied, where: BR - Bom Retiro site (Capivari, SP) and UV Univalem site (Valparaiso, SP); Red and blue dashed lines indicate the conduction period of the experiments installed in dry and wet seasons, respectively. Sources: CEPAGRI (http://www.cpa.unicamp.br) and ESALQ (http://www.leb.esalq.usp.br/posto/).

4. SUGARCANE STRAW MANAGEMENT EFFECTS PLANT GROWTH, BUT NOT STALK YIELD IN SOUTHEASTERN BRAZIL

Abstract

Adoption of unburned sugarcane (*Saccharum* spp.) harvesting systems in Brazil has required development of practices to handle large amounts of straw left on the soil surface each year. The practices must balance multiple needs including: maintaining some sugarcane straw for enhancing soil quality and providing some as feedstock for bioenergy production. Producer concerns regarding negative effects of the straw on crop establishment and stalk yield have led to raking operations to remove the straw from above rows to inter-rows positions. Effectiveness of these operations, which require time and increase equipment cost, remains unclear. A two-year experiment, encompassing both the dry and wet seasons, was conducted at a cool and warm site in southeastern Brazil to evaluate straw management strategies on plant tillering, phytomass accumulation, plant nutritional status and stalk yield. Three treatments: raking straw to inter-rows (rake), bare soil (bare soil), and no straw removal (straw cover) were evaluated. Rake and bare soil treatments improved plant tillering but did not influence final plant population at either site. Straw management had a slight effect on plant growth (*i.e.*, phytomass accumulation) which was described for each ratoon cycle by a sigmoidal model ($r^2 \geq 0.92$, $p < 0.05$). Both leaving and raking the straw increased plant P (Phosphorus) content but not stalk yield. We conclude that raking the straw to inter-rows positions increases time, machinery cost, and may result in compaction without providing agronomic benefits to sugarcane cultivation in southeastern Brazil.

Keywords: Sugarcane; Biomass production; Mulching; Sugarcane harvest residue

4.1 Introduction

Traditionally, sugarcane in Brazil was harvested manually after leaf material was burned, but respiratory diseases caused by air pollution (Cançado et al., 2006; Paraiso and Gouveia, 2015; Le Blond et al., 2017), environmental issues associated with greenhouse gas emissions (Capaz et al., 2013; Galdos et al., 2013) and poor working conditions raised strong social concerns regarding those practices. Therefore, since the early 2000s, sugarcane harvesting has phased out burning and adopted mechanization (*i.e.*, green sugarcane harvesting), which improves sustainability of the entire system (Pongpat et al., 2017; Bordonal et al., 2018). However, the transition has required many crop cultivation changes (Walter et al., 2014; Carvalho et al., 2017) to manage 10 to 20 Mg ha^{-1} of sugarcane residue [*i.e.*, straw consisting of shredded leaves (dry and green) plus small pieces of stalk] left annually in the field (Hassuani et al., 2005).

Without burning before harvest, a large amount of straw is available for bioenergy production (Correa et al., 2017; Guerra et al., 2018). This can help meet the predicted ethanol demand of 200 billion L by 2021 (Goldemberg et al., 2014), since the current ethanol production of 98.6 billion L (REN21, 2017) needs to more than double for the next four years. Using

sugarcane straw as a feedstock for bioethanol (*i.e.*, second-generation ethanol) production can thus help meet the nation's biofuel requirements (Dodo and Mamphweli, 2017; Lisboa et al., 2017). However, leaving some sugarcane straw in the field is important because it is essential for maintaining many soil functions and therefore, improving soil quality (Carvalho et al., 2017: Cherubin et al., 2018).

Leaving a "straw blanket" on the soil surface creates a micro-environment that affects heat, water and gas exchange between the soil and atmosphere (Cherubin et al., 2018). The blanket also affects many other ecosystem services including: (1) a reduction in evaporative water loss and thus an increase in soil moisture (Anjos et al., 2017); (2) creation of a beneficial environment for plants and soil biota (Carvalho et al., 2017; Cherubin et al., 2018), which unfortunately includes some important sugarcane pests (Dinardo-Miranda and Fracasso, 2013); (3) a reduction in light intensity at the plant base which delays sprouting of basal vegetative buds (Toppa et al., 2010); (4) a reduction in soil temperature (Correa et al., 2017), which can slow crop growth and development, especially in cooler portions of Brazil's sugarcane-producing region (Oliveira et al., 2001; Campos et al., 2008; Campos et al., 2010; Landell et al., 2013). Collectively these straw blanket effects may negatively affect stalk density and therefore sugarcane yield (Oliveira et al., 2001; Campos et al., 2010).

However, the reported straw blanket effects on plant growth and stalk yield are variable. Some studies have shown reduction in soil temperature (Sandhu et al., 2013), increased soil moisture during the winter and early spring months, and thus limited plant growth (Viator et al., 2005; Kingston et al., 2005) and reduced stalk yield (Kingston et al., 2005; Viator et al., 2005; Viator and Wang, 2011). In contrast, Sandhu et al. (2017) reported that although the straw blanket negatively affected plant tillering and leaf area index (LAI) from 120 to 200 days, final stalk yield and sucrose concentrations were not influenced under subtropical conditions.

To overcome producer perceptions of potential undesirable effects of the straw blanket on sugarcane ratoons, most mills and farmers in southeastern Brazil have begun to move the straw blanket from plant row to inter-row positions using a tractor-mounted rake (Campos et al., 2008; Campos et al., 2010). Raking, however, requires an additional machinery operation within each ratoon cycle. This can intensify soil compaction, which is already a critical problem in many Brazilian sugarcane fields (Souza et al., 2014; Cherubin et al., 2016; Bordonal et al., 2018). Despite the fact of raking be widely adopted within southeastern Brazil, the agronomic benefits of this management remain unclear (Carvalho et al., 2017). Indeed, in a study conducted recently within the central-southern (*i.e.*, the main sugarcane-producer area), Lisboa et al. (2018) reported that even extremes straw-blanket managements, such as total or no straw removal, slightly affected

plant growth across the ratoons cycles, thus there still uncertainties about the agronomic benefits of raking management for the crop.

Our hypothesis was that sugarcane is a resilient crop able to recover from potential negative effects caused by the straw blanket during the initial growth phases, without significant yield losses. Therefore, raking would be unnecessary to sustain crop yields for green harvested sugarcane fields in southeastern Brazil. The two-year experiment (conducted at two sites and during two harvesting seasons) within Brazil's primary sugarcane-producing region quantified effects on plant tillering, growth, plant nutrient status, and stalk yield.

4.2 Materials and Methods

4.2.1 Study sites and climatic conditions

Field experiments were conducted at two sites that represent typical sugarcane producing-areas within southeastern Brazil and account for more than 65% of the total production (Conab, 2018). The study sites and the climatic conditions at each place were presented in the item 2.2.1.

Within each study site, experiments were set up during the dry and wet seasons for two years. Sugarcane was planted in February 2013 and the treatments were applied following the first cane harvest. Specific dates of experimental set up and harvest are presented in Table 1.

Table 1. Dates of experiments set up and harvesting over two ratoons in both sites (month, year)

Activity	Dry season I	Wet season I	Dry season II	Wet season II
Set up	August 2014	October 2014	August 2015	December 2015
Harvesting	August 2015	December 2015	August 2016	December 2016

I and II denote the first and second sugarcane ratoon, respectively

Sugarcane varieties CTC 14 and RB 867515 were cultivated in Bom Retiro and Univalem, respectively. At both sites, sugarcane was planted using an alternating double row spacing of 1.5 and 0.9 m. Agricultural inputs (*i.e.*, lime, gypsum and fertilizer) for the first and second ratoons were applied according to Raij et al. (1997).

4.2.2 Experimental design

The experimental design was a three treatment (bare soil, straw cover and rake), randomized block, with four replications (plots size ~50 m x 25 m). The experiment was conducted over two ratoons (*i.e.* first and second) and two seasons (dry and wet). In general, annual sugarcane harvesting season extends from April to December in southeastern Brazil. During this period, harvesting is carried out under three seasons (*i.e.*, fall, winter and spring), with different weather conditions. Thus, the straw blanket may influence sugarcane tiller emergence and growth differently based on weather conditions. For this study, straw management treatments were set up in winter and spring as those seasons are usually characterized by dry and wet climates, respectively, within this region.

The rake treatment was imposed shortly after sugarcane harvest by moving the straw to the inter-rows using a tractor mounted rake (DMB Máquinas e Implementos Agrícolas LTDA, Sertãozinho, SP) (Fig. 1).

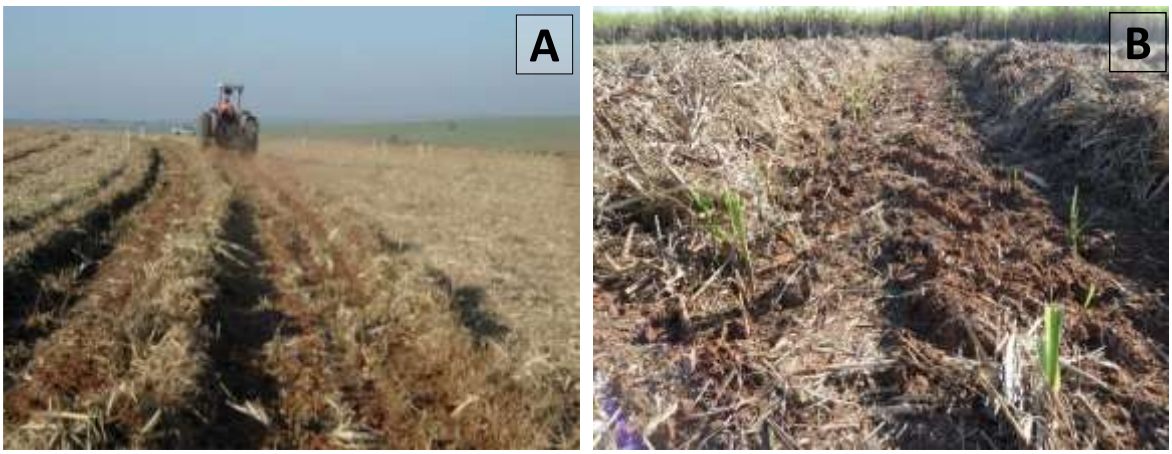

Fig. 1. Sugarcane straw being moved to inter-row positions after harvesting (A); straw piled in the inter-rows, showing crop tillers sprouting after raking (B).

To remove all straw from the soil surface for the bare treatment, the sugarcane harvester was set up with both extractors (*i.e.*, primary and secondary) fans turned off so that the straw was collected with chopped stalks in the wagons. Details regarding harvester set up and efficiency of mechanical straw removal procedures are described in Lisboa et al. (2017). Fallen leaves (*i.e.*, senesced leaves) associated with each ratoon cycle were not removed, since they were not deposited by the harvester. Sugarcane straw retention amounts, by treatment and year, are presented in Table 2.

Table 2. Sugarcane straw retained on the soil surface by management practice.

Sugarcane straw management	Bom Retiro mill				Univalem mill			
	Dry season		Wet season		Dry season		Wet season	
	Year I	Year II	Year I	Year II	Year I	Year II	Year I	Year II
	Straw retained on the soil surface (Mg ha^{-1})*							
Bare soil#	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Straw cover	16.6	14.7	18.9	13.6	15.0	12.4	16.4	13.7
Rake	15.6	17.2	23.3	14.3	13.8	12.1	13.2	13.3

*dry mass; #plus senesced leaves

Soil samples (one per plot) for the 0–10, 10–20, and 20–30 cm depth were collected and characterized for soil texture and chemical attributes (Table 3) at the beginning of each experiment. Total organic carbon (C) and total nitrogen (N) contents were determined by dry combustion using an elemental analyzer (furnace at 1350°C in pure oxygen) (Leco© CN-2000, St. Joseph, Michigan). Phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) concentrations were determined by the ion exchange resin method. While P was quantified colormetrically, Ca and Mg were quantified using atomic absorption spectrophotometry and K by flame atomic-emission spectroscopy (Raij et al., 2001).

Table 3. Soil characterization (0-30 cm) at Bom Retiro and Univalem.

Depth (cm)	pH_{water}	C	P	K	Ca	Mg	BS	AS	Clay	Silt	Sand
	unitless	g kg^{-1}	mg dm^{-3}	mmol$_c$ dm^{-3}			%		g kg^{-1}		
				Bom Retiro							
0-10	5.2	11.3	29.3	9.35	26.1	7.7	68.8	0.8	330	60	610
10-20	4.8	11.0	24.9	5.1	19.0	5.9	54.7	3.5	330	70	600
20-30	4.5	9.4	22.1	3.3	12.5	2.95	36.8	4.2	335	65	600
				Univalem							
0-10	5.2	6.1	17.4	3.3	9.3	2.9	51.1	2.4	112	23	865
10-20	4.8	5.5	14.1	2.6	4.8	1.5	34.8	5.6	113	22	865
20-30	4.5	4.9	12.7	2.1	3.6	1.0	27.5	7.4	120	20	860

BS: Base saturation; AS: aluminum saturation. Adapted from Satiro et al. (2017).

Soon after the treatments were installed, a composite sample of sugarcane straw (one per plot) was collected and analyzed to determine C and macronutrient concentrations. Material and method adopted to analyze C and macronutrients contents within straw tissue were presented on Table 2, item 3.2.1.

4.2.3 Straw blanket management effects on sugarcane growth and yield

Plant growth responses to straw management were evaluated using the following parameters: tillering, phytomass accumulation, and leaf area index (LAI). Tillering was determined by counting the number of new shoots within a 20 m segment of each plot. Each evaluation was made at the same place throughout both ratoon cycles. Dry-season tiller counts at both sites were made 60, 90, 120 and 210 days after harvesting (DAH) during the first year. Wet-season counts were made 60, 90 and 135 DAH. In the second year, dry-season tiller counts were made at 30, 60, 90, 120 and 360 DAH, while wet-season tcounts were at 30, 60, 90, 120, 180 and 360 DAH.

Phytomass accumulation throughout each ratoon cycle was determined using destructive sampling of all aboveground biomass within a 4-m crop row segment. Biomass yield evaluations prior to the fifth month of each ratoon were determined by weighing all of the fresh-phytomass on an electronic scale (maximum capacity 40 kg). It was then ground using a forage grinder, and a representative subsample was collected for analysis. After the fifth month of each ratoon cycle, the plant phytomass was separated into three components: dry leaves, green leaves and stalks. Fresh weight for each component was determined before grinding, subsampling, and determining dry weight by oven-drying at 65° C until the mass was constant. Total phytomass yield per hectare (Mg ha^{-1}) was calculated using a 1.2-m row-spacing with 8333 m of row per hectare.

During the first year at Bom Retiro, biomass evaluations were made at 120, 210, 290 and 360 DAH in the dry-season and at 90, 135, 230 and 370 DAH during the wet-season, while at Univalem, measurements were made at 120, 210, 270 and 360 DAH during the dry season and at 90, 135, 230 and 410 DAH during the wet-season. In the second year, biomass evaluations were made at 180 and 360 DAH in the wet-season treatments and at 210 and 360 days in the dry-season treatments at both sites.

LAI was measured at 15 randomly chosen points within the eight central rows. Each reading was made 0.6 m from the ground surface using a LAI-2200 Plant Canopy Analyzer, (Li-Cor, Lincoln, NE). In the first year, LAI was measured at 170 and 210 DAH within the dry-season experiments, and at 90 and 135 DAH in the wet-season studies. In year two, LAI was measured at 90 and 120 DAH for both seasons and sites.

Tillering, biomass yield evaluations, and LAI readings were planned for the same date in each experiment, but due to different plant-growth conditions at the two sites, that was not feasible. More favorable conditions (*i.e.*, soil temperature and water availability) from the beginning of each ratoon cycle resulted in faster plant growth within the wet season experiments than in those installed during the dry season. Water availability and temperature conditions for

plant growth during each ratoon cycle occurred later in the dry season experiments than in the wet season studies. This in turn delayed tillering, phytomass accumulation, and thus biomass yield evaluations in those studies.

Stalk yield was quantified at the end of each annual growth cycle by mechanically harvesting the five central rows (500 m long) and collecting the material in a wagon equipped with a scale. After weighing, the fresh mass was extrapolated to Mg ha^{-1}.

4.2.4 Sugarcane nutrient status

During the second ratoon cycle (approximately four months after the first harvest), leaves from the third node, with a clearly visible dewlap, were collected to evaluate plant nutrient status, as recommended by Raij et al. (1997). Within each plot, 50 leaves were randomly collected, dried, ground, and analyzed to determine N, P, K, Ca, Mg and S concentrations in the plant tissue. Leaves were separated in three parts. The middle third (without the midrib) was oven-dried at 65° C before grinding for analysis. Also, during the second biomass yield evaluation whole plants were collected, separated into components (*i.e.*, dry leaves, green leaves and stalk), and prepared for N, P, K, Ca, Mg and S analysis. Each plant component was ground in a forage grinder, subsampled, and oven-dried at 65° C. Plant-tissue macronutrient concentrations were determined for both sampling periods according to Malavolta et al. (1997). For reporting, plant-tissue N, P and K concentrations from the first evaluation are referred to as N1, P1, K1 whereas those from the second evaluation are named N2, P2 and K2, respectively.

Sugarcane straw has a high C:N ratio (Table 2, item 3.2.1) and therefore microorganisms tend to immobilize nutrients during decomposition. This may or may not reduce short-term soil-nutrient availability, so based on this assumption, plant nutrient concentrations were measured only during the second growing season, after the straw blanket treatments had an opportunity to influence their availability.

4.2.5 Stalk industrial quality

Before mechanically harvesting each plot, ten plants were chosen randomly and harvested by hand. Several composition and quality parameters [i.e., fiber content (fiber), apparent sucrose in the juice (Pol), soluble solids content (Brix), apparent juice purity (purity), and reducing sugars (RS)] were analyzed using procedures from Consecana (2006).

Our primary goal was to determine effects of different straw blanket management treatments on plant tillering, phytomass accumulation, plant nutritional status and stalk yield, however to expand our database, sugarcane composition and quality were also evaluated.

4.2.6 Statistical analysis

The data were analyzed by: 1) modeling, 2) comparing means (presupposing significant effect from ANOVA), and 3) using multivariate analysis, as described below.

First, a non-linear regression model (Eq. 1) was fitted to plant-growth data (phytomass accumulation) as a function of days after harvesting (DAH). Individual curves were developed for each straw management treatment for each year. The significance of fitted parameters were based on an F-test ($p < 0.05$). The quality of the fitted model was evaluated based on the coefficient of determination (*i.e.*, R squared). All models were written and fitted using the *nls* (Nonlinear Least Square) function available within R Software (R Core Team, 2006).

$$Y = \frac{Y_{max}}{1+e^{-\frac{(DAH-A)}{B}}} \qquad \text{Eq. 1}$$

Where: Y is the phytomass yield (Mg ha^{-1}), Y_{max} is the maximum phytomass yield (Mg ha^{-1}) for each ratoon cycle, DAH is days after harvesting, and A and B are constants (*i.e.*, fitted parameters).

Second, a one-way ANOVA analysis was performed to test differences in response variables (e.g., plant tillering, LAI, and stalk yield) among treatments (bare soil, straw cover and rake). When significant (F-test $p<0.05$), the means were compared using Tukey's test ($p<0.05$). Comparisons of means were performed using the *agricolae* R package (Mendiburu and Simon, 2015) available within R Software (R Core Team, 2006).

Finally, canonical discriminant analysis (CDA) was performed to group total variability of the field experiments into a few variables (*i.e.*, canonical variables). Biplot graphs were created using the first two. Canonical variable means for each treatment were compared by 95% confidence ellipses. When confidence ellipses are overlapped, mean differences were considered non-significant. CDAs were performed using the *candisc* R package, available within R Software (R Core Team, 2006).

4.3 Results and discussion

4.3.1 Plant tillering response to straw management

Plant tillering for bare soil and rake treatments was similar across years, although generally raking enhanced the rate of tillering (Fig. 2). The exception was for the wet-season experiment conducted at Univalem, where tillering did not respond to straw management for either ratoon cycle (Fig. 2 G and H).

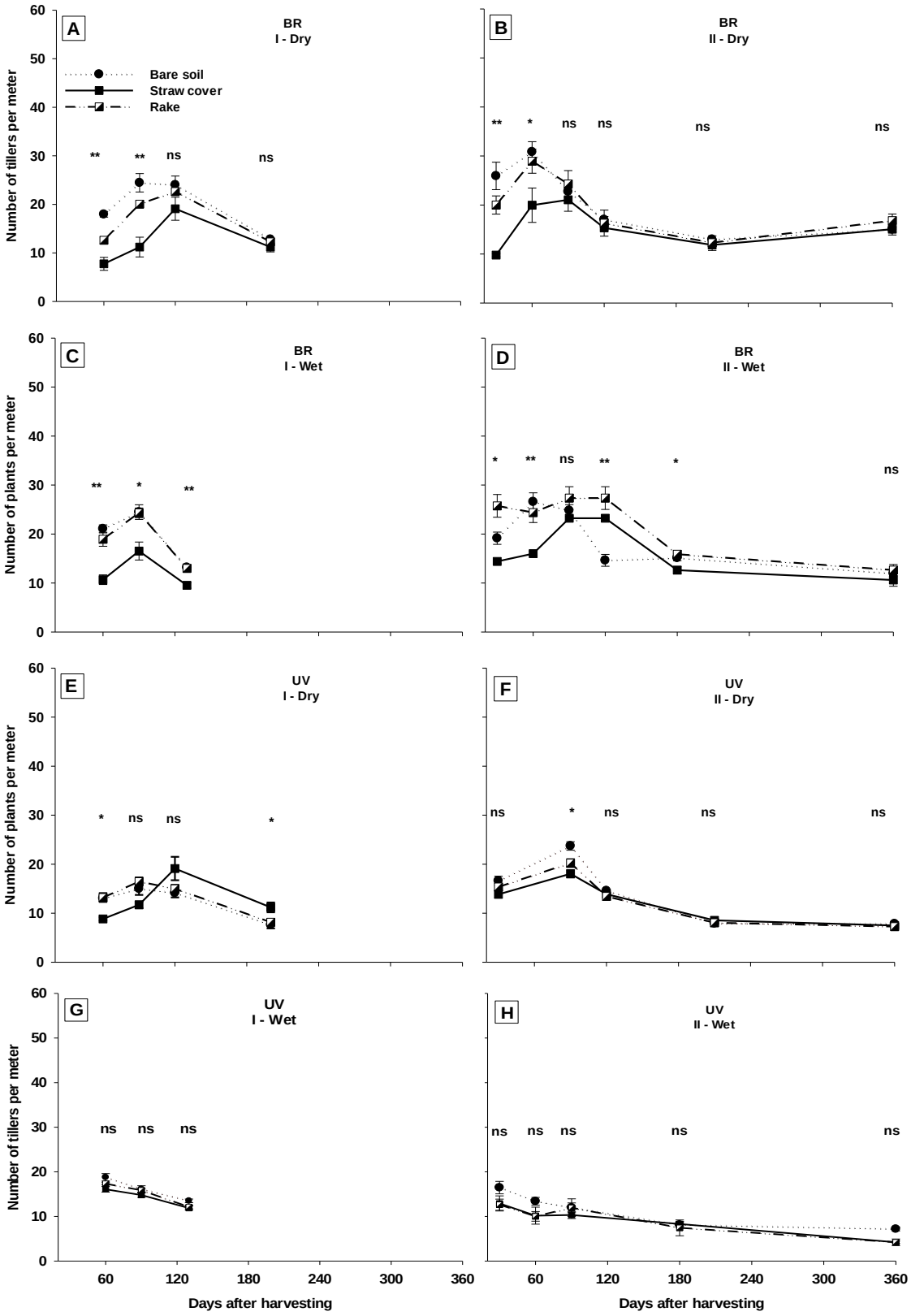

Fig. 2. Sugarcane tillering dynamics under different straw blanket management treatments established during the dry- and wet-season experiments at the Bom Retiro - BR (A to D) and Univalem - UV (E to H) and conducted over two ratoons (I and II). ** and * denotes that means differ significantly according to Tukey's test ($p < 0.01$) and ($p < 0.05$), respectively; ns: non-significant; error bars denote standard error of the mean.

One possible reason for this response was that Univalem experienced higher temperatures than Bom Retiro, especially early during each ratoon cycle (Fig 1S). The higher temperatures may have minimized straw effects on tillering, without influencing tiller number during the wet season for both ratoons (Fig 2. G and H). Also, since leaf emergence is dependent on temperature (Sinclair et al., 2004), conditions at Univalem may have accelerated sprout growth and development resulting in faster canopy closure, which also decreased straw management effects on LAI at Univalem (Fig. 2S, E to H).

After solar radiation, soil temperature is the most important abiotic factor affecting plant tillering (Toppa et al., 2010). Having a straw-blanket directly reduces surface soil temperature (Viator et al., 2005; Sandhu at al., 2013; Awo et al., 2015; Correa et al., 2017) by serving as an insulating barrier between the soil and atmosphere. In addition, the straw blanket acts as a physical barrier that may impair plant tillering. Nevertheless, previous studies have shown variable plant tillering responses to straw cover. Nxumalo et al. (2017) reported straw cover delayed plant emergence and crop establishment, but there were no negative effects late in the growing cycle and final plant population was not decreased. In contrast, Campos et al. (2010) concluded that raking improved plant tillering and final population compared to leaving straw on the soil surface. This was especially true for cooler regions of southeastern Brazil. Our results were similar to those of Campos et al. (2010), especially at Bom Retiro (*i.e.,* cooler site), where the plant-tillering pattern was similar between bare soil and raking treatments. However, we did not find any reduction in final plant population by the end of the ratoon cycle induced by straw cover (Fig. 2).

Overall, effects of straw cover on sugarcane tiller development and final plant population are unclear and variable depending primarily upon the amount of straw and ratoon cycle (Aquino et al., 2017; Lisboa et al., 2018). In Bandeirantes – PR (*i.e.*, southern Brazil) final plant population was significantly affected by straw amounts ranging from 0 to 20 Mg ha^{-1} in the first ratoon, but there was no verifiable negative effect in the second ratoon (Aquino et al., 2017). However, Tavares et al. (2010) reported that tiller number and final plant population were enhanced at the beginning and end of a crop cycles conducted over 16 years in Linhares – ES which is located in southeastern Brazil. These locations are colder and warmer, respectively, compared to the sites where our study was performed.

Reduced rainfall volume between Dec. 2015 to April 2016 at Bom Retiro (Fig. 1S A) and from Dec. 2014 and Jan. 2015 at Univalem (Fig. 1S B) may explain the inversion in plant tillering patterns for the different straw management treatments. For instance, decreased rainfall and consequently low soil moisture may explain reduced tiller production for the bare soil treatment

in the wet-season experiment during the second ratoon at Bom Retiro (Fig. 2 D). Those same conditions may have favored a reduction in the number of tillers for bare soil and rake treatments in the dry-season experiment at Univalem during the fourth and seventh months of the first ratoon (Fig. 2 E). On the other hand, straw cover (*i.e.*, the maintenance of straw on soil surface) probably conserved soil water (Anjos et al., 2017; Correa et al., 2017) and positively affected tiller number for both experiments during those time periods.

4.3.2 Sugarcane straw management effects on phytomass production

Phytomass accumulaltion was fitted using non-sigmoidal models, as previously reported in the literature (Mariano et al., 2016; Leite et al., 2016; Lisboa et al., 2018). Non-linear equations, as a function of DAH (*i.e.*, different periods across each ratoon cycle), fit well at both Bom Retiro ($r^2 \geq 0.92$) and Univalem ($r^2 \geq 0.92$) (Fig. 3).

Overall, phytomass yield for each ratoon cycle and season occurred in three-phases (Fig. 3). It began with a lag-phase characterized by slow phytomass accumulation, which was followed by a linear phase with fast phytomass accumulation, and ended with a stationary phase characterized by low accumulation (Fig. 3). The duration of each phase is shown on Table 1S. Taking into account both ratoons, harvest seasons and straw treatments, the average length for the lag-, linear-, and stationary-phases was 123, 82, and 155 days, respectively. Phytomass accumulation during those phases averaged 19, 75, and 6%, respectively.

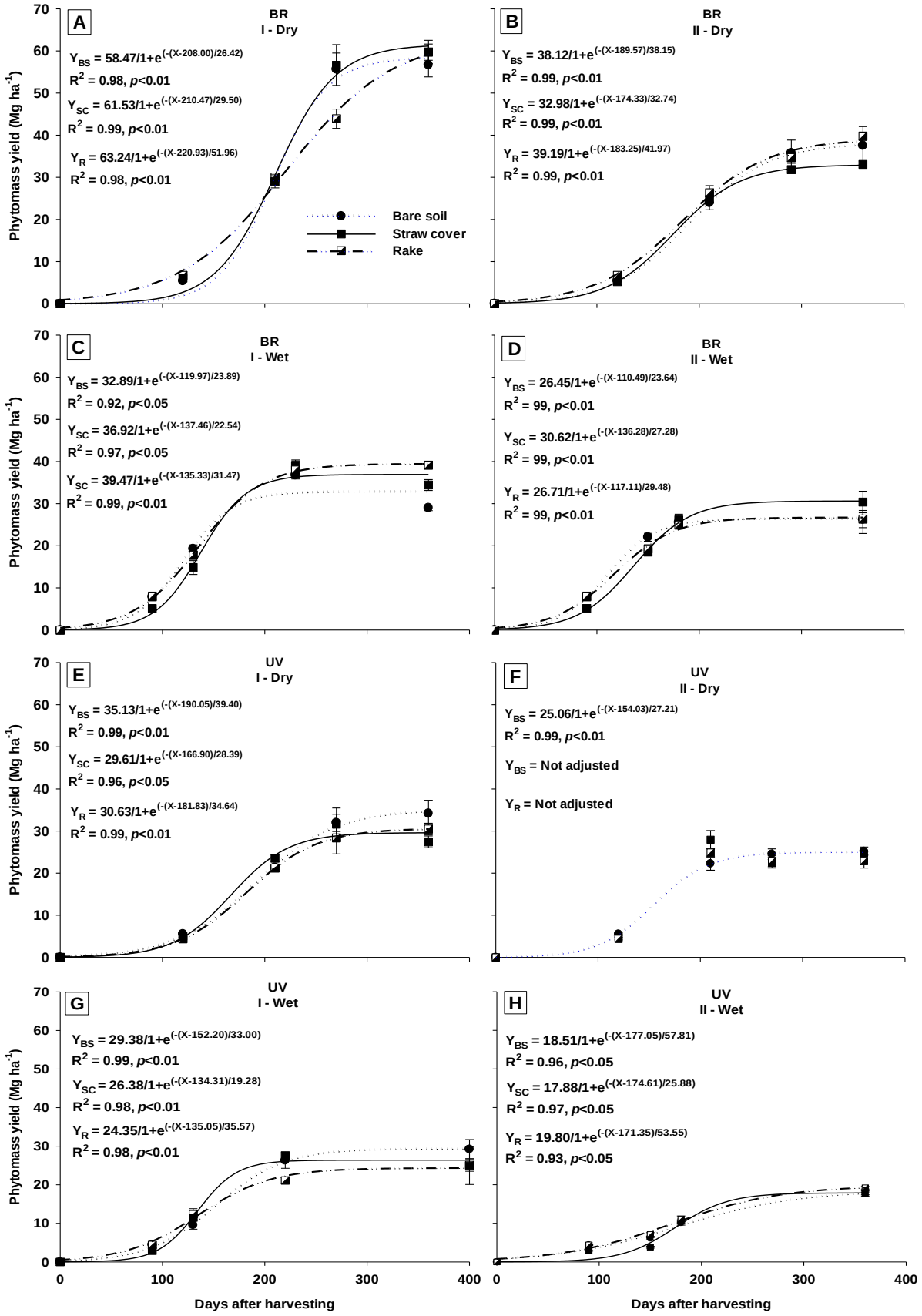

Fig. 3. Phytomass accumulation curves of sugarcane cultivated under different straw management treatments in experiments established during dry and wet-season at Bom Retiro - BR (A to D) and Univalem - UV (E to H) and conducted over the first (I) and second (II) ratoons. Phytomass accumulation curves were derived from equation 1.

There is no single pattern to explain plant growth (*i.e.*, phytomass accumulation) response to the straw management treatments within each ratoon (Fig. 3). At the beginning of each ratoon cycle (*i.e.*, until ~130 DAH), straw cover tended to decrease phytomass accumulation during the wet season. In contrast, rake and bare soil treatments enhanced plant growth in a similar pattern (Fig. 3 C, D, G and H). Although straw cover tended to decrease phytomass accumulation during earlier phases, nutrients released from the straw later in the ratoon cycle may have compensated for the unfavorable early growth conditions. On the other hand, late-season competition for water and nutrients can lead to plant senescence under bare soil management. One reason that response patterns are complex is that sugarcane has a long growth cycle (~one year), which provides enough time for plants to overcome unfavorable initial soil conditions (Wiedenfeld, 2009). Coupled with sugarcane's high efficiency in intercepting radiation (Inman-Bamber, 2013), this crop is one of the most efficient plants for converting energy from sunlight into chemical energy (Tew and Cobill, 2008) and subsequent phytomass accumulation. These plant characteristics, coupled with the different soil conditions (*i.e.*, temperature, water and nutrients contents) confound the straw management treatments and thus contribute to the absence of a phytomass accumulation response pattern (Fig. 3).

During each evaluation period, phytomass yield at Bom Retiro was higher than at Univalem [~48 and 23%, respectively, for dry and wet seasons during the first ratoon, and ~34% higher for both seasons during the second ratoon]. This presumably also reflected more favorable inherent soil chemical properties for crop production (Table 3) as was discussed by Satiro et al. (2017) and thus helps explain the lower phytomass yield at Univalem. Comparisons between the first and second ratoon crop at both sites show that phytomass yield at Bom Retiro was ~37 and 19% lower for treatments imposed during dry and wet-seasons, respectively, while at Univalem they were ~20 and 30% lower, respectively. A reduction in crop yield from one year to the next is well known within the sugarcane industry (Singh et al., 2012; Lisboa et al., 2018). Each ratoon crop requires at least three machinery operations: fertilization, weed control and harvesting. In most fields where straw is not removed for bioenergy production, raking adds an additional machinery operation. Intensive traffic of very heavy machines can lead to soil compaction (Souza et al., 2014; Cherubin et al., 2016; Bordonal et al., 2018), which reduces the root growth (Souza et al., 2014) and the volume of soil which can be effectively explored for nutrients and water (Singh et al., 2012). Compaction thus indirectly decreases aboveground plant growth and, by consequence, phytomass yield across ratoons cycles. Furthermore, heavy machine traffic can uproot plants, thus damaging root systems, leading to plant gaps (*i.e.*, reductions in plant population) (Lisboa et al., 2018), and directly reducing phytomass yield. Despite the increased

risk, raking straw blanket to the inter-row position has been shown to increase the number of tillers (Fig. 2 A to E), as previously reported by Campos et al. (2008) and (2010), but without detectable effects on phytomass accumulation.

4.3.3 Second ratoon plant nutrient status

Maintaining straw on the soil surface (*i.e.*, straw cover or rake treatments) tended to increase plant-tissue P and S concentrations when measure four months after harvesting under poor soil conditions (Univalem). Later in the growth cycle (*i.e.*, 6 to 7 months), there was no a clear pattern to explain plant nutrient status in response to straw managements or season when then treatments were imposed. Despite this fact and with no relationship to treatment, trends observed earlier in the cycle persisted with P increasing the most when straw was kept on the soil surface (Table 4).

Table 4. Plant-tissue nutrient concentration in sugarcane cultivated under different straw blanket managements at both sites and seasons over the second ratoon

	Bom Retiro mill								Univalem mill							
	Dry season				Wet season				Dry season				Wet season			
Macronutrient	Blanket managements				Blanket management				Blanket managements				Blanket managements			
Content (g kg ^{1})	Bare soil	Straw cover	Rake	Mean	Bare soil	Straw cover	Rake	Mean	Bare soil	Straw cover	Rake	Mean	Bare soil	Straw cover	Rake	Mean
First evaluation - fourth month																
Third leaf from top to bottom of the stalk																
N	23.6^{ns}	24.3	24.2	24.0	12.6 ^{ns}	13.0	12.3	12.6	14.6 ^{ns}	15.3	14.4	14.8	21.2 ^{ns}	21.1	25.5	22.6
P	2.3 ^{ns}	2.5	2.4	2.4	1.1 ^{ns}	2.1	2.1	2.0	1.8 b*	2.1 a	2.0 ab	2.0	1.6 b*	2.0 ab	2.2 a	1.9
K	9.4 ^{ns}	11.0	9.9	10.1	9.9 ^{ns}	8.9	9.8	9.5	7.1 ^{ns}	18.1	7.6	10.9	8.0 ^{ns}	9.9	9.4	9.1
Ca	3.3 ^{ns}	4.1	3.4	3.6	3.4 ^{ns}	3.8	3.3	3.5	3.2 ^{ns}	3.8	4.1	3.7	3.6 ^{ns}	3.6	3.4	3.5
Mg	1.5 ^{ns}	1.4	1.4	1.4	1.6 ^{ns}	1.2	1.4	1.4	1.1 ^{ns}	1.3	1.4	1.2	1.6 ^{ns}	2.1	1.9	1.9
S	1.5 ^{ns}	1.7	1.6	1.6	2.3 ^{ns}	2.4	2.4	2.4	0.7 ^{ns}	0.8	0.7	0.2	1.9 c**	2.2 b	2.7 a	2.2
Second evaluation																
(kg ha^{-1})	seventh month				sixth month				seventh month				sixth month			
Dry leaves																
N	22.4^{ns}	30.8	28.0	27.1	20.9^{ns}	19.4	20.1	20.1	6.8^{ns}	10.9	7.7	8.5	6.4b**	12.3a	11.5a	10.1
P	0.53^{ns}	0.95	0.90	0.8	0.59^{ns}	0.64	0.64	0.8	0.9^{ns}	1.2	1.0	1.0	0.9b*	2.0ab	2.2a	1.7
K	11.1^{ns}	24.0	21.5	18.9	16.7^{ns}	16.7	12.2	15.2	8.7^{ns}	10.7	9.6	9.7	6.7^{ns}	6.3	7.0	6.7
Ca	26.9^{ns}	33.1	29.1	29.7	27.4^{ns}	29.1	28.9	28.5	21.9^{ns}	24.6	20.5	22.3	10.6^{ns}	15.7	15.2	13.8
Mg	7.8^{ns}	11.9	10.4	10.1	8.3 ^{ns}	7.4	7.5	7.7	6.0^{ns}	8.7	7.2	7.3	3.3^{ns}	3.8	5.3	4.1
S	8.5^{ns}	9.6	9.0	9.0	5.7 ^{ns}	5.8	4.6	5.4	4.6^{ns}	4.3	4.6	4.5	2.0^{ns}	2.6	2.6	2.4
Green leaves																
N	51.4^{ns}	45.7	52.2	49.8	66.3^{ns}	72.1	64.8	67.7	11.4^{ns}	13.3	13.4	12.7	12.7^{ns}	14.4	16.5	14.5
P	5.1^{ns}	6.8	6.4	6.1	6.9 ^{ns}	9.0	7.6	7.9	1.9^{ns}	1.9	2.0	1.9	2.5^{ns}	2.7	3.1	2.8
K	60.0 ^{ns}	59.0	52.6	57.2	82.7^{ns}	100	88.7	90.4	16.1^{ns}	14.5	15.1	15.2	16.2b*	22.0ab	24.5a	20.9
Ca	13.3 ^{ns}	12.5	13.4	13.1	26.0^{ns}	25.9	24.4	25.5	3.8^{ns}	4.1	4.5	4.1	3.6^{ns}	3.3	3.5	3.5
Mg	8.1^{ns}	6.0	6.0	6.7	9.5 ^{ns}	9.7	10.4	9.9	1.9^{ns}	2.1	2.2	2.1	1.8^{ns}	2.1	2.4	2.13
S	8.4 ^{ns}	9.5	10.1	9.3	12.6^{ns}	15.1	13.2	13.7	1.7^{ns}	1.9	1.8	1.8	1.6^{ns}	1.6	1.7	1.6
Stalks																
N	77.5^{ns}	66.3	70.2	71.3	56.8^{ns}	53.2	50.0	53.3	17.9^{ns}	20.9	16.4	18.4	14.9^{ns}	13.3	15.1	14.5
P	6.4b**	12.8a	6.0b	8.4	6.6 ^{ns}	8.9	7.4	7.6	6.2^{ns}	8.1	8.5	7.6	2.9b*	4.2ab	5.5a	4.2
K	155.3^{ns}	151.0	143.9	150.1	78.3^{ns}	110.1	94.3	94.2	26.7^{ns}	28.9	33.2	29.6	6.1b**	24.6a	26.1a	18.9
Ca	28.1^{ns}	24.7	24.0	25.6	14.6^{ns}	14.3	13.8	14.2	8.0^{ns}	8.2	7.6	7.9	2.4^{ns}	2.7	3.0	2.7
Mg	29.1^{ns}	21.0	23.2	24.4	12.9^{ns}	13.8	15.9	14.2	6.2^{ns}	6.3	6.4	6.3	2.0^{ns}	2.6	3.0	2.6
S	36.1^{ns}	40.3	36.2	37.5	25.3^{ns}	24.8	21.9	24.0	7.9b**	7.6b	11.4a	8.9	2.0^{ns}	2.0	2.3	2.1

Within the same harvesting season and straw blanket management system means values followed by the same letter do not differ between themselves according to Tukey's test ($p < 0.01$)****** and ($p < 0.05$)***; ns**: non-significant

The plant-nutrient response to straw management treatments was greater at Univalem than Bom Retiro, presumably because of low soil fertility conditions within the sandy loam soil of Univalem compared to the sandy clay loam soil at Bom Retiro (Satiro et al., 2017). At Univalem during the dry season, plant-tissue P content was ~15 and 11% higher for the straw cover and raking treatments, respectively, when compared to bare soil management. Similarly, during the wet-season, P content increased ~20 and 27%, respectively, for straw cover and raking treatments (Table 4). Regardless of management (*i.e.*, straw cover or raking), plant-tissue S concentrations increased when straw was retained on the soil surface in the wet-season. Nutrient status four months after harvest and later in the plant growth cycle were similar. Overall, maintaining straw on the soil surface increased the amount of P extracted from the different plant components (*i.e.*, dry and green leaves and stalks) for both seasons and sites (Table 4).

Correlations among straw management treatments and plant nutrient status throughout the second ratoon cycle were determined using canonical analysis. At Bom Retiro, canonical variable 1 (CV1) explained ~98 and 92% of the data variance for experiments conducted within dry (Fig. 4 A) and wet (Fig. 4 B) seasons, respectively. Straw management treatments did not affect N1, P1 or K1 concentrations during either season at Bom Retiro (Table 4). Despite this fact, the straw maintenance on soil surface was strongly correlated with N, P and K content in plant tissue.

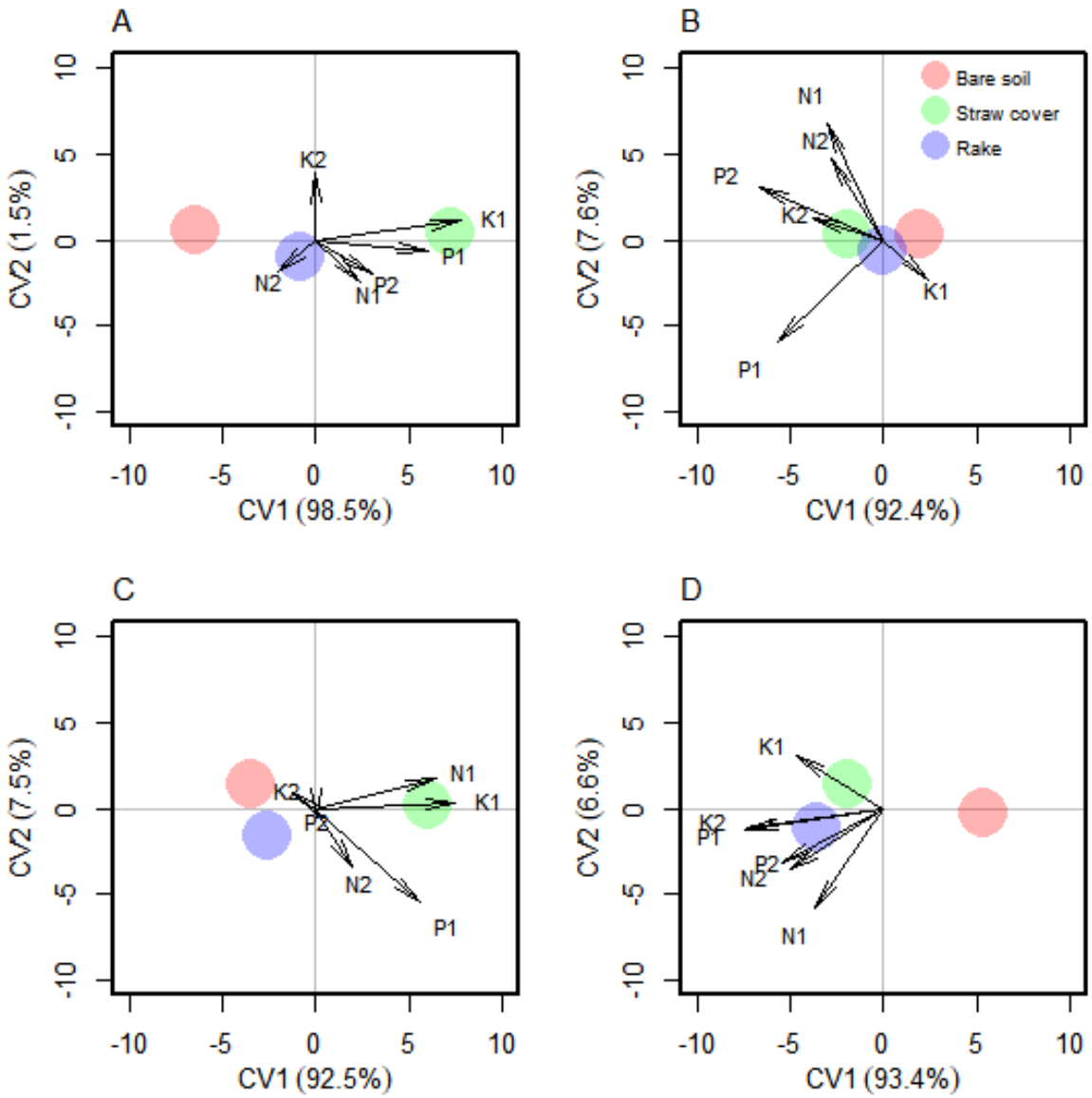

Fig. 4. Correlation between plant nutritional status and straw blanket management treatments within the experiments performed during the dry (A) and wet (B) season at Bom Retiro, while C and D represent the same correlation at dry and wet season at Univalem. Colored balls represent confidences ellipses (95%) for the means of the scores of the two first canonical variables (CV) in a biplot representation; arrows denote how the means of the CVs are affected by original variables in each management. N, P and K followed by 1 and 2 are respectively the plant-tissue content of these elements at 120 and 210 DAH.

At the Univalem site, CV1 also explained ~92 and 93% of the variation among straw managements treatments established during the dry (Fig. 4 C) and wet (Fig. 4 D) seasons, respectively. At this site, straw cover significantly increased N, P and K concentrations in the plant tissue and the amount of N and P removed in green leaves during the fourth and sixth months of the dry season. In contrast, bare soil and rake treatments had minimal effect on the amount of K removed by green leaves (Fig. 4 C). Straw cover and raking treatments were

correlated with N, P and K content in both the fourth and sixth months of the wet season (Fig. 4 D). Bare soil management during this time was negatively correlated with N, P and K content in plant tissue, as well as the amount of these elements within the green leaves in the fourth and sixth months. This response was similar to that observed during the dry-season at Univalem (Fig. 4 C).

In general, both treatments that kept straw on the soil surface (*i.e.*, straw cover and raked) enhanced N and P concentrations in the plant tissue, regardless of the evaluation period (*i.e.*, sixth or seventh month). Increased concentrations of those elements may be due to soil function benefits such as enhanced nutrient cycling (Fortes et al., 2012; Trivelin et al., 2013; Souza Jr. et al., 2018) and/or increased C accumulation (Galdos et al., 2017; Souza Jr. et al., 2018; Cherubin et al., 2018), water storage and infiltration (Anjos et al., 2017; Valim et al., 2016), and biological activity (Paredes et al., 2015). Healthy soils generally have increased availability of N and P for plant uptake, which subsequently increases plant-tissue concentrations of these elements when straw is left on the soil surface (*i.e.,* straw cover and rake treatments). Since sugarcane cultivation is carried out across a wide range of soil textural classes in Brazil (Satiro et al., 2017) and raking reduces soil cover, additional studies are needed to determine how this practice affects soil conservation and subsequently soil quality.

4.3.4 Stalk yield and quality

Sugarcane straw management did not affect stalk yield for either season, ratoon or site (Fig. 5). Averaged over two years, maintenance of straw on the soil surface generally reduced stalk yield at Univalem in the wet-season experiment (Fig. 5 D). Stalk yield was not affected by raking when compared to covered soil ($p = 0.466$).

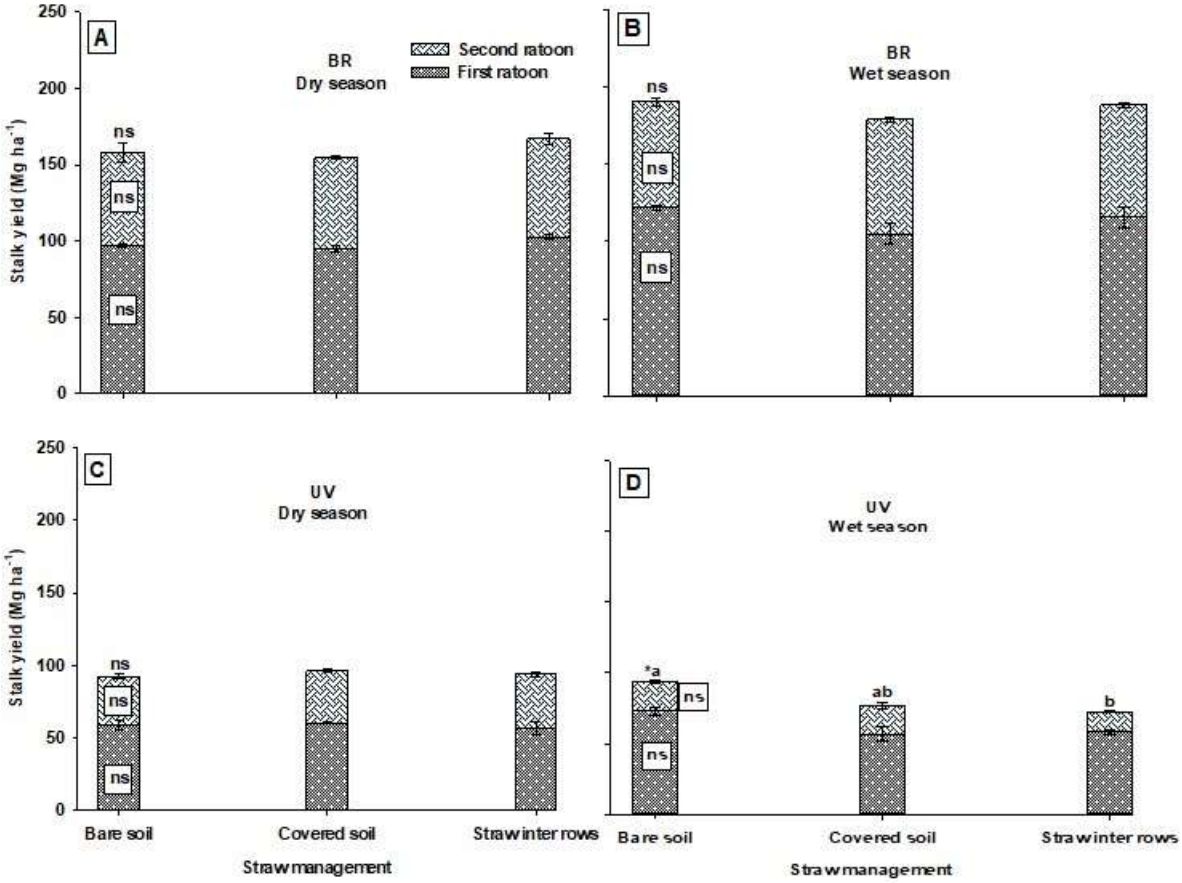

Fig. 5. Stalk yield of sugarcane cultivated under different straw blanket managements treatments established during the dry and wet-season at Bom Retiro – BR (A and B) and Univalem - UV (C and D) over two ratoons; * significant by Tukey's test ($p < 0.05$); ns: non-significant; error bars denote standard error of the mean.

Although short-term the maintenance of straw on the soil surface improved soil chemical and physical attributes, the changes were restricted to upper soil layers (Satiro et al., 2017; Souza Jr., 2018) and neither plant growth nor stalk yield were greatly affected (Lisboa et al., 2018). The minimal impact of straw management during this 2-year experiment presumably accounts for the minimal response (Fig. 5). Therefore, long-term studies, such as that performed by Aquino et al. (2018) in southern Brazil, are essential for understanding how straw management will affect plant growth and stalk yield over time.

Overall, the benefits of straw blanket management (*i.e.*, raking) can be especially important for plant growth and stalk yield under wet and cold conditions within subtropical regions, where the crop has less than one year to complete the growing season. Within these climatic conditions, the straw blanket delays plant tillering during the winter and earlier spring, which reduces the time with suitable conditions for phytomass accumulation over cycle (Viator et al., 2005). In contrast, within tropical conditions, ratoon cycle is longer and low temperatures may

not occur and even integral straw retention (*i.e.*, without raking) was not able to influence tillering and development (Bordonal et al., 2018).

4.3.5 Stalks-industrial quality

Straw management did not affect any parameters associated with industrial sugarcane quality in either season. However, stalks from the wet-season experiments tended to have lower quality than those harvested during the dry-season (for further details see supplementary discussion).

4.4 Conclusions

Managing sugarcane straw by raking, which is widely used in southeastern Brazil, enhanced sprouting but did not affect phytomass accumulation, final plant population, or yield regardless of soil and climate conditions. Overall, plant nutrient status was slightly affected by straw management. Straw retention did increase plant-tissue P and K concentrations, especially under the poorest inherent soil conditions. Since the straw management practices adopted in this study did not affect yields or stalk quality in either ratoon or season over two years, we conclude raking is an unnecessary practice in southeastern Brazil and one that can potentially increase soil compaction.

Furthermore, since neither maximum removal (bare soil) nor retention (straw cover) influenced plant growth and stalk yield within the short term in southeastern Brazil, moderate sugarcane straw removal may be a feasible way to supply feedstock for the scenario of high bioenergy demand, while the benefits of this harvesting residue for the soil-plant system would not be disregard.

REFERENCES

Anjos, J.C.R.D, Andrade Jr., A.S.D., Bastos, E.A., Noleto, D.H., Melo, F.D.B., and R.R.D. Brito. 2017. Water storage in a Plinthaqualf cultivated with sugarcane under straw levels. Pesq. agropec. bras 52:464-473. doi.org/10.1590/s0100-204x2017000600010

Aquino, G.S., de Conti Medina, C., da Costa, D.C., Shahab, M., and A.D. Santiago. 2017. Sugarcane straw management and its impact on production and development of ratoons. Ind Crops and Prod. 102:58-64. doi.org/10.1016/j.indcrop.2017.03.018

Aquino, G.S., de Conti Medina, C., Shahab, M., Santiago, A.D., Cunha, A.C., Kussaba, D.A., Carvalho, J.B., and A. Moreira. 2018. Does straw mulch partial-removal from soil interfere in yield and industrial quality sugarcane? A long term study. Ind Crops and Prod. 111:573-578. doi.org/10.1016/j.indcrop.2017.11.026

Awe, G.O., Reichert, J.M., and O.O. Wendroth. 2015. Temporal variability and covariance structures of soil temperature in a sugarcane field under different management practices in southern Brazil. Soil Tillage Res. 150:93–106. doi.org/10.1016/j.still.2015.01.013

Bordonal, R.O., Carvalho, J.L., Lal, R., de Figueiredo E.B., de Oliveira, B.G., and N. La Scala. 2018. Sustainability of sugarcane production in Brazil. A review. Agron. Sustain. Dev. 38 (2):13. doi.org/10.1007/s13593-018-0490-x

Bordonal, R.O., Menandro, L.M.S., Barbosa, L.C., Lal, R., Milori, D.M.B.P., Kolln, O.T., Franco, H.C.J. and J.L.N. Carvalho. 2018. Sugarcane yield and soil carbon response to straw removal in south-central Brazil. Geoderma. 328:79-90. doi.org/10.1016/j.geoderma.2018.05.003

Campos, L.H.F., Carvalho, S.J.P., Christoffoleti, P.J., Fortes, C., and J.S. Silva. 2008. Crescimento e produtividade da cana-de-açúcar (Var. SP83-2847) submetida a três manejos da palhada. STAB. 26:33-36.

Campos, L.H.F.D., Carvalho, S.J.P.D., Christoffoleti, P.J., Fortes, C. and J.S.D. Silva. 2010. Straw management systems influence biomass accumulation and yield of sugarcane crop (var. RB855453). Acta Sci., Agron. 32:345-350. doi.org/10.4025/actasciagron.v32i2.3703

Cançado, J.E., Saldiva, P.H., Pereira, L.A., Lara, L.B., Artaxo, P., Martinelli, L.A., Arbex, M.A., Zanobetti, A., and A.L. Braga. 2006. The impact of sugar cane–burning emissions on the respiratory system of children and the elderly. Environ. Health. Perspect. doi:10.1289/ehp.8485

Capaz, R.S., Carvalho, V.S.B., and L.A.H. Nogueira. 2013. Impact of mechanization and previous burning reduction on GHG emissions of sugarcane harvesting operations in Brazil. Appl. Energy. 102:220-228. doi.org/10.1016/j.apenergy.2012.09.049

Carvalho, J.L.N., Nogueirol, R.C., Menandro, L.M.S., Bordonal, R.D.O., Borges, C.D., Cantarella H., and H.C.J. Franco. 2017. Agronomic and environmental implications of sugarcane straw removal: a major review. Glob. Chang. Biol. 9:1181-1195. dx.doi: 10.1111/gcbb.12410

Cherubin, M.R., Karlen, D.L., Franco, A.L., Tormena, C.A., Cerri, C.E.P., Davies, C.A., and C.C. Cerri. 2016. Soil physical quality response to sugarcane expansion in Brazil. Geoderma 267:156–168. doi.org/10.1016/j.geoderma.2016.01.004

Cherubin, M.R., Oliveira, D.M., Feigl, B.J., Pimentel, L.G., Lisboa, I.P., and M.R. Gmach et al. 2018. Crop residue harvest for bioenergy production and its implications on soil functioning and plant growth: A review. Sci. Agric. 75(3):255-72. doi.org/10.1590/1678-992x-2016-0459

Conab - Companhia Nacional de Abastecimento e Conab, Acompanhamento da safra brasileira de cana-de-açúcar. v. 4, Safra 2017/18, n. 3, Primeiro Levantamento, Brasília. 2017. Retrieved March 23, 2018 from http://www.conab.gov.br/OlalaCMS/uploads/arquivos/18_01_08_09_08_38_cana_dezembro_novo.pdf

Consecana - Conselho dos Produtores de Cana-de-Açúcar, Açúcar e Álcool do Estado de São Paulo. 2006. Manual de Instruções. 5° ed. Piracicaba-SP, Consecana-SP. 112p.

Correa, S.T.R., Carvalho, J.L.N., Hernandes, T.A.D., Barbosa, L.C., Menandro, L.M.S., and M.R.L.V. Leal. 2017. Assessing the effects of different amounts of sugarcane straw on temporal variability of soil moisture content and temperature in 25th European Biomass Conference and Exhibition, 12-15 June 2017, Stockholm, Sweden.

Dinardo-Miranda, L.L., and J.V. Fracasso. 2013. Sugarcane straw and the populations of pests and nematodes. Sci. Agric. 70:305-310. doi.org/10.1590/S0103-90162013000500012

Dodo, C.M., Mamphweli, S., and O. Okoh. 2017. Bioethanol production from lignocellulosic sugarcane leaves and tops. J. of energy South. Afr. 28(3):1-11. doi.org/10.17159/2413-3051/2017/v28i3a2354

Fortes, C., Vitti, A.C., Otto, R., Ferreira, D.A., Franco, H.C.J., and P.C.O. Trivelin. 2013. Contribution of nitrogen from sugarcane harvest residues and urea for crop nutrition. Sci. agric. 70:313-320. doi.org/10.1590/S0103-90162013000500005

Fortes, C., Trivelin, P.C.O. and Vitti, A.C., 2012. Long-term decomposition of sugarcane harvest residues in Sao Paulo state, Brazil. Biomass and Bioenergy, 42, pp.189-198.

Galdos, M., Cavalett, O., Seabra, J.E., Nogueira, L.A.H., and A. Bonomi. 2013. Trends in global warming and human health impacts related to Brazilian sugarcane ethanol production considering black carbon emissions. Appl. Energy. 104:576-582. doi.org/10.1016/j.apenergy.2012.11.002

Galdos, M.V., Cantarella, H, Hastings, A, Hillier, J., and P. Smith. 2017. Environmental Sustainability Aspects of Second Generation Ethanol Production from Sugarcane. In:

Buckeridge, M.S., de Souza, A.P. (Eds.), Advances of Basic Science for Second Generation Bioethanol from Sugarcane . Springer, Cham, 177-195. doi.org/10.1007/978-3-319-49826-3_10

Goldemberg, J., Mello, F.F., Cerri, C.E., Davies, C.A., and C.C. Cerri. 2014. Meeting the global demand for biofuels in 2021 through sustainable land use change policy. Energy Policy. 69:14-8. doi.org/10.1016/j.enpol.2014.02.008

Guerra, J.P., Cardoso, F.H., Nogueira, A., and L. Kulay. 2018. Thermodynamic and Environmental Analysis of Scaling up Cogeneration Units Driven by Sugarcane Biomass to Enhance Power Exports. Energies. 11(1):73. doi.org/10.3390/en11010073

Hassuani, S.J., Leal, M.R.L.V., and I. Macedo. 2005. Biomass power generation. Sugar cane bagasse and trash Published by Programa das Nacoes Unidas para o Desenvolvimento and Centro de Technologia Canavieriva, Piracicaba, 217p.

Inman-Bamber, G. 2013. Sugarcane Yields and Yield-Limiting Processes. In: Moore, P.H., and F.C. Botha (Eds.), Sugarcane: Physiology, Biochemistry, and Functional Biology. Wiley- lackwell, Oxford, 579-600. doi.org/10.1002/9781118771280.ch21

Kingston, G., Donzelli, J.L., Meyer, J.H., Richard, E.P., Seeruttun, S., and J. Torres. 2005. Impact of the green cane harvest and production system on the agronomy of sugarcane. In Proc. ISSCT, 25:521-531

Landell, M.G.D.A., Scarpari, M.S., Xavier, M.A., Anjos, I.A.D., Baptista, A.S., and C.L.D Aguiar at al. 2013. Residual biomass potential of commercial and pre-commercial sugarcane cultivars. Sci. Agric. 70:299-304. doi.org/10.1590/S0103-90162013000500003

Le Blond, J.S., Woskie, S., Horwell, C.J., and B.J. Williamson. 2017. Particulate matter produced during commercial sugarcane harvesting and processing: A respiratory health hazard? Atmos. Environ. 149:34-46. doi.org/10.1016/j.atmosenv.2016.11.012

Leite, J.M., Ciampitti, I.A., Mariano, E., Vieira-Megda, M.X., and P.C.O. Trivelin. 2016. Nutrient partitioning and stoichiometry in unburnt sugarcane ratoon at varying yield levels. Front Plant Sci. 7:466. doi.org/10.3389/fpls.2016.00466

Lisboa, I.P., Cherubin, M.R., Cerri, C.C., Cerri, D.G., and C.E.P. Cerri. 2017. Guidelines for the recovery of sugarcane straw from the field during harvesting. Biomass Bioenergy. 96:69-74. doi.org/10.1016/j.biombioe.2016.11.008

Lisboa, I.P., Cherubin, M.R., Lima, R.P., Cerri, C.C., Satiro, L.S., Wienhold, B.J., Schmer, M.R., Jin, V.L., and C.E.P. Cerri. 2018. Sugarcane straw removal effects on plant growth and stalk yield. Industrial Crops and Prod. 111:794-806. doi.org/10.1016/j.indcrop.2017.11.049

Malavolta, E, Vitti, G.C., and A.S. Oliveira. 1997. Avaliação do estado nutricional das plantas: princípios e aplicações. 2ª.ed. Piracicaba: Associação Brasileira para Pesquisa da Potassa e do Fosfato.

Mariano, E., Leite, J.M., Vieira-Megda, M.X., Ciampitti, I.A., Vitti, A.C., Faroni, C.E., Franco, H.C., and P.C.O. Trivelin. 2016. Biomass and nutrient content by sugarcane as affected by fertilizer nitrogen sources. Crop Sci. 56:1234 -1244. doi:10.2135/cropsci2015.06.0349

Mendiburu, F., and R. Simon. 2015. Agricolae - Ten years of an open source statistical tool for experiments in breeding, agriculture and biology. PeerJ PrePrints 3:e1404v1. doi.org/10.7287/peerj.preprints.1404v1

Nxumalo, N., Ramburan, S., and J.M. Steyn. 2017. Growth and yield responses of commercial sugarcane cultivars to mulching in the coastal rainfed region of South Africa. S Afr J Plant & Soil. 34:9-18. doi.org/10.1080/02571862.2016.1148787

Oliveira, J.C.M., Timm, L.C., Tominaga, T.T., Cassaro, F.A.M., Reichardt, K., Bacchi, O.O.S., Dourado-Neto, D., and G.D.S Câmara. 2001. Soil temperature in a sugar-cane crop as a function of the management system. Plant soil. 230 (1):61-66. doi.org/10.1023/A:1004820119399

Paraiso, M.L.D.S., and N. Gouveia. 2015. Health risks due to pre-harvesting sugarcane burning in São Paulo State, Brazil. Rev Bras Epidemiol, 18 (3):691-701.

Le Blond, J.S., Woskie, S., Horwell, C.J., and B.J. Williamson. 2017. Particulate matter produced during commercial sugarcane harvesting and processing: A respiratory health hazard? Atmos. Environ. 149:34-46. doi.org/10.1590/1980-5497201500030014

Paredes Jr. F., Rosa Portilho, I.I., and F. Martins Mercante. 2015. Microbiological attributes of the soil under cultivation of sugar cane with and without burning straw. Semina: Ciênc. Agrár. 36:151-164. doi: 10.5433/1679-0359.2015v36n1p151

Pongpat, P., Gheewala, S., and T. Silalertruksa. 2017. An assessment of harvesting practices of sugarcane in the central region of Thailand. J Clean Prod. 142:1138-1147. doi.org/10.1016/j.jclepro.2016.07.178

R Core Team. 2016. R. A Language and Environment for Statistical Computing [Internet]. R Foundation for Statistical Computing, Vienna, Austria (Accessed on: 11 Mach 2018). Available at: http://www.R-project.org/.

Raij, B.V., Cantarella H., Quaggio, J.A., and A.M.C. Furlani. 1997. Recomendações de adubação e calagem para o estado de São Paulo. Campinas: Instituto Agronômico/Fundação IAC. Boletim técnico 100, 285 p.

Raij van, B., de Andrade, J.C., Cantarella, H., and J.A. Quaggio. 2001. Análise química para Avaliação da Fertilidade de Solos Tropicais. Campinas: Instituto Agronômico de Campinas. 285 p.

REN21 -Highlights of the REN21 Renewables. 2017. Global Status Report in perspective – Available: http://www.ren21.net/wp-content/uploads/2017/06/GSR2017_Highlights_FINAL.pdf

Sandhu, H.S., Gilbert, R.A., Kingston, G., Subiros, J.F., Morgan K., Rice R.W., Baucum L., Shine J.M., and L. Davis. 2013. Effects of sugarcane harvest method on microclimate in Florida and Costa Rica. Agric for. Meteorol. 177:101-109. doi.org/10.1016/j.agrformet.2013.04.011

Sandhu, H.S., Singh, M.P., Gilbert, R.A., Subiros-Ruiz, F., Rice R.W., and J.M Shine. 2017. Harvest management effects on sugarcane growth, yield and nutrient cycling in Florida and Costa Rica. Field Crops Res. 214:253-260. doi.org/10.1016/j.fcr.2017.09.002

Satiro, L.S., Cherubin, M.R., Safanelli, J.L., Lisboa, I.P., da Rocha Junior, P.R., Cerri, C.E.P., and C.C. Cerri. 2017. Sugarcane straw removal effects on Ultisols and Oxisols in south-central Brazil. Geoderma Regional. 11:86-95. doi.org/10.1016/j.geodrs.2017.10.005

Sinclair, T.R., Gilbert, R.A., Perdomo, R.E., Shine Jr. J.M., Powell, G., and G. Montes. 2004. Sugarcane leaf area development under field conditions in Florida, USA. Field Crops Research. 88(2):171-178. doi.org/10.1016/j.fcr.2003.12.005

Singh. S.N., Singh, A.K., Malik, J.P.S., Kumar, R., and M. L. Sharma. 2012. Cultural-practice packages and trash management effects on sugarcane ratoons under sub-tropical climatic conditions of India. The Journal of Agricultural Science, 150(2):237-247. doi.org/10.1017/S0021859611000499

Sousa Jr., J.G., Cherubin, M.R., Oliveira, B.G., Cerri, C.E.P., Cerri, C.C., and B.J. Feigl. 2018. Three-Year Soil Carbon and Nitrogen Responses to Sugarcane Straw Management. Bioenerg. Res. 1-13. doi.org/10.1007/s12155-017-9892-x

Souza, G.S. D., Souza, Z.M.D., Silva, R.B.D., Barbosa, R.S., and F.S. Araújo. 2014. Effects of traffic control on the soil physical quality and the cultivation of sugarcane. Rev. Bras. Ciênc. Solo. 38(1):135-146. doi.org/10.1590/S0100-06832014000100013

Tavares, O.C.H., Lima, E., and E. Zonta. 2010. Crescimento e produtividade da cana planta cultivada em diferentes sistemas de preparo do solo e de colheita. Acta Sci Biol Sci. 32:61-68. doi.org/10.4025/actasciagron.v32i1.2051

Tew, T.L., and R.M. Cobill. 2008. Genetic improvement of sugarcane (*Saccharum* spp.) as an energy crop. In Genetic improvement of bioenergy crops, Springer New York, 273-294. doi.org/10.1007/978-0-387-70805-8_9

Toppa, B.E.V., Jadoski, C.J., Julianetti, A., Hulsbof, T., Ono, E.O., and J.D, Rodrigues. 2010. Physiology development in the vegetative stage of sugarcane. Appl. Res. & Agrotec. 3:177-185. doi.org/10.5777/paet.v3i2.1064

Trivelin, P.C., Franco, H.C., Otto, R., Ferreira, D.A., Vitti, A.C., Fortes, C., Faroni, C.E., Oliveira, E.C., and H. Cantarella. 2013. Impact of sugarcane trash on fertilizer requirements for São Paulo, Brazil. Sci. agric. 70(5):345-352. doi.org/10.1590/S0103-90162013000500009

Valim, W.C., Panachuk, E., Pavei, D.S., Sobrinho, T.A., and W.S. Almeida. 2016. Effect of sugarcane waste in the control of interrill erosion. Semin: Cien Agrar. 37:1155-1164. doi.org/10.5433/1679-0359.2016v37n3p1155

Viator, H.P., and J.J. Wang. 2011. Effects of residue management on yield after three production cycles of a long-term sugarcane field trial in Louisiana. J. of the Am. Soc. of Sug. Cane Technol. 31:15-24.

Viator, R.P., Johnson, R.M., E.P., and Jr. Richard. 2005. Challenges of post-harvest residue management in the Louisiana sugarcane industry. Proc Int Soc Sugar Cane Technol. 25:238–244.

Walter, A., Galdos, M.V., Scarpare, F.V., Leal M.R.L.V., Seabra J.E.A., and M. da Cunha et al. 2014. Brazilian sugarcane ethanol: developments so far and challenges for the future. Wiley Interdisciplinary Reviews: Energy and Environ. 3:70-92. doi.org/10.1002/wene.87

Wiedenfeld, B. 2009. Effects of green harvesting vs burning on soil properties, growth and yield of sugarcane in south Texas. J. Am. Soc. Sugar Cane Technol. 29:102-109.

Supplementary materials

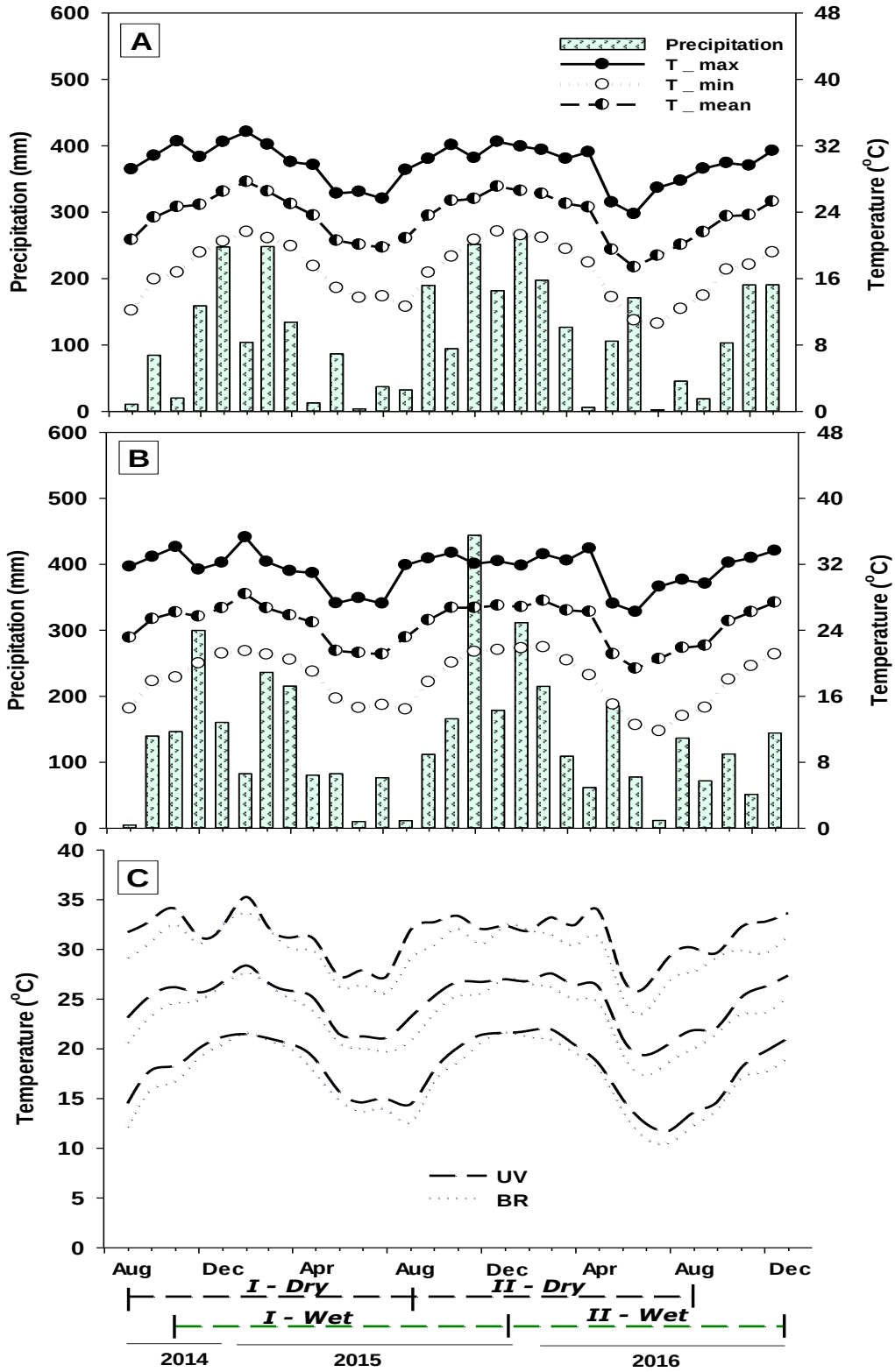

Fig. 1 S. Mean monthly temperature (maximum, mean and minimum) (°C) and monthly precipitation (mm) in Bom Retiro – BR, (Capivari, SP) (A) and Univalem - UV (Valparaiso, SP) (B). Comparison of mean monthly temperature (maximum, mean and minimum) in the two sites studied (C). Black and green dashed lines indicate the conduction period of the experiments installed in dry and wet seasons, respectively. I and II denotes the first and second ratoons. Sources: CEPAGRI (http://www.cpa.unicamp.br) and ESALQ (http://www.leb.esalq.usp.br/posto/).

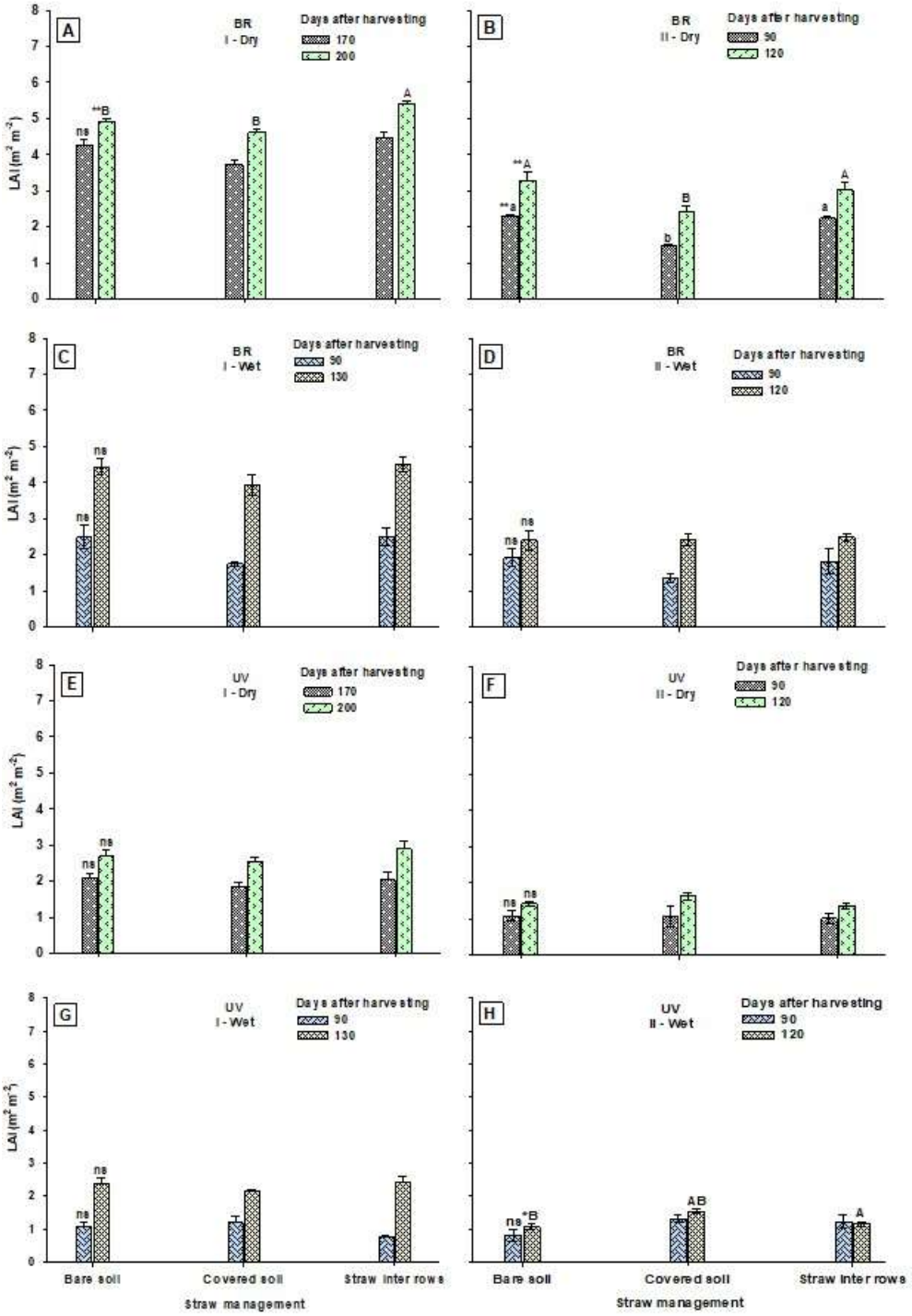

Fig. 2S. Leaf area index (LAI) of sugarcane cultivated under different straw blanket management treatments during the dry and wet-season at Bom Retiro – BR (A and B) and Univalem - UV (C and D) over two ratoons ** and * significant by Tukey's test ($p < 0.01$) and ($p < 0.05$), respectively; ns: non-significant; error bars denote standard error of the mean.

Table 1S. Time required for phytomass accumulation in all trials across each ratoon cycle in both mills

First year						Second year					
Dry season			Wet season			Dry season			Wet season		
Bom Retiro mill											
Phases	**Period (days)**	**Dry mass yield (%)**	**Phases**	**Period (days)**	**Dry mass yield (%)**	**Phases**	**Period (days)**	**Dry mass yield (%)**	**Phases**	**Period (days)**	**Dry mass yield (%)**
Lag	136	14	**Lag**	100	22	**Lag**	130	20	**Lag**	80	19
Linear growth	126	80	**Linear growth**	63	75	**Linear growth**	93	73	**Linear growth**	70	76
Stationary	96	6	**Stationary**	197	3	**Stationary**	137	7	**Stationary**	210	5
Univalem mill											
Lag	136	22	**Lag**	173	19	**Lag**	110	13	**Lag**	119	25
Linear growth	74	72	**Linear growth**	70	72	**Linear growth**	63	82	**Linear growth**	98	71
Stationary	150	6	**Stationary**	117	9	**Stationary**	187	5	**Stationary**	143	4

Sugarcane industrial quality under different straw blanket managements

Straw blanket managements did not affect sugarcane industrial quality (Table 1). This result is in line with those reported by Aquino et al. (2016).

The sucrose accumulation (*i.e.*, ripening process) on stalks is increased by moderate drought (Silva and Caputo, 2012), associated to low air temperature (van Heerden et al., 2013). In our study, these events occurred from February to September of each year (Figs. 2 and 1S A and B), which lead to natural ripening process of stalks. However, drought is pointed as the main drive of the sugarcane ripening process within the most important Brazilian producing areas, with low water availability on soil. By consequence, it occurs with plant dehydration (Cardozo and Sentelhas, 2013). In this context, it was expected that stalks from managements with straw above soil surface (*i.e.*, covered soil and rake managements) would present lower industrial quality, since the increasing on water content is pointed out as one of the main benefits of straw maintenance on soil surface to the plant-soil system (Ball-Coelho et al., 1993; Tavares et al., 2010; Nxumalo et al., 2017; Anjos et al., 2017). Despite our expectation, even extremes straw managements, such as all straw removal or keeping it above soil surface, did not influence sugarcane industrial quality (Table 1). Although plants under straw cover and rake managements may have available soil water content for plant growth, low soil nitrogen content associated with the decreasing on soil temperature may have limited plant growth, which in turn lead to sucrose accumulation on the stalks under the treatments with straw, without reducing stalk industrial quality. High rates of nitrogen immobilization (*i.e.,* unavailability in short term) can occur on soil under straw blanket (Basanta et al., 2003; Meier et al., 2006; Trivelin et al., 2013; Ferreira et al., 2016).

Table 1. Industrial quality of sugarcane stalk at the end of each experiment

Parameters (%)	First year						Second year					
	Dry season			Wet season			Dry season			Wet season		
	Amount of straw (Mg ha^{-1})											
	0.0	**15.6#**	**16.6**	**0.0**	**18.9**	**23.3#**	**0.0**	**14.7**	**17.2#**	**0.0**	**13.6**	**14.3#**
	Bom Retiro mill											
Brix	18.4^{ns}	17.9	18.0	18.4^{ns}	17.7	17.6	19.5^{ns}	19.0	19.4	16.1^{ns}	15.7	15.7
Pol	16.0^{ns}	15.7	15.8	16.3^{ns}	15.5	15.4	17.2^{ns}	16.4	17.1	13.4^{ns}	12.9	13.0
RS	0.65^{ns}	0.63	0.62	0.60^{ns}	0.62	0.65	0.61^{ns}	0.68	0.62	0.79^{ns}	0.80	0.80
Fiber	12.1^{ns}	11.9	12.5	12.4^{ns}	12.7	12.1	14.5 ^{ns}	14.3	14.8	13.8^{ns}	13.4	13.2
Purity	87.2 ^{ns}	87.7	87.2	88.6 ^{ns}	87.7	87.3	88.3 ^{ns}	86.8	88.0	83.3^{ns}	82.7	82.9
	Amount of straw (Mg ha^{-1})											
	0.0	**15.0**	**13.8#**	**0.0**	**13.2#**	**16.4**	**0.0**	**12.1#**	**12.4**	**0.0**	**13.3#**	**13.7**
	Univalem mill											
Brix	18.2^{ns}	18.3	18.0	18.8^{ns}	19.1	18.0	18.8^{ns}	19.0	19.0	14.9^{ns}	14.6	15.0
Pol	20.3^{ns}	20.3	20.2	16.7^{ns}	16.9	15.9	21.4^{ns}	21.5	21.4	17.4^{ns}	17.3	17.4
RS	0.41^{ns}	0.43	0.42	0.48^{ns}	0.50	0.49	0.45^{ns}	0.46	0.49	0.48^{ns}	0.48	0.49
Fiber	13.9^{ns}	13.8	14.4	13.1^{ns}	13.5	13.2	16.4^{ns}	16.2	15.6	19.0^{ns}	19.8	18.7
Purity	91.3^{ns}	90.9	91.1	89.2^{ns}	88.4	88.5	89.3^{ns}	89.0	88.3	87.4^{ns}	87.2	87.3

#Rake management; Brix: soluble solids content; Pol: apparent sucrose content; RS: reducing sugars; Fiber: fiber content; Purity: apparent juice purity; ns: within the same season, means are not significant by Tukey's test ($p < 0.05$).

Overall, stalks from the wet season presented lower industrial quality compered to stalk harvested in the dry season, this is especially remarkable on the treatments installed at Univalem mill (Table 2S). Rainfall events combined with the increase on temperature months after harvesting may increase stalk hydration, which reduces Brix and pol parameters (*i.e.*, indirect way to evaluate sucrose content) concentration. In contrast, the increasing on reducing sugars (AR) percentage would be a consequence of the sucrose breaks down to short-chain hexoses (*i.e.*, reducing sugars), these sugars would be demanded for new plant tissue formation, such as tillers sprouting. Finally, the reduction on stalk purity also may be associated to the increase on rain precipitations and temperature months after harvesting. These two conditions later on the cycle favor plant tillering, these unripened plants are harvested and milled along with ripened stalk, which reduce the purity of the juice. Higher soil water content at the end of the cycle, mainly associated with wind, favors plant lodging which difficult harvesting performance. Thus, during harvesting more impurities (*i.e.*, soil and senescent leaves) are taken to the mill, which also decreasing juice purity.

Table 2. Industrial quality of sugarcane stalk as affected by trial season set up in three straw blanket management treatments at both sites over two years

	First year						Second year					
	Straw blanket management											
Parameter	Bare soil		Straw cover		Rake		Bare soil		Straw cover		Rake	
(%)	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season	Dry season	Wet season
Bom Retiro mill												
Brix	18.4^{ns}	18.4	18.0^{ns}	17.6	17.9^{ns}	17.6	19.5a**	16.1b	19.0a*	15.7b	19.4a**	15.7b
Pol	16.0^{ns}	16.3	15.8^{ns}	15.5	15.7^{ns}	15.4	17.2a**	13.4b	16.4a*	12.9b	17.1a**	13.0b
RS	0.65^{ns}	0.60	0.64^{ns}	0.63	0.63^{ns}	0.65	0.61b**	0.79a	0.68b**	0.80a	0.62b**	0.80a
Fiber	12.1^{ns}	12.4	12.4^{ns}	12.7	11.9^{ns}	12.1	14.5^{ns}	13.8	14.3 ^{ns}	13.4	14.8a**	13.2b
Purity	87.2 ^{ns}	88.6	87.4^{ns}	87.7	87.7 ^{ns}	87.3	88.3a**	83.3b	86.3a*	82.7b	88.0a**	82.9
Univalem mill												
Brix	18.2^{ns}	18.7	18.3^{ns}	18.0	18.0^{ns}	19.1	18.8 a**	14.9b	19.2 a**	15.0b	19.0 a**	14.6b
Pol	20.3a**	16.7b	20.3a**	16.0b	20.2a**	16.9b	21.4 a**	17.4b	21.4 a**	17.4b	21.5 a**	17.3b
AR	0.41b*	0.48a	0.43b**	0.49a	0.41^{ns}	050	0.45^{ns}	0.48	0.48 ^{ns}	0.48	0.46 ^{ns}	0.48
Fiber	13.9^{ns}	13.1	13.8^{ns}	13.2	14.4^{ns}	13.5	16.4b*	19.0a	15.6b*	18.7a	16.2b*	19.7a
Purity	91.3a	89.2b	90.9 ^{ns}	88.5	91.1 ^{ns}	88.4	89.3 ^{ns}	87.4	88.3 ^{ns}	87.3	89.0 ^{ns}	87.2

Brix: soluble solids content; **Pol:** apparent sucrose content; **RS:** reducing sugars; **Fiber:** fiber content; **Purity**: apparent juice purity; within the same straw management system means values followed by the same letter do not differ between themselves according to Tukey's test ($p < 0.01$)****** and ($p < 0.05$)*****; **ns**: non-significant

REFERENCES

Anjos, J.C.R.D., Andrade Júnior, A.S.D., Bastos, E.A., Noleto, D.H., Melo, F.D.B., and R.R.D. Brito. 2017. Water storage in a Plinthaqualf cultivated with sugarcane under straw levels. Pesq. agropec. bras 52:464-473. doi.org/10.1590/s0100-204x2017000600010

Aquino, G.S., de Conti Medina, C., Junior, A.D.O.M., Pasini, A., Brito, O.R., Cunha, A.C.B., dos Santos Junior J.H., Kussaba D.A.O., and L.F. Almeida. 2016. Impact of harvesting with burning and management of straw on the industrial quality and productivity of sugarcane. Afr. J. Agric. Res. 11 (28):2462-2468. doi.org/10.5897/AJAR2016.11014

Ball-Coelho, B., Tiessen, H., Stewart, J.W.B., Salcedo I.H., and E.V.S.B. Sampaio. 1993. Residue management effects on sugarcane yield and soil properties in Northeastern Brazil. Agron. J. 85, 1004–1008. doi:10.2134/agronj1993.00021962008500050009x

Basanta, M.V., Dourado-Neto, D., Reichardt, K., Bacchi, O.O., Oliveira, J.C., Trivelin, P.C., Timm, L.C., Tominaga T.T., Correchel, V., Cássaro, F.A., and L.F. Pires. 2003. Management effects on nitrogen recovery in a sugarcane crop grown in Brazil. Geoderma. 116(1-2):235-248. doi.org/10.1016/S0016-7061(03)00103-4

Cardozo, N.P., and P.C. Sentelhas. 2013. Climatic effects on sugarcane ripening under the influence of cultivars and crop age. Sci. Agric. 70:449-456. doi.org/10.1590/S0103-90162013000600011

Ferreira, D.A., Franco, H.C., Otto, R, Vitti, A.C., Fortes, C., Faroni, C.E., Garside, A.L. and P.C.O. Trivelin. 2016. Contribution of N from green harvest residues for sugarcane nutrition in Brazil. Gcb Bioenergy, 8(5):859-866. doi.org/10.1111/gcbb.12292

Meier, E.A., Thorburn, P.J., Wegener, M.K., and K.E. Basford. 2006. The availability of nitrogen from sugarcane trash on contrasting soils in the wet tropics of North Queensland. Nutr Cycl in Agroecosyst, 75(1-3), pp.101-114. doi.org/10.1007/s10705-006-9015-0

Nxumalo, N., Ramburan, S., and J.M. Steyn. 2017. Growth and yield responses of commercial sugarcane cultivars to mulching in the coastal rainfed region of South Africa. S Afr J Plant & Soil. 34:9-18. doi.org/10.1080/02571862.2016.1148787

Silva, M.A., and M.M. Caputo. 2012. Ripening and the use of ripeners for better sugarcane management. In: Marin, F.R., (Ed.) Crop management: cases and tools for higher yield and sustainability. InTech, 2-24. doi: 10.5772/28958

Tavares, O.C.H., Lima, E, and E. Zonta. 2010. Crescimento e produtividade da cana planta cultivada em diferentes sistemas de preparo do solo e de colheita. Acta Sci Biol Sci. 32:61-68. doi.org/10.4025/actasciagron.v32i1.2051

Trivelin, P.C., Franco, H.C., Otto, R., Ferreira, D.A., Vitti, A.C., Fortes, C., Faroni, C.E., Oliveira, E.C., and H. Cantarella. 2013. Impact of sugarcane trash on fertilizer requirements for São Paulo, Brazil. Sci. agric. 70(5):345-352. doi.org/10.1590/S0103-90162013000500009

van Heerden, P.D., Eggleston, G., and R.A. Donaldson. 2013. Ripening and postharvest deterioration. In: Moore PH, Botha FC (Eds.) Sugarcane: Physiology, Biochemistry, and Functional Biology. Wiley-Blackwell, Oxford, 55-84. doi: 10.1002/9781118771280.ch4

5. APPLYING SOIL QUALITY ASSESSMENT FRAMEWORK (SMAF) ON SHORT-TERM SUGARCANE STRAW REMOVAL IN BRAZIL

Abstract

There is a growing interest by the Brazilian sugarcane (*Saccharum sp.*) industry in removing sugarcane straw from the field to use as raw material for increasing bioenergy production (*e.g.*, second generation and co-generation). In contrast, straw has an essential role in sustaining many soil functions, thus indiscriminate straw removal can jeopardize soil quality leading to crop yield reduction. The objective of this study was: (i) to apply Soil Management Assessment Framework (SMAF) tool to investigate the effects of sugarcane straw removal on a sandy clay loam Oxisol and on a sandy loam Ultisol, and ii) to correlate soil attributes (*i.e.*, chemical, physical and biological) and Soil Quality (SQ) under straw removal with phytomass yield (straw and stalk). A 2-year experiment was conducted in a randomized block with three percentiles of straw removal: 0, 50 and 100% (*i.e.*, total removal, moderate removal and no removal) and four replications. Soil samples were taken at 0-5, 5-10, 10-20 and 20-30 cm and analyzed for the attributes: physical [bulk density (BD)], chemical [soil-pH, phosphorus (P) and potassium (K) content] and biological [soil organic carbon (C) and microbial biomass carbon (MBC)]. Scoring curves existent in SMAF were used to transform measured values in scores ranging from 0 to 1. Individual attribute scores are then combined to generate a Soil Quality Index (SQI). Lower scores of soil-physical attribute were observed under 100% straw removal at 5-10 and 10-20 cm in the Oxisol. At this site, 100% straw removal decreased SQI in the 0-20 cm depth, while for the 0% and 50% straw removal rates enhanced SQIs at the 0-5 ($p = 0.024$); 5-10 ($p = 0.003$) and 10-20 cm depths ($p = 0.013$). At the Ultisol site, straw removal management did not influence SQI in the short-term, however taking into account the long-term benefits of the straw on the soil-plant system, indiscriminate straw removal is not advocated. At the Oxisol site, 50% straw removal sustained soil quality and increased feedstock availability for bioenergy production. Straw and stalk yields are correlated to the scores of soil-physical attribute and SQI score evaluated within 0-10 cm at the Oxisol. Based on our findings, total straw removal leads to Oxisol physical quality degradation even in the short term. Thus, soil physical attribute should be prioritized and actions taken to improve it and overall soil quality and, consequently, sustain crop yield. Partial straw removal can be a win-win scenario in Brazil, where a considerable volume of biomass can be used for bioenergy production without (or with minimum) negative impacts on the soil quality.

Keywords: Sugarcane; Sugarcane straw removal; Bioenergy feedstock; Soil Quality; SMAF

5.1 Introduction

Brazil is the world's largest sugarcane (*Saccharum spp.*) producer with ~9 Mha planted with the crop and 633 millions tons of stalks harvested (Conab, 2018), the country is also globally known for producing and using sugarcane ethanol for more than 40 years (Moraes et al., 2017). To attend the increasing demand for bioethanol and sugar consumption, areas cropped with sugarcane is raising fast (Hess et al., 2016). The sugarcane mechanical harvesting has been

adopted since early 2000s (Lisboa et al., 2017) and large amount of straw (*i.e.*, 10-20 Mg ha^{-1}) is left on the field with this practice (Hassuani et al., 2005), once for each Mg of stalk harvested, 0.12-0.14 Mg of straw is generated (Leal et al., 2013; Pierossi et al., 2016). This harvesting residue has a potential to be used as a feedstock for bioenergy production (*e.g.*, second generation and co-generation) (Lisboa et al., 2017; Menandro et al., 2017; Correa et al., 2017 Vasconcelos et al., 2018; Silveira et al., 2018). Second generation ethanol is pointed out to supply the national demand of this biofuel (Damaso et al., 2014).

In contrast, the maintenance of crop residue on soil surface protect the soil against the direct impact of raindrop, preventing soil disaggregation, surface sealing and reduction in water infiltration in the soil (Johnson et al. 2016). In addition, the thick layer of straw regulates soil temperature, reduces water losses by evaporation (Correa et al., 2017) and increase soil water retention (Anjos et al., 2017) and soil resistance to compaction (Satiro et al., 2017). In sugarcane fields, straw decomposition promotes increments in soil organic C stocks (Bordonal et al., 2018b; Sousa Jr et al., 2018; Vasconcelos et al., 2018), biological activity (Paredes Jr. et al., 2015), nutrient cycling (Fortes et al., 2012; Almeida et al. 2015), and potential increase on plant-available N in the long-term (Trivelin et al., 2013). Therefore, straw retention has an important role in sustaining and improving soil functioning (Cherubin et al., 2018) and consequently to agronomic sustainability of sugarcane production system (Carvalho et al., 2017).

Therefore, to capture the integrated effects of sugarcane straw removal on soil quality (SQ) [*i.e.*, the soil's capacity to perform its functions (Karlen et al., 1997)], it is imperative to apply integrative approaches that encompassing chemical, physical and biological soil attributes (Bünemann et al., 2018; Idowu et al., 2008). Since late 90s, several approaches for assessing SQ have been developed (Acton and Gregorich, 1995; Andrews at al., 2004; Idowu et al., 2008; Cherubin et al., 2016a; Moebius-Clune et al., 2016). Among these approaches, Soil Management Assessment Framework (SMAF) has been successfully applied for different ecosystems around the world; this tool was developed by Andrews at al. (2004) for assessing soil conditions in the USA. The main advantage of using SMAF is that among 81 potential indicators available, it can be quite flexible to set up a minimum dataset for soil quality assessment (Bünemann et al., 2018).

In Brazil, the SMAF was introduced to evaluate the impacts of land use change scenarios for sugarcane expansion on the quality of tropical soils in Cerrado (Cherubin et al., 2016b). Afterwards, SMAF was used to evaluate the effects of several management practices on quality of subtropical soils with contrasting texture in southern region (Cherubin et al., 2017). Despite that, there is no available studies in the literature in which potential SQ changes under sugarcane straw removal management were assessed using SMAF, as well as are unknown the implications of

those changes on SQ, induced by straw removal, on plant growth. We tested two hypothesis in this study: i) sugarcane straw removal reduces SQ - even under short term - and SMAF is able to detect those potentials changes; and ii) Plant growth is affected by SQ changes under straw removal management. For testing our hypothesis, we conducted two experiments at different soil types (*i.e.*, Oxisol and Ultisol) within the main sugarcane-producer area in Brazil aiming to assess SQ changes and consequent impacts on crop yield in the short-term.

5.2 Material and methods

5.2.1 Description of study sites, climatic conditions and sugarcane varieties

The field experiments were conducted at two sites over two years. Both areas are located within southeastern Brazil at São Paulo state and they represent typical producing-areas of sugarcane. Sites, climatic conditions and sugarcane varieties are described at table 1.

Table 1. Location and brief description of climate and sugarcane varieties used at each study site

Soil type	Parameter	Description
Oxisol	Location	Lat. 22°59'42" S; Long. 47°30'34" W (Capivari, São Paulo)
	Climate[a]	The climate type (Cwa) for this location is subtropical humid characterized by dry winter and hot summer, with a mean annual temperature of 21.8 °C and annual precipitation of 1,289 mm. Annual precipitations are within the spring and summer (October to April) and the dry season occurs in the autumn and winter (May to September). Details about precipitation across each year are shown in Lisboa et al. (2018).
	Sugarcane variety	CTC 14: recognized by high productivity (over 90 Mg ha^{-1}) and drought tolerance, with excellent ratoon longevity. This variety is also resistant to rust, scalding, yellowing and to the borer (Goes et al., 2011).
Ultisol	Location	Lat. 21°14'48" S; Long. 50°47'04" W (Valparaiso, São Paulo)
	Climate[a]	The climate type (Aw) for this location is tropical characterized by dry winter, with a mean annual temperature of 23.4 °C and annual precipitation of 1,241 mm. Precipitations over the year are similar to the previous location and details presented at Lisboa et al. (2018)
	Sugarcane variety	RB 867515: Characterized for not requires soils highly fertile and presenting optimum sprouting, especially under straw blanket. In addition, the variety is drought tolerant and rarely blooming (Marin et al., 2009).

[a] Köppen classification

Within each study site, the sugarcane was planted in February/2013 and the treatments were applied immediately after plant cane (first cycle) harvesting, in August /2014. First and second harvesting were performed in August of 2015 and 2016, respectively. Sugarcane was planted using an alternating double row spacing scheme (*i.e.*, 1.5 and 0.9 m in the same area) and the inputs (lime and fertilizers) were managed for the crop according to recommended by Raij et al. (1997).

5.2.2 Treatments set up and experimental design

In order to remove different rates of sugarcane straw from the field, we set up the harvester with different angular velocity on the primary extractor fan and keep the secondary extractor fan off or on. Initially, our goal was to remove the amount of straw proportional to 0, 50 and 100% of the straw yielded in each area, however these exactly proportions of straw were no reached on field conditions. Despite of this fact, the amount of straw obtained on each treatment is very close to that intended (Table 2). Details about different angular velocity used on the primary extractor fan as well as the machinery efficiency in removing different amount of

straw are described in Lisboa et al. (2017). The experimental design was randomized blocks with three treatments (*i.e.*, straw removal rates) and four replications (plots of ~50 x 25 m).

Table 2. Sugarcane straw amount left on soil surface in each treatment and year

Sugarcane straw removal rate	Bom Retiro mill		Univalem mill	
	Year I	Year II	Year I	Year II
	Straw amount left on the soil surface (Mg ha^{-1})§			
100	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)	0.0 (±0.0)
50	7.8 (±0.6)	9.7 (±0.4)	8.4 (±0.7)	7.9 (±0.1)
0	16.6 (±1.6)	14.7 (±0.8)	15.0 (±1.1)	12.4 (±0.8)

§dry mass; $^{(I)}$ and $^{(II)}$ denote the first and second sugarcane ratoon, respectively; the standard error associated to the mean (n = 12) is presented between brackets

5.2.3 Soil characterization

Soon after setting up the treatments (*i.e.,* August/2014) soil samples were taken in both sites for physical and chemical characterization (Table 3, item 4.2.2). One year after treatments establishment (August/2015), harvesting was performed and different rates of straw reapplied. To assess the potentials effects of different rates of straw on soil chemical, physical and biological attributes over 2-years experiment conduction, soil samples were taken again on August/2016, soon after sugarcane harvesting.

Soil samples were taken on three points within a transect in each plot. At each sampling point, a small trench (~30 cm x 30 cm x 30 cm) was dug between sugarcane rows and disturbed soil samples were collected from the 0-2.5, 2.5-5, 5-10, 10-20, and 20-30 cm layers for the characterization of chemical attributes and soil C content. In addition, undisturbed soil samples were also collected using a ring of (~100 cm^{-3}) to determine bulk density (BD), these samples were taken at the central trench of each transect at 0-5, 5-10, 10-20 and 20-30 cm depths.

Disturbed soil samples were air dried and sieved through a 2 mm mesh an the levels of calcium (Ca), magnesium (Mg), phosphorous (P) and potassium (K) were extracted using an ion exchange resin method. The phosphorous was determined in the molecular absorption spectrophotometer and the other soil macronutrients in an atomic absorption spectrophotometer (Raij et al., 2001). In order to determine carbon (C) and nitrogen (N) contents on each layers soil sub-sample was ground to a fine powder and sieved with 100 mesh (0.149 mm), total C and N were determined by dry oxidation, using an elemental analyzer (Leco© Truspec®, St. Joseph, Michigan) according to Nelson and Sommers (1996). The pH was determined in water at a soil:solution ratio of 1:2.5. The soil bulk density was determined by dividing the soil dry mass by

the volume of the ring. The microbial biomass carbon (MBC) at the 0-5 and 5-10 cm soil layers was quantified by fumigation method, according to Reis Junior and Mendes (2007).

5.2.4 Soil quality assessment

Three steps are needed for soil quality assessment through SMAF:

i) selection of a minimum dataset: in this study, pH, P, K, BD, MBC and SOC were the indicators used to evaluate SQ within the 0-5 and 5-10 cm layers, while pH, P, K, BD and SOC were the indicators chosen for the 10-20 and 20-30 cm layers. According to SMAF guidelines, five indicators are the minimum required to SQ assessment through this tool, with at least an indicator representing soil biological, chemical and physical attributes (Karlen et al., 2008). The importance of each selected indicator was widely discussed by Cherubin et al. (2016c, 2017);

ii) interpretation of the indicators: the SMAF spreadsheet has scoring curves (algorithms) for 13 soil indicators, which transform the measured value in a score ranging from 0 to 1, according to type of soil, soil texture, mineralogy, climate, sampling season, slope, crop and analytical method (Andrews et al., 2004; Wienhold et al. 2009; Stott et al. 2010). These factors that affecting directly the algorithms are categorized in classes within the SMAF spreadsheet, as presented in table 3.

Table 3. Factor classes used for each study site and respective scoring curves affected by these factors.

Factor	Oxisol	Ultisol	Indicator scoring curve
	Classes		
Soil type	4 (OM low)	4 (OM low)	SOC
Texture	4 (Sandy clay)	2 (Sandy loam)	SOC, BD, MBC, P
Soil mineralogy	3 (Slightly- all others)		BD
Weathering class	2 (High weathering)		P
Slope of the field	2 (2-5%)	4 (9-15%)	P
Climate	1(≥170 ºC d and ≥550 ºC mm)#		SOC, P and MBC
Sampling season	3 (Fall)		MBC
Crop	Sugarcane		pH and P
P method	5 (Resin)		P

#Mean of annual precipitation

iii) integrate the indicator scores into an index: the scores of each attribute is composed in an overall soil quality index (SQI) that also range from 0 to 1. The SQI is then expressed as a fraction or percentage of a such soil performs its functions for crop productivity, nutrient cycling, or environmental protection (Andrews et al., 2004). In our case, the comparison of SQIs allows

us to identify the straw removal effect on soil's capacity to function and sustain the crop productivity.

The SQI was calculated following the simple additive approach, using the equation 2.

$$\text{SQI} = \sum_{i=1}^{n} \frac{Si}{n} \tag{2}$$

where, SQI is soil quality index; Si is the indicator score, n the number of indicators integrated in the index.

The overall SQI was also subdivided into chemical (pH, P, and K), physical (BD), and biological (SOC and MBC) sectors, as well as their relative contributions to the overall SQI. It allows us identifying of managements (rates of straw removal) of greatest concern (*i.e.*, lowest index scores) so that land managers can take action and efficiently restore or improving SQ at a specific location (Stott et al., 2013; Karlen et al., 2014).

5.2.5 Stalk and final straw yields response to sugarcane straw removal

One year after harvesting the first ratoon, total above ground phytomass was determined. The plants within 4 m on raw were separated in stalk, dry and green leaves then the fresh phytomass of each component was determined through an electronic scale. Thereafter, total phytomass of each component was ground in a forage grinder, subsampled and over-dried at 65 ^{o}C. Subsamples were re-waited for dry mass determination and total dry mass yield per hectare was estimated using row-space of 1.2 m and one hectare with 8,333 meters of rows.

Stalk yield was quantified at the end of each ratoon cycle, approximately one year from previous harvesting. The stalk fresh mass mechanically harvested from the five central rows 500 m long (525 m^2) of each plot was weighed in the field using a wagon coupled with a scale and extrapolated to Mg ha^{-1}.

5.2.6 Statistical analysis

One-way ANOVA analysis was performed to test differences in response variables [*i.e.*, soil attributes (Chem = chemical, Bio = biological and Phy = physical) and SQI] among treatments (100, 50, 0% of straw removal). When significant (F-test $p<0.05$), the means were compared using Tukey's test ($p<0.05$). Comparisons of means were performed using the *agricolae* R package (Mendiburu and Simon, 2015) available within R Software (R Core Team, 2006).

Finally, a Principal Component Analysis (PCA) was performed to understand the relationship among each soil attributes and SQI as affected by straw removal management and phytomass yield (*i.e.,* straw yield = SwY and stalk = SkY). PCAs were performed using the *princomp stats* package available within R Software (R Core Team, 2006).

5.3 Results

5.3.1 Straw removal effects on soil quality

Oxisol was the most sensitive to straw removal rates in the short term. However, there is no a single pattern to explain sugarcane straw removal effects on chemical, biological and physical scores at both soil types (Table 4). Overall, soil chemical parameters (*i.e.*, pH, P and K scores) were little affected by straw removal rates (Table 1S), this same pattern was verified for the scores of each indicators. Among the three chemical parameters, straw removal rates reduced only K score in the deepest layer at the Ultisol condition, while total straw removal decreased pH score within 5-10 cm at the Oxisol condition. In both soil types, SOC scores were slightly reduced under total removal for the 0-5 cm, where MBC values reached the maximum scores for all treatment. Bulk density scores were not affected by straw removal rates at Ultisol, whereas total straw removal reduced BD score within the 5-10 and 10-20 cm layers at the Oxisol (Table 4).

Table 4. SMAF scores of soil quality indicators for the 0.00 – 0.05, 0.05 – 0.1, 0.1-0.2 and 0.2 a 0.3 m layers under three straw managements in both sites

Straw removal (%)	Oxisol						Ultisol					
	pH (H2O)	P	K	BD	SOC	MBC	pH (H2O)	P	K	BD	SOC	MBC
	SMAF Scores 0.00 – 0.05 m											
100 - total removal	0.96 ^{ns}	1.00^{ns}	0.67^{ns}	0.30^{ns}	0.94 b*	1.00^{ns}	0.99^{ns}	0.97^{ns}	0.47^{ns}	0.26^{ns}	0.36 b*	1.00^{ns}
50 - partial removal	0.96	1.00	0.76	0.34	0.97 a	1.00	0.98	0.95	0.51	0.27	0.39 ab	1.00
0 - no removal	0.97	1.00	0.79	0.41	0.98 a	1.00	0.99	0.97	0.46	0.27	0.45 a	1.00
	SMAF Scores 0.05 – 0.1 m											
100 - total removal	0.97 b*	1.00^{ns}	0.45^{ns}	0.27 b**	0.91^{ns}	1.00^{ns}	0.98^{ns}	0.90^{ns}	0.30^{ns}	0.23^{ns}	0.27^{ns}	1.00^{ns}
50 - partial removal	0.99 a	1.00	0.52	0.31 b	0.94	1.00	0.98	0.86	0.29	0.23	0.27	1.00
0 - no removal	0.98 ab	1.00	0.52	0.37 a	0.93	1.00	0.99	0.95	0.33	0.24	0.30	1.00
	SMAF Scores 0.1 – 0.2 m											
100 - total removal	0.94^{ns}	1.00 ^{ns}	0.36^{ns}	0.29 b	0.87^{ns}	-----	0.94^{ns}	0.79^{ns}	0.18^{ns}	0.23^{ns}	0.21^{ns}	-----
50 - partial removal	0.97	1.00	0.43	0.36 a	0.90	-----	0.97	0.68	0.19	0.26	0.20	-----
0 - no removal	0.98	1.00	0.43	0.36 a	0.90	-----	0.96	0.82	0.24	0.22	0.23	-----
	SMAF Scores 0.2 – 0.3 m											
100 - total removal	0.85^{ns}	0.99^{ns}	0.40^{ns}	0.32^{ns}	0.82^{ns}	-----	0.91^{ns}	0.63 ^{ns}	0.17 b*	0.23^{ns}	0.19^{ns}	-----
50 - partial removal	0.84	0.99	0.32	0.36	0.82	-----	0.90	0.60	0.18 b	0.23	0.19	-----
0 - no removal	0.81	1.00	0.35	0.44	0.78	-----	0.93	0.63	0.26 a	0.22	0.22	-----

** and * significant by Tukey's test ($p < 0.01$) and ($p < 0.05$), respectively; ns: non-significant.

SMAF was able to detect changes on SQI induced by straw removal rates within the 0-20 cm, and moderate straw removal rate did not reduce SQI on this depth. However, the same rate of straw removal did not influence the scores of chemical and biological attributes in the short-term, while partial or no straw removal improved soil physical quality within the 5-20 cm layer in Oxisol (Fig. 1).

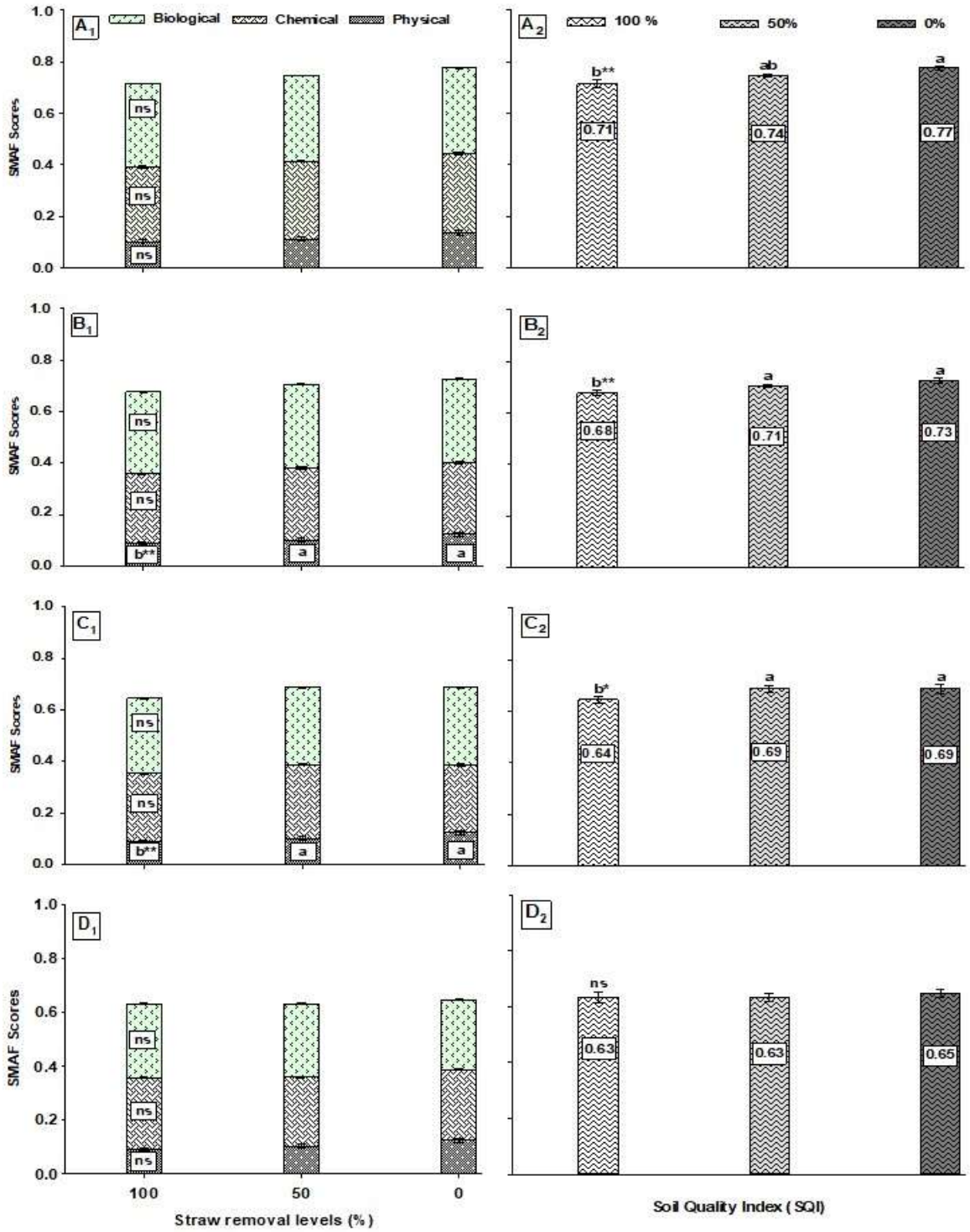

Fig. 1. SMAF scores of each soil attribute (1 subscribed) and SQI (2 subscribed) as affected by straw removal rates in an Oxisol; A, B, C and D are respectively the depths 0.00-0.05, 0.05-0.10, 0.10-0.20 and 0.20-0.30 m; ** and * significant by Tukey's test ($p < 0.01$) and ($p < 0.05$), respectively; ns: non-significant.

Despite the fact of straw removal rates treatments did not affect none of the soil attributes (*i.e.*, chemical, physical and biological) within the 0-5 cm, total straw removal decreased

overall SQI in this layer. It compared to total straw removal, SQI scores were ~ 4 and 8 % higher under moderate and no straw removal respectively (Fig 3. A_2). Although SQI scores decreased in depth, the same pattern verified within the 0-5 cm was kept on the following two layers, *i.e.*, 5-10 (Fig. 1 B_2) and 10-20 (Fig. 1 C_2) cm, and even moderate amount of straw retention was able to increase SQI scores. It compared to total straw removal, SQI scores were 3 and 5% higher, respectively under moderate and no straw removal in 5-10 cm, while within the 10-20 cm layer partial or no straw removal increased SQI scores in 5%. Even though none of the straw rates adopted on this study did influence soil attributes-scores (Fig. 1 D_1) and SQI score on deepest layer, it remains the trend of improving SQI score under no straw removal treatment (Fig 1. D_2).

The different rates of straw removal slightly influenced individual scores of soil quality indicators (*i.e.*, pH, P, K, BD, SOC and MBC) in the short term (Table 4); as a consequence of it, SMAF did not detect any change on Ultisol attributes and SQI scores within 0-20 cm layer as a result of sugarcane straw removal rates (Fig. 2).

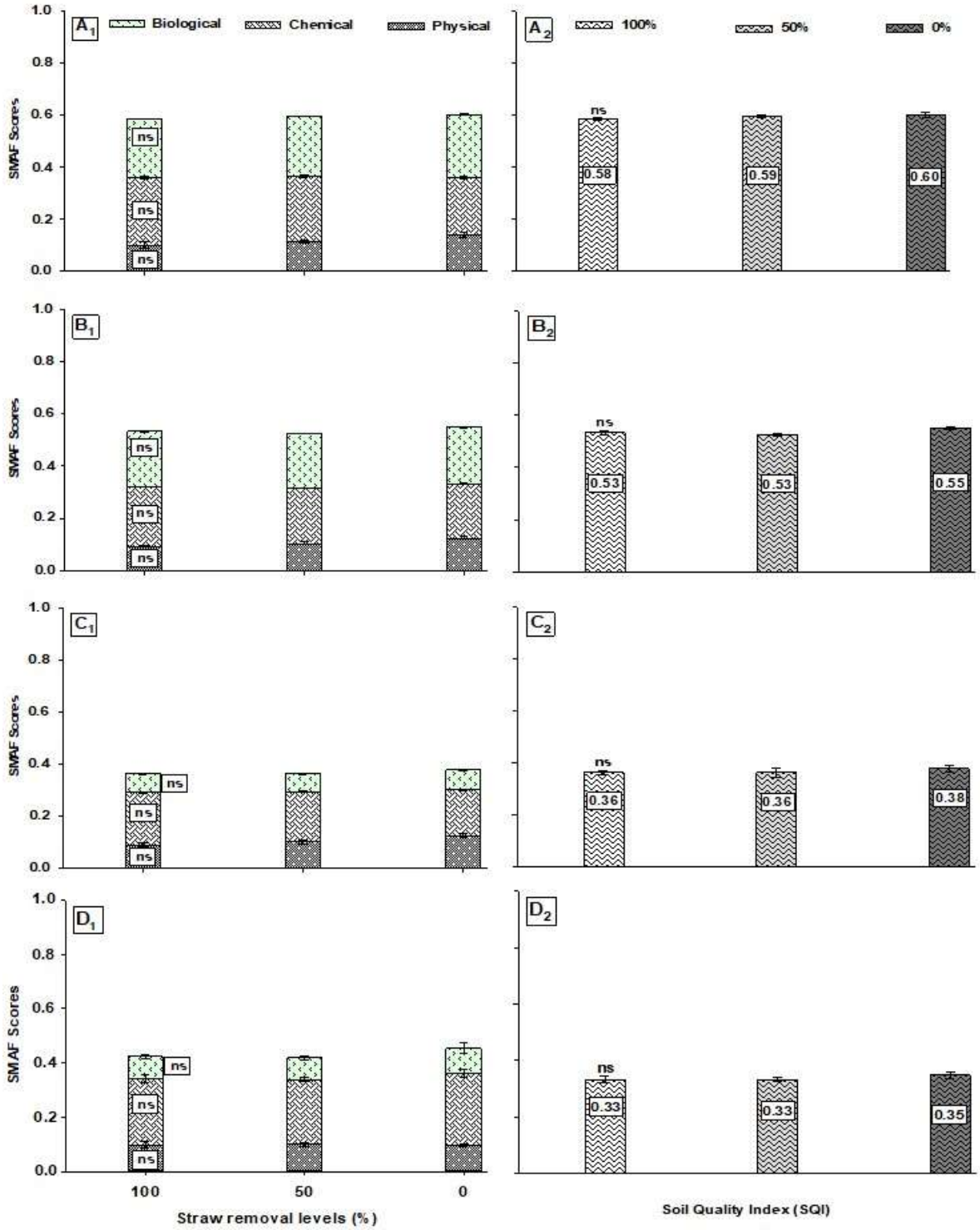

Fig. 2. SMAF Scores of each soil attribute (1 subscribed) and SQI (2 subscribed) as affected by three levels of straw removal in an Ultisol; A, B, C and D are respectively the depths 0.00-0.05, 0.05-0.10, 0.10-0.20 and 0.20-0.30 m; ns: non-significant by Tukey's test ($p < 0.05$).

5.3.2 Soil quality changes under straw removal and their impacts on plant growth

The relationship of SQ changes and sugarcane yield (stalk and straw) was investigated by PCA analysis (Fig. 3). The first two components explained 65 and 70% of data variance, respectively for the 0-10 (Fig. 3 A) and 10-20 cm (Fig. 3 B) at Oxisol. Overall, all scores of soil chemical, physical and biological indicator as well as the score of SQI within the 0-10 cm are positively related with straw maintenance on the soil surface (0% of straw removal) (Fig. 3 A). Despite this fact, total straw yield (SwY) and total stalk yield (SkY) over both ratoons were correlated only with SQI-physical score within the same depth. The soil attributes and SQI within the 10-20 cm layer tend to enhance with straw maintenance on the Oxisol surface. Moreover, among the soil attributes, the physical attribute is the one most closely related to SQI in the 10-20 cm layer in the same depth and soil type (Fig. 3). In this same depth, straw yield (SwY) was associated to chemical-attribute score, while stalk yield (SkY) was related to the score of soil physical attribute and SQI score.

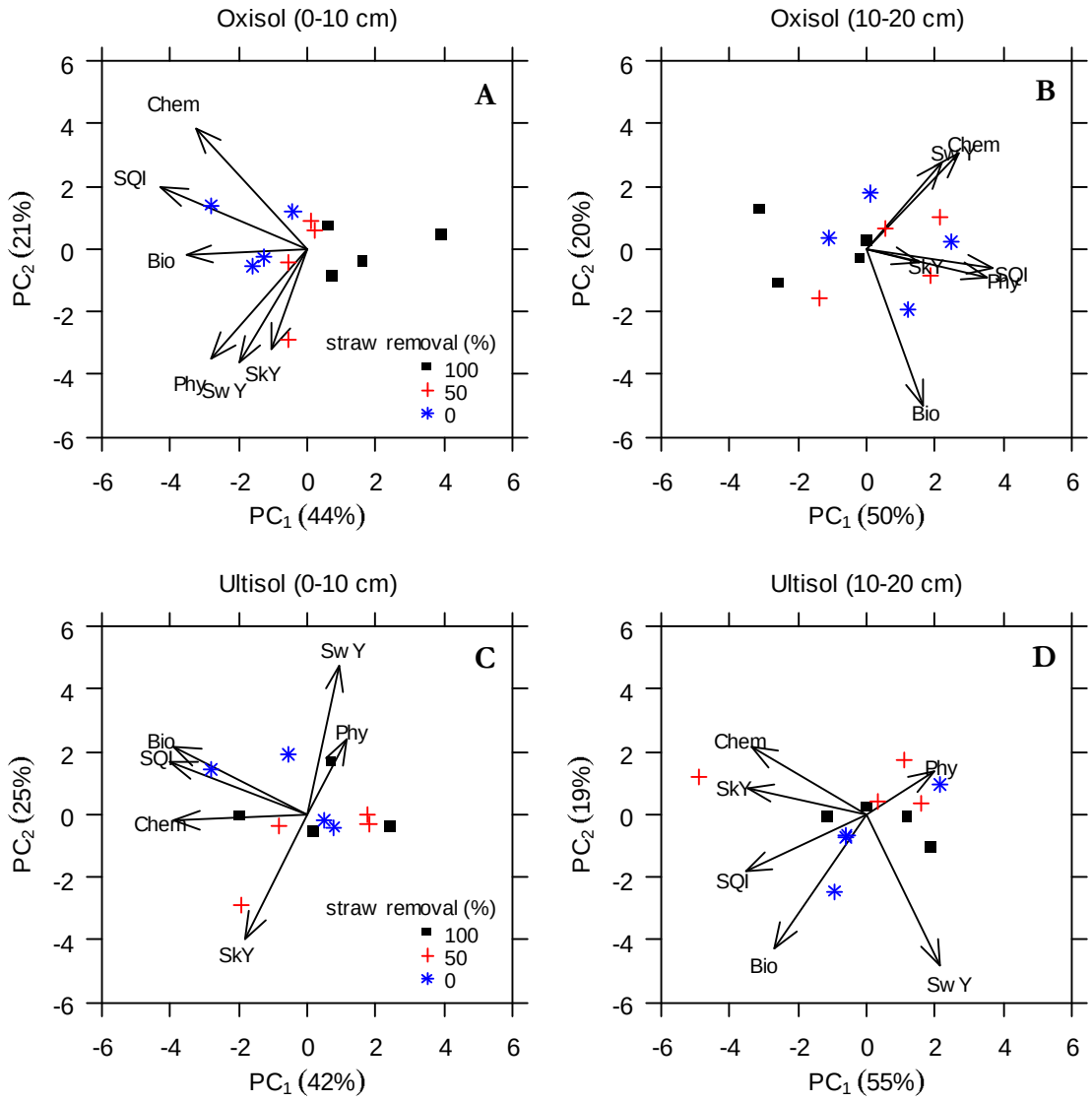

Fig 3. Principal components analysis (PCA) describing the relationship among soil quality index (SQI), soil attributes (Chem = chemical, Bio = biological and Phy = physical) and their effects on straw (SwY) and stalk (SkY) yields determined over both ratoons.

The first and second components explained 67 and 74% of data variance, respectively at 0-10 (Fig. 3 C) and 10-20 cm (Fig. 3 D) at Ultisol. However, there is no a clear pattern to explain how the scores of soil attributes and SQI score in both depths were affected by straw removal rates, as well as how phytomass yield (*i.e.*, stalk and straw) was influenced by the soil attributes and SQI changes under the same straw management.

5.4 Discussion

5.4.1 Sugarcane straw removal and impacts on soil quality

The magnitude of crop residues removal effects may vary according to soil properties and types (Blanco-Canqui et al., 2007; Bordonal et al., 2018). Indeed, over a short term, the impacts of sugarcane straw removal on SQI are higher at Oxisol compared to those verified at the Ultisol (Fig. 1 *vs.* 2). Even total straw removal was not able to reduce SQI scores within the 0-30 cm layer in the last soil condition, while moderate straw removal (*i.e.*, partial removal) improved SQI scores within the 0-20 cm layer at the Oxisol condition. Among soil attributes evaluated on this study, total straw removal induced physical quality degradation in a short time at Oxisol (Fig. 1). Crops residues have an important role on preventing soil physical degradation, through dissipating and absorbing compaction pressure imposed by machines' wheels (Braida et al., 2006; Blanco-Canqui and Lal, 2009), acting as a physical barrier alleviating compaction process (Rosim et al., 2012). Thus, integral crop residues removal affects parameters associated to soil physical quality (Blanco-Canqui et al., 2006; Shaver et al., 2010; Tormena et al., 2017). Indeed, total straw removal increased bulk density at Oxisol within the 5-10 and 10-20 cm layers (Table S1) and, as consequence, soil physical scores were reduced in these layers (Fig. 1 B_1 and C_1). The importance of crop residues for soil functions was widely discussed in literature reviews (Lal, 2009; Carvalho et al., 2017 and Cherubin et al., 2018).

Sugarcane straw retention improves Oxisol physical quality, which directly enhanced SQI (Figs. 1) of this type of soil. In fact, resistance to penetration was lower in a covered soil compared to uncover soil in sugarcane field (Silva et al., 2016; Satiro et al., 2017). In this study, the scores of soil-physical attribute is positively correlated to phytomass yield (stalk and straw) (Fig 3 A). Thus, in a context of sugarcane straw removal for bioenergy production, at least part of the straw must be maintained on soil to alleviate soil compaction, which is one of the main issue to be addressed in Brazilian sugarcane fields (Bordonal et al. 2018), where machinery traffic decreases physical quality and jeopardizing plant and root growth (Souza et al., 2014).

5.4.2 Soil quality and crop yield

The main implications of sugarcane straw removal on plant growth and yield were subject of a few studies in Brazil. Overall, plant growth is little affected by different rates of straw removal (Lisboa et al., 2018), while stalk yield is not impacted when around 50% of straw is removed as a feedstock for bioenergy (Aquino et al., 2017; Aquino et al., 2018; Lisboa et al., 2018). However, the amount of straw to be removed may vary through the different ratoons

(Oliveira et al., 2016) and at least 7 Mg of straw are necessary to enhance or keeping the benefits of the this harvesting residue for the soil-plant system (Carvalho et al., 2017).

Since sugarcane is widespread in various soil types within Brazil (Satiro et al., 2017), to define the amounts of straw to be removed and retained on the field is a challenger, they are dependent on the specific edaphoclimatic conditions (Marin et al., 2014; Satiro et al., 2017; Cherubin et al., 2018; Bordonal et al., 2018). Thus, to establish the quantity of straw to be removed it mandatory to consider among other parameters, initial SOC and soil texture (*e.g.*, clay content) (Bordonal et al., 2018). Indeed, our findings show that the short-term effects of sugarcane straw removal on soil quality were more detectable in the Oxisol (higher clay content) compared to Ultisol (Fig. 1 *vs* 2). Moreover, in both soils types, total straw removal decreased SOC content (Table 1S) and the scores associated to this indicator (Table 4). Thus, as reported by Blanco-Canqui and Lal (2007), the indiscriminate crop residues removal may lead to decrease on SOC and crop yields.

Overall, over a short term, total straw removal reduced Oxisol quality (Fig. 1), while Ultisol seemed to be more resistant to SQ degradation over the same period (Fig. 2). Although total straw removal negatively affected biological (*i.e.*, MBC and SOC) and few chemical (*i.e.*, pH, P and K) indicators (Table 4), the scores of both attributes did not change significatively ($p < 0.05$) under different rates of straw removal in both soil types (Figs. 1 and 2). In contrast, total straw removal increased BD at Oxisol within 5-20 cm (Table 1S), this leaded to reduction of the soil-physical attribute at this soil type (Table 4) and overall soil quality (Fig. 1). Further, soil-physical score at the 0-10 cm layer is positively correlated to straw (SwY) and stalk (SkY) yields (Fig 3 A). This same pattern occurs with soil-physical scores within the 10-20 m layer and stalk yield is closely correlated to SQI and with soil-physical scores, while straw yield is most correlated to soil-chemical attributes (Fig 3 B).

Although chemical and biological attributes deserve attention in order to improve overall soil quality and sustain a good plant nutritional status, our findings highlight the importance to prioritize soil physical attribute to sustain sugarcane yield in Brazil. The main implications of soil physical degradation are the reduction on total soil-porosity, increasing on BD and resistance to penetration, which impair root system growth (Otto et al., 2011; Souza et al., 2014; Baqueiro et al., 2012), and consequently, plant growth and stalk yield (Souza et al., 2014; Souza et al., 2015). Thus, adoption of traffic control practice (Braunack et al., 2006; Gonçalves et al., 2014) combined with track width (Bangita and Rao, 2012) and autopilot are pointed out as an alternative way to reduce soil physical quality degradation effects on plant growth (Souza et al., 2014) and stalk yield (Braunack et al., 2006).

The sugarcane is a long-term commercial crop (~5 to 8 years) and the usage of tools to monitor soil physical quality degradation across the years may be adopted, such as a visual evaluation of soil structure (VESS), which is on-farm index, performed with low cost and well correlated with soil-physical quality (Cherubin et al., 2016c). Thus, once detected reduction on the soil-physical attribute, it can be improved through rippering (Garbiate et al., 2016) and hilling of the wheel traffic zone (Bangita and Rao, 2012). In addition, the adoption of cover crop at sugarcane-replanting period (interval between cycles) is an efficient way to improve SOC (Cherubin et al., 2016c; Bordonal et al., 2018) and may avoid the decreasing on the SOC as consequence of partial straw removal (Table 1S).

5.5 Conclusions

The short-term effects of sugarcane straw removal on soil quality indicators and on overall soil quality index were efficiently detected by SMAF and Oxisol responds faster to sugarcane straw removal than Ultisol over a short term. The greatest magnitude of soil quality degradation was noticed in surface layers (*i.e* 0-15 cm) at Oxisol, where total straw removal reduces soil physical quality.

Therefore, these findings may help to guide stakeholders to take action and improving soil physical quality, which must be prioritized to properly manage sugarcane crop in a context of straw removal for bioenergy proposal. Moreover, since soil attributes and quality are affected in different magnitudes by straw removal rates in the short term, this straw management must be site-specify, taking into account each local edaphoclimatic condition.

Since Oxisol and Ultisol are functioning 34 and 55%, respectively below of their highest potential capacity within the 0-30 cm layer under total straw removal, partial amount of straw retained along with the application of byproducts from sugarcane industry (*i.e.*, filter cake, vinasse and ashes) can be good strategies to enhance overall SQ and crop yield. While another part of straw would be used as a feedstock to meet the high bioenergy demand.

REFERENCES

Acton, D.F., and Gregorich, L.J., 1995. The Health of Our Soils: toward Sustainable Agriculture in Canada. Centre for Land and Biological Resources Research, Research Branch, Agriculture and Agri-Food Canada, Ottawa, Ont xiv + 138 pp.

Almeida, H.J., Cruz, F.J.R., Pancelli, M.A., Flores, R.A., Vasconcelos, R.D.L. and de Mello Prado, R., 2015. Decreased potassium fertilization in sugarcane ratoons grown under straw in different soils. Australian Journal of Crop Science, 9(7), p.596.

Andrews, S.S., Karlen, D.L. and Cambardella, C.A., 2004. The soil management assessment framework. Soil Science Society of America Journal, 68(6), pp.1945-1962.

Anjos, J.C.R.D., Andrade Júnior, A.S.D., Bastos, E.A., Noleto, D.H., Melo, F.D.B. and Brito, R.R.D., 2017. Water storage in a Plinthaqualf cultivated with sugarcane under straw levels. Pesquisa Agropecuária Brasileira, 52(6), pp.464-473.

Aquino, G.S., de Conti Medina, C., da Costa, D.C., Shahab, M. and Santiago, A.D., 2017. Sugarcane straw management and its impact on production and development of ratoons. Industrial crops and products, 102, pp.58-64.

Aquino, G.S., de Conti Medina, C., da Costa, D.C., Shahab, M. and Santiago, A.D., 2017. Sugarcane straw management and its impact on production and development of ratoons. Industrial crops and products, 102, pp.58-64.

Aquino, G.S., de Conti Medina, C., Shahab, M., Santiago, A.D., Cunha, A.C.B., Kussaba, D.A.O., Carvalho, J.B. and Moreira, A., 2018. Does straw mulch partial-removal from soil interfere in yield and industrial quality sugarcane? A long term study. Industrial Crops and Products, 111, pp.573-578.

Bangita, B. and Rao, B.R., 2012. Impacts of compaction relief treatments on soil physical properties and performance of sugarcane (Saccharum spp.) under zonal tillage system. Geoderma, 189, pp.351-356.

Baquero, J.E., Ralisch, R., Medina, C.D.C., Tavares Filho, J. and Guimarães, M.D.F., 2012. Soil physical properties and sugarcane root growth in a red oxiso. Revista Brasileira de Ciência do Solo, 36(1), pp.63-70.

Blanco-Canqui, H. and Lal, R., 2007. Soil and crop response to harvesting corn residues for biofuel production. Geoderma, 141(3-4), pp.355-362.

Blanco-Canqui, H. and Lal, R., 2009. Crop residue removal impacts on soil productivity and environmental quality. Critical reviews in plant science, 28(3), pp.139-163.

Blanco-Canqui, H., Lal, R., Post, W.M., Izaurralde, R.C. and Owens, L.B., 2006. Corn stover impacts on near-surface soil properties of no-till corn in Ohio. Soil Science Society of America Journal, 70(1), pp.266-278.

Blanco-Canqui, H., Lal, R., Post, W.M., Izaurralde, R.C. and Shipitalo, M.J., 2007. Soil hydraulic properties influenced by corn stover removal from no-till corn in Ohio. Soil and Tillage Research, 92(1-2), pp.144-155.

Bordonal, R.O., Carvalho, J.L.N., Lal, R., de Figueiredo, E.B., de Oliveira, B.G. and La Scala, N., 2018a. Sustainability of sugarcane production in Brazil. A review. Agronomy for Sustainable Development, 38(2), p.13.

Bordonal, R.O., Menandro, L.M.S., Barbosa, L.C., Lal, R., Milori, D.M.B.P., Kolln, O.T., Franco, H.C.J. and Carvalho, J.L.N., 2018b. Sugarcane yield and soil carbon response to straw removal in south-central Brazil. Geoderma, 328, pp.79-90.

Braida, J.A., Reichert, J.M., Veiga, M.D. and Reinert, D.J., 2006. Resíduos vegetais na superfície e carbono orgânico do solo e suas relações com a densidade máxima obtida no ensaio Proctor. Revista Brasileira de Ciência do Solo, 30(4).

Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T.W., Mäder, P. and Pulleman, M., 2018. Soil quality–A critical review. Soil Biology and Biochemistry, 120, pp.105-125.

Carvalho, J.L.N., Nogueirol, R.C., Menandro, L.M.S., Bordonal, R.D.O., Borges, C.D., Cantarella, H. and Franco, H.C.J., 2017. Agronomic and environmental implications of sugarcane straw removal: a major review. Gcb Bioenergy, 9(7), pp.1181-1195.

Cherubin, M.R., Karlen, D.L., Cerri, C.E., Franco, A.L., Tormena, C.A., Davies, C.A. and Cerri, C.C., 2016a. Soil quality indexing strategies for evaluating sugarcane expansion in Brazil. PloS one, 11(3).

Cherubin, M.R., Karlen, D.L., Franco, A.L., Cerri, C.E., Tormena, C.A. and Cerri, C.C., 2016b. A Soil Management Assessment Framework (SMAF) evaluation of Brazilian sugarcane expansion on soil quality. Soil Science Society of America Journal, 80(1), pp.215-226.

Cherubin, M.R., Karlen, D.L., Franco, A.L., Tormena, C.A., Cerri, C.E., Davies, C.A. and Cerri, C.C., 2016c. Soil physical quality response to sugarcane expansion in Brazil. Geoderma, 267, pp.156-168.

Cherubin, M.R., Oliveira, D.M.D.S., Feigl, B.J., Pimentel, L.G., Lisboa, I.P., Gmach, M.R., Varanda, L.L., Morais, M.C., Satiro, L.S., Popin, G.V. and Paiva, S.R.D., 2018. Crop residue harvest for bioenergy production and its implications on soil functioning and plant growth: A review. Scientia Agricola, 75(3), pp. 255-272.

Cherubin, M.R., Tormena, C.A. and Karlen, D.L., 2017. Soil Quality Evaluation Using the Soil Management Assessment Framework (SMAF) in Brazilian Oxisols with Contrasting Texture. Revista Brasileira de Ciência do Solo, 41.

Conab - Companhia Nacional de Abastecimento. 2018. Acompanhamento da safra brasileira de Cana-de-açúcar: Quarto levantamento. CONAB. http://www.conab.gov.br (acessado em 01/05/2018).

Correa, S.T.R., Carvalho, J.L.N., Hernandes, T.A.D., Barbosa, L.C., Menandro, L.M.S., Leal, M.R.L.V., 2017. Assessing the effects of different amounts of sugarcane straw on temporal variability of soil moisture content and temperature in 25th European Biomass Conference and Exhibition, 12-15 June 2017, Stockholm, Sweden.

Damaso, M.C.T., Machado, C.M.M., de Sousa Rodrigues, D., Belem, S.G. and Salum, T.F.C., 2014. Bioprocesses for biofuels: an overview of the Brazilian case. Chemical and Biological Technologies in Agriculture, 1(1), p.6.

Fortes, C., Trivelin, P.C.O. and Vitti, A.C., 2012. Long-term decomposition of sugarcane harvest residues in Sao Paulo state, Brazil. Biomass and Bioenergy, 42, pp.189-198.

Garbiate, M.V., Vitorino, A.C.T., Prado, E.A.F.D., Mauad, M. and Pellin, D.M.P., 2016. Hydrophysical Quality of an Oxisol and Sugarcane Yield in Chisel Plow-Based Sugarcane Ratoon Management. Revista Brasileira de Ciência do Solo, 40.

Goes, T., Marra, R., de Araújo, M., Alves, E. and Souza, M.O.D., 2011. Sugarcane in Brazil Current technologic stage and perspectives. Revista de Política Agrícola, 20(1), pp.52-65.

Gonçalves Braunack, M.V., McGarry, D. and Venture, S.Y.D.J., 2006. Traffic control and tillage strategies for harvesting and planting of sugarcane (Saccharum officinarum) in Australia. Soil and Tillage Research, 89(1), pp.86-102.

Hassuani, S.J., Leal, M.R.L.V. and Macedo, I., 2005. Biomass power generation. Sugar cane bagasse and trash Published by Programa das Nacoes Unidas para o Desenvolvimento and Centro de Technologi a Canavieriva, Peracicaba, Brazil. 217p.

Hess, T.M., Sumberg, J., Biggs, T., Georgescu, M., Haro-Monteagudo, D., Jewitt, G., Ozdogan, M., Marshall, M., Thenkabail, P., Daccache, A. and Marin, F., 2016. A sweet deal? Sugarcane, water and agricultural transformation in Sub-Saharan Africa. Global Environmental Change, 39, pp.181-194.

Idowu, O.J., van Es, H.M., Abawi, G.S., Wolfe, D.W., Ball, J.I., Gugino, B.K., Moebius, B.N., Schindelbeck, R.R. and Bilgili, A.V., 2008. Farmer-oriented assessment of soil quality using field, laboratory, and VNIR spectroscopy methods. Plant and Soil, 307(1-2), pp.243-253.

Johnson, J.M., Strock, J.S., Tallaksen, J.E. and Reese, M., 2016. Corn stover harvest changes soil hydrology and soil aggregation. Soil and Tillage Research, 161, pp.106-115.

Karlen, D.L., Andrews, S.S., Wienhold, B.J. and Zobeck, T.M. 2008. Soil quality assessment: past, present and future. Journal of Integrative Biosciences 6:1, pp. 3-14.

Karlen, D.L., D.E. Stott, C.A. Cambardella, R.J. Kremer, K.W. King, and G.W. McCarty. 2014. Surface soil quality in five midwestern cropland Conservation Effects Assessment Project watersheds. J. Soil Water Conserv. 69:393–401. doi:10.2489/jswc.69.5.393;.

Karlen, D.L., Mausbach, M.J., Doran, J.W., Cline, R.G., Harris, R.F. and Schuman, G.E., 1997. Soil quality: a concept, definition, and framework for evaluation (a guest editorial). Soil Science Society of America Journal, 61(1), pp.4-10.

Lal, R., 2009. Soil quality impacts of residue removal for bioethanol production. Soil and tillage research, 102(2), pp.233-241.

Leal, M.R.L., Galdos, M.V., Scarpare, F.V., Seabra, J.E., Walter, A. and Oliveira, C.O., 2013. Sugarcane straw availability, quality, recovery and energy use: a literature review. Biomass and Bioenergy, 53, pp.11-19.

Lisboa, I.P., Cherubin, M.R., Cerri, C.C., Cerri, D.G., Cerri, C.E., 2017. Guidelines for the recovery of sugarcane straw from the field during harvesting. Biomass Bioenergy 96, 69–74.

Lisboa, I.P., Cherubin, M.R., Lima, R.P., Cerri, C.C., Satiro, L.S., Wienhold, B.J., Schmer, M.R., Jin, V.L. and Cerri, C.E., 2018. Sugarcane straw removal effects on plant growth and stalk yield. Industrial Crops and Products, 111, pp.794-806.

Marin, F.R., Thorburn, P.J., da Costa, L.G. and Otto, R., 2014. Simulating long-term effects of trash management on sugarcane yield for Brazilian cropping systems. Sugar Tech, 16(2), pp.164-73.

Marin, R. 2009. Arvore do conhecimento – cana-de-açúcar. Available at: http://www.agencia.cnptia.embrapa.br/gestor/cana-de-acucar/arvore/CONTAG01_42_1110200717570.html , acessed on: June, 10, 2018.

Mendiburu, F., and R. Simon. 2015. Agricolae - Ten years of an open source statistical tool for experiments in breeding, agriculture and biology. PeerJ PrePrints 3:e1404v1. doi.org/10.7287/peerj.preprints.1404v1

Menandro, L.M.S., Cantarella, H., Franco, H.C.J., Kölln, O.T., Pimenta, M.T.B., Sanches, G.M., Rabelo, S.C., Carvalho, J.L.N., 2017. Comprehensive assessment of sugarcane straw: implications for biomass and bioenergy production. Biofuels Bioprod. Biorefin. 11, 488–504.

Moebius-Clune, B.N., Moebius-Clune, D.J., Gugino, B.K., Idowu, O.J., Schindelbeck, R.R., Ristow, A.J., Van Es, H.M., Thies, J.E., Shayler, H.A., McBride, M.B., Wolfe, D.W., Abawi, G.S., 2016. Comprehensive Assessment of Soil Health. The Cornell framework manual. third ed. Cornell University, Geneva, NY.

Moraes, M.A.F.D., Rodrigues, L. and Kaplan, S., 2017. The Sugarcane Industry and the Use of Fuel Ethanol in Brazil: History, Challenges, and Opportunities. In Handbook of Bioenergy Economics and Policy: Volume II (pp. 39-63). Springer, New York, NY.

Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon, and organic matter. In: Sparks, D.L.; Page, A.L., Helmke, P.A., Loeppert, R.H.; Soluanpour, P.N., Tabatabai, M.A., Johnston, C.T., Sumner, M.E. (Eds). Methods of soil analysis part 3: Chemical methods. Soil Science Society of America, Inc. and American Society of Agronomy, Inc., Madison, Wisconsin, USA. p. 961-1010.

Oliveira, M.A., Zucareli, C., Neves, C.S.V.J., Domingues, A.R., de Conti Medina, C., de Assis Moraes, L.A., 2016. Agronomic performance of sugarcane cultivated under quantities of sugarcane straw on the soil surface. Semin: Cien. Agrar. 37, 3983–3996.

Otto, R., Silva, A.P., Franco, H.C.J., Oliveira, E.C.A. and Trivelin, P.C.O., 2011. High soil penetration resistance reduces sugarcane root system development. Soil and tillage research, 117, pp.201-210.

Paredes Junior, F.P., Portilho, I.I.R., Mercante, F.M., 2015. Atributos microbiológicos de um latossolo sob cultivo de cana-de- açúcar com e sem queima da palhada. Semina: Ciências Agrárias 36, 151–164.

Pierossi, M.A. and Bertolani, F.C., 2018 - Sugarcane Trash as Feedstock for Biorefineries: Agricultural and Logistics Issues In: Technologies, Commercialization, Policy Issues and Paradigm Shift for Bioethanol and By-Products, pg 17-39, Advances in Sugarcane Biorefinery.

R Core Team. 2016. R. A Language and Environment for Statistical Computing [Internet]. R Foundation for Statistical Computing, Vienna, Austria (Accessed on: 11 Mach 2018). Available at: http://www.R-project.org/.

Raij BV, Cantarella H, Quaggio JA, Furlani AMC. 1997. Recomendações de adubação e calagem para o estado de São Paulo. Campinas: Instituto Agronômico/Fundação IAC. Boletim técnico 100, 285 p.

Raij van, B., de Andrade, J.C., Cantarella H., Quaggio, J.A. 2001. Análise química para Avaliação da Fertilidade de Solos Tropicais. Campinas: Instituto Agronômico de Campinas. 285 p.

Reis Junior, F. B.; mendes, I. C. 2007. Biomassa microbiana do solo. Planaltina: Embrapa Cerrados, 40p. (Documentos, 205).

Rosim, D.C., De Maria, I.C., Lemos e Silva, R. and Pires da Silva, Á., 2012. Compactação de um latossolo vermelho distroférrico com diferentes quantidades e manejos de palha em superfície. Bragantia, 71(4).

Satiro, L.S., Cherubin, M.R., Safanelli, J.L., Lisboa, I.P., da Rocha Junior, P.R., Cerri, C.E.P. and Cerri, C.C., 2017. Sugarcane straw removal effects on Ultisols and Oxisols in south-central Brazil. Geoderma Regional, 11, pp.86-95.

Shaver, T., 2010, February. Crop residue and soil physical properties. In Proceedings of the 22nd Annual Central Plains Irrigation Conference, Kearney, NE (pp. 22-27).

Silva, R.B.D., Iori, P., Souza, Z.M.D., Pereira, D.D.M.G., Vischi Filho, O.J. and Silva, F.A.D.M., 2016. Contact pressures and the impact of farm equipment on Latosol with the presence and absence of sugarcane straw. Ciência e Agrotecnologia, 40(3), pp.265-278.

Silveira, M.H.L., Vanelli, B.A., and Chandel, A.K., 2018 - Second Generation Ethanol Production: Potential Biomass Feedstock, Biomass Deconstruction, and Chemical Platforms for Process Valorization, In: Technologies, Commercialization, Policy Issues and Paradigm Shift for Bioethanol and By-Products, pp. 135–152

Souza, G.S.D., Souza, Z.M.D., Cooper, M. and Tormena, C.A., 2015. Controlled traffic and soil physical quality of an Oxisol under sugarcane cultivation. Scientia Agricola, 72(3), pp.270-277.

Souza, G.S.D., Souza, Z.M.D., Silva, R.B.D., Barbosa, R.S. and Araújo, F.S., 2014. Effects of traffic control on the soil physical quality and the cultivation of sugarcane. Revista Brasileira de Ciência do Solo, 38(1), pp.135-146.

Stott, D. E., S. S. Andrews, M. A. Liebig, Brian J. Wienhold, and D. L. Karlen. 2010. "Evaluation of β-Glucosidase Activity as a Soil Quality Indicator for the Soil Management Assessment Framework. Soil Science Society of America Journal 74, 1: 107-119.

Stott, D.E., D.L. Karlen, C.A. Cambardella, and R.D. Harmel. 2013. A soil quality and metabolic activity assessment after fifty-seven years of agricultural management. Soil Sci. Soc. Am. J. 77: 903–913.

Tormena, C.A., Karlen, D.L., Logsdon, S. and Cherubin, M.R., 2017. Corn stover harvest and tillage impacts on near-surface soil physical quality. Soil and Tillage Research, 166, pp.122-130.

Trivelin, P.C.O., Franco, H.C.J., Otto, R., Ferreira, D.A., Vitti, A.C., Fortes, C., Faroni, C.E., Oliveira, E.C., Cantarella, H., 2013. Impact of sugarcane trash on fertilizer requirements for São Paulo, Brazil. Sci. Agric. 70, 345–352.

Vasconcelos, A.L.S., Cherubin, M.R., Feigl, B.J., Cerri, C.E., Gmach, M.R. and Siqueira-Neto, M., 2018. Greenhouse gas emission responses to sugarcane straw removal. Biomass and Bioenergy, 113, pp.15-21.

Wienhold, B.J., Karlen, D.L., Andrews, S.S. and Stott, D.E., 2009. Protocol for indicator scoring in the soil management assessment framework (SMAF). Renewable agriculture and food systems, 24(4), pp.260-266.

Supplementary materials

Table 1S. Mean values of phosphorus (P), potassium (K), soil organic carbon (SOC) and microbial biomass carbon (MBC) contents and bulk density for 0.00 – 0.05, 0.05 – 0.1, 0.1-0.2 and 0.2 a 0.3 m layers under three straw managements in both sites

Straw removal (%)	Bom Retiro						Univalem					
	pH (H2O)	P	K	BD	SOC	MBC	pH (H2O)	P	K	BD	SOC	MBC
		mg dm^{-3}		Mg m^{-3}	g kg^{-1}	mg kg^{-1}		mg dm^{-3}		Mg m^{-3}	g kg^{-1}	mg kg^{-1}
Mean values 0.00 – 0.05 m												
100 - total removal	5.8^{ns}	29.5 ^{ns}	106.7 b*	1.76 ^{ns}	12.2 b*	365.5 c**	6.2^{ns}	17.4^{ns}	61.2^{ns}	1.81^{ns}	6.1^{ns}	409.2 c**
50 - partial removal	5.8	30.3	134.6 ab	1.67	14.3 ab	464.1 b	6.0	14.6	68.1	1.79	6.3	462.4 b
0 - no removal	5.8	31.0	145.2 a	1.60	14.9 a	505.6 a	6.1	18.5	60.6	1.80	6.8	485.6 a
Mean values 0.05 – 0.1 m												
100 - total removal	5.8^{ns}	26.5^{ns}	58.2^{ns}	1.78 a*	11.5^{ns}	261.2 c**	6.1 b**	14.9 ^{ns}	34.8^{ns}	1.92^{ns}	5.8^{ns}	349.89 b**
50 - partial removal	6.2	30.1	69.1	1.72 ab	12.7	318.7 b	6.2 b	9.5	32.5	1.91	5.3	387.14 b
0 - no removal	6.0	29.4	71.0	1.64 b	12.2	404.2 a	6.4 a	15.9	39.5	1.87	5.6	428.51 a
Mean values 0.1 – 0.2 m												
100 - total removal	5.7 ^{ns}	25.5^{ns}	42.6^{ns}	1.73 a**	10.8^{ns}	-----	5.8^{ns}	9.4^{ns}	19.1^{ns}	1.93^{ns}	4.8^{ns}	-----
50 - partial removal	5.9	25.6	54.2	1.65 b	11.3	-----	5.9	6.9	20.0	1.88	4.6	-----
0 - no removal	5.8	25.6	56.5	1.65 b	11.4	-----	6.1	10.9	27.2	1.97	4.9	-----
Mean values 0.2 – 0.3 m												
100 - total removal	5.2^{ns}	24.4^{ns}	50.4 ^{ns}	1.68^{ns}	10.2 ^{ns}	-----	5.5 ^{ns}	6.3^{ns}	18.7 b*	1.91^{ns}	4.5^{ns}	-----
50 - partial removal	5.2	23.4	36.5	1.64	10.0	-----	5.4	5.8	19.0 b	1.92	4.5	-----
0 - no removal	5.0	25.7	41.0	1.60	9.8	-----	5.6	6.4	29.1a	1.96	4.7	-----

Adapted from Satiro et al. (2017).

6. FINAL REMARKS

The sugarcane straw is highlighted as an important feedstock for bioenergy production in Brazil (Vasconcelos et al., 2018; Guerra et al., 2018) and studies have focused on defining the amount of straw that can be sustainably removed from the field (Aquino et al., 2017; Aquino et al., 2018). Moreover, chopped stalk plus straw was pointed out as the most cost-effective route to straw recovery from field (Cardoso et al., 2013), thus in the first chapter we presented a step-by-step guideline in which sugarcane harvester was used to quantify different rates of straw removal along with chopped stalk. In this chapter, we found a positive linear correlation between the amount of straw removed and the increasing on the primary extractor fan's angular velocity.

The implications of increasing rates of straw removal on plant growth, stalk yield and stalk-industrial quality were presented throughout the second chapter. Overall, the effects of sugarcane straw removal on plant growth differ across the cycle (*i.e.*, ratoon). Especially on colder regions, straw removal improved plant tillering with minimal effects on growth, while stalk yield was reduced under no straw removal, regardless of the edaphoclimatic conditions. Moreover, in the second chapter we noticed lower industrial quality of stalks harvested in the wet season (October, November, December, January and February) than those harvested in the dry season (April to September), however this parameter was unaffected by straw removal. The amount of straw required to sustain highest stalk yields ranged from 4-9 Mg ha^{-1} (dry base) and varied within each ratoon.

The agronomic benefits of straw-blanket raking management were evaluated in the third chapter and this practice tends to enhance sugarcane tillering, especially within southeastern Brazil in colder producer areas, as reported by Campos et al. (2010). However, this straw management did not influence plant growth and stalk yield. This must be associated with the crop resilience, which enables the plants overcome unfavorable effects of the straw blanket within the beginning of ratoon cycle. In this context, to rake the straw seems to be an unnecessary practice within southeastern Brazil, without bringing benefits for the crop. In addition, since straw raking requires an additional machinery operation, this management may increase soil compaction, which already is pointed out as a main adverse factor for the crop under Brazilian conditions (Bordonal et al., 2018). In this chapter, we also observed an increasing on P content in plant tissue under poorest inherent soil conditions when straw was not removed, regardless of blanket management.

An integrated approach of soil quality under straw removal was made with SMAF in the fourth and last chapter. The SMAF was sensitive to detect soil quality changes under straw

management and Oxisol responds faster to the straw removal than Ultisol in a short term. Total straw removal leads to soil physical quality degradation of the Oxisol over the same period. The SMAF also indicated that both soils were functioning far below of their highest capability (*i.e.*, SQI =1), thus strategies to enhance chemical, physical and biological indicators must be adopted to raise up the scores of all soil attributes and, by consequence SQI's score.

Overall, this study brought insights on integrated-harvesting system route (*i.e.*, straw recovery plus stalk) and evaluated the main consequences of different sugarcane straw removal managements on soil quality as well as on plant growth (Fig. 1). Thus, these findings may be useful for stakeholders to make decision on straw blanket management, to perform a sustainable straw removal for bioenergy, without disregarding the essential role of sugarcane straw on the soil-plant system (Carvalho et al., 2017). Some actions also may be taken to enhance soil quality and minimize plant loses the potential of phytomass yield across cycle (*i.e.*, ratoons), such as: the adoption of traffic control on sugarcane fields; the returning of filter cake, vinasse and ashes to the fields, which leads to the cycling of nutrients contained within these byproducts.

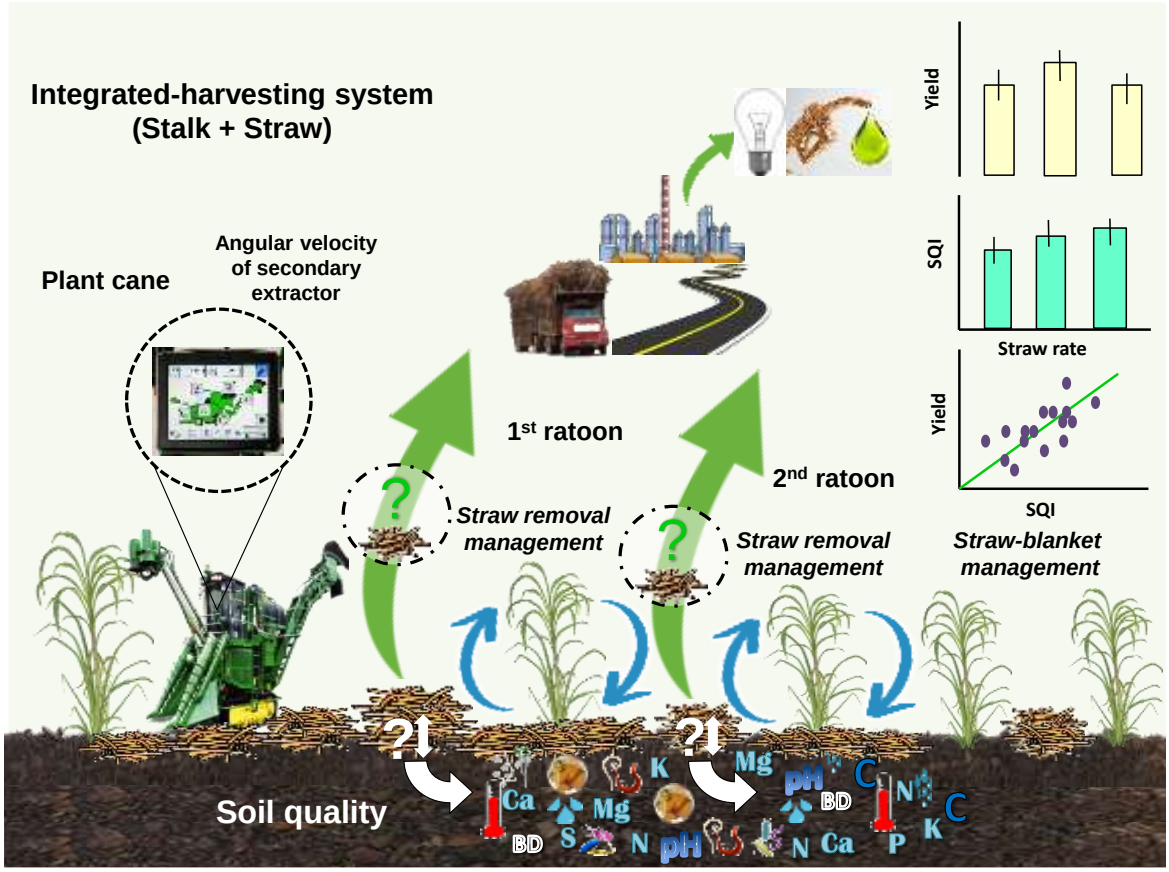

Fig. 1. General view of the different topics framed within this study.

According to the findings presented in this study, part of straw can be removed as a feedstock for bioenergy production with minimum impacts on soil quality and crop yield. However, we highlight that to define the amount of straw to be sustainable removed for

bioenergy production, site-specific conditions and plant losses the potential of yield across cycles should be taken into account. Further studies are necessary to develop tillage practices in order to minimize SOC loses during sugarcane replanting, which may ensure higher rates of straw removal and the sustainability of the crop cultivation.

REFERENCES

Aquino, G.S., de Conti Medina, C., da Costa, D.C., Shahab, M. and Santiago, A.D., 2017. Sugarcane straw management and its impact on production and development of ratoons. Industrial crops and products, 102, pp.58-64.

Aquino, G.S., de Conti Medina, C., Shahab, M., Santiago, A.D., Cunha, A.C.B., Kussaba, D.A.O., Carvalho, J.B. and Moreira, A., 2018. Does straw mulch partial-removal from soil interfere in yield and industrial quality sugarcane? A long term study. Industrial Crops and Products, 111, pp.573-578.

Campos, L.H.F.D., Carvalho, S.J.P.D., Christoffoleti, P.J., Fortes, C. and Silva, J.S.D., 2010. Straw management systems influence biomass accumulation and yield of sugarcane crop (var. RB855453). Acta Scientiarum. Agronomy, 32(2), pp.345-350.

Cardozo, N.P. and Sentelhas, P.C., 2013. Climatic effects on sugarcane ripening under the influence of cultivars and crop age. Scientia Agricola, 70(6), pp.449-456.

Carvalho, J.L.N., Nogueirol, R.C., Menandro, L.M.S., Bordonal, R.D.O., Borges, C.D., Cantarella, H. and Franco, H.C.J., 2017. Agronomic and environmental implications of sugarcane straw removal: a major review. Gcb Bioenergy, 9(7), pp.1181-1195.

Guerra, J.P., Cardoso, F.H., Nogueira, A. and Kulay, L., 2018. Thermodynamic and Environmental Analysis of Scaling up Cogeneration Units Driven by Sugarcane Biomass to Enhance Power Exports. Energies, 11(1), p.73.

Vasconcelos, A.L.S., Cherubin, M.R., Feigl, B.J., Cerri, C.E., Gmach, M.R. and Siqueira-Neto, M., 2018. Greenhouse gas emission responses to sugarcane straw removal. Biomass and Bioenergy, 113, pp.15-21.