RESSALVA

Atendendo solicitação do autor, o texto completo desta tese será disponibilizado somente a partir de 04/02/2018.

UNIVERSIDADE ESTADUAL PAULISTA – UNESP
CÂMPUS DE JABOTICABAL

SOIL GREENHOUSE GAS EMISSIONS AND THEIR RELATIONS TO SOIL ATTRIBUTES IN A SUGARCANE AREA

Elton da Silva Bicalho
Engenheiro Agrônomo

2016

UNIVERSIDADE ESTADUAL PAULISTA – UNESP
CÂMPUS DE JABOTICABAL

SOIL GREENHOUSE GAS EMISSIONS AND THEIR RELATIONS TO SOIL ATTRIBUTES IN A SUGARCANE AREA

Elton da Silva Bicalho
Orientador: Prof. Dr. Newton La Scala Júnior
Coorientador: Prof. Dr. Alan Rodrigo Panosso

Tese apresentada à Faculdade de Ciências Agrárias e Veterinárias – Unesp, Câmpus de Jaboticabal, como parte das exigências para a obtenção do título de Doutor em Agronomia (Produção Vegetal)

2016

B583s

Bicalho, Elton da Silva
Soil greenhouse gas emissions and their relations to soil attributes in a sugarcane area / Elton da Silva Bicalho. – – Jaboticabal, 2016
x, 80 p. : il. ; 29 cm

Tese (doutorado) - Universidade Estadual Paulista, Faculdade de Ciências Agrárias e Veterinárias, 2016
Orientador: Newton La Scala Júnior
Coorientador: Alan Rodrigo Panosso
Banca examinadora: Carlos Eduardo Pellegrino Cerri, Janaina Braga do Carmo, Gener Tadeu Pereira, Teresa Cristina Tarlé Pissarra
Bibliografia

1. Dióxido de carbono. 2. Metano. 3. Óxido nitroso. 4. Produção potencial. 5. Respiração do solo. 6. Transporte gasoso. I. Título. II. Jaboticabal-Faculdade de Ciências Agrárias e Veterinárias.

CDU 631.42:633.61

Ficha catalográfica elaborada pela Seção Técnica de Aquisição e Tratamento da Informação – Serviço Técnico de Biblioteca e Documentação – UNESP, Câmpus de Jaboticabal.

UNIVERSIDADE ESTADUAL PAULISTA

Câmpus de Jaboticabal

CERTIFICADO DE APROVAÇÃO

TÍTULO DA TESE: SOIL GREENHOUSE GAS EMISSIONS AND THEIR RELATIONS TO SOIL ATTRIBUTES IN A SUGARCANE AREA

AUTOR: ELTON DA SILVA BICALHO
ORIENTADOR: NEWTON LA SCALA JUNIOR
COORIENTADOR: ALAN RODRIGO PANOSSO

Aprovado como parte das exigências para obtenção do Título de Doutor em AGRONOMIA (PRODUÇÃO VEGETAL), pela Comissão Examinadora:

Prof. Dr. ALAN RODRIGO PANOSSO
Departamento de Matemática / FEIS / UNESP - Ilha Solteira/SP

Prof. Dr. CARLOS EDUARDO PELLEGRINO CERRI
Departamento de Ciência do Solo / ESALQ - USP - Piracicaba/SP

Profa. Dra. JANAINA BRAGA DO CARMO
Departamento de Engenharia Florestal / UFSCAR / Câmpus Sorocaba - Sorocaba/SP

Prof. Dr. GENER TADEU PEREIRA
Departamento de Ciências Exatas / Faculdade de Ciencias Agrarias e Veterinarias de Jaboticabal

Profa. Dra. TERESA CRISTINA TARLE PISSARRA
Departamento de Engenharia Rural / Faculdade de Ciencias Agrarias e Veterinarias de Jaboticabal

Jaboticabal, 04 de fevereiro de 2016

CURRICULAR ACTIVITIES OF THE AUTHOR

Elton da Silva Bicalho was born in São Paulo, SP, Brazil on June 21, 1985. He earned his Bachelor of Science Degree in Agronomy in February, 2010 from the Faculty of Agrarian and Veterinary Sciences, Jaboticabal campus of the São Paulo State University (FCAV–UNESP). At that time, he was awarded for attaining the highest grade point average of the 2009 graduating class with the Faculty of Agrarian and Veterinary Sciences Award (Jaboticabal, SP, Brazil), and for best student of the 2009 graduating class with the Engineering Institute Award (São Paulo, SP, Brazil). During his bachelor's degree, he was grantee of the National Council for Scientific and Technological Development (CNPq) during the period between August, 2007 and August, 2009. In February, 2012, he earned his Master in Agronomy (Crop Production) from the FCAV–UNESP, and was grantee of the CNPq. In March, 2012, he joined to the Graduate Program in Agronomy (Crop Production) at the FCAV–UNESP, with a collaborative period from March, 2014 to February, 2015 in the University of Minnesota, Department of Soil, Water and Climate, St Paul, MN, USA, and was grantee of the São Paulo Research Foundation (FAPESP).

“In the living of life, things get mixed up. Life is like that: first it blows hot, then, cold; it tightens, then loosens; it soothes, then disquiets. What life demands of us is courage.”

“The Devil to Pay in the Backlands”
by João Guimarães Rosa

To my mom

ACKNOWLEDGEMENTS

I am grateful to my advisors Newton La Scala Júnior, Alan Rodrigo Panosso and Kurt A. Spokas, who helped me a lot and made easier the processes of learning and writing this doctoral dissertation.

I am really grateful to my great friends Daniel De Bortoli Teixeira and Mara Regina Moitinho; without the help of them all, this work would not have been possible.

I am grateful to Adriana, Norival, Shirley and Zezé, from the Department of Exact Sciences of the Faculty of Agrarian and Veterinary Sciences, Jaboticabal campus of the São Paulo State University (FCAV–UNESP), for being available for any help.

I am grateful to the Graduate Program in Agronomy (Crop Production) of the Faculty of Agrarian and Veterinary Sciences, Jaboticabal campus of the São Paulo State University (FCAV–UNESP).

I am grateful to the Department of Soil, Water, and Climate of the University of Minnesota for the support and facilities for conducting all the laboratory experiments, to the United States Department of Agriculture, Agricultural Research Service (USDA–ARS), and especially to Martin G. DuSaire for all the help.

I am grateful to the Coordination for the Improvement of Higher Education Personnel (CAPES) and to the São Paulo Research Foundation (FAPESP) for the financial support (processes number 2013/00360–7 and 2013/24926–0).

And I am also grateful to the São Martinho Mill for providing the area and facilities to this work.

SUMMARY

EMISSÃO DE GASES DE EFEITO ESTUFA E SUA RELAÇÃO COM ATRIBUTOS DO SOLO EM ÁREA DE CANA-DE-AÇÚCAR

RESUMO – A produção dos principais gases de efeito estufa (GEE: CO_2, CH_4 e N_2O) é influenciada por práticas agrícolas que causam alterações nos atributos físicos, químicos e biológicos do solo, afetando diretamente sua emissão para a atmosfera. O objetivo deste estudo foi investigar a emissão de CO_2 do solo (F_{CO_2}) em condições de campo e a produção potencial de CO_2, CH_4 e N_2O do solo (P_{CO_2}, P_{CH_4} e P_{N_2O}, respectivamente) em condições de laboratório, além de suas relações com os atributos do solo em uma área de cana-de-açúcar colhida mecanicamente. A área experimental constituiu-se de um gradeado simétrico radialmente de 50 × 50 m contendo 133 pontos espaçados em distâncias mínimas de 0,5 m no centro da malha amostral. Foram conduzidas oito avaliações para F_{CO_2}, temperatura e umidade do solo durante um período de 19 dias. Os atributos físicos e químicos do solo foram determinados por meio de amostragem na profundidade de 0–10 cm. A quantificação de P_{CO_2}, P_{CH_4} e P_{N_2O} consistiu de incubação em laboratório e determinação da concentração dos gases por meio de cromatografia gasosa. F_{CO_2} apresentou um valor de emissão média de 1,19 µmol CO_2 m^{-2} s^{-1}, enquanto a produção de GEE em laboratório foi de 2,34 µg C–CO_2 g^{-1} d^{-1} e 0,20 ng N–N_2O g^{-1} d^{-1} respectivamente para P_{CO_2} e P_{N_2O}. Não foi observada produção ou oxidação significativa de CH_4. A análise de fatores mostrou a formação de dois processos independentes que explicaram quase 72% da variância total observada nos dados. O primeiro processo foi relacionado ao transporte de F_{CO_2} em campo e sua relação com atributos físicos do solo, tais como microporos, macroporos, relação C/N, umidade e densidade, mostrando a dependência entre F_{CO_2} e a porosidade do solo. O segundo processo foi relacionado à produção potencial de CO_2 e N_2O do solo em condições de laboratório e sua relação com atributos químicos do solo, tais como soma de bases, pH e fósforo disponível, os quais afetam a atividade microbiana e contribuem para a produção de GEE. Embora apresentados como independentes, esses processos estão relacionados e ocorrem simultaneamente no solo, fornecendo informações sobre sua variabilidade e mostrando se as emissões em campo são devidas aos processos de transporte de gás ou aos níveis de carbono no solo e sua qualidade. Além disso, a dependência espacial de F_{CO_2} está relacionada à porosidade do solo, assim como a dependência espacial de P_{CO_2} e P_{N_2O} está relacionada aos atributos químicos do solo. Adicionalmente, foi observada anisotropia principalmente em condições de campo, principalmente para os atributos relacionados à porosidade do solo, já que o solo pulverizado utilizado no laboratório perde sua estrutura e, consequentemente, o efeito do manejo encontrado em condições de campo.

Palavras-chave: dióxido de carbono, metano, óxido nitroso, produção potencial, respiração do solo, transporte gasoso

SOIL GREENHOUSE GAS EMISSIONS AND THEIR RELATIONS TO SOIL ATTRIBUTES IN A SUGARCANE AREA

ABSTRACT – The production of the main soil greenhouse gases (GHG: CO_2, CH_4 and N_2O) is influenced by agricultural practices that causes changes in soil physical, chemical and biological attributes, directly affecting their emission to the atmosphere. The aim of this study was to investigate the infield soil CO_2 emissions (F_{CO_2}) and the soil CO_2, CH_4 and N_2O production potentials (P_{CO_2}, P_{CH_4} and P_{N_2O}, respectively) in laboratory conditions, and their relationship to soil attributes in a mechanically harvested sugarcane area. The experimental area consisted of a 50 × 50-m radially symmetrical grid containing 133 points spaced at minimum distances of 0.5 m in the center of the sample grid. It was carried out eight evaluations of F_{CO_2}, soil temperature and soil moisture over a period of 19 days. Soil physical and chemical attributes were determined by sampling at a depth of 0–10 cm. The quantification of P_{CO_2}, P_{CH_4} and P_{N_2O} consisted of laboratory incubation and determination of gas concentration by gas chromatography. F_{CO_2} presented an infield average emission value of 1.19 μmol CO_2 m^{-2} s^{-1}, while GHG production in laboratory was 2.34 μg C–CO_2 g^{-1} d^{-1} and 0.20 ng N–N_2O g^{-1} d^{-1} for P_{CO_2} and P_{N_2O}, respectively. No significant production or oxidation was observed for CH_4. The factor analysis showed the formation of two independent processes that explained almost 72% of the total variance observed in the data. The first process was related to the transport of F_{CO_2} and its relation to soil physical attributes, such as microporosity, macroporosity, the C/N ratio, soil moisture and soil bulk density, showing the dependence between F_{CO_2} and soil porosity. The second process was related to the soil CO_2 and N_2O production potentials in laboratory conditions and their relation to soil chemical attributes, such as sum of bases, pH and available phosphorus, which affects the microbial activity and contributes to the GHG production. Although presented as independent, these processes are coupled and occur simultaneously in the soil, in addition to provide information about their variability, showing if the infield emissions are due to the gas transport processes or to soil carbon levels and their quality. Furthermore, the spatial dependence of F_{CO_2} is related to soil porosity, as well as the spatial dependence of P_{CO_2} and P_{N_2O} is related to soil chemical attributes. In addition, anisotropy occurred mainly under infield conditions, mostly for the attributes related to soil porosity since disturbed soils used under laboratory conditions lose their structure and hence the effect of the management found under infield conditions.

Keywords: carbon dioxide, methane, nitrous oxide, production potentials, soil respiration, gas transport

1 INTRODUCTION

Anthropogenic emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have increased since the preindustrial era. These greenhouse gases (GHG) are mainly related to the burning of fossil fuels, land use and land use change, especially in agriculture, being mostly responsible for climate change (SCHNEIDER et al., 2001). The concentration of CO_2 in the atmosphere increased from 278 ppm in 1750 to 390.5 ppm in 2011; during the same period, there was an increase in the atmospheric concentration of CH_4, increasing from 722 ppb to 1,803 ppb; it was also observed in the concentration of N_2O, which increased from 271 ppb in 1750 to 324.2 ppb in 2011 (CIAIS et al., 2013).

In Brazil, in 2005, the total CO_2 emissions were estimated to be 1,638 Tg, especially in the sector of land use change and forestry, which accounted for 77% of these emissions (BRASIL, 2010). It should be noted that this total includes the emissions related to lime use in soils, which accounted for 7.5 Tg of CO_2. The CH_4 emissions were estimated to be 18.1 Tg, primarily attributed to the agricultural sector, which accounted for 70% of the total CH_4 emission (BRASIL, 2010). Similarly, N_2O emissions were estimated to be 546 Gg, with the agricultural sector accounting for 87% of the total N_2O emission (BRASIL, 2010).

Agricultural activities, such as soil tillage, influence GHG emission from soil to the atmosphere (LA SCALA; BOLONHEZI; PEREIRA, 2006; CORRADI et al., 2013; MOITINHO et al., 2013; SILVA-OLAYA et al., 2013; TEIXEIRA et al., 2013a; IAMAGUTI et al., 2015) since agricultural management practices in the production systems result in significant physical changes in the soil, altering the gains and losses of soil organic matter (EPRON et al., 2004; SARTORI et al., 2006; LAL, 2009). In agricultural areas, such variations occur mainly in the 0–30-cm soil layer, and are mostly due to mechanized soil disturbances and induced changes in quantity and quality of organic matter (JENKINSON et al., 1992; CHAN, 2001). In tropical soils, the set of all those variations could represent up to 50% of the initial carbon stock in the first 20 cm of the soil (FELLER; BEARE, 1997).

Similarly, soil porosity is also influenced by agricultural activities, directly affecting the transport of GHG in the soil (XU; QI, 2001; JASSAL et al., 2004; EPRON et al., 2006; BALL, 2013). In this case, gas exchange between soil and the atmosphere is regulated by the oxygen entry into the soil and the escape of GHG, which is directly related to the number and interconnectivity of pores in the soil, which could also limit soil oxygenation and thus microbial activity (FANG et al., 1998; BALL, 2013). In the same way, in a study conducted in Australia, in a sugarcane area under burning management and nitrogen fertilization, it was observed elevated rates of soil N_2O emissions for five months, which were related to increased soil porosity, frequent soil wetting and high content of soil organic carbon (DENMEAD et al., 2010).

Sugarcane is produced commercially worldwide and it is an important source of biomass used for the production of the ethanol, which is an alternative to fossil fuels. Brazil has a sugarcane crop area of approximately 9 million hectares and it is expected to produce in the 2015/2016 cropping season approximately 663 million tons of this culture (CONAB, 2015). The large amounts of crop residues left on the soil surface after harvest in mechanically harvested sugarcane areas have tremendous impact on the production processes and on the biogeochemical cycling of carbon and nitrogen, affecting soil organic matter dynamics and consequently GHG emissions (CERRI et al., 2013). In addition to influencing the carbon and nitrogen cycles, the environmental conditions and soil management practices adopted during the sugarcane crop cultivation may result in changes in soil physical, chemical and biological attributes, directly affecting microbial activity and thus the production of CO_2, CH_4 and N_2O and their exchanges between soil and the atmosphere (BLAIR, 2000; SARTORI et al., 2006; CERRI et al., 2007, 2013; DENMEAD et al., 2010; ALLAIRE et al., 2012; BALL, 2013; SIGNOR; CERRI, 2013; SIGNOR; PISSIONI; CERRI, 2014; TAVARES et al., 2015).

Considering that the sugarcane production could play an important role in soil GHG emissions because soil management may interfere with the fluxes of carbon and nitrogen between terrestrial ecosystems and the atmosphere, the aim of this study was to investigate the infield soil CO_2 emissions and the soil CO_2, CH_4 and N_2O production potentials in laboratory conditions, and their relationship to soil attributes in a mechanically harvested sugarcane area.

5 CONCLUSION

The production and emission of soil greenhouse gas in a mechanically harvested sugarcane area located in southern Brazil, evaluated infield and in laboratory conditions, have been associated with two processes: the production in the soil and its transport to the atmosphere. Under infield conditions, only the process related to the transport of CO_2 was more easily observed, showing the correlation between soil CO_2 emission and soil porosity; under laboratory conditions, soil chemical attributes have a greater importance in the process of production potentials of CO_2 and N_2O. Although presented as independent, these processes are coupled and occur simultaneously in the soil, in addition to provide information about their variability, showing if the infield emissions are due to the gas transport processes or to soil carbon levels and their quality, i.e., the gas production processes.

Furthermore, the spatial dependence of soil CO_2 emission showed similarities to soil physical attributes related to soil porosity, as well as the spatial dependence of soil CO_2 and N_2O production potentials showed similarities to soil chemical attributes. In addition, the anisotropy occurred mainly under infield conditions, mostly for the attributes related to soil porosity since disturbed soils used under laboratory conditions lose their structure and hence the effect of the management found under infield conditions

6 REFERENCES

ABEDINI, M. J.; SHAGHAGHIAN, M. R. Exploring scaling laws in surface topography. **Chaos, Solitons & Fractals**, Oxford, v. 42, n. 4, p. 2373–2383, 2009.

AL-KAYSSI, A. W. Spatial variability of soil temperature under greenhouse conditions. **Renewable Energy**, Oxford, v. 27, n. 3, p. 453–462, 2002.

ALLAIRE, S. E.; LANGE, S. F.; LAFOND, J. A.; PELLETIER, B.; CAMBOURIS, A. N.; DUTILLEUL, P. Multiscale spatial variability of CO_2 emissions and correlations with physico-chemical soil properties. **Geoderma**, Amsterdam, v. 170, n. 1, 251–260, 2012.

AMUNDSON, R. G.; DAVIDSON, E. A. Carbon dioxide and nitrogenous oxide gases in the soil atmosphere. **Journal of Geochemical Exploration**, Amsterdam, v. 38, n. 1–2, p. 13–41, 1990.

ANDERSON, J. P. E.; DOMSCH, K. H. A physiological method for the quantitative measurement of microbial biomass in soils. **Soil Biology and Biochemistry**, Oxford, v. 10, n. 3, 215–221, 1978.

ARAH, J. R. M.; SMITH, K. A.; CRICHTON, I. J.; LI, H. S. Nitrous oxide production and denitrification in Scottish arable soils. **European Journal of Soil Science**, Oxford, v. 42, n. 3, p. 351–367, 1991.

BALL, B. C. Soil structure and greenhouse gas emissions: a synthesis of 20 years of experimentation. **European Journal of Soil Science**, Oxford, v. 64, n. 3, 357–373, 2013.

BALL, B. C.; SMITH, K. A. Gas movement and air-filled porosity. In: SMITH, K. A., MULLINS, C. E. (Eds.). **Soil and environmental analysis:** physical methods. 2. ed. New York: Marcel Dekker, 1991. p. 499–538.

BALL, B. C.; SCOTT, A.; PARKER, J. P. Field N_2O, CO_2 and CH_4 fluxes in relation to tillage, compaction and soil quality in Scotland. **Soil and Tillage Research**, Amsterdam, v. 53, n. 1, p. 29–39, 1999.

BARBIERI, D. M.; MARQUES JÚNIOR, J.; PEREIRA, G. T. Variabilidade espacial de atributos químicos de um argissolo para aplicação de insumos à taxa variável em diferentes formas de relevo. **Engenharia Agrícola**, Jaboticabal, v. 28, n. 4, p. 645–653, 2008.

BARTLETT, K. B.; CRILL, P. M.; SEBACHER, D. I.; HARRISS, R. C.; WILSON, J. O.; MELACK, J. M. Methane flux from the central Amazonian floodplain. **Journal of Geophysical Research: Atmospheres**, Hoboken, v. 93, n. D2, 1571–1582, 1988.

BERNARDI, A. C. C.; RABELLO, L. M.; INAMASU, R. Y.; GREGO, C. R.; ANDRADE, R. G. Variabilidade espacial de parâmetros físico-químicas do solo e biofísicos de superfície em cultivo do sorgo. **Revista Brasileira de Engenharia Agrícola e Ambiental**, Campina Grande, v. 18, n. 6, p. 623–630, 2014

BERNOUX, M.; CARVALHO, M. C. S.; VOLKOFF, B.; CERRI, C. C. Brazil's soil carbon stocks. **Soil Science Society of America Journal**, Madison, v. 66, n. 3, p. 888–896, 2002.

BICALHO, E. S.; PANOSSO, A. R.; TEIXEIRA, D. B.; MIRANDA, J. G. V.; PEREIRA, G. T.; LA SCALA, N. Spatial variability structure of soil CO_2 emission and soil attributes in a sugarcane area. **Agriculture, Ecosystems & Environment**, Amsterdam, v. 189, n. 1, 206–215, 2014.

BLAIR, N. Impact of cultivation and sugar-cane green trash management on carbon fractions and aggregate stability for a Chromic Luvisol in Queensland, Australia. **Soil and Tillage Research**, Amsterdam, v. 55, n. 3–4, p. 183–191, 2000.

BODEGOM, P. M. van; STAMS, A. J. M. Effects of alternative electron acceptors and temperature on methanogenesis in rice paddy soils. **Chemosphere**, Oxford, v. 39, n. 2, p. 167–182, 1999.

BRASIL, Ministério da Ciência e Tecnologia. **Segunda comunicação nacional do Brasil à Convenção-Quadro das Nações Unidas sobre mudança do clima**. Brasília: Ministério da Ciência e Tecnologia, 2010. 520 p.

BRITO, L. F.; MARQUES JÚNIOR, J.; PEREIRA, G. T.; LA SCALA, N. Spatial variability of soil CO_2 emission in different topographic positions. **Bragantia**, Campinas, v. 69, supl., 19–27, 2010.

BRITO, L. F.; MARQUES JÚNIOR, J.; PEREIRA, G. T.; SOUZA, Z. M.; LA SCALA, N. Soil CO_2 emission of sugarcane fields as affected by topography. **Scientia Agricola**, Piracicaba, v. 66, n. 1, p. 77–83, 2009.

BURROUGH, P. A. Fractal dimensions of landscapes and other environmental data. **Nature**, London, v. 294, n. 5838, p. 240–242, 1981.

BURROUGH, P. A. **Principles of geographical information systems for land resources assessment**. Oxford: Clarendon Press, 1986. 193 p.

BURROUGH, P. A.; MCDONNELL, R. A. **Principles of geographical information system**. Oxford: Oxford University Press, 1998, 333 p.

BURTON, A. J.; PREGITZER, K. S. Field measurements of root respiration indicate little to no seasonal temperature acclimation for sugar maple and red pine. **Tree Physiology**, Oxford, v. 23, n. 4, 273–280, 2003.

CABRERA, M. L. Modeling the flush of nitrogen mineralization caused by drying and rewetting soils. **Soil Science Society of America Journal**, Madison, v. 57, n. 1, p. 63–66, 1993.

CAMBARDELLA, C. A.; MOORMAN, T. B.; NOVAK, J. M.; PARKIN, T. B.; KARLEN, D. L.; TURCO, R. F.; KONOPKA, A. E. Field-scale variability of soil properties in central Iowa soils. **Soil Science Society of America Journal**, Madison, v. 58, n. 5, p. 1501–1511, 1994.

CANELLAS, L. P.; BUSATO, J. G.; DOBBSS, L. B.; BALDOTTO, M. A.; RUMJANEK, V. M.; OLIVARES, F. L. Soil organic matter and nutrient pools under long-term non-burning management of sugar cane. **European Journal of Soil Science**, Oxford, v. 61, n. 3, p. 375–383, 2010.

CANELLAS, L. P.; VELLOSO, A. C. X.; MARCIANO, C. R.; RAMALHO, J. F. G. P.; RUMJANEK, V. M.; REZENDE, C. E.; SANTOS, G. A. Propriedades químicas de um Cambissolo cultivado com cana-de-açúcar, com preservação do palhiço e adição de vinhaça por longo tempo. **Revista Brasileira de Ciência do Solo**, Viçosa, v. 27, n. 5, p. 935–944, 2003.

CANTERO, J. J.; LEON, R.; CISNEROS, J. M.; CANTERO, A. Habitat structure and vegetation relationships in central Argentina salt marsh landscapes. **Plant Ecology**, Dordrecht, v. 137, n. 1, p. 79–100, 1998.

CAPECHE, C. L.; MACEDO, J. R.; MELO, A. S.; ANJOS, L. H. C. **Parâmetros técnicos relacionados ao manejo e conservação do solo, água e vegetação:** perguntas e respostas. Rio de Janeiro: Embrapa Solos, 2004. 16 p.

CARDELLINI, C.; CHIODINI, G.; FRONDINI, F. Application of stochastic simulation to CO_2 flux from soil: mapping and quantification of gas release. **Journal of Geophysical Research**, Hoboken, v. 108, n. B9, p. 2425, 2003.

CARMO, J. B.; FILOSO, S.; ZOTELLI, L. C.; SOUSA NETO, E. R.; PITOMBO, L. M.; DUARTE-NETO, P. J.; VARGAS, V. P.; ANDRADE, C. A.; GAVA, G. J. C.; ROSSETTO, R.; CANTARELLA, H.; ELIA NETO, A.; MARTINELLI, L. A. Infield greenhouse gas emissions from sugarcane soils in Brazil: effects from synthetic and organic fertilizer application and crop trash accumulation. **Global Change Biology Bioenergy**, Chichester, v. 5, n. 3, 267–280, 2013.

CERRI, C. E. P.; GALDOS, M. V.; CARVALHO, J. L. N.; FEIGL, B. J.; CERRI, C. C. Quantifying soil carbon stocks and greenhouse gas fluxes in the sugarcane agrosystem: point of view. **Scientia Agricola**, Piracicaba, v. 70, n. 5, 361–368, 2013.

CERRI, C. E. P.; SPAROVEK, G.; BERNOUX, M.; EASTERLING, W. E.; MELILLO, J. M.; CERRI, C. C. Tropical agriculture and global warming: impacts and mitigation options. **Scientia Agricola**, Piracicaba, v. 64, n. 1, p. 83–89, 2007.

CHAN, K.Y. Soil particulate organic carbon under different land use and management. **Soil Use and Management**, Oxford, v. 17, n. 4, p. 217–221, 2001.

CIAIS, P.; SABINE, C.; BALA, G.; BOPP, L.; BROVKIN, V.; CANADELL, J.; CHHABRA, A.; DEFRIES, R.; GALLOWAY, J.; HEIMANN, M.; JONES, C.; LE QUÉRÉ, C.; MYNENI, R. B.; PIAO, S.; THORNTON, P. Carbon and other biogeochemical cycles. In: STOCKER, T. F.; QIN, D.; PLATTNER, G.; TIGNOR, M.; ALLEN, S. K.; BOSCHUNG, J.; NAUELS, A.; XIA, Y.; BEX, V.; MIDGLEY, P. M. (Eds.). **Climate change 2013:** the physical science basis. Cambridge e New York: Cambridge University Press, 2013. p. 465–570.

CONAB, Companhia Nacional de Abastecimento. **Acompanhamento da safra brasileira de cana-de-açúcar, segundo levantamento**. Brasília: Conab, 2015. 33 p.

CONCILIO, A.; CHEN, J. Q.; MA, S.; NORTH, M. Precipitation drives interannual variation in summer soil respiration in a Mediterranean-climate, mixed-conifer forest. **Climatic Change**, Dordrecht, v. 92, n. 1–2, p. 109–122, 2009.

CONEN, F.; DOBBIE, K. E.; SMITH, K. A. Predicting N_2O emissions from agricultural land through related soil parameters. **Global Change Biology**, Oxford, v. 6, n. 4, p. 417–426, 2000.

CORÁ, J. E.; ARAÚJO, A. V.; PEREIRA, G. T.; BERALDO, J. M. G. Variabilidade espacial de atributos do solo para adoção do sistema de agricultura de precisão na cultura de cana-de-açúcar. **Revista Brasileira de Ciência do Solo**, Viçosa, v. 28, n. 6, p. 1013–1021, 2004.

CORRADI, M. M.; PANOSSO, A. R.; MARTINS FILHO, M. V.; LA SCALA, N. Crop residues on short-term CO_2 emissions in sugarcane production areas. **Engenharia Agrícola**, Jaboticabal, v. 33, n. 4, p. 699–708, 2013.

COSTA, F. S.; BAYER, C.; ZANATTA, J. A.; MIELNICZUK, J. Estoque de carbono orgânico no solo e emissões de dióxido de carbono influenciadas por sistemas de manejo no sul do Brasil. **Revista Brasileira de Ciência do Solo**, Viçosa, v. 32, n. 1, p. 323–332, 2008.

DASSELAAR, A. P.; CORRÉ, W. J.; PRIEMÉ, A.; KLEMEDTSSON, Å. K.; WESLIEN, P.; KLEMEDTSSON, L.; STEIN, A.; OENEMA, O. Spatial variability of methane, nitrous oxide, and carbon dioxide emissions from drained grasslands. **Soil Science Society of America Journal**, Madison, v. 62, n. 3, p. 810–817, 1998.

DENMEAD, O. T.; MACDONALD, B. C. T.; BRYANT, G.; NAYLOR, T.; WILSON, S.; GRIFFITH, D. W. T.; WANG, W. J.; SALTER, B.; WHITE, I.; MOODY, P. W. Emissions of methane and nitrous oxide from Australian sugarcane soils. **Agricultural and Forest Meteorology**, Amsterdam, v. 150, n. 6, p. 748–756, 2010.

DOMINY, C. S.; HAYNES, R. J.; ANTWERPEN, R. van. Loss of soil organic matter and related soil properties under long-term sugarcane production on two contrasting soils. **Biology and Fertility of Soils**, Heidelberg, v. 36, n. 5, p. 350–356, 2002.

DONAGEMA, G. K.; CAMPOS, D. V. B.; CALDERANO, S. B.; TEIXEIRA, W. G.; VIANA, J. H. M. **Manual de métodos de análise de solo**. 2. ed. Rio de Janeiro: Embrapa Solos, 2011. 230 p.

DUAH-YENTUMI, S.; RONN, R.; CHRISTENSEN, S. Nutrients limiting microbial growth in a tropical forest soil of Ghana under different management. **Applied Soil Ecology**, Amsterdam, v. 8, n. 1–3, p. 19–24, 1998.

EGHBALL, B.; HERGERT, G. W.; LESOING, G. W.; FERGUSON, R. B. Fractal analysis of spatial and temporal variability. **Geoderma**, Amsterdam, v. 88, n. 3–4, p. 349–362, 1999.

EPRON, D.; BOSC, A.; BONAL, D.; FREYCON, V. Spatial variation of soil respiration across a topographic gradient in a tropical rain forest in French Guiana. **Journal of Tropical Ecology**, Cambridge, v. 22, n. 5, p. 565–574, 2006.

EPRON, D.; FARQUE, L.; LUCOT, E.; BADOT, P. Soil CO_2 efflux in a beech forest: dependence on soil temperature and soil water content. **Annals of Forest Science**, Paris, v. 56, n. 3, p. 221–226, 1999.

EPRON, D.; NOUVELLON, Y.; ROUPSARD, O.; MOUVONDY, W.; MABIALA, A.; SAINT-ANDRÉ, L.; JOFFRE, R.; JOURDAN, C.; BONNEFOND, J.; BERBIGIER, P.; HAMEL, O. Spatial and temporal variations of soil respiration in a *Eucalyptus* plantation in Congo. **Forest Ecology and Management**, Amsterdam, v. 202, n. 1–3, p. 149–160, 2004.

FANG, C.; MONCRIEFF, J. B.; GHOLZ, H. L.; CLARK, K. L. Soil CO_2 efflux and its spatial variation in a Florida slash pine plantation. **Plant and Soil**, Dordrecht, v. 205, n. 2, p. 135–146, 1998.

FELLER, C.; BEARE, M. H. Physical control of soil organic matter dynamics in the tropics. **Geoderma**, Amsterdam, v. 79, n. 1–4, p. 69–116, 1997.

FIERER, N.; SCHIMEL, J. P. A proposed mechanism for the pulse in carbon dioxide production commonly observed following the rapid rewetting of a dry soil. **Soil Science Society of America Journal**, Madison, v. 67, n. 3, p. 798–805, 2003.

FRANKLIN, R. B.; MILLS, A. L. Multi-scale variation in spatial heterogeneity for microbial community structure in an eastern Virginia agricultural field. **FEMS Microbiology Ecology**, Oxford, v. 44, n. 3, p. 335–346, 2003.

FOLLETT, R. F. Soil management concepts and carbon sequestration in cropland soils. **Soil and Tillage Research**, Amsterdam, v. 61, n. 1–2, p. 77–92, 2001.

FUENTES, J. P.; BEZDICEK, D. F.; FLURY, M.; ALBRECHT, S.; SMITH, J. L. Microbial activity affected by lime in a long-term no-till soil. **Soil and Tillage Research**, Amsterdam, v. 88, n. 1–2, p. 123–131, 2006.

GALDOS, M. V.; CERRI, C. C.; CERRI, C. E. P. Soil carbon stocks under burned and unburned sugarcane in Brazil. **Geoderma**, Amsterdam, v. 153, n. 3–4, p. 347–352, 2009.

GONÇALVES, A. C. A.; FOLEGATTI, M. V.; MATA, J. D. V. Análises exploratória e geoestatística da variabilidade de propriedades físicas de um Argissolo Vermelho. **Acta Scientiarum**, Maringá, v. 23, n. 5, p. 1149–1157, 2001.

GRAHAM, M. H.; HAYNES, R. J. Organic matter status and the size, activity and metabolic diversity of the soil microbial community in the row and inter-row of sugarcane under burning and trash retention. **Soil Biology and Biochemistry**, Oxford, v. 38, n. 1, p. 21–31, 2006.

GREGORICH, E. G.; ROCHETTE, P.; HOPKINS, D. W.; MCKIM, U. F.; ST-GEORGES, P. Tillage-induced environmental conditions in soil and substrate limitation determine biogenic gas production. **Soil Biology and Biochemistry**, Oxford, v. 38, n. 9, p. 2614–2628, 2006.

HAIR JUNIOR, J. F.; ANDERSON, R. E.; TATHAM, R. L.; BLACK, W. C. **Análise multivariada de dados**. 5. ed. Porto Alegre: Bookman, 2005. 600 p.

HERBST, M.; PROLINGHEUER, N.; GRAF, A.; HUISMAN, J. A.; WEIHERMÜLLER, L.; VANDERBORGHT, J. Characterization and understanding of bare soil respiration spatial variability at plot scale. **Vadose Zone Journal**, Madison, v. 8, n. 3, p. 762–771, 2009.

HERBST, M.; PROLINGHEUER, N.; GRAF, A.; HUISMAN, J. A.; WEIHERMÜLLER, L.; VANDERBORGHT, J.; VEREECKEN, H. Multivariate conditional stochastic simulation of soil heterotrophic respiration at plot scale. **Geoderma**, Amsterdam, v. 160, n. 1, p. 74–82, 2010.

HUANG, C.; BRADFORD, J. M. Applications of a laser scanner to quantify soil microtopography. **Soil Science Society of America Journal**, Madison, v. 56, n. 1, p. 14–21, 1992.

IAMAGUTI, J. L.; MOITINHO, M. R.; TEIXEIRA, D. B.; BICALHO, E. S.; PANOSSO, A. R.; LA SCALA, N. Preparo do solo e emissão de CO_2, temperatura e umidade do solo em área canavieira. **Revista Brasileira de Engenharia Agrícola e Ambiental**, Campina Grande, v. 19, n. 5, p. 497–504, 2015.

ISAAKS, E. H.; SRIVASTAVA, R. M. **An introduction to applied geostatistics**. New York: Oxford University Press, 1989. 561 p.

ISHIZUKA, S.; ISWANDI, A.; NAKAJIMA, Y.; YONEMURA, S.; SUDO, S.; TSURUTA, H.; MURIYARSO, D. Spatial patterns of greenhouse gas emission in a tropical rainforest in Indonesia. **Nutrient Cycling in Agroecosystems**, Dordrecht, v. 71, n. 1, p. 55–62, 2005.

JASSAL, R. S.; BLACK, T. A.; DREWITT, G. B.; NOVAK, M. D.; GAUMONT-GUAY, D.; NESIC, Z. A model of the production and transport of CO_2 in soil: predicting soil CO_2 concentrations and CO_2 efflux from a forest floor. **Agricultural and Forest Meteorology**, Amsterdam, v. 124, n. 3–4, p. 219–236, 2004.

JEFFERS, J. N. R. **An introduction to system analysis:** with ecological applications. London: Edward Arnold, 1978. 198 p.

JENKINSON, D. S.; HARKNESS, D. D.; VANCE, E. D.; ADAMS, D. E.; HARRISON, A. F. Calculating net primary production and annual input of organic matter to soil from the amount and radiocarbon content of soil organic matter. **Soil Biology and Biochemistry**, Oxford, v. 24, n. 4, p. 295–308, 1992.

JOURNEL, A. G.; HUIJBREGTS, C. J. **Mining geostatistics**. London: Academic Press, 1978. 600 p.

KAISER, H. F. The varimax criterion for analytic rotation in factor analysis. **Psychometrika**, New York, v. 23, n. 3, p. 187–200, 1958.

KANG, S.; KIM, S.; OH, S.; LEE, D. Predicting spatial and temporal patterns of soil temperature based on topography, surface cover and air temperature. **Forest Ecology and Management**, Amsterdam, v. 136, n. 1–3, p. 173–184, 2000.

KARHU, K.; AUFFRET, M. D.; DUNGAIT, J. A. J.; HOPKINS, D. W.; PROSSER, J. I.; SINGH, B. K.; SUBKE, J.; WOOKEY, P. A.; ÅGREN, G. I.; SEBASTIÀ, M.; GOURIVEAU, F.; BERGKVIST, G.; MEIR, P.; NOTTINGHAM, A. T.; SALINAS, N.; HARTLEY, I. P. Temperature sensitivity of soil respiration rates enhanced by microbial community response. **Nature**, London, v. 513, n. 7516, p. 81–84, 2014.

KEMMITT, S. J.; LANYON, C. V.; WAITE, I. S.; WEN, Q.; ADDISCOTT, T. M.; BIRD, N. R. A.; O'DONNELL, A. G.; BROOKES, P. C. Mineralization of native soil organic matter is not regulated by the size, activity or composition of the soil microbial biomass—a new perspective. **Soil Biology and Biochemistry**, Oxford, v. 40, n. 1, p. 61–73, 2008.

KHOMIK, M.; ARAIN, M. A.; MCCAUGHEY, J. H. Temporal and spatial variability of soil respiration in a boreal mixedwood forest. **Agricultural and Forest Meteorology**, Amsterdam, v. 140, n. 1–4, p. 244–256, 2006.

KLINKENBERG, B. Fractals and morphometric measures: is there a relationship? **Geomorphology**, Amsterdam, v. 5, n. 1–2, p. 5–20, 1992.

KONDA, R.; OHTA, S.; ISHIZUKA, S.; ARAI, S.; ANSORI, S.; TANAKA, N.; HARDJONO, A. Spatial structures of N_2O, CO_2, and CH_4 fluxes from *Acacia mangium* plantation soils during a relatively dry season in Indonesia. **Soil Biology and Biochemistry**, Oxford, v. 40, n. 12, p. 3021–3030, 2008.

KOSUGI, Y.; MITANI, T.; ITOH, M.; NOGUCHI, S.; TANI, M.; MATSUO, N.; OHKUBO, S.; NIK, A. R. Spatial and temporal variation in soil respiration in a Southeast Asian tropical rainforest. **Agricultural and Forest Meteorology**, Amsterdam, v. 147, n. 1–2, p. 35–47, 2007.

LA SCALA, N.; BOLONHEZI, D.; PEREIRA, G. T. Short-term soil CO_2 emission after conventional and reduced tillage of a no-till sugar cane area in southern Brazil. **Soil and Tillage Research**, Amsterdam, v. 91, n. 1–2, p. 244–248, 2006.

LA SCALA, N.; PANOSSO, A. R.; PEREIRA, G. T. Modelling short-term temporal changes of bare soil CO_2 emissions in a tropical agrosystem by using meteorological data. **Applied Soil Ecology**, Amsterdam, v. 24, n. 1, p. 113–116, 2003.

LA SCALA, N.; MARQUES JÚNIOR, J.; PEREIRA, G. T.; CORÁ, J. E. Short-term temporal changes in the spatial variability model of CO2 emissions from a Brazilian bare soil. **Soil Biology and Biochemistry**, Oxford, v. 32, n. 10, p. 1459–1462, 2000a.

LA SCALA, N.; MARQUES JÚNIOR, J.; PEREIRA, G. T.; CORÁ, J. E. Carbon dioxide emission related to chemical properties of a tropical bare soil. **Soil Biology and Biochemistry**, Oxford, v. 32, n. 10, p. 1469–1473, 2000b.

LA SCALA, N.; PANOSSO, A. R.; PEREIRA, G. T.; PAZ GONZÁLEZ, A.; MIRANDA, J. G. V. Fractal dimension and anisotropy of soil CO_2 emission in na agricultural field during fallow. **International Agrophysics**, Lublin, v. 23, n. 4, p. 353–358, 2009.

LAL, R. World cropland soils as a source or sink for atmospheric carbon. **Advances in Agronomy**, Madison, v. 71, n. 1, p. 145–191, 2001.

LAL, R., Challenges and opportunities in soil organic matter research. **European Journal of Soil Science**, Oxford, v. 60, n. 2, p. 158–169, 2009.

LAL, R.; FAUSEY, N. R.; ECKERT, D. J. Land use and soil management effects on emissions of radiatively active gases from two soils in Ohio. In: LAL, R.; KIMBLE, J.; LEVINE, E.; STEWART, B. A. (Eds.). **Soil management and greenhouse effect**. Boca Raton: Lewis Publishers, 1995. p. 41–59.

LLOYD, J.; TAYLOR, A. On the temperature dependence of soil respiration. **Functional Ecology**, Oxford, v. 8, n. 3, p. 315–323, 1994.

LUCA, E. F.; FELLER, C.; CERRI, C. C.; BARTHÈS, B.; CHAPLOT, V.; CAMPOS, D. C.; MANECHINI, C. Avaliação de atributos físicos e estoques de carbono e nitrogênio em solos com queima e sem queima de canavial. **Revista Brasileira de Ciência do Solo**, Viçosa, v. 32, n. 2, p. 789–800, 2008.

MANDELBROT, B. B. **Fractals:** form, chance, and dimension. San Francisco: W.H. Freeman, 1977. 365 p.

MARK, D. M.; ARONSON, P. B. Scale-dependent fractal dimensions of topographic surfaces: an empirical investigation, with applications in geomorphology and computer mapping. **Mathematical Geology**, Heidelberg, v. 16, n. 7, p. 671–683, 1984.

MATHERON, G. Principles of geostatistics. **Economic Geology**, Littleton, v. 58, n. 8, p. 1246–1266, 1963.

MIRANDA, J. G. V. **Análisis fractal del microrrelieve del suelo**. 2000. 313 f. Tese (Doutorado em Edafologia) – Faculdade de Ciências, Universidade de A Coruña, A Coruña, Epanha, 2000.

MOITINHO, M. R.; PADOVAN, M. P.; PANOSSO, A. R.; LA SCALA, N. Efeito do preparo do solo e resíduo da colheita de cana-de-açúcar sobre a emissão de CO_2. **Revista Brasileira de Ciência do Solo**, Viçosa, v. 37, n. 6, p. 1720–1728, 2013.

MOITINHO, M. R.; PADOVAN, M. P.; PANOSSO, A. R.; TEIXEIRA, D. B.; FERRAUDO, A. S.; LA SCALA, N. On the spatial and temporal dependence of CO_2 emission on soil properties in sugarcane (*Saccharum* spp.) production. **Soil and Tillage Research**, Amsterdam, v. 148, n. 1, p. 127–132, 2015.

NGAO, J.; EPRON, D.; DELPIERRE, N.; BREDA, N.; GRANIER, A.; LONGDOZ, B. Spatial variability of soil CO_2 efflux linked to soil parameters and ecosystem characteristics in a temperate beech forest. **Agricultural and Forest Meteorology**, Amsterdam, v. 154–155, n. 1, p. 136–146, 2012.

OHASHI, M.; GYOKUSEN, K. Temporal change in spatial variability of soil respiration on a slope of Japanese cedar (*Cryptomeria japonica* D. Don) forest. **Soil Biology and Biochemistry**, Oxford, v. 39, n. 5, p. 1130–1138, 2007.

OLIVEIRA, B. G.; CARVALHO, J. L. N.; CERRI, C. E. P.; CERRI, C. C.; FEIGL, B. J. Soil greenhouse gas fluxes from vinasse application in Brazilian sugarcane areas. **Geoderma**, Amsterdam, v. 200–201, n. 1, p. 77–84, 2013.

OLIVEIRA, V. S.; ROLIM, M. M.; VASCONCELOS, R. F. B.; COSTA, Y. D. J.; PEDROSA, E. M. R. Compactação de um Argissolo Amarelo distrocoeso submetido a diferentes manejos. **Revista Brasileira de Engenharia Agrícola e Ambiental**, Campina Grande, v. 14, n. 9, p. 914–920, 2010.

OYONARTE, C.; REY, A.; RAIMUNDO, J.; MIRALLES, I.; ESCRIBANO, P. The use of soil respiration as an ecological indicator in arid ecosystems of the SE of Spain: spatial variability and controlling factors. **Ecological Indicators**, Amsterdam, v. 14, n. 1, p. 40–49, 2012.

PACHEPSKY, Y.; CRAWFORD, J. W. Fractal analysis. In: HILLEL, D. (Ed.). **Encyclopedia of soils in the environment**. Waltham: Academic Press, 2004. v. 2, p. 85–98.

PALMER, M. W. Fractal geometry: a tool for describing spatial patterns of plant communities. **Vegetatio**, Dordrecht, v. 75, n. 1–2, p. 91–102, 1988.

PANOSSO, A. R.; MARQUES JÚNIOR., J.; PEREIRA, G. T.; LA SCALA, N. Spatial and temporal variability of soil CO_2 emission in a sugarcane area under green and slash-and-burn managements. **Soil and Tillage Research**, Amsterdam, v. 105, n. 2, p. 275–282, 2009.

PANOSSO, A. R.; MARQUES JÚNIOR, J.; MILORI, D. M. B. P.; FERRAUDO, A. S.; BARBIERI, D. M.; PEREIRA, G. T.; LA SCALA, N. Soil CO_2 emission and its relation to soil properties in sugarcane areas under slash-and-burn and green harvest. **Soil and Tillage Research**, Amsterdam, v. 111, n. 2, p. 190–196, 2011.

PANOSSO, A. R.; PERILLO, L. I.; FERRAUDO, A. S.; PEREIRA, G. T.; MIRANDA, J. G. V.; LA SCALA, N. Fractal dimension and anisotropy of soil CO_2 emission in a mechanically harvested sugarcane production area. **Soil and Tillage Research**, Amsterdam, v. 124, n. 1, p. 8–16, 2012.

PERFECT, E.; KAY, B. D. Applications of fractals in soil and tillage research: a review. **Soil and Tillage Research**, Amsterdam, v. 36, n. 1–2, p. 1–20, 1995.

PETERS, V.; CONRAD, R. Sequential reduction processes and initiation of CH_4 production upon flooding of oxic upland soils. **Soil Biology and Biochemistry**, Oxford, v. 28, n. 3, p. 371–382, 1996.

PONNAMPERUMA, F. N. The chemistry of submerged soils. **Advances in Agronomy**, Madison, v. 24, n. 1, p. 29–96, 1972.

RAIJ, B. van. Mecanismos de interação entre solos e nutrientes. In: RAIJ, B. van (Ed.). **Avaliação da fertilidade do solo**. Piracicaba: Instituto da Potassa e Fosfato, 1981. p. 17–31.

RAIJ, B. van; ANDRADE, J. C.; CANTARELLA, H.; QUAGGIO, J. A. **Análise química para avaliação da fertilidade de solos tropicais**. Campinas: Instituto Agronômico, 2001. 284 p.

RAZAFIMBELO, T.; BARTHÈS, B.; LARRÉ-LARROUY, M.; LUCA, E. F.; LAURENT, J.; CERRI, C. C.; FELLER, C. Effect of sugarcane residue management (mulching versus burning) on organic matter in a clayey Oxisol from southern Brazil. **Agriculture, Ecosystems & Environment**, Amsterdam, v. 115, n. 1–4, p. 285–289, 2006.

ROBERTSON, F. A.; THORBURN, P. J. Crop residue effects on soil C and N cycling under sugarcane. In: REES, R. M.; BALL, B. C.; CAMPBELL, C. D.; WATSON, C. A. (Eds.). **Sustainable management of soil organic matter**. Wallingford: CABI Publishing, 2001. p. 112–119.

RYU, S.; CONCILIO, A.; CHEN, J.; NORTH, M.; MA, S. Prescribed burning and mechanical thinning effects on belowground conditions and soil respiration in a mixed-conifer forest, California. **Forest Ecology and Management**, Amsterdam, v. 257, n. 4, p. 1324–1332, 2009.

SARTORI, F.; LAL, R.; EBINGER, M. H.; PARRISH, D. J. Potential soil carbon sequestration and CO_2 offset by dedicated energy crops in the USA. **Critical Reviews in Plant Sciences**, Philadelphia, v. 25, n. 5, p. 441–472, 2006.

SCHNEIDER, S.; SARUKHAN, J.; ADEJUWON, J.; AZAR, C.; BAETHGEN, W.; HOPE, C.; MOSS, R.; LEARY, N.; RICHELS, R.; YPERSELE, J. van. Overview of impacts, adaptation, and vulnerability to climate change. In: MCCARTHY, J. J.; CANZIANI, O. F.; LEARY, N. A.; DOKKEN, D. J.; WHITE, K. S. (Eds.). **Climate change 2001:** impacts, adaptation, and vulnerability. Cambridge e New York: Cambridge University Press, 2001. p. 75–104.

SCHWENDENMANN, L.; VELDKAMP, E.; BRENES, T.; O'BRIEN, J. J.; MACKENSEN, J. Spatial and temporal variation in soil CO_2 efflux in an old-growth neotropical rain forest, La Selva, Costa Rica. **Biogeochemistry**, Dordrecht, v. 64, n. 1, p. 111–128, 2003.

SIGNOR, D.; CERRI, C. E. P. Nitrous oxide emissions in agricultural soils: a review. **Pesquisa Agropecuária Tropical**, Goiânia, v. 43, n. 3, p. 322–338, 2013.

SIGNOR, D.; PISSIONI, L. L. M.; CERRI, C. E. P. Emissões de gases de efeito estufa pela deposição de palha de cana-de-açúcar sobre o solo. **Bragantia**, Campinas, v. 73, n. 2, p. 113–122, 2014.

SILVA-OLAYA, A. M.; CERRI, C. E. P.; LA SCALA, N.; DIAS, C. T. S.; CERRI, C. C. Carbon dioxide emissions under different soil tillage systems in mechanically harvested sugarcane. **Environmental Research Letters**, Bristol, v. 8, n. 1, p. 015014, 2013.

SILVEIRA, P. M.; STONE, L. F. Sistemas de preparo do solo e rotação de culturas na produtividade de milho, soja e trigo. **Revista Brasileira de Engenharia Agrícola e Ambiental**, Campina Grande, v. 7, n. 2, p. 240–244, 2003.

SIX, J.; ELLIOTT, E. T.; PAUSTIAN, K. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. **Soil Science Society of America Journal**, Madison, v. 63, n. 5, p. 1350–1358, 1999.

SIX, J.; FREY, S. D.; THIET, R. K.; BATTEN, K. M. Bacterial and fungal contributions to carbon sequestration in agroecosystems. **Soil Science Society of America Journal**, Madison, v. 70, n. 2, p. 555–569, 2006.

SNEATH, P. H. A.; SOKAL, R. R. **Numerical taxonomy:** the principles and practice of numerical classification. San Francisco: W. H. Freeman, 1973. 573 p.

SOUZA, Z. M.; MARQUES JÚNIOR, J.; PEREIRA, G. T. Variabilidade espacial da estabilidade de agregados e matéria orgânica em solos de relevos diferentes. **Pesquisa Agropecuária Brasileira**, Brasília, v. 39, n. 5, p. 491–499, 2004.

SOUZA, Z. M.; PRADO, R. M.; PAIXÃO, A. C. S.; CESARIN, L. G. Sistemas de colheita e manejo da palhada de cana-de-açúcar. **Pesquisa Agropecuária Brasileira**, Brasília, v. 40, n. 3, p. 271–278, 2005.

SPOKAS, K. A. Impact of biochar field aging on laboratory greenhouse gas production potentials. **Global Change Biology Bioenergy**, Chichester, v. 5, n. 2, p. 165–176, 2013.

SPOKAS, K. A.; REICOSKY, D. C. Impacts of sixteen different biochars on soil greenhouse gas production. **Annals of Environmental Science**, v. 3, n. 1, p. 179–193, 2009.

STOTZKY, G.; NORMAN, A. G. Factors limiting microbial activities in soil. **Archiv für Mikrobiologie**, Heidelberg, v. 40, n. 4, p. 341–369, 1961.

STOYAN, H.; DE-POLLI, H.; BÖHM, S.; ROBERTSON, G. P.; PAUL, E. A. Spatial heterogeneity of soil respiration and related properties at the plant scale. **Plant and Soil**, Dordrecht, v. 222, n. 1, p. 203–214, 2000.

SUN, W.; XU, G.; GONG, P.; LIANG, S. Fractal analysis of remotely sensed images: a review of methods and applications. **International Journal of Remote Sensing**, Essex, v. 27, n. 22, p. 4963–4990, 2006.

TAVARES, R. L. M.; FARHATE, C. V. V.; SOUZA, Z. M.; LA SCALA, N.; TORRES, J. L. R.; CAMPOS, M. C. C. Emission of CO_2 and soil microbial activity in sugarcane management systems. **African Journal of Agricultural Research**, Lagos, v. 10, n. 9, p. 975–982, 2015.

TEDESCHI, V.; REY, A.; MANCA, G.; VALENTINI, R.; JARVIS, P. L.; BORGHETTI, M. Soil respiration in a Mediterranean oak forest at different developmental stages after coppicing. **Global Change Biology**, Oxford, v. 12, n. 1, p. 110–121, 2006.

TEIXEIRA, D. B.; PANOSSO, A. R.; CERRI, C. E. P.; PEREIRA, G. T.; LA SCALA, N. Soil CO_2 emission estimated by different interpolation techniques. **Plant and Soil**, Dordrecht, v. 345, n. 1, p. 187–194, 2011.

TEIXEIRA, L. G.; CORRADI, M. M.; FUKUDA, A.; PANOSSO, A. R.; REICOSKY, D.; LOPES, A.; LA SCALA, N. Soil and crop residue CO_2–C emission under tillage systems in sugarcane-producing areas of southern Brazil. **Scientia Agricola**, Piracicaba, v. 70, n. 5, p. 327–335, 2013a.

TEIXEIRA, D. B.; BICALHO, E. S.; PANOSSO, A. R.; CERRI, C. E. P.; PEREIRA, G. T.; LA SCALA, N. Spatial variability of soil CO_2 emission in a sugarcane area characterized by secondary information. **Scientia Agricola**, Piracicaba, v. 70, n. 3, p. 195–203, 2013b.

THORBURN, P. J.; MEIER, E. A.; COLLINS, K.; ROBERTSON, F. A. Changes in soil carbon sequestration, fractionation and soil fertility in response to sugarcane residue retention are site-specific. **Soil and Tillage Research**, Amsterdam, v. 120, n. 1, p. 99–111, 2012.

THORNTHWAITE, C. W. An approach toward a rational classification of climate. **The Geographical Review**, Hoboken, v. 38, n. 1, p. 55–94, 1948.

TOMINAGA, T. T.; CÁSSARO, F. A. M.; BACCHI, O. O. S.; REICHARDT, K.; OLIVEIRA, J. C. M.; TIMM, L. C. Variability of soil water content and bulk density in a sugarcane field. **Australian Journal of Soil Research**, Clayton, v. 40, n. 4, p. 604–614, 2002.

TRANGMAR, B. B.; YOST, R. S.; UEHARA, G. Application of geostatistics to spatial studies of soil properties. **Advances in Agronomy**, Madison, v. 38, n. 1, p. 45–94, 1986.

TSAI, S. M.; BARAIBAR, A. V. L.; ROMANI, V. L. M. Efeitos de fatores físicos e químicos sobre os microrganismos do solo umidade e aeração. In: CARDOSO, E. J. B. N.; TSAI, S. M.; NEVES, M. C. P. (Eds.). **Microbiologia do solo**. Campinas: Sociedade Brasileira de Ciência do Solo, 1992. p. 60–89.

USOWICZ, B.; LIPIEC, J. Spatial distribution of soil penetration resistance as affected by soil compaction: the fractal approach. **Ecological Complexity**, Amsterdam, v. 6, n. 3, p. 263–271, 2009.

USSIRI, D. A. N.; LAL, R. Long-term tillage effects on soil carbon storage and carbon dioxide emissions in continuous corn cropping system from an alfisol in Ohio. **Soil and Tillage Research**, Amsterdam, v. 104, n. 1, p. 39–47, 2009.

VARGAS, L. K.; SCHOLLES, D. Biomassa microbiana e produção de C–CO_2 e N mineral de um Podzólico Vermelho-Escuro submetido a diferentes sistemas de manejo. **Revista Brasileira de Ciência do Solo**, Viçosa, v. 24, n. 1, p. 35–42, 2000.

VARGAS, V. P.; CANTARELLA, H.; MARTINS, A. A.; SOARES, J. R.; CARMO, J. B.; ANDRADE, C. A. Sugarcane crop residue increases N_2O and CO_2 emissions under high soil moisture conditions. **Sugar Tech**, New Delhi, v. 16, n. 2, p. 174–179, 2014.

VAUCLIN, M.; VIEIRA, S. R.; VACHAUD, G.; NIELSEN, D. R. The use of cokriging with limited field soil observations. **Soil Science Society of America Journal**, Madison, v. 47, n. 2, p. 175–184, 1983.

VELDKAMP, E. Organic carbon turnover in three tropical soils under pasture after deforestation. **Soil Science Society of America Journal**, Madison, v. 58, n. 1, p. 175–180, 1994.

VESTERDAL, L.; SCHMIDT, I. K.; CALLESEN, I.; NILSSON, L. O.; GUNDERSEN, P. Carbon and nitrogen in forest floor and mineral soil under six common European tree species. **Forest Ecology and Management**, Amsterdam, v. 255, n. 1, p. 35–48, 2008.

VIDAL VÁZQUEZ, E.; MIRANDA, J. G. V.; PAZ GONZÁLEZ, A. Characterizing anisotropy and heterogeneity of soil surface microtopography using fractal models. **Ecological Modelling**, Amsterdam, v. 182, n. 3–4, p. 337–353, 2005.

VIDAL VÁZQUEZ, E.; VIEIRA, S. R.; DE MARIA, I. C.; PAZ GONZÁLEZ, A. Fractal dimension and geostatistical parameters for soil microrelief as a function of cumulative precipitation. **Scientia Agricola**, Piracicaba, v. 67, n. 1, p. 78–83, 2010.

WANG, G. X.; GERTNER, G.; SINGH, V.; SHINKAREVA, S.; PARYSOW, P.; ANDERSON, A. Spatial and temporal prediction and uncertainty of soil loss using the revised universal soil loss equation: a case study of the rainfall–runoff erosivity *R* factor. **Ecological Modelling**, Amsterdam, v. 153, n. 1–2, p. 143–155, 2002.

WASSMAN, R.; LANTIN, R. S.; NEUE, H. **Methane emissions from major rice ecosystems in Asia**. Dordrecht: Kluwer Academic Publishers, 2000. 394 p.

XU, M.; QI, Y. Soil-surface CO_2 efflux and its spatial and temporal variations in a young ponderosa pine plantation in northern California. **Global Change Biology**, Oxford, v. 7, n. 1, p. 667–677, 2001.

XU, T.; MOORE, I. D.; GALLANT, J. C. Fractals, fractal dimensions and landscapes – a review. **Geomorphology**, Amsterdam, v. 8, n. 4, p. 245–262, 1993.