Revista Brasileira de Ciência do Solo
ISSN: 0100-0683
revista@sbcs.org.br
Sociedade Brasileira de Ciência do Solo
Brasil

Comissão 2.4 - Química do solo

METHANE EFFLUX IN RICE PADDY FIELD UNDER DIFFERENT IRRIGATION MANAGEMENTS[1]

Diovane Freire Moterle[2], Leandro Souza da Silva[3], Vagner João Moro[4], Cimélio Bayer[5], Tiago Zschornack[6], Luis Antonio de Avila[7] & Ângela da Cas Bundt[8]

SUMMARY

Paddy rice fields may contribute to methane (CH_4) emission from soil due to anaerobic conditions after flooding. Alternatives to continuous flooding irrigation in rice have been developed to mitigate CH_4 efflux into the atmosphere. This study aims to investigate the effects of irrigation managements in the CH_4 efflux during the rice growing season. An experiment was carried out at in Santa Maria, Rio Grande do Sul State, Brazil, during 2007/08 and 2009/10 growing seasons. The treatments were continuous flooding and intermittent irrigation in 2007/08 and continuous flooding, intermittent irrigation and flush irrigation in 2009/10. Intermittent irrigation is effective in mitigating CH_4 efflux from rice fields when climatic conditions enable water absence during cultivation, but its efficiency depends on the electrochemical soil conditions during the flooding cycles.

Index terms: greenhouse gas, flooding irrigation, intermittent irrigation, redox potential.

---

[1] Parte da Tese de Doutorado do primeiro autor apresentada no PPG em Ciência do Solo da UFSM. Recebido para publicação em 8 de fevereiro de 2012 e aprovado em 30 de janeiro de 2013.

[2] Professor do Instituto Federal do Rio Grande do Sul, Campus Bento Gonçalves. Av. Osvaldo Aranha, 540. Bairro Juventude da Enologia. CEP 95700-000 Bento Gonçalves (RS). E-mail: diovane.moterle@bento.ifrs.edu.br

[3] Professor Associado, Departamento de Solos, UFSM. Av. Roraima 1000, Camobi. CEP 97105-900 Santa Maria (RS). Bolsista de Produtividade em Pesquisa do CNPq. E-mail: leandro@smail.ufsm.br

[4] Mestrando do Programa de Pós Graduação em Ciência do Solo, UFSM. E-mail: vagnermoro@yahoo.com.br

[5] Professor Associado, Departamento de Solos, Universidade Federal do Rio Grande do Sul. Bolsista de Produtividade em Pesquisa do CNPq. E-mail: cimelio.bayer@ufrgs.br

[6] Pesquisador do Instituto Rio-Grandense do Arroz - IRGA. Av. Bonifácio Carvalho Bernardes, 1494. CEP 94930-030 Cachoeirinha (RS). E-mail: tiago.zsc@gmail.com

[7] Professor Adjunto, Departamento de Fitossanidade, Universidade Federal de Pelotas - UFPel. Bolsista de Produtividade em Pesquisa do CNPq. Pelotas (RS). E-mail: laavilabr@gmail.com

[8] Doutoranda do Programa de Pós-Graduação em Fitossanidade, UFPel. E-mail: angelabundt@hotmail.com

RESUMO: ***EFLUXO DE METANO EM ARROZ IRRIGADO SUBMETIDO A DIFERENTES MANEJOS DE IRRIGAÇÃO***

O cultivo de arroz irrigado pode contribuir com a emissão de metano (CH_4), em razão das condições anaeróbicas, após o alagamento do solo. Alternativas ao alagamento contínuo da irrigação na cultura do arroz têm sido desenvolvidas a fim de mitigar o efluxo de CH_4 para a atmosfera. O objetivo deste estudo foi verificar o efeito do regime de irrigação contínua, intermitente e por banhos no efluxo de CH_4 em arroz irrigado. Para tal, foi conduzido um experimento no Departamento de Fitotecnia da Universidade Federal de Santa Maria, durante os anos agrícolas 2007/2008 e 2009/2010. Os tratamentos consistiram em irrigação contínua e intermitente, em 2007/2008, e irrigação contínua, intermitente e por banhos, em 2009/2010. A prática da irrigação intermitente é eficiente em abrandar o efluxo de CH_4 no cultivo do arroz irrigado, quando as condições climáticas permitem a ausência da lâmina de água durante o cultivo. A eficiência em suavizar o efluxo de CH_4 pelo manejo intermitente da irrigação na cultura do arroz depende das condições eletroquímicas do solo, durante a intermitência dos ciclos de alagamento da cultura.

Termos de indexação: gás de efeito estufa, irrigação por alagamento, irrigação intermitente, potencial redox.

INTRODUCTION

The increase in greenhouse gas content, such as carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4), in the atmosphere during the last years, could be responsible for the increase of the planet's temperature (IPCC, 2007). Methane is a greenhouse gas produced by the decomposition of organic compounds in anaerobic conditions, including flooded rice crop fields (Peters & Conrad, 1996). Rice crops may contribute with up to 25.6 Tg year^{-1} of CH_4 emission, representing 12 % of total anthropic emission (Smith et al., 2007).

Aiming to obtain high grain yields, flooded rice crops tend to use a large volume of water during cultivation (Minami & Yagi, 1998), especially when under continuous flooding (SOSBAI, 2010). According to some authors (Beltrame & Louzada, 1991; Machado et al., 2006), water use may vary from 5,000 to 15,000 m^3 ha^{-1} during a flooded rice cycle. Alternatives to continuous flooding have been developed with different objectives, such as to reduce the volume of water used and increase water use efficiency (Bouman, 2001; Bouman & Tuong, 2001), to reduce toxicity effects of organic compounds and inorganic ions (Bouman et al., 2007); to reduce risks of water reservoir contamination by pesticides (Martini et al., 2012); and to mitigate CH_4 emission (Solomon et al., 2007). Another advantage of these alternative systems could be better soil and water conservation (Stone, 2005).

Alternative irrigation systems, such as intermittent irrigation, are based on the concept that less water may be used in rice crops and high yields may still be maintained. However, the water absence enables soil oxidation changing soil electrochemical conditions (Vahl & Sousa, 2004). Under soil oxidation, methanogenic bacteria activity is affected and CH_4 emission is reduced (Zhang et al., 2011). Because of this, intermittent irrigation has been recommended as a more sustainable technique (IPCC, 2007; Johnson-Beebout et al., 2009). However, different results with this irrigation system have been obtained by different authors. Lima et al. (2003) found 12 % more CH_4 emission with intermittent irrigation than with continuous flooding, while Setyanto & Bakar (2005) found 62 % less CH_4 emission using the same irrigation systems. On the other hand, Nugroho et al. (1997) did not find any effect of irrigation systems on CH_4 emission.

These contradictory results could be related to the fact that environmental conditions greatly influence soil water content, which in turn influence CH_4 emission (Sing, 2001). Although the irrigation systems control the amount of water used, it is impossible to control water from rainfall. Consequently, soil water content may vary regardless of the irrigation system used. Due to these factors, it is very difficult to evaluate the real potential of alternative irrigation systems on CH_4 emission mitigation (Nugroho et al., 1997; Lima et al., 2003; Setyanto & Bakar, 2005, Johnson-Beebout et al., 2009). This study aims to evaluate different irrigation systems on CH_4 emission from a paddy soil (Albaqualf) cultivated with rice.

MATERIAL AND METHODS

Methane emission was evaluated in a field experiment carried out at the Crop Science Department at Federal University of Santa Maria (RS, Brazil), during 2007/08 and 2009/10 growing seasons. The soil is a paddy soil (Albaqualf) and the treatments were two irrigation managements in 2007/08 (continuous flooding and intermittent irrigation), and three irrigation managements in 2009/10 (continuous flooding, intermittent irrigation, and flush irrigation).

The experimental design was completely randomized with three replications in 2007/08 and two replications in 2009/10.

In the continuous flooding irrigation, a water sheet 0.10 m tall was maintained during both growing seasons. In the intermittent irrigation, soil was flooded as in the continuous flooding system (0.10 m water sheet), but the irrigation was suspended until the water sheet was no longer visible, then the irrigation was applied again. Four water applications were carried out in 2007/08 growing season and only one in 2009/10 growing season. In the flush irrigation, 0.02 m of water was applied three times, considering climate and soil conditions, rice development, and rice water requirement in 2009/10 growing season.

The rice plots (15 x 3.8 m) were separated by levees built to isolate each irrigation system and to avoid lateral infiltration and water transference among treatments. Water sheet height was controlled daily by a pre-installed gauge and irrigation was applied automatically and independently in each plot. More details about experimental units are described in Martini et al. (2012). In 2007/08 growing season, rice was cultivated in the conventional system and sowing was carried out in November 08, 2007, using 120 kg ha^{-1} of IRGA 422 CL cultivar seeds. In 2009/10 growing season, rice was cultivated in the no-tillage system and sowing was carried out in October 13, 2009, using 105 kg ha^{-1} of IRGA 422 CL cultivar seeds. Fertilization following CQFSRS/SC (2004) recommendations was the same for all treatments in both growing seasons.

Methane was sampled using the closed static chamber method (Mosier, 1989). The chambers consisted of a metallic square base (0.6 m side and 0.25 m high), a lid (0.6 m side and 0.2 m high), and extensions (0.6 m side and 0.2 m high). The base was placed 5 cm deep into the soil before flooding and extensions were added as needed during plant development. The lid had two fans to homogenize the air inside the chamber and a digital thermometer to record temperature. The lid was placed on the base (or on extensions) just during sampling. The air inside the chamber was extracted in different times after flooding by a plastic 20 mL syringe at 5, 10, 15, 20 and 25 min after the lid was placed, throughout the rice cycle.

Just after sampling, water sheet height and temperature, air temperature, and rice plant height were recorded. The CH_4 concentration in air samples was analyzed by gas chromatography with flame ionization detector (FID) at 250 °C (Shimadzu GC-2014 - model "greenhouse" equipped with three packed columns operating at 70 °C, N_2 as a carrier gas with flow of 26 mL min^{-1}, injector strap direct sampling of 1 mL). Methane flow was calculated by equation 1:

$$f = \frac{\Delta Q}{\Delta t}\frac{PV}{RT} \qquad (1)$$

Where f is CH_4 flow (µg CH_4 m^{-2} h^{-1}), Q is the quantity of gas in the chamber at sampling (µg CH_4/chamber), P is the atmospheric pressure (atm) within the chamber, which was assumed to be 1 atm, V is the volume of the chamber (L), t is the sampling time, R is the ideal gas constant (0.08205 mol atm L^{-1} K^{-1}), and T is the temperature (K) within the chamber at sampling. The rate of gas concentration within the chamber was obtained by a linear equation between gas concentration and sampling time.

Methane effluxes in each sample were given as daily averages (Costa et al., 2008). Total CH_4 emission of rice cycle was estimated integrating the area under the curve obtained by interpolation of the CH_4 efflux values from each sampling time during the experiment (Gomes et al., 2009).

Soil solution was sampled along with CH_4. To enable soil solution sampling, a PVC pipe (20 cm long and 2.5 cm diameter) covered with 80 µm pore polyamide screen was buried 5 cm deep near the chamber base before flooding. A second plastic pipe (50 cm long and 0.3 cm diameter) was linked to it allowing a plastic syringe (60 mL) to be connected during soil solution sampling. Soil solution pH and redox potential (Eh) were determined immediately after sampling using portable potentiometers.

Plant height and grain yield data were also obtained from Mezzomo (2009). The ratio between total CH_4 emission and rice yield was calculated to obtain CH_4 emission per kg of rice grain. Rainfall, average temperature and solar radiation were obtained from the UFSM weather station, no more than 1 km away from the experimental site. Total methane emissions, rice yield, methane emission per kg of rice grain and plant height were submitted to variance analysis and, when significant, Tukey test was applied ($p \leq 0.01$).

RESULTS AND DISCUSSION

In 2007/08 growing season, CH_4 efflux started on the 5th day after flooding (DAF) along with soil reduction and continued rising until approximately 28 to 33 DAF (Figures 1a and 2a,b). This is because labile C from soil organic matter (SOM) was used as substrate by methanogenic bacteria (Cai et al., 1997). In addition, rice was cultivated in conventional system, which contributes to SOM decomposition, increasing CH_4 emission (Costa, 2005). The first CH_4 efflux peak in continuous flooding (26.3 mg of CH_4 m^{-2} h^{-1}) was higher than intermittent irrigation (19.0 mg de CH_4 m^{-2} h^{-1}). A second CH_4 efflux peak during flowering (near 67 DAF) was observed, but there was no relevant difference between treatments (31.1 mg of CH_4 m^{-2} h^{-1} in continuous flooding and 35.3 mg of CH_4 m^{-2} h^{-1} in intermittent irrigation) (Figure 1a). Near flowering, high CH_4 efflux probably occurs due to the large root exudation serving as a source of carbon (C) (Wassmann & Aulakh, 2000). In addition, at this stage, aerenchyma are fully mature throughout the entire plant, working as continuous channels transporting CH_4 into the atmosphere. In this condition, CH_4 efflux would not be highly dependent of irrigation managements if soil is reduced (Wassmann & Aulakh, 2000). After flowering, a constant decrease in CH_4 efflux was observed for both treatments until final sampling at 102 DAF (Figure 1a) due to the lack of conditions to produce CH_4 caused by the end of irrigation and plant senescence, when labile organic C compounds are no longer released by roots (Cai et al., 1997).

During 2007/08 growing season, water absence in intermittent irrigation was observed four times at 17, 38, 56, and 83 DAF (Figure 1a). Less CH_4 efflux was also observed in this treatment between 33rd and 56th DAF (Figure 1a), which is associated with changes in soil solution pH and Eh values observed during this time (Figure 2a,b). Towprayoon et al. (2005) and Minamikawa & Sakai (2006) also observed irrigation systems affecting soil electrochemical conditions in

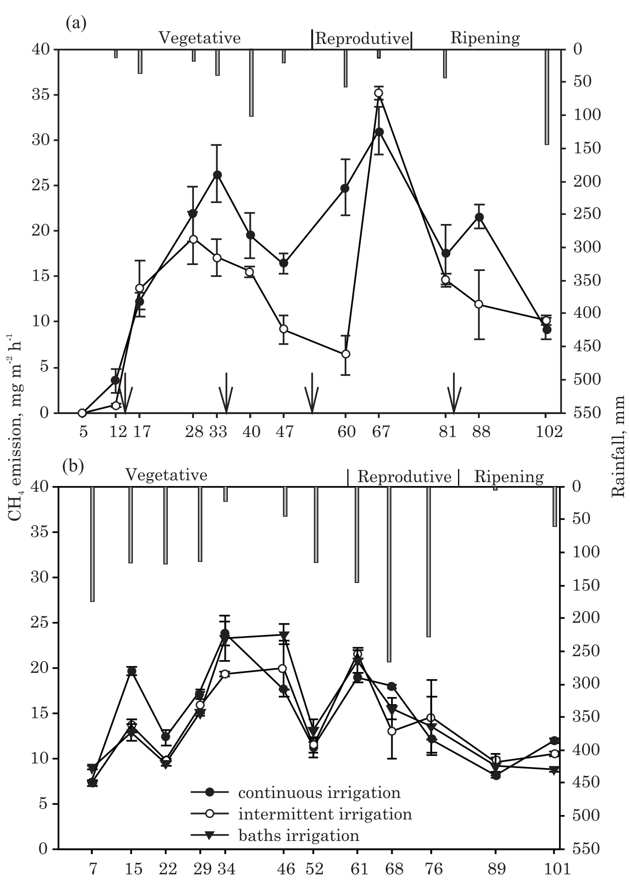

Figure 1. Methane efflux in different irrigation systems (lines and symbols) and rainfall (top bars) in each sample during 2007/08 (a) and 2009/10 (b) growing seasons. Vertical lines indicate standard mean deviation and arrows indicate moments when water sheet is no longer visible.

rice fields, with high soil solution Eh when soil was drained. In these conditions, methanogenic bacteria reduce their activity and activity of CH_4 oxidant bacteria is stimulated, thus reducing CH_4 emission (Zhang et al., 2011).

In the 2009/10 growing season, CH_4 efflux was observed in the first sampling, probably due to high rainfall during this period (Figure 1b), which enables soil reduction before applying irrigation treatments. As a consequence, the first CH_4 efflux peak occurred earlier (15 DAF) than in the 2007/08 growing season. In general, the three treatments had similar behavior on CH_4 efflux during rice cycle. The high rainfall during 2009/10 growing season enabled similar soil electrochemical conditions among irrigation treatments (Figure 2c,d), which determines similar CH_4 emission (Figure 1b). Lower CH_4 efflux peaks were also observed in this 2009/2010 growing season when compared with 2007/08 growing season (Figure 1a,b). In the 2009/10 growing season, as a consequence of high rainfall, less solar radiation, especially during rice flowering (average of 474 cal cm^{-2} day^{-1}), was observed (Figure 3), which affected plant photosynthetic activity and, consequently, less C compounds from root exudation were released for methanogenic bacteria (Aulakh et al., 2001). Hence, less total CH_4 emission was observed in 2009/10 growing season than 2007/08 (Table 1), which had more solar radiation during flowering period (average of 499 cal cm^{-2} day^{-1}). Minamikawa & Sakai (2006), in a two-year field experiment found less CH_4 efflux when there was high rainfall and low temperature during the rice cycle. Consequently, climatic conditions during rice cycle may determine yield potential and total CH_4 emission (Neue et al., 1997; Wassmann et al., 2000; Minamikawa & Sakai, 2006).

The efficiency of alternative irrigation systems in mitigating the CH_4 efflux depends on how water availability in the soil is controlled during the rice cycle. In the absence of water, soil is oxygenated and CH_4 efflux is mitigated (Setyanto & Bakar, 2005; Johnson-Beebout et al., 2009). However, climatic conditions may affect soil moisture and suspending irrigation alone may not be enough to promote soil oxidation. In the 2007/08 growing season, *La niña* phenomena was observed (CPTEC, 2011), with low rainfall (564 mm). Low rainfall enabled four cycles of intermittent irrigation, which influenced soil electrochemical conditions and promoted 25 % less total CH_4 emission when compared with continuous flooding (Table 1). Sass et al. (1992) observed that soil drainage for two days was enough to reduce CH_4 efflux. It was also observed by Johnson-Beebout et al. (2009), who pointed out that the influence of intermittent irrigation on CH_4 efflux reduction occurs when water absence is observed.

In the 2009/10 growing season, *El niño* phenomena was observed (CPTEC, 2011), with high rainfall during this period (1,411 mm). With the large amount

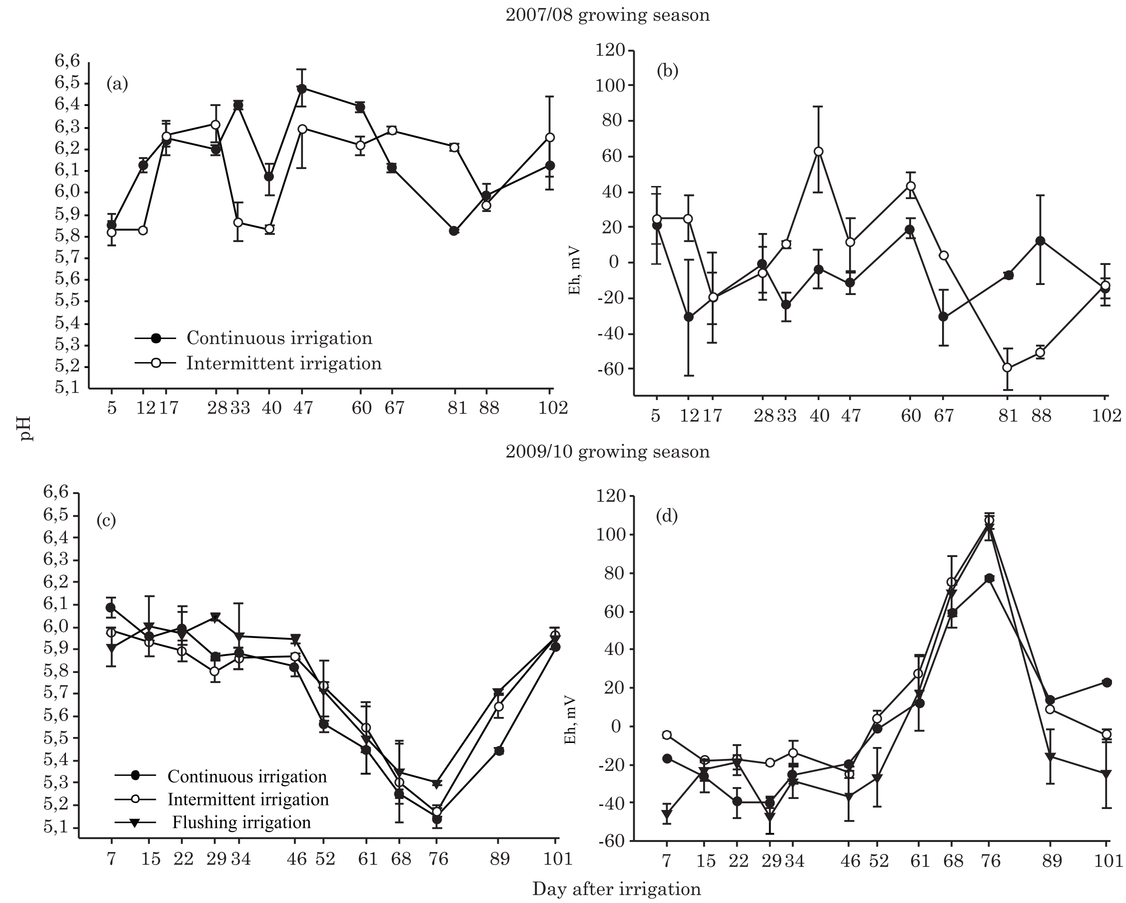

Figure 2. pH values (a) and (c), and Eh values (b) and (d) of the soil solution according to irrigation systems. Vertical lines indicate standard mean deviation.

Table 1. Rice yield, total methane emission, methane emission per rice grain production and plant height in different irrigation managements in 2007/08 and 2009/10 growing seasons

Irrigation system	Growing season	Yield[1]	Total CH_4	CH_4	Plant height
		kg ha^{-1}		g kg^{-1} of rice grain	cm
Continuous flooding	07/08	$9{,}247^{ns}$	$423.0a^{(2)}$	$45.6a^{(2)}$	81.6^{ns}
Intermittent irrigation		9,209	315.0b	34.2b	78.4
Continuous flooding	09/10	$7{,}057^{ns}$	340.8^{ns}	47.4^{ns}	67.4^{ns}
Intermittent irrigation		6,748	312.0^{ns}	47.2	68.0
Flushing irrigation		6,443	322.9^{ns}	51.6	66.8

(2) Different letters indicate significant differences among treatments by Tukey test ($p \leq 0{,}01$); ns: not significant. (1) Data from Mezzomo (2009).

of rainfall, all the treatments remained flooded during almost the entire rice cycle, because there was not enough time between one rainfall event an the other to reduce the amount of water in the field. For this reason, the treatments had the similar soil electrochemical conditions (Figure 2) and similar total CH_4 emission, regardless of irrigation systems (Figure 1b and Table 2). Wassmann et al. (2000) also observed less or null effect of intermittent irrigation in growing seasons with high rainfall. On the other hand, growing seasons with high rainfall enable high water efficiency use, helping rice production with use of less natural resources (Bouman, 2001).

Rice yield and plant height were not significantly different among irrigation systems in each growing season (Table 1). Other authors also found similar

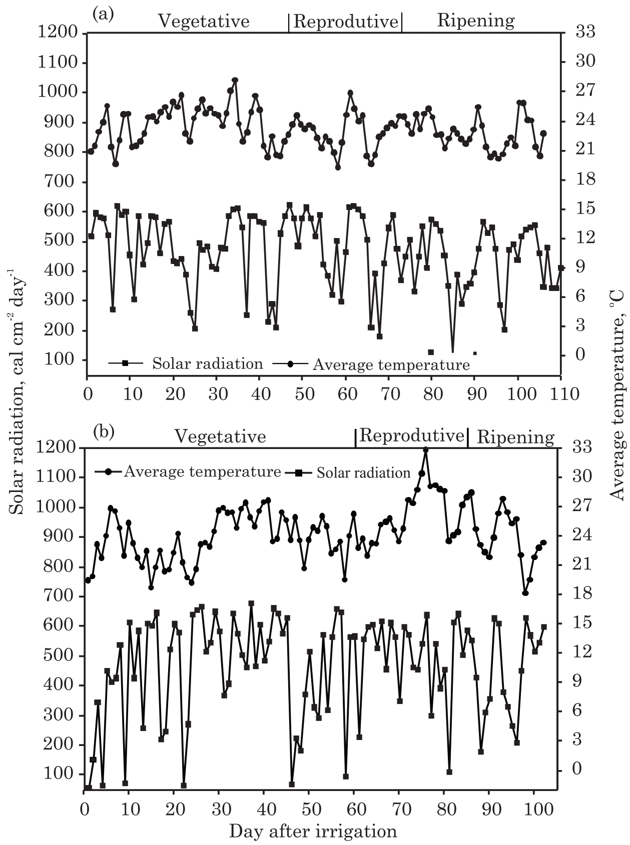

Figure 3. Average temperature and solar radiation during rice cycle in Santa Maria (RS, Brazil).

results (Bouman & Tuong, 2001; Lima et al., 2003; Setyanto & Bakar, 2005; Minamikawa & Sakai, 2006; Bouman et al., 2007). Thus, alternative irrigation systems to continuous flooding do not affect rice production, but a precise water control and other crop managements that affect rice yield, especially weed control, are necessary. The quantity of CH_4 emitted per kg of rice grain was higher in continuous flooding than in intermittent irrigation in 2007/08 growing season, but no differences were observed among irrigation treatments in 2009/10 growing season (Table 1), due to different climatic conditions. Hence, the efficiency of alternative irrigation systems to continuous flooding, such as intermittent irrigation, on CH_4 emission mitigation also depends on climatic conditions. In this sense, it is possible to produce rice with more water use efficiency and less environmental impact using different irrigation managements, but its effects depend on climatic conditions in each growing season.

CONCLUSION

Intermittent irrigation is effective in mitigating CH_4 efflux in rice crops when climatic conditions enable water absence during cultivation, but its efficiency depends on the electrochemical soil conditions during the flooding cycles.

ACKNOWLEDGEMENTS

The authors acknowledge National Council for Scientific and Technological Development (CNPq) and Foundation of Research Support in Rio Grande do Sul (FAPERGS) for financial support (grant and research fellowship for L.S. Silva, C. Bayer, L.A. Avila, D. F. Moterle and T. Zschornack). We also acknowledge to Eng. Agron. Rafael Mezzomo and Luiz Fernando Dias Martini for research data from their experiments.

LITERATURE CITED

AULAKH, M.S.; WASSMANN, R.; BUENO, C. & RENNENBERG, H. Impact of root exudates of different cultivars and plant development stages of rice (*Oryza sativa L.*) on methane production in a paddy soil. Plant Soil, 230:77-86, 2001.

BELTRAME, L.S. & LOUZADA, J.A. Water use rationalization in rice irrigation by flooding. In: INTERNATIONAL SEMINAR ON EFFICIENT WATER USE, 1., México, 1991. Anais... México, IWRA, 1991. p.337-345.

BOUMAN, B.A.M. Water-efficient management strategies in rice production. Inter. Rice Res. Notes, 16:17-22, 2001.

BOUMAN, B.A.M. & TUONG, T.P. Field water management to save water and increase its productivity in irrigated rice. Agric. Water Manage., 49:11-30, 2001.

BOUMAN, B.A.M.; LAMPAYAN, R.M. & TUONG, T.P. Water management in irrigated rice: Coping with water scarcity. Los Baños, International Rice Research Institute, 2007. 54p.

CAI, Z.; XING, G.; YAN, X.; XU, H.; TSURUTA, H.; YAGI, K. & MINAMI, K. Methane and nitrous oxide emissions from paddy fields as affected by nitrogen fertilizers and water management. Plant Soil, 196:7-14, 1997.

CENTRO DE PREVENÇÃO DE TEMPO E ESTUDOS CLIMÁTICOS - CPTEC. El niño e La niña. Disponível em: <http://enos.cptec.inpe.br>. Acesso em 25 jul. 2011.

COMISSÃO DE QUIMICA E FERTILIDADE DO SOLO - CQFSRS/SC. Manual de adubação e calagem para os Estados do Rio Grande do Sul e de Santa Catarina. 10.ed. Porto Alegre, Sociedade Brasileira de Ciência do Solo/ Núcleo Regional Sul, 2004. 400p.

COSTA, F.S. Estoques de carbono orgânico e efluxos de dióxido de carbono e metano de solos em preparo convencional e plantio direto no subtrópico brasileiro. Porto Alegre, Universidade Federal do Rio Grande do Sul, 2005. 128p. (Tese de Doutorado)

COSTA, F.S.; BAYER, C.; LIMA, M.A.; FRIGHETTO, R.T.S.; MACEDO, V.R.M. & MARCOLIN, E. Variação diária da emissão de metano em solo cultivado com arroz irrigado no Sul do Brasil. Ci. Rural, 38:2049-2053, 2008.

GOMES, J.; BAYER, C.; COSTA, F.S.; PICCOLO, M.C.; VIEIRA, F.C.B. & SIX, J. Soil nitrous oxide emission as affected by long term tillage, crop rotations and fertilization in a subtropical environment. Soil Tillage Res., 101:36-44, 2009.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE - IPCC. Climate Change 2007: The physical science basis: Summary for policymakers. Geneva, Intergovernmental Panel on Climate Change, 2007. 22p.

JOHNSON-BEEBOUT, S.E.; ANGELES, O.R.; ALBERTO, M.C.R. & BURESH, R.J. Simultaneous minimization of nitrous oxide and methane emission from rice paddy soils is improbable due to redox potential changes with depth in a greenhouse experiment without plants. Geoderma, 149:45-53, 2009.

LIMA, M.A.; VILELLA, O.V.; FRIGHETTO, R.T.S. & PARAIBA, L.C. Influence of continuous and intermittent water regime on methane emission from irrigated rice crops in the Southeast of Brazil. In: INTERNATIONAL METHANE AND NITROUS OXIDE MITIGATION CONFERENCE, 3., Beijing, 2003. Proceedings… Beijing, China Coal Information Institute, 2003. p.17-21.

MACHADO, S.L.O.; MARCHEZAN, E.; RIGHES, A.A.; CARLESSO, R.; VILLA, S.C.C. & CAMARGO, E.R. Consumo de água e perdas de nutrientes e de sedimentos na água de drenagem inicial do arroz irrigado. Ci. Rural, 36:65-71, 2006.

MARTINI, L.F.D.; AVILA, L.A.; CASSOL, G.V.; ZANELLA, R.; MACHADO, S.L.O.; MARQUES, M.S. & DEVICARI, M. Transporte de agrotóxicos em lavoura de arroz irrigado sob três manejos de irrigação. Planta Daninha, 30:799-808, 2012.

MEZZOMO, R. Irrigação contínua e intermitente em arroz irrigado: Uso de água, eficiência agronômica e dissipação de imazethapyr, imazapic e fipronil. Santa Maria, Universidade Federal de Santa Maria, 2009. 61p. (Dissertação de Mestrado)

MINAMI, K. & YAGI, K. Mitigation of methane emissions from rice cultivation. Global Environ. Res., 2:15-19, 1998.

MINAMIKAWA, K. & SAKAI, N. The practical use of water management based on soil redox potential for decreasing methane emission from a paddy ûeld in Japan. Agric. Ecosyst. Environ., 116:181-188, 2006.

MOSIER, A.R. Chamber and isotopic techniques. In: ANDREAE, M.O. & SCHIMEL, D.S., eds. Exchange of traces gases between terrestrial ecosystems and the atmosphere: Report of the Dahlem Workshop. Berlin, John Wiley & Sons, 1989. p.175-187.

NEUE, H.U.; WASSMANN, R.; KLUDZE, H.K.; BU, J. & LANTIN, R.S. Factors and processes controlling methane emission from rice fields. Nutr. Cycl. Agroecosyst., 49:111-117, 1997.

NUGROHO, S.G.; SUNYOTO, LUMBANRAJA, J.; SUPRAPTO, H.; ARDJASA, W.S. & KIMURA, M. Effect of rice variety on methane emission from an Indonesian paddy field. Soil Sci. Plant Nutr., 43:799-809, 1997.

PETERS, V. & CONRAD, R. Sequential reduction processes and initiation of CH_4 production upon flooding of oxic upland soils. Soil Biol. Biochem., 28:371-382, 1996.

SASS, R.L.; FISHER, F.M.; WANG, Y.B.; TURNER, F.T. & JUND, M.F. Methane emission from rice ûelds: The effect of ûood water management. Global Biogeochem. Cycles, 6:249-262, 1992.

SETYANTO, P. & BAKAR, R.A. Methane emission from paddy fields as influenced by different water regimes in central Java. Indonesian J. Agric. Sci., 6:1-9, 2005.

SING, S.N. Exploring correlation between redox potential and other edaphic factors in field and laboratory conditions in relation to methane efflux. Environ. Inter., 27:265-274, 2001.

SMITH, P.; MARTINO, D.; CAI, Z.; GWARY, D.; JANZEN, H.; KUMAR, P.; McCARL, B.; OGLE, S.; O'MARA, F.; RICE, C.; SCHOLES, B. & SIROTENKO, O. Agriculture. In: CLIMATE CHANGE 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, Cambridge University Press, 2007.

SOCIEDADE SUL-BRASILEIRA DE ARROZ IRRIGADO - SOSBAI. Arroz irrigado: Recomendações técnicas da pesquisa para o Sul do Brasil. Porto Alegre, 2010. 188p.

SOLOMON, S.; QIN, D.; MANNING, M.; ALLEY, R.B.; BERNTSEN, T.; BINDOFF, N.L.; CHEN, Z.; CHIDTHAISONG, J.M. GREGORY, G.C.; HEIMANN, M.; HEWITSON, B.; HOSKINS, B.J.; JOOS, F.; JOUZEL, J.; KATTSOV, V.; LOHMANN, U.; MATSUNO, T.; MOLINA, M.; NICHOLLS, N.; OVERPECK, J.; RAGA, G.; RAMASWAMY, V.; REN, J.; RUSTICUCCI, M.; SOMERVILLE, R.; STOCKER, T.F.; WHETTON, P.; WOOD, R.A. & WRATT, D. Technical Summary. In: CLIMATE CHANGE 2007: The physical science basis. Contribution of Working Group I to the Fourth, Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, Cambridge University Press, 2007.

STONE, L.F. Eficiência do uso da água na cultura do arroz irrigado. Santo Antônio de Goiás, Embrapa Arroz e Feijão, 2005. 48p. (Documentos, 176)

TOWPRAYOON, S.; SMAKGAHN, K. & POONKAEW, S. Mitigation of methane and nitrous oxide emissions from drained irrigated rice ûelds. Chemosphere, 59:1547-1556, 2005.

VAHL, L.C. & SOUSA, R.O. Aspectos físico-químicos de solos alagados. In: GOMES, A.S. & MAGALHÃES Jr., A.M., eds. Arroz irrigado no Sul do Brasil. Brasília, Embrapa Informação Tecnológica, 2004. p.97-118.

WASSMANN, R. & AULAKH, M.S. The role of rice plants in regulating mechanisms of methane emissions. Biol. Fert. Soils, 31:20-29, 2000.

WASSMANN, R.; NEUE, H.U.; LANTIN, R.S.; BUENDIA, L.V. & RENNENBERG, H. Characterization of methane emissions from rice fields in Asia. I. Comparison among field sites in five countries. Nutr. Cycl. Agroecosyst., 58:1-12, 2000.

ZHANG, G.; ZHANG, X.; MA, J.; XU, H. & CAI, Z. Effect of drainage in the fallow season on reduction of CH_4 production and emission from permanently flooded rice fields. Nutr. Cycl. Agroecosyst., 89:81-91, 2011.