Does soil type hold a role in the dynamic of carbon dioxide (CO$_2$) emission from paddy rice fields?

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Abstract. Soil holds a vital role in forming greenhouse gas (GHG) emission from paddy rice fields. There are three main GHG from paddy rice, namely Methane (CH$_4$), nitrous oxide (N$_2$O) and carbon dioxide (CO$_2$). This research aimed solely to explore the dynamic of CO$_2$ emission from paddy rice with different soil types, namely sandy loam and clay soil. In each site, two-factor treatments were applied. There was water regime namely 1) continuously flooded, and 2) alternate wetting-drying (AWD) as the first factor and organic matter application namely 1) without organic matter (OM), 2) bio-compost 5 t ha$^{-1}$, and 3) bio-compost 10 t ha$^{-1}$. Carbon dioxide flux in sandy loam soil ranged between -11.50 to -0.47 mg CO$_2$ m$^{-2}$ d$^{-1}$ under continuously flooded conditions and -7.64 to 3.03 mg CO$_2$ m$^{-2}$ d$^{-1}$ alternate wetting-drying conditions. The clay soil was lower, ranging between -7.43 to 0.51 mg CO$_2$ m$^{-2}$ d$^{-1}$ under continuously flooded conditions and -5.54 to 0.47 mg CO$_2$ m$^{-2}$ d$^{-1}$ under alternate wetting-drying conditions. Clay soil tended to emit less CO$_2$ emission than sandy soil. The result showed that soil physical characteristic plays an important role in controlling CO$_2$ from paddy rice.

1. Introduction

Climate change and ozone depletion have been grown as a widespread concern over the past two decades. It is mainly caused by the abundant increase of anthropogenic greenhouse gases (GHG) concentration in the earth’s atmosphere [1]. Carbon dioxide is the most important GHG; even its absorbs less heat per molecule than the others, its concentration is the highest [2]. Agriculture is one of many sectors that contributes to this anthropogenic GHG. Smith et al [3] mentioned that CO$_2$ emissions from fossil fuels are much lesser than those from respiration in soil and vegetation.

According to Shahbandeh [4], Indonesia is the third paddy rice producer globally, after China and India. Aside from being a producer, they consume as well. Rice is the foremost food for about 95% of peoples in the country. Indonesia nearly has 55 Mt of raw rice production and 111,58 kg daily per capita consumption [5]. Emissions of CO$_2$ from cropland occur in three ways, namely plant residual decay, respiration, and organic carbon oxidation. Soil holds an essential role in CO$_2$ fluxes as well as other
GHGs from agriculture. Soil's microbial processes resulted in the production or consumption of CO$_2$; however, the dynamics of the gases emitted to the air determined soil physical and chemical factors [3].

Various crop managements such as water regimes, fertilizer management, tillage, rice cultivar are considered to affect CO$_2$. Recent studies on GHG emissions mitigation options have concluded that alternating water in the soil between wetting and drying is the most promising option [6]. This condition will be affecting the dynamics of organic carbon in soil and soil chemical properties through the change between anaerobic-aerobic conditions [7]. A study by Ariani et al [8] concluded that aerobic-anaerobic change caused by alternate wetting-drying (AWD) affects several soil chemical compositions producing CH$_4$ and N$_2$O emission. Thus, the alternate wetting-drying condition will also have a substantial impact on soil CO$_2$ fluxes. This impact will also determine soil physical condition to control soil's gas movement [3]. A coarse soil emits more CO$_2$ than fine or clay soil since it has high air-filled porosity. Rice plants using CO$_2$ to generate energy from sunlight and respire it at night time. The amount of CO$_2$ emitted from rice system to open air during the day were the net fluxes between the amount using for photosynthesis and emitted from soil [9]. This research aimed solely to explore the dynamic of CO$_2$ emission from paddy rice with different soil types, namely sandy loam and clay soil.

2. Materials and methods

2.1. Site description

The research took place in two sites at Pati Regency, Central Java. The first site was at Indonesian Agricultural Environment Research Institute at Jakenan Sub-Regency, which represents sandy loam soil (SS), and the second sites were at a farmer’s field in Wedarijaksa Sub-Regency represent clay soil (CS). Both were conducted in dry season 2020 (April-June). SS has 39% sand, 49% silt, 10% clay, C-organic (%) 0.71, N-total (%) 0.05, while CS has 8% sand, 47% silt, 49% clay, C-organic (%) 1.09, N-total (%) 0.09. Altitude in Pati ranges from 10 to 40 m above sea level, the annual mean temperature is 30 °C and annual rainfall averages 1503-2100 mm. Both sites were supported by an artificial irrigation system, Embung in Jakenan and an irrigation dam in Wedarijaksa.

2.2. Experimental Design

The experimental design at the two sites was the same. Transplanted rice was established during the research, which was performed 21 days after seedling. Inpari 32 rice cultivar was transplanted into each 5 m × 4 m plot, with 20 cm × 20 cm plant spacing and one seedling per hill. The experiments were arranged in a randomized factorial block design with three replications. Treatments consist of two factors; the first factor was water regime, namely 1) continuously flooded (A1), and 2) alternate wetting-drying (AWD, or A2). Continuously flooded means that the water were maintain at 5 cm high above the soil surface for the entire rice-growing season. Plastic covers were installed around the plot of A1. Alternate wetting-drying means that re-flooding 5 cm when the surface water level naturally declined to 15 cm below the soil surface. The second factor was organic matter application, namely 1) without OM (B0), 2) Bio-compost OM 5 t ha$^{-1}$ (B1), and 3) Bio-compost OM 10 t ha$^{-1}$ (B2). Bio-compost is mixed from compost and rice husk biochar (4:1). Rice husk biochar was created with pyrolysis at a temperature of 600 °C, containing organic C (14.97%), N (0.36%), P (1.5%), and K (7.2%). Organic matters were applied after soil puddling at five days before transplanting. The maintenance of AWD plots and inorganic fertilizer management was described in Ariani et al [8].

2.3. Gas sampling and measurement

A static closed chamber method was used in this experiment since these techniques were more suitable and accurate for plot scale studies [10]. The closed chamber material, shape, and placement were described by Ariani et al [8]. The CO$_2$ gas measurement covers rice plants during the day considered flux from rice ecosystem (rice and soil). The chamber covers four rice plants. Gas samples were collected weekly at 7-9 a.m. Twenty ml plastic syringes were used to take the gas samples from the chamber at 10, 20, 30, and 40 min during chamber closure. The gas samples were analyzed immediately
in the laboratory on the same day of sampling using a GC (Shimadzu 14B series equipped with a Thermal Conductivity Detector). The methods for calculating the gas flux were the same as those described by Minamikawa et al [11] as Equation (1).

\[
E = \frac{Bm \times \Delta C}{Vm} \times \frac{V}{A} \times \frac{273.2}{T + 273.2}
\]  

(1)

Where \(E\) is CO\(_2\) (mg m\(^{-2}\) min\(^{-1}\)), \(Bm\) is molecular weight of CO\(_2\) (g), \(Vm\) is molecular volume of CO\(_2\) at standard temperature and pressure (22.41l), \(\Delta C/\Delta t\) is the slope of linear regression of CO\(_2\) changes over time (ppm/min), \(V\) is headspace volume (m\(^3\)), \(A\) is chamber area (m\(^2\)) and \(T\) is mean air temperature inside the chamber during gas sampling (°C).

2.4. Soil sampling and analyses

Soil samples (0-20 cm) were taken to analyze soil texture, total N (Kjeldahl method) and total C (Spectrophotography).

2.5 Statistical analysis

A general linear model to generate two-way analysis of variance (ANOVA ) in Minitab version 16 Software was performed to analyze the effect of different treatments and soil types. When significant differences were detected at \(P = 0.01\) and \(P = 0.05\), the mean values were then compared using Tukey’s pairwise comparison test.

3. Result and discussion

3.1. Dynamics of CO\(_2\) flux

CO\(_2\) fluxes pattern from sandy loam soil (a) and clay soil (b) are shown in Figure 1. CO\(_2\) displayed negative fluxes during the day measurement for both soil types and treatments, except during early days of growth and the period of maturing in sandy loam soil (Figure 1a). A study in Myanmar on a rice field under conventional and conservation practices showed the same result [9]. Fluxes CO\(_2\) among management practices overall showed the same pattern in the two soil types. Fluxes were a bit high during the early transplanting stage. As the plant grows, CO\(_2\) tends to be lesser, which was due to CO\(_2\) in the photosynthesis process. The plant growth stage uses a different amount of CO\(_2\) in their photosynthesis. More negative fluxes indicate that the amount of CO\(_2\) used by plants was higher than CO\(_2\) produced and released by soil. The active tillering stage has the most active photosynthesis process, which resulted in high CO\(_2\) absorption [12]. In sandy soil (Figure 1a), there are two times of positives CO\(_2\), which occur a week after transplanting and about a week before harvesting (maturing stage). Positives fluxes indicate the CO\(_2\) being emit into the atmosphere. The CO\(_2\) dynamics fluxes also a result of the alternating condition between aerobic-anaerobic under AWD. The fluxes under this water regime tend to be higher than under CF (small negative flux).

The dynamics of CO\(_2\) fluxes from clay soil (Figure 1b) showed a slightly different maturity stage than fluxes from sandy soil. There are no positives fluxes during the maturity stage, but higher negatives fluxes also showed during the active tillering stage. The dynamics of CO\(_2\) seasonal fluxes between treatments were identical despite the different bio-compost addition rates. The plots under AWD tend to have low negative flux than the plots under CF. The plot with AWD water regime has lesser CO\(_2\) fluxes than that from the plot under CF. Under flooding conditions, CO\(_2\) production is extremely restricted due to anaerobic conditions [7]. During the flooding period, soil pores will completely be filled with water, replacing the gas phase. It seems that flooding decreases topsoil diffusivity and may have decreased soil CO\(_2\) diffusivity [13].
Figure 1. The dynamics of CO$_2$ fluxes under water regimes and organic matter application in (a) sandy loam soil and (b) clay soil, DS 2020 (A1= CF, A2= AWD, B0= No OM, B1= 5 t ha$^{-1}$, B2= 10 t ha$^{-1}$)

Miyata $et al$ [14] found out that CO$_2$ flux from rice fields in drained conditions was significantly larger than when it was flooded. As the field was drained, diffusion barriers were removed at the same time. This condition leads to an increase in the release of the CO$_2$ flux. Researches on the effects of biochar addition on the CO$_2$ flux resulted in different findings. Cui $et al$ [15] stated that CO$_2$ emissions were not significantly affected by biochar addition. Fan $et al$ [16] reported a condition of a more poorly developed soil pore structure after biochar addition, which inhibited soil CO$_2$ production and diffusion. Another study by Yang $et al$ [1] reported a significant difference in CO$_2$ absorption from biochar addition at a high rate under the long-term application.
3.2. Relationships between soils and treatments

Water management only has a significant effect on CO₂ flux if implemented in clay soil; according to this research finding, there is no significant effect in sandy loam soil. Clay soil tends to have high water holding capacity. The fine texture of clay soil has less air-filled porosity than sandy soil, this condition lowering gas diffusivity, which inhibits CO₂ from being released into the atmosphere. Analysis of variance between sites indicates a significant effect of water management and highly significant soil type to CO₂ fluxes. It can be explained that any microbial process in the soil which produces GHG depended on water condition. Many studies have suggested that aerobic-anaerobic conditions play a vital role in GHG processes, depending on soil physical characteristics. More fine soil texture will be likely stored more gasses than a coarse soil texture and related to water management.

**Table 1.** Significance difference in CO₂ fluxes in different water management and organic matter amendment from two soil types

|                           | CO₂          | Sandy loam mg m⁻² d⁻¹ | Clay soil mg m⁻² d⁻¹ |
|---------------------------|-------------|------------------------|----------------------|
| Water management          |             |                        |                      |
| CF                        | -4,234 A    | -3,377 B               |                      |
| AWD                       | -3,911 A    | -1,992 A               |                      |
| Organic matter amendment  |             |                        |                      |
| No OM                     | -4,822 A    | -2,562 A               |                      |
| Bio-compost 5 t h⁻¹       | -2,446 A    | -2,551 A               |                      |
| Bio-compost 10 t h⁻¹      | -4,949 A    | -2,941 A               |                      |

ANOVA (between sites)
Water management *
OM amendment ns
Soil **

*P < 0.05, **P < 0.01, ns, not significant. Values in each column are means of three replicates. Different letters vertically indicate significant differences between means at P = 0.05, according to Tukey’s Honestly Significant Different (HSD-test).

Bio-compost as an organic matter amendment does not significantly affect CO₂ fluxes, according to this research finding. Many studies resulted that long term organic matter application may be beneficial to the soil like increase soil aggregate and lead to reduces the risk of erosion [17]; increases soil porosity, therefore increasing water holding capacity (WHC), water infiltration and percolation [18]; and mobilizes C and N in the soil [19]. He et al [20] found significant impacts of several variables, including the length of field study, soil texture and pH, biochar pH and application rate. There could be concluded that the impact of organic matter amendment will be significant to the soil structure and processes related to GHG production in a long-term application, in which a study regarding this matter should be conducted in the long term.

4. Conclusion
The CO₂ seasonal flux in rice-fields under alternate wetting-drying and organic matter amendments showed a particular dynamic following the rice growth stages. Daytime CO₂ fluxes measurement expressed that rice field served as a sink for CO₂. AWD only has a significant effect on CO₂ flux on clay soil. The short-term bio compost application had no significant effect on CO₂ flux. Soil type has a highly significant effect in regard to water management practices. The alternate wetting-drying water management would be the better option to implement in clay soil type.
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