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Can soil-improving cropping systems increase rice production while reducing greenhouse gas emission?

A STUDY ON SUSTAINABLE RICE PRODUCTION IN THE VIETNAMESE MEKONG DELTA

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2. ACKNOWLEDGEMENTS

Forsan et haec olim meninisse iuvabit.

As Virgil once wrote, one day I will remember this and smile.
Because I pushed myself harder than ever before, because I met fantastic people along the way, because I learned innumerable things about scientific research conduct and about myself, and maybe mostly because it will all be in the past. I am grateful for the opportunities I have received conducting this fascinating research. Completing my thesis was a bumpy road, but every challenge was overcome with the help of the people surrounding me.

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3. TABLE OF CONTENTS

4. LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
CA	Amended with cow manure+rice straw compost
CH_4	Methane
CO^2	Carbon dioxide
CO^2-eq.	CO_2-equivalents
DAS	Days after sowing
DM	Dry matter
Eh	Redox potential
Fe^{2+}	Ferrous iron
Fe^{2+}-eq.	Fe^{2+}-equivalents
Fe^{3+}	Ferric iron
GC	Gas chromatography
GDP	Gross domestic product
GHG	Greenhouse gas
GWP	Global warming potential
N_2O	Nitrous oxide
NA	Not amended
OM	Organic matter
R-R-R	Rice-Rice-Rice crop rotation system
R-Se-R	Rice-Sesame-Rice crop rotation system
SO_4^{2-}	Sulfate
SOC	Soil organic carbon
SOM	Soil organic matter
VMD	Vietnamese Mekong Delta

5. ABSTRACT

Rice agriculture heavily impacts global warming by the emission of greenhouse gasses (GHGs) due to prevailing anaerobic soil conditions inherent to paddy rice production. Particularly in the Vietnamese Mekong Delta, current rice cropping systems are highly non-sustainable due to soil degradation resulting from intensive rice monocultures with three crops per year and to the emission of GHGs. Improving crop productivity while adapting to climate change and restructuring agriculture are among the top priorities of the agricultural sector in Vietnam. This study aims to determine if a combination of shift to a rice-upland crop rotation and addition of organic amendments positively affects rice yield and keeps greenhouse gas emissions under control, in order to achieve a sustainable farming system. We measured methane (CH_4) and carbon dioxide (CO_2) emissions and agronomic parameters over 1 year, using sesame as upland crop during the dry season in an otherwise triple rice rotation in the Vietnamese Mekong Delta. The organic amendments considered are composted cow manure and rice straw. Results showed statistically equal yields in all seasons. We observed surprisingly high CO_2 emission flux rates (up to 2300 mg m^2 h^{-1}), and low CH_4 emission flux rates (<2 mg m^2 h^{-1}) for all treatments in all seasons, and. We observed a high organic carbon concentration (approx. 2,5%) in the paddy soil, which serves as explanation for the high CO_2 effluxes, and we suspect a considerable amount of sulfate reduction in the soil, which could have inhibited methanogenesis. Effect of OM amendment on any parameter was insignificant, probably because the applied dose (2 ton ha^{-1}) was too small to contribute to the already high soil organic matter content. Although the rice-sesame rotation showed few significant effects on GHG emission, yield and other agronomic parameters, it was obvious that the rice-sesame rotation emitted more carbon than the rice monoculture (26% more SOC emission in the Summer- Autumn and Autumn-Winter seasons). CO_2 emission was also the main controlling factor of total GHG emissions and by contributing approximately 90% to the global warming potential (GWP). Thus, the rice-sesame rotation resulted in a GWP of on average 9669 kg CO_2-eq. ha^{-1}, while the rice monoculture generated a GWP of on average 7240 kg CO_2-eq. ha^{-1}. These results demand an affirming study on sulfate concentrations in this experimental site and, in a wider context, imply that CO_2 emissions from rice paddy soils should definitely not be discarded from future research on GHG mitigation in rice paddy soils.

INTRODUCTION

1. BACKGROUND

Vietnam's economy largely depends on the growth of agricultural production and 52% of its population is engaged in the agricultural sector which contributes to 22% of the country's GDP. Rice is the major economic crop and more than 53% of the Vietnamese rice fields is located in the Mekong Delta, where more than 90% of the land is under rice. However, several recent studies demonstrate that even though farmers add yearly more mineral fertilizer and use improved varieties, the productivity of rice and hence farmer's income is declining. This is primarily due to soil degradation resulting from intensive rice monocultures with three crops per year, sea level rise and declined river flow with associated saline water intrusion, and floods and droughts (MARD, 2013). Moreover, the increase of nitrogen application has been subject to critique because overuse causes environmental problems, such as global warming and eutrophication. Nitrogen fertilization has to be reduced and rice has the lowest nitrogen use efficiency of all cereal crops, so it will have an impact on yields. This means there is a need to develop more nitrogen use-efficient varieties and integrated managerial practices that can overcome the yield losses caused by lesser nitrogen fertilization (Mahapatra et al., 2011; Chauhan et al., 2017). The integration of upland crops into the crop rotation is one of the practices currently studied to improve yields and insure income.

The flooded rice fields are also a major source for atmospheric methane (CH_4) and nitrous oxide (N_2O), and can be a source for carbon dioxide (CO_2), three major greenhouse gasses (GHGs). The high CH_4 emissions from paddy fields are the result of the decomposition of organic matter under anaerobic conditions in permanently flooded soils (Witt et al., 2000; Janz et al., 2019). To our knowledge, there are few emission records published on GHG emissions from fields in the Vietnamese Mekong Delta (VMD). Farmers in the VMD have begun to integrate other crops in the crop rotation, such as maize, chili, sesame and soybean in the dry season, to ensure an income and to help save water in the more frequent droughts ("Plans to Grow Other Crops", 2019). An important effect of this trend, is the possible decrease in CH_4 emissions from the rice fields.

2. OBJECTIVES

Several recent studies have shown that cultivation of rice in rotation with upland crops can significantly improve rice yield compared to rice monoculture (Linh et al., 2015a; Linh et al., 2015b; Xuan et al., 2012; Filizadeh et al., 2007; Mandal et al., 2014). Introducing such a more diversified cropping system can also reduce soil GHG emissions (Breidenbach et al., 2016; Weller et al., 2016, 2015). In addition, use of organic amendments have become an effective practice to improve soil fertility in terms of physical, chemical and biological aspects and maintain rice yield (Xu et al., 2008; Bi et al., 2009; Diacono et al., 2011; Thangarajan et al., 2013). However, despite the potential in improving soil quality and crop productivity, organic amendments could induce GHG emissions in flooded soils (Liu et al., 2011; Thangarajan et al., 2013; Pandey et al., 2014).

In this thesis we set out to study if a combination of shift to a rice-upland crop rotation and addition of organic amendments positively affects rice yield and keeps greenhouse gas emissions under control, in order to achieve a sustainable farming system. We also seek to explore the interactive effect of both factors: crop rotation and addition of organic matter. We used sesame as upland crop during the dry season in an otherwise triple rice rotation in the Vietnamese Mekong Delta. The organic amendments considered here are cow manure and rice straw. **We hypothesize that the introduction of sesame as an upland crop in the crop rotation improves soil conditions by affecting the chemical properties of the soil solution, leading to rice grain yield increase and a reduction in greenhouse gas emissions. Secondly, we expect that use of rice straw and cow manure compost helps increase rice production without increasing GHG emission.**

LITERATURE REVIEW

1. INTRODUCTION TO RICE

2.1. Economic importance and geographical distribution

Rice is the third most produced cereal crop in the world (770 million tonnes in 2017; FAOSTAT, 2017) and is the most important staple crop for half the world's population (Chauhan et al., 2017). A total area of 167 million ha of paddy rice was harvested in 2017, or 12% of the world's cultivated land. About 87% of the paddy fields were situated in Asia, and 30% in South-Eastern Asia alone. In the same year, 92% of all rice was produced in Asia (FAOSTAT, 2017).

Rice is of major importance to many Asian populations, providing food and livelihood, especially in rural regions (Mahapatra et al., 2011). It is the most nutritious cereal crop in the world: it provides 20% of the world population's total caloric requirement and 15% of its protein needs, and it is a cheap source of minerals and fiber (Zain et al., 2014). The rice straw and husk residues can be used as compost, animal feed, renewable energy sources and construction material (Linh, 2016).

2.2. Ecology

The environment dictates rice yields by influencing the physiological processes involved in plant growth and grain production, but also by influencing prevalence of pests and diseases (Sheehy et al., 2007). Drought has become a severe problem for rice production, since the crop's production quantity and quality are often severely decreased under limited water supply at critical growth stages (Zain et al., 2014). Every variety demands different growing conditions, so choosing the right cultivar is essential for reaching high yields.

2.3. Physiology

The duration of the life cycle of direct seeded rice is 90 to 160 days, depending on variety. A rice plant goes through three major growth stages: a vegetative, a reproductive and a ripening phase. The vegetative stage begins with the germination of the seed and lasts until the initiation of the panicle primordia (Yoshida, 1981). The formation of spikelets determines the start of the reproductive phase. The plant is said to be heading when the panicle is fully visible. The ripening stage starts after fertilization and dictates the final yield potential of the rice plant. Rice usually performs well in different environments, but environmental stress can drastically reduce crop productivity by affecting growth and production stages throughout the plant life (Nawaz et al., 2017; Yoshida, 1981).

2.4. Cultivation practices for wetland rice

Wetland rice requires various specific practices for land preparation. The land is usually diked and levelled, then tilled and finally puddled. The dikes retain water on the field and prevent runoff. Levelling ensures a uniform distribution of water on the field and is a form of weed control. Tilling breaks soil compactions, ventilates the soil, stimulates the early germination of weeds, minimizes residual plant material, distributes organic matter in the soil and increases soil permeability. Puddling happens in wet soil conditions, shortly before sowing or planting, and in repetition. It destroys weeds, incorporates amendments, fertilizers and plant residues in the soil, creates favorable sowing and planting conditions and results in the formation of an impenetrable soil layer underneath the puddle layer. This layer restricts water and plant nutrient losses during submergence of the field. After puddling, rice can be either directly seeded or transplanted (Linh, 2016; Sanchez, 2019). Farmers irrigate and usually apply a range of fertilizers and pesticides during crop growth

2. GREENHOUSE GAS EMISSION FROM RICE PADDY FIELDS

2.1. Global warming potential of GHGs

A GHG is an atmospheric gas that contributes to the greenhouse effect by absorbing and re-emitting infrared radiation (thermal radiation). The primary GHGs in earth's atmosphere are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The planet's atmosphere naturally contains GHGs, but human activity has strongly raised GHG emission into the atmosphere leading to atmospheric CO_2, CH_4 and N_2O levels well beyond pre-industrial concentrations. This has caused global warming and climate change, which has had widespread impacts on human and natural systems (IPCC, 2014).

GHGs have been attributed a global warming potential (GWP) value. CO_2 is given the GWP reference index value of 1, and other GHGs received a value that is expressed as a factor of the reference value, according to how much more heat a gas mass traps compared to an equal mass of CO_2 (IPCC, 2007). GWP for the most important greenhouse gasses are given in **Table 1**. The 100-year GWP of CH_4 demonstrates that CH_4 is a 28 times stronger GHG than CO_2 in a time horizon of 100 years.

***Table 1**. Greenhouse gases and their global warming potentials (GWP) over time horizons of 20 and 100 years.*
(IPCC, 2013).

Greenhouse gas	20-year GWP	100-year GWP
CO_2	1	1
CH_4	84	28
N_2O	264	265

Agriculture accounts for approximately 10 to 12% of total global anthropogenic emissions of greenhouse gases (Smith et al., 2007). Each year, over 36 billion tonnes of CO_2 is emitted globally, a number that continues to grow (Roser, 2019). Agricultural practices, inculding rice cultivation, contribute 14% to the total CO_2 emission. Around 60% of global CH_4 emissions originate from anthropogenic activities (Karakurt et al., 2012). Rice paddies are one of the largest sources of atmospheric CH_4 and make up for 5 to 19% of total global CH_4 (IPCC, 2007). So while the unique semiaquatic nature of the rice plant allows it to grow productively in places no other crop could exist, it is also the reason for its emissions of CH_4, as will be explained further on. Since rice is a staple food for the growing population in Asia and it is becoming a more popular food in the world, rice production is increasing and the contribution of rice paddies to global CH_4 emissions is growing as well (Van Nguyen et al., 2006).

2.2. Biogeochemistry of paddy soils

Paddy soils are soils used for cultivating rice and other semiaquatic crops. They can originate from any type of soil, but are highly modified by the management practices, altering the soils original character. Management practices can include artificial or natural flooding, maintaining a layer of standing water, draining and drying, puddling, hoeing, plowing and fertilizing (Kögel-Knabner et al., 2010; Ponnamperuma, 1972). During flooding, the oxygen supply to the soil is closed off. The trapped oxygen is depleted from the upper soil layer 24 to 72 hours by aerobic organisms and the soil becomes virtually oxygen free (except in a thin surface layer) (Boivin et al., 2002; Ponnamperuma, 1972). Afterwards, anaerobic and facultative organisms reduce the soil by using a series of oxidized soil components as electron acceptors for their respiration. Draining and drying reverse these reduction processes. The soil reduction results in important chemical and physiochemical processes, such as (Ponnamperuma, 1972):

- the decrease in soil redox potential (Eh)
- pH changes
- reduction of Fe^{3+} and Mn^{4+} contained in various soil minerals (mainly pedogenic (hydr)oxides) into Fe^{2+} and Mn^{2+}
- accumulation of CO_2
- production of organic acids, which can be further converted into CH_4

The paddy management practices result in the formation of the typical paddy soil pedogenic horizons (Kögel-Knabner et al., 2010) (**Fig**. **1**):

1) A thin layer of standing water (W). This layer is mainly oxic and hosts bacteria, phytoplankton, macrophytes and small fauna.
2) A (partly) oxic horizon (Ap). The depth of this horizon may range from several millimeters to several centimeters and deepens throughout the growing season until the plants start releasing oxygen from their roots.
3) The upper part of the anthraquic horizon (Arp). This zone lacks free oxygen in the soil solution and is the reduced layer.
4) The lower part of the anthraquic horizon (Ardp) or plough pan. This horizon is more than 7 cm thick, it is compacted (by puddling the Arp) and has a platy structure. It has high mechanical strength and low hydraulic conductivity, obstructing water drainage to the underlying B or C horizons, in which either oxic or reducing conditions may occur.

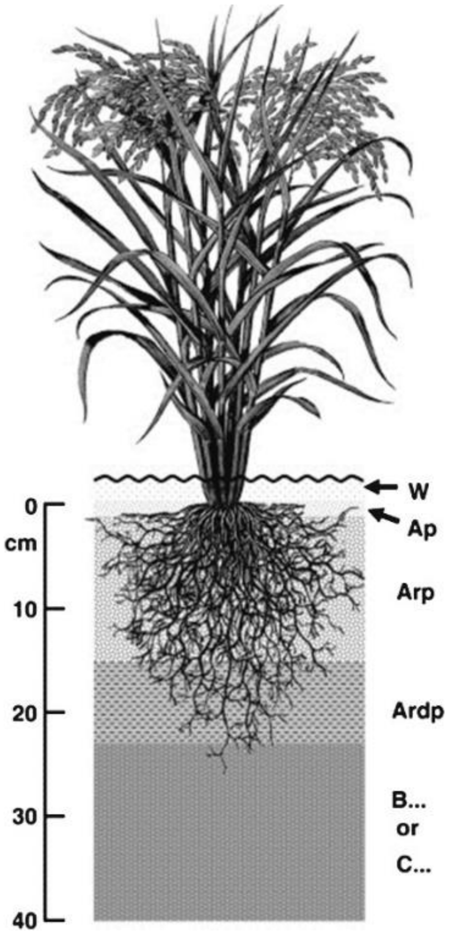

Fig 1. *Horizons in paddy soils* (source: *Kögel-Knabner et al., 2010*).

2.3. CH_4 emission from rice paddy soils

2.3.1. Methanogenesis in rice paddy fields

Methane is an end product of organic matter decomposition under anaerobic soil conditions (Conrad, 2002). The CH_4 is produced by methanogens, an obligate anaerobe group of archaea microorganisms. Methanogenesis is a lower energy yielding metabolic pathway process compared to aerobic respiration and iron, manganese and sulfate reduction. Methanogens require depletion of these preferred oxidants and a low redox potential for CH_4, which is usually present in flooded rice paddies after several weeks of submergence (Dalal et al., 2008). Soil organic matter (SOM), organic amendments and carbon containing plant exudates are the electron donors for methanogenesis. Two pathways of methanogenesis can occur, depending on the substrate source. The first is the hydrogenotrophic pathway, in which H_2 and CO_2 are used as substrates, the second is the acetoclastic pathway, in which acetate (CH_3COO^-) is used as a substrate (Conrad, 1999). They contribute about 30% and 70%, respectively, to total CH_4 production and the acetoclastic methanogenic archaea usually dominate in flooded rice paddy soils (Conrad, 2009, 2005). The methanogenic reactions in paddy soils are (Wassmann et al., 2000):

$$CO_2 + 4\ H_2 \rightarrow CH_4 + 2\ H_2O$$
$$CH_3COO^- + H^+ \rightarrow CO_2 + CH_4$$
$$2\ (CH_2O) \rightarrow CO_2 + CH_4$$

2.3.2. Methanotrophy and CH_4 leaching in rice paddy fieds

Not all produced CH_4 is emitted to the atmosphere. Firstly, CH_4 can be used as an energy source by methanotrophs, mostly unicellular microorganisms which are active in oxic zones. Methanotrophy occurs in paddy soils in the rhizospheres and when the soil is oxidized by draining and drying. Thus, the CH_4 in paddy soils produced from methanogenesis, is partly oxidized for methanotrophy, resulting in a lesser net CH_4 emission into the atmosphere (Serrano-Silva et al., 2014). Secondly, in well drained rice fields, part of the produced CH_4 leaches from the plow layer to the subsoil layer by percolating water. The amount of leached CH_4 also increases as more rice straw is applied to the field (Kimura et al., 2004). Hence, measured CH_4 emission fluxes do not represent CH_4 production.

2.3.3. Methane emission processes in rice paddy soils

CH_4 enters the atmosphere by three possible mechanisms: i) diffusion of dissolved CH_4 through soil and water, ii) ebullition, which is the release of CH_4-containing gas bubbles through water, and iii) plant-mediated transport, in which CH_4 is transported via the aerenchyma of vascular plants (**Fig**. **2**). Diffusion is generated by a concentration gradient from deeper soil layers, where CH_4 production is large and CH_4 oxidation is small, to upper layers where CH_4 production is limited and CH_4 oxidation is large. Diffusion is a slow process and makes up for less than 1% of total CH_4 emissions from rice fields, but it is important because it promotes CH_4 oxidation in upper layers by facilitating contact between CH_4 and methanotrophs. Ebullition, the formation of gas bubbles, is a fast process. It is common in paddy fields and contributes 10% of total CH_4 emission during crop growth. Plant mediated transport is the major mechanism for CH_4 emission in rice paddies, in which CH_4 is transported through the plant via the aerenchyma. CH_4 transport is generated by a concentration gradient inside the aerenchyma, which causes CH_4 to diffuse from soil into the roots, and by a pressure gradient, which leads the CH_4 to migrate along the plant through the aerenchyma (bulk flow). Plant-mediated transport is a very efficient and fast emission mechanism and is responsible for over 90% of total CH_4 emissions from rice fields (Serrano-Silva et al., 2014).

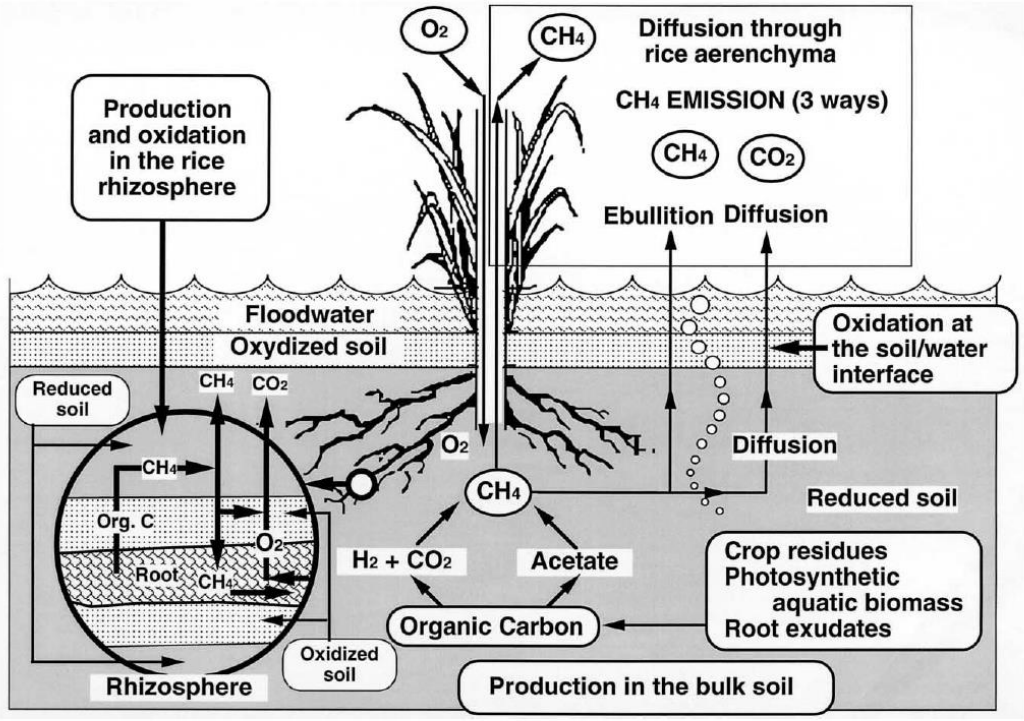

Fig. 2 *Methane production, oxidation and emission from rice paddy soils* (Holzapfel-Pschorn et al., 1986).

2.4. CO_2 emission from rice paddy soils

2.4.1. CO_2 production processes in rice paddy soils

Emitted CO_2 from rice paddies originates from one of six processes (Kuzyakov, 2006; Oertel et al., 2016):

1) Photorespiration of the rice plants, sometimes referred to as “above ground respiration”
2) root respiration
3) rhizomicrobial respiration, which is the microbial decomposition of rhizodeposits from living roots
4) microbial decomposition of plant residues
5) the “priming effect” induced by root exudation or by addition of plant residues, which is the microbial decomposition of SOM in soil that is affected by roots or plant residues
6) basal respiration by microbial decomposition of soil organic matter (SOM) in root free soil without undecomposed plant remains

These CO_2 sources can be grouped in plant-derived CO_2 (1, 2, 3, 4) and SOM-derived CO_2 (5, 6). The evaluation of SOM-derived CO_2 concentrations permits the evaluation of a soil as a source or sink of atmospheric CO_2. In anoxic paddy rice soils, fermenting bacteria start anaerobically degrading soil organic matter, in which soil organic carbon (SOC, sugars) is used as a substrate (**Fig**. **3**) (Liesack et al., 2000). Theoretically, CO_2 emission from paddy soils is limited during the submerged period of rice growth, because the heterotrophic respiration in the deoxidized soil decreases and because of carbon fixation by algae (Dossou-Yovo et al., 2016). Nishimura (2008) found a soil carbon accumulation in paddy rice fields in Japan of +79 to +137 g C m^2 y^{-1}, while upland rice lost 343 to 275 g C m^2 y^{-1}. However, drainage of paddies can turn these soils into carbon sources, because of increased soil aeration. Fertilization also boosts CO_2 emission (Maljanen et al., 2010; Joosten et al., 2002). Soil CO_2 emissions strongly vary between cropping seasons: dry seasons will result in higher CO_2 emissions as a result of more soil oxidation and more aerobic decomposition of the soil organic matter (Smith, 1980).

2.4.2. CO_2 assimilation and leaching in rice paddy soils

Not all produced CO_2 is emitted to the atmosphere. Firstly, algae and submerged weeds assimilate part of the CO_2 present in the in the floodwater by means of photosynthesis, although they also produce CO_2 through respiration. Secondly, CO_2 is present in the soil as bicarbonate ions (HCO_3^-). Water from the plow layer percolates to subsoil layers and thus leaches HCO_3^-, along with a variety of cations and anions (Kimura et al., 2004).

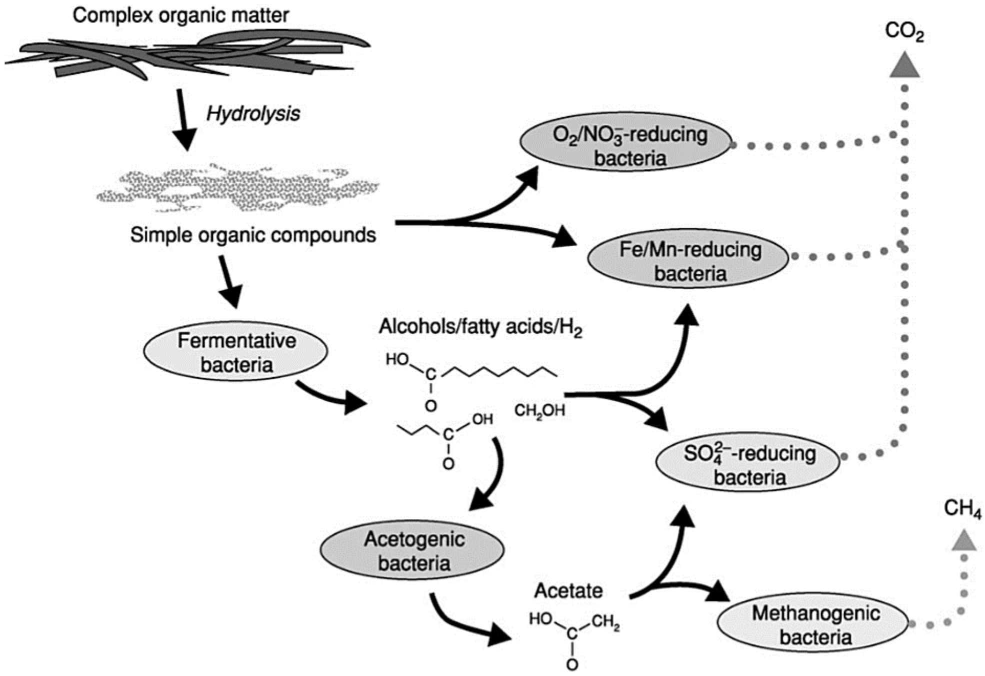

***Fig. 3** CO_2 producing decomposition processes of soil organic matter.* (Inglett et al., 2004)

2.5. Factors regulating CH_4 and CO_2 emissions from rice paddy soils

2.5.1. Soil redox conditions

Methane formation usually requires redox potentials of -150 to -190 mV. The Eh in flooded rice soils can be as low as -250 to -300 mV (Neue et al., 1996; Pacey et al., 1986). According to Yagi et al. (1997), methane fluxes are highest near the late stages of the cropping season, when the Eh drops to -200 mV. It is important to keep in mind that the measured Eh is not always a correct representation of the soil reducing conditions, because the Eh in different soil zones can vary due to aerobic and anaerobic microsites around the rhizosphere and in the bulk soil (Shine et al., 1990). The magnitude of redox changes in paddy soils can vary from one soil to another. After draining and drying the paddy soil, the redox potential also increases rapidly from negative to positive values of 300-600 mV, thus decreasing CH_4 emissions (Moormann et al., 1978).

Submergence and soil drying are obviously dominant determinants of soil redox potential and therefore occurrence of methanogenesis. Several authors logically reported a positive correlation between CH_4 emissions and the water table depth (Serrano-Silva et al., 2014; Linquist et al., 2012). **In conclusion, the irrigation management of a rice field is one of the most important factors influencing CH_4 emissions.**

2.5.2. Soil pH

The pH range of most methanogens is 6.0–8.0, so a neutral pH is favorable for CH_4 production (Garcia et al., 2000). The exact optimum for methanogenesis, however, is influenced by the type of soil (Minami, 1995). CH_4 production is inhibited when the pH drops below 6 (Pacey & DeGier, 1986). Soil pH is variable during rice cultivation as soil reduction is accompanied by pH changes. Acid soils can obtain a higher pH due to the consumption of protons, and in alkaline soils a lower pH can be observed because of the increase in partial pressure of CO_2 (Kögel-Knabner et al., 2010; Sahrawat, 2005). As a result in submerged paddy fields soil pH normally evolves towards neutral conditions, i.e. favorable for methanogenesis.

2.5.3. Soil temperature

Soil temperature influences the rate of microbial activity, thus the CH_4 and CO_2 production in the soil. Most methanogens function in a temperature range of 20 to 40 °C, with an optimum of 30 °C, but methanogens can be found in the range from 4 to 110 °C (Garcia et al., 2000; Neue et al., 1996). Pacey and DeGier (1986) showed a major reduction of CH_4 emission when temperatures decreased to 10 - 15 °C, and a stop in CH_4 emissions above a temperature of 60 °C.

2.5.4. Fe and Mn

The oxidation-reduction potential (Eh) of the electron accepting soil components determines which soil component is depleted first when soil is becoming increasingly reduced. The sequence is determined by thermodynamics and includes, from high Eh to low Eh: aerobic respiration, nitrification, denitrification, Mn^{+4} reduction, Fe^{+3} reduction, SO_4^{-2} reduction and methanogenesis (**Fig. 4**) (Ponnamperuma, 1972; Garcia et al., 2000; Dalal et al. 2008).

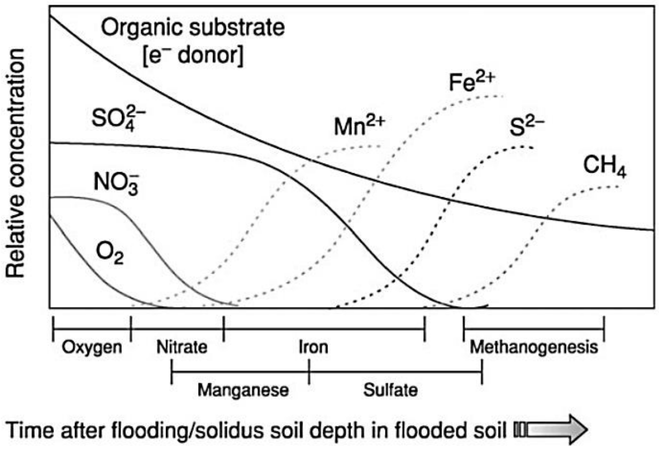

Fig. 4 *Sequential reduction of oxidants and accumulation of reductants (–— oxidized com-pounds, - - - reduced compounds) in rice paddy fields.* (Inglett et al., 2004)

Theoretically, CH_4 is not produced before all reducible Fe^{3+} and Mn^{4+} is depleted, which happens at a higher Eh (around -100 mV) than methanogenesis (around -200 mV). Fe^{3+} is by far the most important oxidant in rice paddies in terms of quantity (Yao et al., 1999). In soils with high Fe and SOM concentrations, the Eh first rapidly falls to -50 mV and then slowly declines to -200 mV over a period of a month. On the other hand, in soils low in Fe concentrations with high SOM concentration, an Eh value of -200 to -300 mV is attained within only two weeks after submergence (Ponnamperuma, 1972). **Thus the amount of reducible forms of Fe and Mn present in the soil, determines the duration period in which soil organic matter is oxidized to CO_2 , and CH_4 production does not yet begin**. The CO_2 / CH_4 ratio depends on the soil oxidizing capacity, which is expressed by the amount of O_2, NO_3^-, Mn^{4+} and Fe^3. It should be kept in mind though that as explained above the Eh throughout the soil puddle layer is heterogeneous and iron reduction and methanogenesis can co-exist. Also, while Fe^{3+} is abundantly present in soil, the rate at which it is available for reduction may also be too slow and so methanogens use SOM for respiration before all Fe^{3+} is depleted.

2.5.5. Fertilization

a) Application of nitrogen fertilizers

The net effect of N-fertilizer application on CH_4 emission seems to be N-dosage dependent. Linquist et al. (2012) in a meta-analysis found that on average at low N rates (averaging 79 kg N ha^{-1}) CH_4 emissions increased significantly by 18% (95% CI: 0.01–39%) (**Fig**. **5**). At moderate N rates, there was no significant effect of N additions on CH_4 emissions but at high N rates (averaging 249 kg N ha^{-1}) CH_4 emissions were significantly reduced by 15% (95% CI: −28% to −1%). Linquist et al.

(2012) hypothesized that these results can be explained by the various effects of N fertilization on CH_4 production, oxidation and transport. Nitrogen generally limits rice growth in flooded soils; therefore, at low N rates plant growth increases more per unit of N applied than at high N rates. Compared to unfertilized smaller plants, fertilized larger plants provide more carbon substrate for methanogenesis as roots and root exudates serve as a major carbon source for CH_4 production. In contrast, the relative effect of N rate on plant productivity diminishes at higher N rates, leaving more NH^{4+} in the soil solution to stimulate CH_4 oxidation. Excess soil NH^{4+}, as would be expected at high N rates, has the net effect of promoting CH_4 oxidation rather than inhibiting CH_4 consumption, thereby reducing CH_4 emissions at the field scale compared to low N rates and the control. The type of N-fertilizer also results in different CH_4 emissions. In a 3-year field experiment by Zou et al. (2005), CH_4 emissions decreased after urea (CH_4N_2O) application, and when ammonium sulfate was applied, CH_4 emissions were lower compared to when urea was used as a fertilizer. This was explained by the competition of methanogens and sulfate-reducing bacteria. Linquist et al. (2012) also found that replacing urea with ammonium sulfate at the same N rate, CH_4 emissions were reduced significantly by 40%.

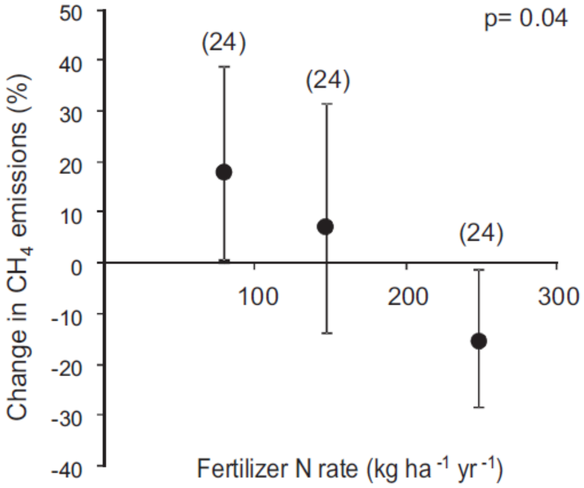

Fig. 5 *The effect of inorganic N additions on CH_4 emissions relative to when no fertilizer was applied. The numbers between parentheses indicate the number of observations used in the meta-analysis of Linquist et al. (2012). The 95% confidence intervals are presented by the error bars. (Linquist et al., 2012).*

Fertilization also has shown contradictory effects on soil CO_2 flux. N-fertilization can result in suppression of CO_2 emission, enhancement or no effects. However, many experiments observed a positive effect of N-application on CO_2 emission. Theoretically, use of N-fertilizers increases crop production, which results in a higher residue input in the soil, which means an increased SOM content. N-addition can also boost decomposition rates of soil organic matter, by enhancing the efficiency of

C-mineralization for microbial growth. This results in higher CO_2 emissions. (Iqbal, 2016).

b) Application of organic amendments

Organic amendments such as crop residues, compost and livestock manure are frequently applied to paddy soils worldwide. As amendments increase SOM concentrations, which serve as carbon substrates for soil microorganisms, microbial fermentation activity increases and so do CO_2 and CH_4 emissions (Jeong et al., 2018). **Thus, high SOM levels result in high CH_4 and CO_2 production rates.** Biochar and composted organic sources, such as Azolla compost, have less effect on methanogenesis than fresh organic materials, resulting in a smaller CH_4 emission increase caused by applying amendments (Serrano-Silva et al., 2014; Jeong et al., 2018). However, it should be noted that the composting processes in se can release high amounts of GHGs and the effect of compost application on total GHG emission from rice cultivation is uncertain. A study by Pandey et al. (2014) found an increase in CH_4 emissions of 230%, 150% and 38%, when applying farmyard manure, straw compost and straw biochar, respectively. Application of poultry manure on the other hand, increases CO_2 emission because of the carbon supply, but reduces CH_4 emission as its high sulfur content inhibits methanogenic microorganisms (Serrano-Silva et al., 2014). Generally per unit dry matter (DM) applied, the emission of CH_4 is stronger for green manures than composts or farmyard manure as the former are better biodegradable.

3. INCORPORATION OF UPLAND CROPS IN THE RICE BASED CROPPING SYSTEM

Rice is usually cultivated as a monoculture. The soil conditions required for rice cultivation are created by specific management practices. In rice monocropping, the soil is puddled before the start of every growing season, which creates a plow layer, through which water cannot easily percolate, resulting in enhanced water and nutrient efficiency of rice (Mousavi et al., 2009). However, puddling also deteriorates soil physical properties forming hardpans at shallow depths, which has potential negative effects on the next rice crop, and has significant negative effects on any upland crop that may follow the rice crop (Gathala et al., 2011).

The use of upland crops in a rice rotation system is an alternative strategy to control unfavorable aspects of rice monoculture, which also improves soil characteristics and diversifies agricultural activities (Lima et al., 2002). The impending water scarcity and Asia’s rapid economic and social development is driving farmers to incorporate upland crops into their crop rotation (Janz et al., 2019). Often drought tolerant upland rice is chosen as an upland crop, but more and more farmers use maize in their crop rotation, due to the increasing demand for livestock and biomass for biofuel production (Timsina et al., 2010). The rice-upland crop rotation is the most applied agricultural production system in Bangladesh, China and India, the rice-wheat rotation system in particular (Timsina et al., 2001). **In conclusion, the traditional paddy rice cropping system is being transitioned towards the integration of upland cropping practices, at least during the dry season** (Janz et al., 2019).

When shifting from long-term monocropping to a rice-upland crop rotation, the soil properties of the rice paddy fields change. Among others, the introduction of an upland crop into the cropping system, brings a transition in microbial C and N cycling through changes in soil aeration (Janz et al., 2019). During the upland crop season, there is no water basin and soil is kept aerated during the entire season. Soil microorganisms then decompose SOM aerobically, inhibiting methanogenesis. Moreover, the frequent cycling between aerobic (upland crop season) and aerobic (rice crop season) soil conditions result in a greater decomposition of SOC in general, resulting in higher CO_2 emissions (Xu et al., 2007; Motschenbacher et al., 2011). Weller et al. (2015) found that a shift from a rice-rice system to a rice-maize system significantly mitigated CH_4 emissions due to higher soil aeration. However, N_2O emissions were increased and soil carbon stocks were mobilized. The benefits of the CH_4 mitigation were consequently partly diminished. But the study by Weller et al. (2015) is in fact one of the only investigations of the impact of upland crop introduction in rice-based rotations on soil greenhouse gas balance. It cannot represent all possible combinations of crop rotations/climates/soil types and further work is needed to see if introduction of upland crops is indeed a sound CH_4 emission strategy.

The introduction of upland crops in rice cropping systems moreover does not only create a shift in GHG emission pattern, it also affects soil fertility. According to Witt et al. (2000), the cultivation of high yielding rice and maize hybrids requires increased nutrient supplies in intensified crop rotations. This often results in imbalanced fertilizer use, soil nutrient mining and a decline in SOC content. Consequently, such cropping systems often have low productivity. However, improved crop and nutrient management may negate these negative effects (Timsina et al., 2010). Xuan et al. (2012) has reported the positive effect of crop rotation in the Vietnamese Mekong Delta (VMD) on the rice yield and the soil bacterial community structure. A 10-year field experiment by Linh et al., (2015b) in the VMD with maize and mung bean in the crop rotation, resulted in a rice yield that was 32–36% higher compared to the control, due to improved physical quality and consequently deeper rooting depth and root mass density of the rice crops. It was concluded that crop rotation increased rice yield and promotes sustainable agriculture because soil-damaging excessive puddling and tillage are limited in upland crop management (Filizadeh et al., 2007; Mandal et al., 2014).

RESEARCH SETTING

1. INTRODUCTION TO THE UPLAND CROP: SESAME

1.1. Geographical distribution and economic importance

Sesame is mostly grown in arid and semi-arid tropics (Islam et al., 2016; Boureima et al., 2011). Global yield was 5.53 million tonnes in 2017, grown on an area of 9.98 million ha. From 2007 to 2017, global production increased by 52%, mostly by African production (FAOSTAT, 2017). Whereas Asia used to provide the largest share of sesame seed in the world, Africa is becoming increasingly important to anticipate growing demand.

Sesame seeds are primarily used as food or food flavoring. They are especially valued for their high oil content, being around 50% of the seed weight (Ashri, 1998; Boureima et al., 2011; Islam et al., 2016). Because of its taste and chemical composition, the extracted oil is considered to be of superior quality compared to other edible oils (Bedigian et al., 1986). Sesame oil serves as edible oil used for culinary purposes, as lamp oil or as an ingredient in soaps, lubricants, pharmaceuticals and cosmetics. The expression process leaves the press cake as a waste product, which can be used as a protein rich animal feed (Bedigian, 2004; Anastasi et al., 2017).

1.2. Ecology

Sesame grows well under many circumstances. The crop adapts well to high temperatures and tropical climates. It is sensitive to chilling stress and its seeds need sufficient soil moisture to emerge (Boureima et al., 2011; Ashri & Singh, 2007), but otherwise the crop is well-known for its tolerance to drought stress and its susceptibility to waterlogging. Due to the excessive root system, the soil becomes more permeable, which makes sesame a good candidate for crop rotation. The crop can grow in a range of soil types, but prefers well-drained, moderate fertile soils at a neutral pH (5.4 to 7.7). Since sesame requires low nutrient inputs, it can be grown after more soil-exhaustive crops (Ashri et al., 2007; Bedigian et al., 1986; Islam et al., 2016). However, these low requirement conditions promise low to very low yields compared to what the crop could achieve in fertile soils with high inputs.

1.3. Physiology

The sesame plant has a vegetative, reproductive, ripening and a drying phase. The duration of the phases is highly variable. Because sesame is an indeterminate species, the reproductive, ripening and drying phase overlap, causing the capsules to be mature at different times. The vegetative stage reaches from germination until 50% of flowers have opened. The reproductive phase ends when 90% of the flowers have terminated flowering At the ripening phase, the seeds mature in the capsule. The drying phase starts when the seed of ¾ of the capsules on the main stem have their final color and a dark tip. The crop is ready for harvest when 99% of the plants have completely dried capsules. It might be difficult to determine the best time for harvest since sesame capsules finish the drying period at different times, especially when the field soil is not uniform, which is very often the case (Langham, 2007). Depending upon the variety, sesame can be harvested 75-150 days after sowing (Ashri & Singh, 2007)

1.4. Cultivation practices

To prepare for the sesame crop, the land should be levelled to prevent waterlogging, and irrigated or watered by rains to ensure germination. Shortly before planting, the soil is harrowed to stop weed growth, since sesame has slow initial seedling growth and weed control is difficult at the seedling stage (Weiss et al.,1983). Fertilizer is added commensurate to the ground moisture and depending on the residual nitrogen from previous crops (Langham, 2008)

2. THE VIETNAMESE MEKONG DELTA (VMD)

The Mekong Delta is the world's third largest delta (Li et al., 2017). It stretches through the south of Cambodia and Vietnam and is fed by river branches and canals originating from the Mekong River (Reiner Wassmann et al., 2004). About 65% of the delta is located within Vietnamese borders, covering 3.9 million ha (39,000 km^2) of which 2.9 million ha are cultivated. In 2000, rice production constituted 78% of the land use in the VMD. (Reiner Wassmann et al., 2004). Nearly 18 million people (20% of the Vietnamese population) are living in the VMD and the region has the largest agricultural activity in Vietnam (Renaud et al., 2012; Kontgis et al., 2019). Depending on a region's ecology, rice is cultivated in two or three cropping seasons per year (Linh, 2016). The VMD's agricultural practices have intensified the past few decades (Renaud et al., 2012).

Vietnam produced 29,754 tonnes of sesame seed in 2017 on an area of 37,038 ha. The average seed yield was 803 kg ha^{-1}, which is higher than the global average of 554 kg ha^{-1}. Vietnam is a net-import country (75,107 tons in 2016) (FAOSTAT, 2017). In the VMD, sesame is mostly cultivated by smallholder farmers (Le, 2018).

The VMD is nearly at sea level (<2m, Wassmann et al., 2004). The region has a tropical monsoon climate and is characterized by a dry (November-May) and a wet (June-October) season (Lu & Sieuw, 2006). The crops are irrigated by the Mekong river or rainfed in the wet season. The average monthly temperature varies between 25 and 28°C. Fluvisols are the most prevalent soil type in the delta, covering 31% of the land, mostly along the Mekong river banks (Linh, 2016).

MATERIALS AND METHODS

1. STUDY SITE

To tackle this MSc-thesis’ research objectives, greenhouse gas emissions and yield parameters were followed in a field experiment established and managed by Can Tho University in the Vietnamese Mekong Delta. More specifically this trial was laid out at the My Loi hamlet, Thien My commune, Tra On district, Vinh Long province (9°57'13.07" N, 105° 55' 58.01" E) (**Fig. 6** , **Fig. 7**). The paddy fields were located within a 150m distance of the Song Tra On river, a tributary of the Song Hau river.

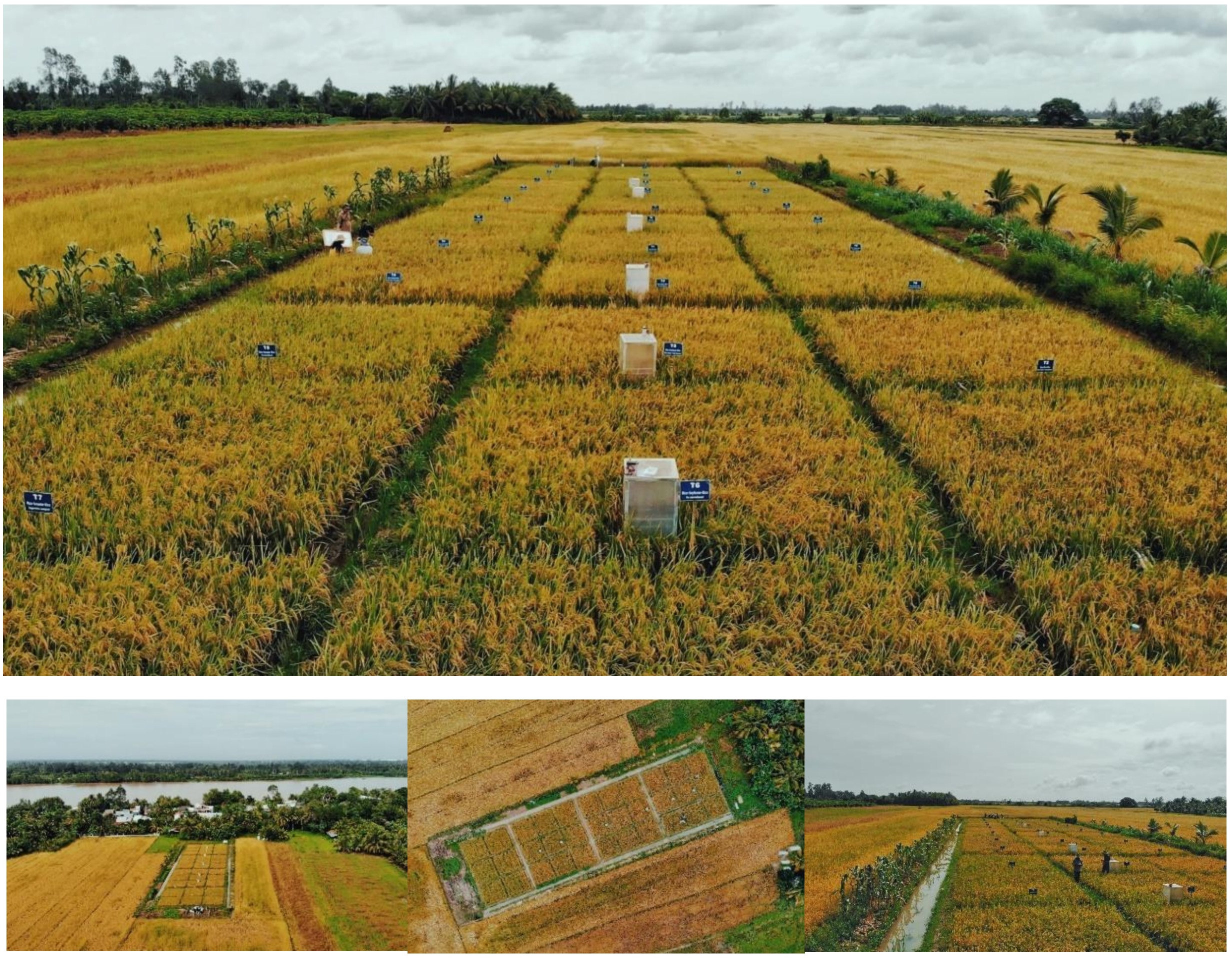

Fig. 6 *Photos of the field experiment during Summer-Autumn season in Vinh Long province in the Vietnamese Mekong Delta (2019).*

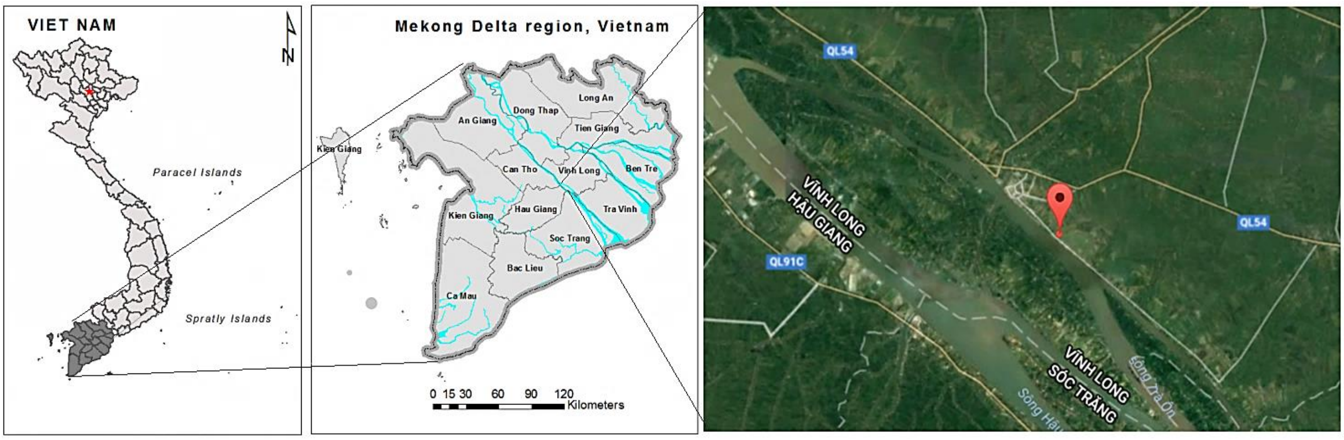

Fig. 7 *Location of the field experiment in Vinh Long province in the Vietnamese Mekong Delta.*

The study area had a tropical monsoon climate and is characterized by a dry season (November-May) and a wet season (June-October). The mean daily temperature was 27°C. The soil of the study site was a young alluvial soil, more specifically Rhodi-Gleyic Luvisols (FAO/Unesco). This soil type is representative for a large part of the Mekong delta. Soil horizon details are given in **Table 2**.

Table 2 *Details of the soil horizons at the field expemriment in Vinh Long province in the Vietnamese Mekong Delta.*

Soil horizon	**Texture**				**% OM**
	% sand	**% silt**	**% clay**	**USDA/Taxonomy**	
Ap (0-15 cm)	1,36	53,54	45,10	Silty clay	5,52
Bg1 (15-45 cm)	0,89	48,37	50,74	Silty clay	0,60
Bg2 (45-100 cm)	1,09	45,68	53,23	Silty clay	0,60
Cg (100-180 cm)	1,10	45,27	53,62	Silty clay	0,94

2. FIELD EXPERIMENT

1.5. Experimental design

The field experiment involved the comparison of a rice monoculture cropping system (R-R-R) and a rice-sesame-rice rotation (R-Se-R) as principal factor. In addition a second factor was amendment of exogenous organic matter. For this thesis, plots amended with a mixture of cow manure and rice straw (CA) were compared with no applied amendment (NA) as control. The field was laid out in a split-plot design with the crop rotation system as the main factor and amendment application as a subfactor, with three replications.

The original experiment also included a third crop rotation treatment with soybean and a third amendment treatment with sugar cane compost, which fell beyond the scope of this thesis. The experimental site thus consisted of 27 plots, of which 12 under investigation in this thesis research. The size of the subplots was 5.5m x 5.5m each. Main plots were separated by big bunds (50 cm wide, 40 cm high), while subplots were separated by small bunds (40cm wide, 30cm high). In addition, ditches (50cm wide and 30cm deep) between replicate blocks were made for irrigation and for discharge purposes (**Fig. 8**). In order to limit lateral movement of water between rice and upland crop plots, plastic sheets were installed along the center of the bunds to a depth of 10-15 cm.

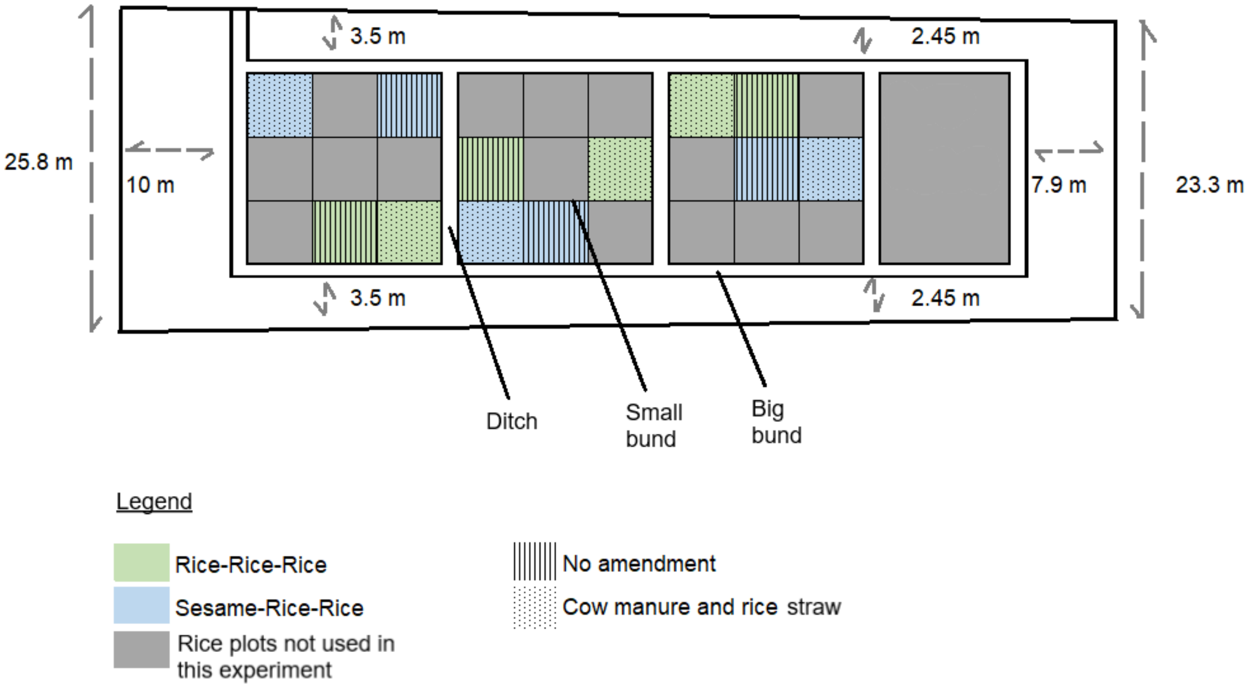

Fig. 8 *Layout of the field experiment.*

The field experiment was carried out during three cropping seasons in 2018-2019 (Spring-Summer, Summer-Autumn and Autumn-Winter), covering all agricultural practices across a single year (**Fig. 9**). The described treatments had already been applied on the same plots the previous year. The experiment started in February 2017, but only samples of the second year, starting in February 2018, were considered in this thesis. This means that all results in this thesis could have been influenced by the effects of the treatments in the previous year.

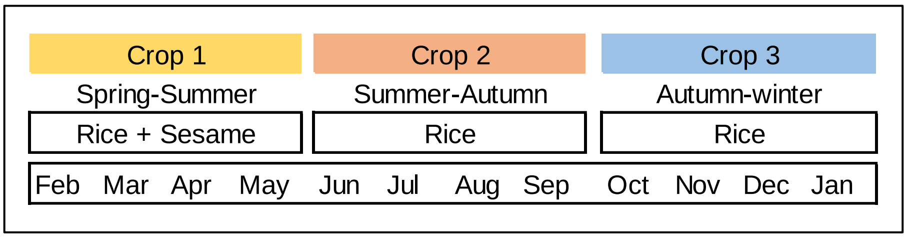

Fig. 9 *Cropping schedule from February 2018 until January 2019.*

2.2 Land preparation

In order to prepare the land for rice cultivation, rice straw and stubble of the previous season were removed from the field. The land preparation practices included hoeing, puddling under shallow flooded condition and leveling under wet condition prior to seeding. For sesame cultivation, rice straw and stubble were also removed from the field. The soil was never plowed.

2.3 Crop variety and plant establishment

The rice variety used for the field experiments is a local short-duration variety (OM50404) with a growing season of 90-95 days. This variety is distributed by the Cuu Long Rice Research Institute in the Mekong Delta. Pre-germinated seeds were broadcasted uniformly on wet soil surface with an amount of 200 kg per ha. The sesame variety Me Den was used with a density of 333 plants ha^{-1}. Its growing season lasts 80-85 days. Holes of 20 cm depth and 20 cm spacing were made before sowing. Row spacing was 30 cm and two seeds were placed in each hole.

2.4 Fertilizer management

2.4.1 Inorganic fertilizer

Inorganic fertilizer doses were adjusted to the crop and organic amendment treatment combination (**Table 3**). Nitrogen, phosphorus and potassium were applied in the form of pellet urea (46% N), superphosphate (16% P_2O_5) and potassium chloride (KCl, 60% K_2O). The fertilizer recommendations for rice and sesame were given by the Department of Soil Science and the Department of Genetics and Plant Breeding of Can Tho University, and the Department of Agricultural and Development of Vinh Long province, respectively. These doses match common practice in the area.

For rice, urea was applied at 10, 20 and 40 days after sowing (DAS), as 20%, 40% and 40% of the total N dose, respectively. KCl was applied at 20 and 40 DAS in equal doses. All superphosphate was applied at once prior to sowing (**Fig**. **10**). For sesame, urea was applied in equal amounts 15 and 30 DAS. KCl was applied in equal amounts 15 DAS and 40 DAS. All superphosphate was applied once prior to sowing (Fig.)

Table 3 *Fertilizer doses for rice and sesame.*

Crop	N (kg)	P (kg)	K (kg)
Rice	100	45	30
Sesame	60N	60	45

Fig. 10 *Timing of fertilization for the field experiment in 2017 Spring-Summer season. (DAS = days after sowing)*

2.4.2 Composts

Cow manure was collected from the local farmer's cow farm next to the field trial and rice straw was collected from the field experiment. The rice straw-cow manure mixture consisted of equal fresh matter amounts of both components (i.e. a 50:50 mixture). The manure and rice straw were mixed and incubated at the experimental site (**Fig**. **11**). The amount of fresh compost applied was 2 ton ha^{-1} at a 25% moisture level for both rice and sesame, based on local recommendations. The compost was spread on the soil surface prior to sowing for both crops (**Fig**. **10**).

Fig. 11 *Mixing of rice straw and cow manure for composting.*

2.5 Irrigation and water management

Surface irrigation was applied as basin irrigation in both rice and sesame. This irrigation method is suitable for upland crops grown in rice-based soils according to Moridis and Alagcan (1992). The field was irrigated by pumping water from a pond located next to the field. In the rice plots, standing water was maintained at a level of 5-10 cm until about 1 to 2 weeks before harvest, while sesame was irrigated periodically.

2.6 Weed and pest management

Weeds and pests were controlled with herbicides and pesticides according to local recommendations as well as to the procedures of the International Rice Research Institute (IRRI) described by Chauhan (2012). Weed control in the rice plots was done before sowing by hoeing and puddling. Two or three DAS, pre-emergence herbicides were applied. During crop growth, weed control was done by manually removing weeds and/or by using post-emergence herbicides. Furthermore, the maintenance of field water level helped to suppress weed emergence. For sesame, pre-emergence herbicides were used at the beginning of the cropping season. In later stages, weeds were controlled by hand and/or by using post-emergence herbicides. In addition, fungicides and insecticides were applied when necessary.

2.7 Meteorological data collection

Daily climatic data were collected on site with a meteorological station. The station measured rainfall, daily maximum and minimum temperature, relative humidity, sunshine hours, solar radiation (if any) and wind speed.

3. SAMPLING AND MEASUREMENTS

Sampling schedules for Spring-Summer, Summer-Autumn and Autumn-Winter season are presented in Appendix A.

3.1. Redox potential

Soil redox potential was monitored in all treatments with soil redox probes (MVH Consult, the Netherlands) consisting of nylon rods outfitted with multiple Pt-electrodes. A single Ag/AgCl-reference electrode was inserted into the paddy field shortly prior to Eh measurements and Eh was measured as the potential (in mV) by connecting both electrodes with a Fluke 175 TRUE-RMS digital multimeter (**Fig. 12a**). The measured Eh was corrected for the Ag/AgCl-reference electrode's offset vs. a standard hydrogen electrode. Permanent Eh probes were installed at the center of the three soil horizons: 7.5 cm, 22.5 cm and 37.5 cm.

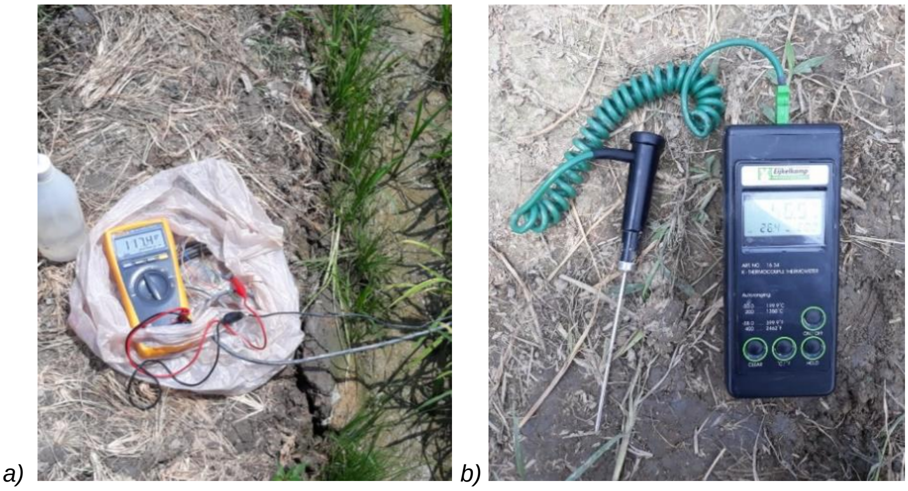

Fig. 12 *a) Digital voltmeter with permanently installed Pt-electrode and the Ag/AgCl-reference electrode. b) Thermocouple thermometer for soil temperature measurement.*

3.2. Soil Temperature

Soil temperature was measured in-situ at each gas sampling event using a K-thermocouple thermometer (Eijkelkamp, The Netherlands) at the same depths as redox potential measurement: 7.5 cm, 22.5 cm and 37.5 cm (**Fig. 12b**).

3.3. Soil pH

Soil pH was also measured at each gas sampling event and at depths of being 7.5, 22.5 and 37.5 cm. For lack of an in-situ soil pH meter, soil was taken with an auger at two depths (0-15) and (15-30) and brought to the lab, where pH was measured.

3.4. Soil pore solution

The soil pore solution was sampled in every treatment after gas sampling in order to track progressive dissolution of Fe and Mn, indicative of Fe^{3+} and $Mn^{4+/3+}$ reduction. Solution samples were collected by connecting permanently installed porous macro rhizon samplers (Rhizosphere products, The Netherlands) with pre-evacuated 10 ml plastic vacutainers (**Fig**. **13**). Soil solution was collected at depths of 15, 30 and 45 cm. The samples were only taken in frequently flooded plots, meaning in all seasons for the rice treatments, but only in rice growing seasons for the sesame treatments, i.e. Summer-Autumn and Autumn-Winter season.

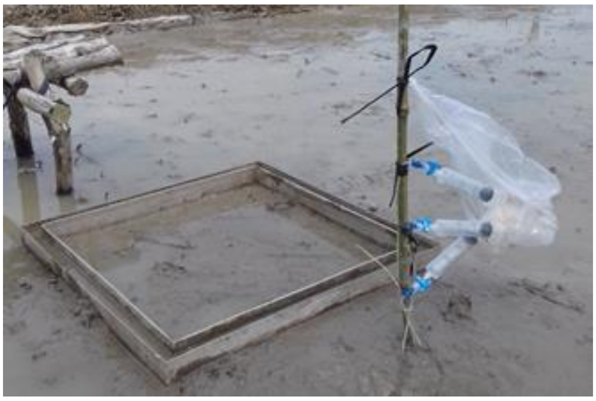

***Fig. 13** Permanently installed macro rhizon samplers for soil solution sampling at the base of a gas chamber.*

3.5 Yield components

The above-ground biomass was estimated after harvest. For both rice and sesame, plant samples were collected within an area of 5 m^2. The grains and pods were separated and the remaining straw was oven-dried at 105 °C for 48 hours until constant weight. The dried straw samples were weighed and the estimated above-ground biomass (straw, without rice grains or sesame seeds) per ha was calculated.

3.6 Soil greenhouse gas effluxes

Gas samples were collected periodically from non-steady-state closed chambers installed in the field in order to analyze carbon dioxide (CO_2) and methane (CH_4)

emissions (**Fig**. **14**). The chambers consisted of a base collar, which was permanently installed in the field, and a lid, which was only used during sampling. The bases measured 50 cm long x 50 cm wide x 20 cm high and were made of stainless steel, while the chamber lids measured 100 cm or 50 cm in height and were made of acrylic glass. The acrylic glass was covered with reflective aluminum foil to prevent a temperature build-up inside the chambers during sampling. The lids were equipped with a circulating fan to ensure gas mixing inside the chamber and a valve through which the sample could be collected. During gas sampling, the lid was placed over the base and partially contained either the rice or sesame plants inside as well. Each of the bases was outfitted with a water-filled ditch to ensure airtight sealing between lid and collar. A 50 ml gas sample was taken from the chamber headspace with a syringe by piercing the rubber septum on top. These gas samples were then directly injected into 12 ml pre-evacuated glass exetainer vials.

Fig. 14 *Gas sampling with a closed chamber and a syringe in a rice plot.*
a) Chamber of 50 cm height, b) Chamber of 100 cm height.

Gas samples were taken from all treatments before sowing, one day before and three days after every N fertilization, every two weeks before harvesting and at harvest. At sampling, 6 collars were used simultaneously, and these were then rotated across the remaining treatment plots. First all rice treatments were measured, afterwards all sesame treatments. On the date of sampling, four samples were collected with an interval of 15 minutes between 9h00 and 12h00, to allow derivation of the soil gas efflux based on change in concentration of either CO_2 or CH_4 inside the chamber. At each gas sampling, air temperature around the chambers was measured by a thermometer.

4. ANALYSIS

4.1. CH_4 and CO_2 concentration

All headspace gas samples were analyzed for CH_4 and CO_2 concentration (in ppmV) simultaneously through gas chromatography (GC). Samples were injected with a 1 mL gas tight glass syringe with needle with a conical tip with a side hole, in splitless mode at 90°C. The oven temperature was 70 °C and the carrier gas was helium. The system had two packed columns, coupled in series, with a length of 0.25 m and 2 m successively. Total flow was 22 ml min^{-1} and after 0.8 minutes (when all CO_2 and CH_4 had passed the first column), the first column was removed from the series in order to rinse the H_2O and other slowly eluting components out of the column in the opposite direction. Meanwhile, the flow passed the second column, at 22 ml min^{-1}. The gas chromathographer was equipped with a thermal conductivity detector (TCD), used for CO_2 concentration detection, and a flame ionization detector (FID), for CH_4 concentration detection.

After GC, the amount of GHG inside the gas chamber (µL) was calculated by multiplying the measured GHG concentration (ppm) by the chamber volume (L). The GHG mass inside the gas chamber was then calculated by means of the ideal gas law as follows:

$$[gas] = \frac{P_{atm} * V_{gas} * M_{gas}}{R * (273K + T)}$$

With

- [gas] = the mass of GHG inside the gas chamber [mg]
- P_{atm} = atmospheric pressure = 1 atm
- V_{gas} = calculated volume of the GHG inside the gas chamber [L]
- M_{gas} = molar mass of the GHG [mg mol^{-1}]
- R = gas constant = 0.082058 L atm $(K\ mol)^{-1}$
- T = the air temperature around the chamber recorded during gas sampling

Then GHG flux rate was calculated by evaluating the change in GHG concentration inside the gas chamber through time (evaluation of four samples taken within the hour with 15 minutes apart).

4.2. Dissolved Fe and Mn

Soil solution samples were analyzed for dissolved Fe, Mn, Ca and Mg concentrations by ICP-OES analysis. When samples showed any precipitate, drops of concentrated HNO_3 were added to redissolve any re-oxidized Fe and Mn. Because oxidized Fe^{3+} and Mn^{4+} have very low solubility at normal pH, virtually any detected Fe and Mn could be assumed to be Fe^{2+} and Mn^{2+}. Furthermore, build-up of Ca^{2+} and Mg^{2+} in soil solution was taken into account because part of initially dissolved Fe^{2+} is readily exchanged for Ca and Mg on the surface of soil colloids. One mole of additionally dissolved Ca^{2+} or Mg^{2+} on top of initial soil solution levels was taken equal as one mole of Fe^{2+}.

4.3. Statistical data-analysis

Statistical analysis was applied to investigate the effects of not only the cropping systems and compost amendments, but also of the interaction effects of these practices on the GHG emissions and crop yields. The experimental data was preliminary checked for normality and homoscedasticity. The data was then analyzed using a t-test when studying the effect of one factor, and a two-way analysis of variance (ANOVA) was used when studying the effect of two factors. To investigate significant effects, a Tukey's test was applied. All statistical analysis was done with the R software.

RESULTS

1. ENVIRONMENTAL SOIL VARIABLES

1.1. Soil temperature

The soil temperature was measured in every treatment plot at a depth of 10cm at gas sampling events. **Fig**. **15** shows the evolution of the soil temperature in the Spring-Summer, Summer-Autumn and Autumn-Winter season. In the Spring-Summer season, soil temperature evolution differed between R-R-R and R-Se-R rotations. The temperature in R-R-R increased from 27°C to 32°C, with local maxima around 9, 44 and 75 days after sowing (DAS), while in case of R-Se-R, temperature increased the first 46 DAS from 27°C to 29°C and decreased thereafter to 27°C. In the Summer-Autumn season and in the Autumn-Winter season, all treatments exhibited similar trends. In the Summer-Autumn season, soil temperature decreased from 29°C to 27°C, with a temperature peak of 33°C at 20 DAS. The soil temperature in the Autumn-Winter season gradually decreased from around 30°C to 26°C in all treatments.

Air temperature at the experimental field during all three seasons is given in Appendix B.

1.2. Soil pH

Soil from every treatment was taken at two depths (0-15) and (15-30) and brought to the lab, where pH was measured. The pH measurements mainly ranged from 5 to 6,5 throughout the cropping season. Since reduction reactions usually consume protons the ambient pH in the field normally reaches higher values. It seems very likely that measurements in the laboratory did not represent ambient pH in the field because of fast re-oxidation (and release of protons) in sampled soil slurries. The interpretation of pH as measured here is therefore not very helpful for interpretation of soil biochemical processes and not elaborated upon in the discussion. The pH evolution in the Spring-Summer season is shown in **Fig**. **16** and graphs of the Summer-Autumn and Autumn-winter season are presented in Appendix C.

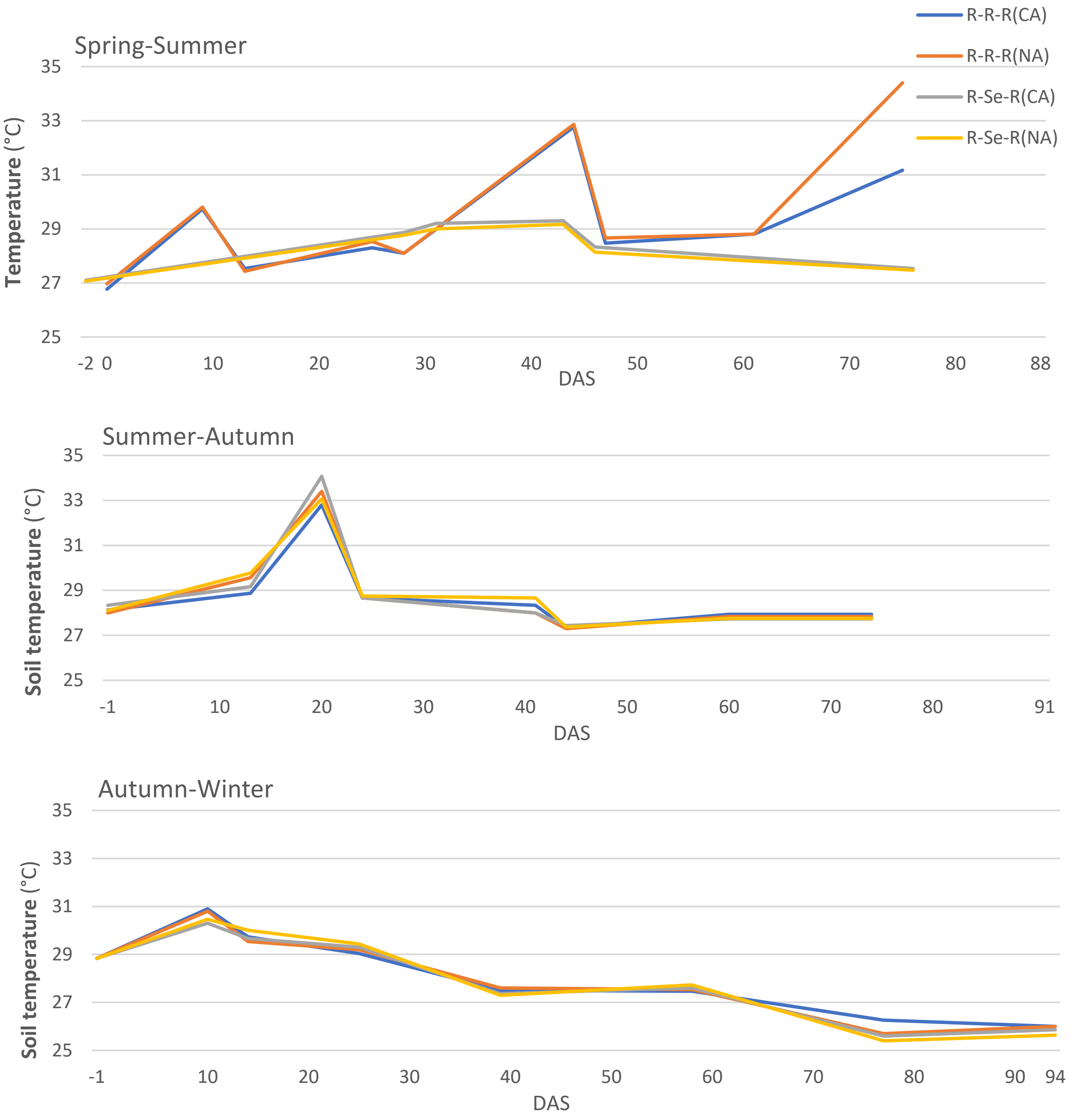

Fig. 15 *Evolution of the seasonal soil temperature variation at a depth of 10 cm under different cropping and OM amendment treatments.*

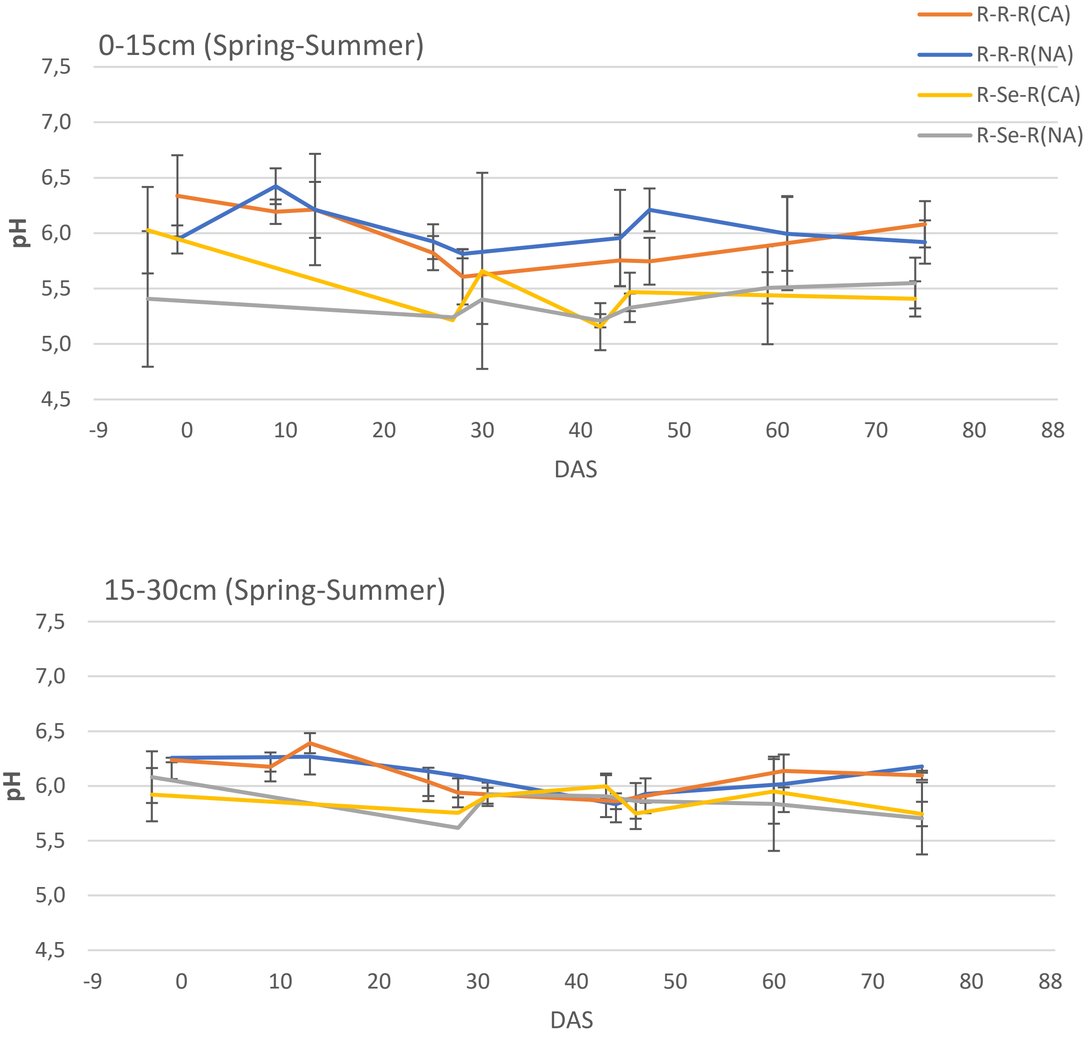

Fig. 16 *Evolution of the soil pH under different cropping and OM amendment treatments in the Spring-Summer season in the upper soil layer (0-15cm depth) and lower soil layer (15-30 cm depth).*

1.3. Soil redox potential

Soil redox potential (Eh) was measured in the rice treatments in the Spring-Summer season and in all treatments in the Summer-Autumn and Autumn-Winter season. Note that in the figures the scales of Eh figures were adjusted in order to compare treatments rather than progression of Eh among seasons.

During the Spring-Summer season (**Fig. 17**), sesame was grown in the plots of the R-Se-R treatments. Because the fields were not flooded for sesame cultivation and Spring-Summer is the dry season, with no standing field water level and no anaerobic microbial activity expected, we did not measure Eh in the R-Se-R treatments. The Spring-Summer season showed similar Eh fluctuations for both studied R-R-R treatments at 10 cm depth. A very low Eh of -500 mV (probably physically unrealistic – this measurement should be disregarded) was observed at 9 DAS, after which the Eh increased quickly to -150 mV, within expected ranges of paddy soil Eh. The rest of the growing period, Eh fluctuated between -300 mV and -100 mV, with a higher Eh after the second and third N-application.

Eh evolution in the Summer-Autumn (**Fig**. **18**) season also depicted similar trends in all treatments. In all four soil layers, Eh suggested strongly reducing conditions (<100 mV) after an initial fast drop between the first two field measurements. At 5 cm depth, the Eh was lowest, ranging from -300 to -100 mV. In deeper layers, soil Eh was throughout less negative and fluctuated from -250 to -50 mV at 12,5 cm and 20 cm depth, and from -200 to -70 mV at 30 cm depth.

In the Autumn-Winter season (**Fig**. **19**) soil Eh again followed a similar trend for all treatments. No distinct effect of crop rotation or OM-amendment could be readily discerned. Three days after every N-application, Eh increased as in previous seasons, but decreased again afterwards until the next N-application. The soil Eh became less negative and treatment trends were more similar in deeper soil layers, ranging from -310 to -90 mV, -340 to -100 mV, -300 to -110 mV and -240 to -100 mV for the -5 cm, -12,5 cm, -20 cm and -30cm soil layers respectively.

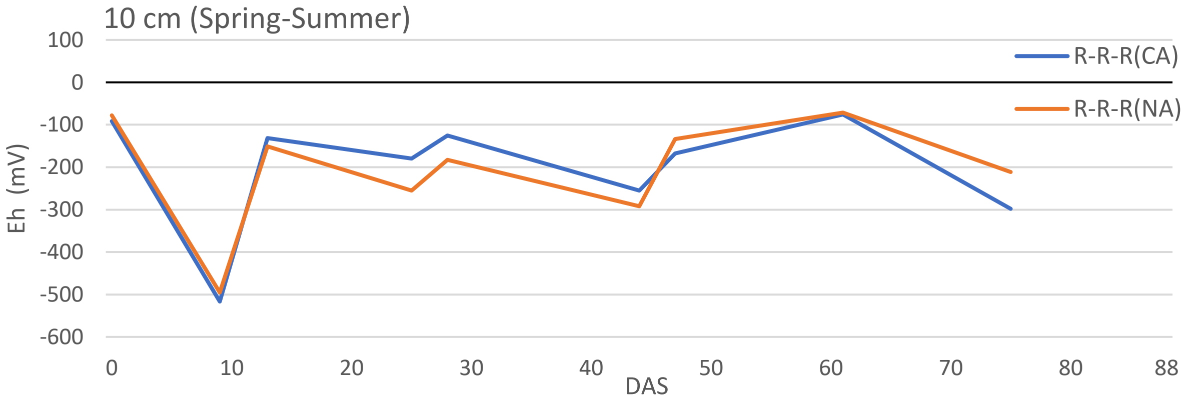

Fig. 17 *Seasonal evolution of Eh under OM amendment treatments in the Spring-Summer season, measured at 10 cm depth.*

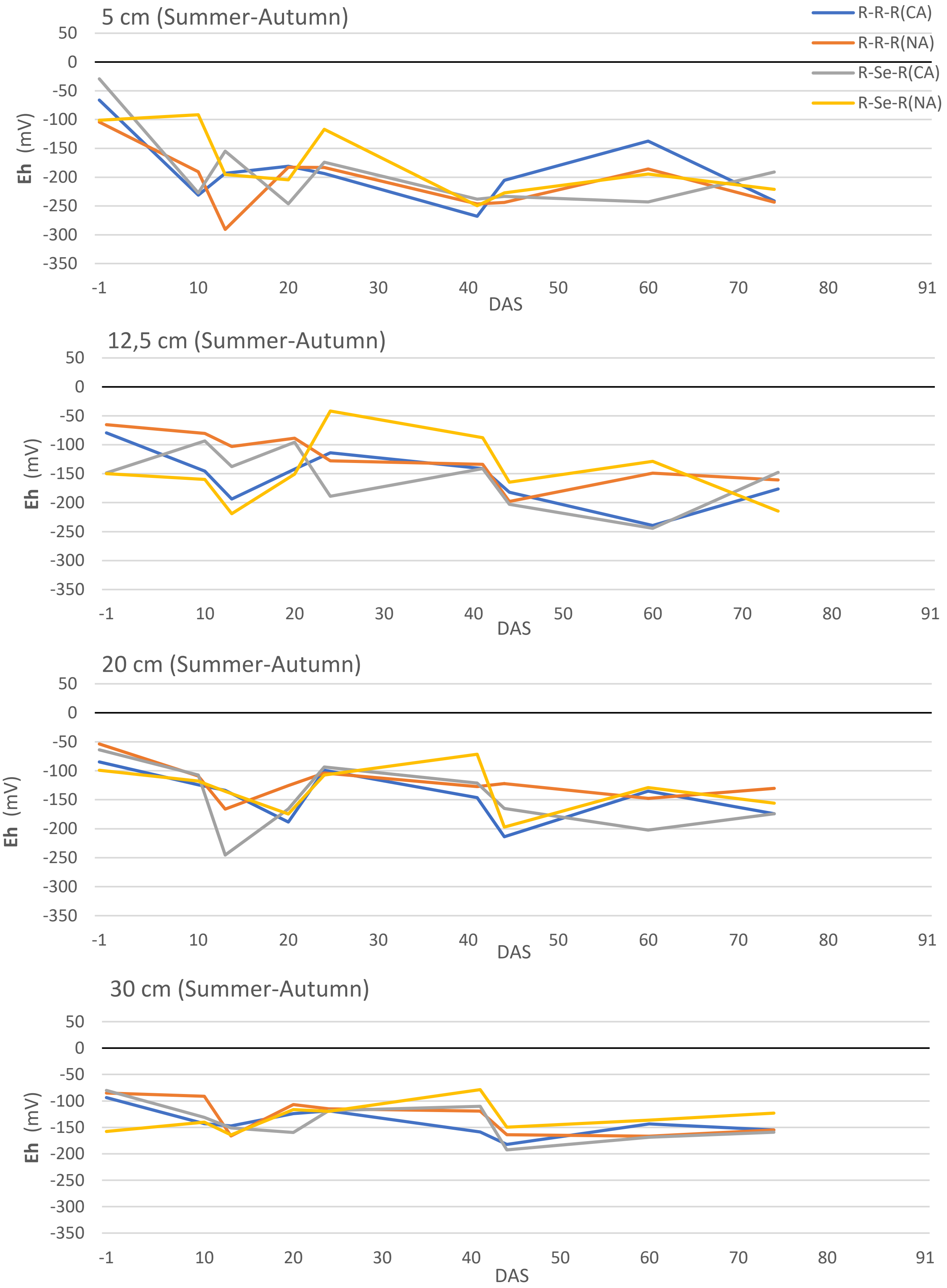

Fig. 18 *Seasonal evolution of Eh under different cropping and OM amendment treatments in the Summer-Autumn season, measured at depths of 5 cm, 12.5 cm, 20 cm and 30 cm.*

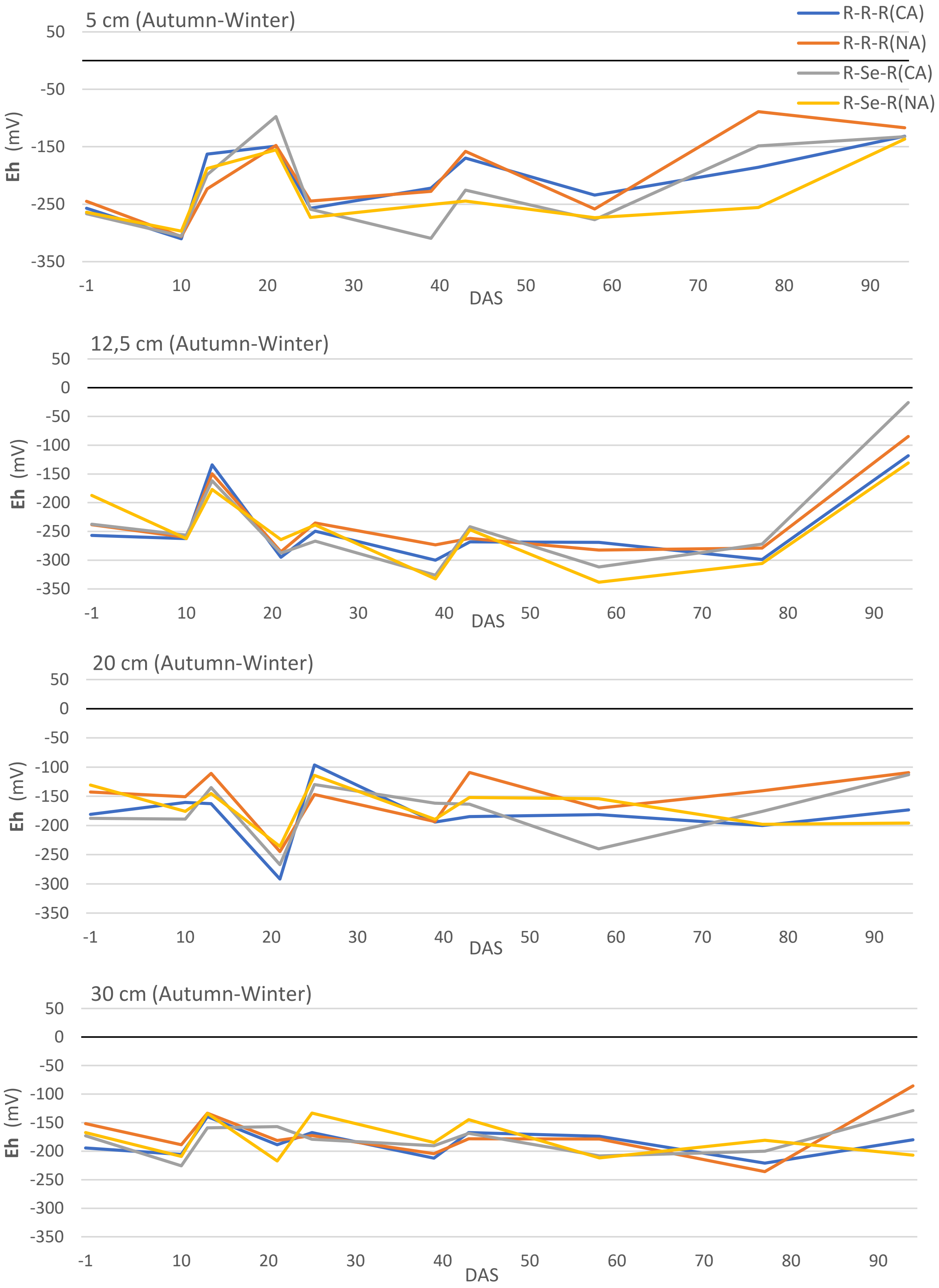

Fig. 19 *Seasonal evolution of Eh under different cropping and OM amendment treatments in the Autumn-Winter season, measured at depths of 5 cm, 12.5 cm, 20 cm and 30 cm.*

2. SOIL SOLUTION IRON AND MANGANESE LEVELS

We monitored progression of Fe and Mn dissolved in the soil solution to relatively appreciate the extent of Fe^{3+} and $Mn^{3+/4+}$ reduction between the treatments. The monitored concentrations of the soil solution components are presented in **Fig**. **20** , **Fig**. **21** and **Fig**. **22** for the Spring-Summer, Summer-Autumn and Autumn-Winter season, respectively. The Ca^{2+}, Mg^{2+} and Fe^{2+} levels were jointly used to calculate Fe^{2+}-equivalents (Fe^{2+}-eq.) in the graphs on the left. It is well known that a substantial part of extra dissolved Fe^{2+} released from reductive dissolution of Fe-(hydr)oxides does not remain in soil solution but instead quickly displaces primarily Ca^{2+} and Mn^{2+} from the negatively charged surface of soil colloids (clays and soil OM). The build-up of Ca^{2+} and Mg^{2+} soil solution is then proportional to this release. Mn^{2+} concentrations were also shown in the graphs on the right. The three seasons showed a different evolution for soil solution Fe^{2+}-eq. and Mn^{2+} concentrations. A t-test was used to test cropping treatment effects in Spring-Summer, and a two-way ANOVA was applied to the Fe^{2+}-eq. and Mn^{2+} concentrations at 61, 60 and 58 DAS in the Spring-Summer, Summer-Autumn and Autumn-Winter seasons, respectively.

In the Spring-Summer season (**Fig**. **20**), the Fe^{2+}-eq. and Mn^{2+} concentrations did not significantly differ between amendment treatments for the R-R-R rotation (there were no measurements for R-Se-R treatments because of sesame cultivation). Fe^{2+}-eq. concentrations remained below 15 mg L^{-1} at the 0-15 and 15-30 cm soil layers and lower than 5 mg L^{-1} at the 30-45 cm layer. Mn^{2+} concentrations fluctuated between 0 and 2 mg L^{-1} in all three soil layers.

Crop rotation significantly affected Fe^{2+} levels in the Summer-Autumn season at a depth of 15-30 cm (p=0,047) at 60 DAS (**Fig**. **21**). In the R-R-R treatments the Fe^{2+}-eq. concentration was about 250% higher than in the R-Se-R treatments. No other significant effects of any treatments were found at 60 DAS in this season. Maxima of Fe^{2+}-equivalent and Mn^{2+} concentrations were observed at 20 DAS, but only one sample was taken per treatment at 20 DAS so no statistical tests could be done. In the first 20 DAS higher Fe^{2+}-eq. concentrations (between 20 and 100 mg L^{-1}) occurred in the R-R-R treatments. At the end of the season, all Fe^{2+}-eq. concentrations remained between 0 and 20 mg L^{-1}, and 0 and 40 mg L^{-1} for the 0-15 cm soil layer and 15-30, 30-45 cm soil layers, respectively. Mn^{2+} concentrations fluctuated between 0 and 2 mg L^{-1} in all three soil layers.

In the Autumn-Winter season (**Fig. 22**), all treatments showed similar trends in soil solution Fe^{2+} and Mn^{2+} at all depths. At 60 DAS, a significantly higher Mn^{2+} concentration was found in the 15-30 cm soil layer in the R-R-R compared to the R-Se-R rotation. No other significant differences were found. In the 0-15 cm soil layer, Fe^{2+}-equivalent concentrations varied between 10 and 60 mg L^{-1}, while in deeper layers the concentrations were lower than 10 mg L^{-1}. The Mn^{2+} concentrations were on average 1, 1.5 and 2 mg L^{-1} in the 0-15 cm, 15-30 cm and 30-45 cm soil layers, respectively.

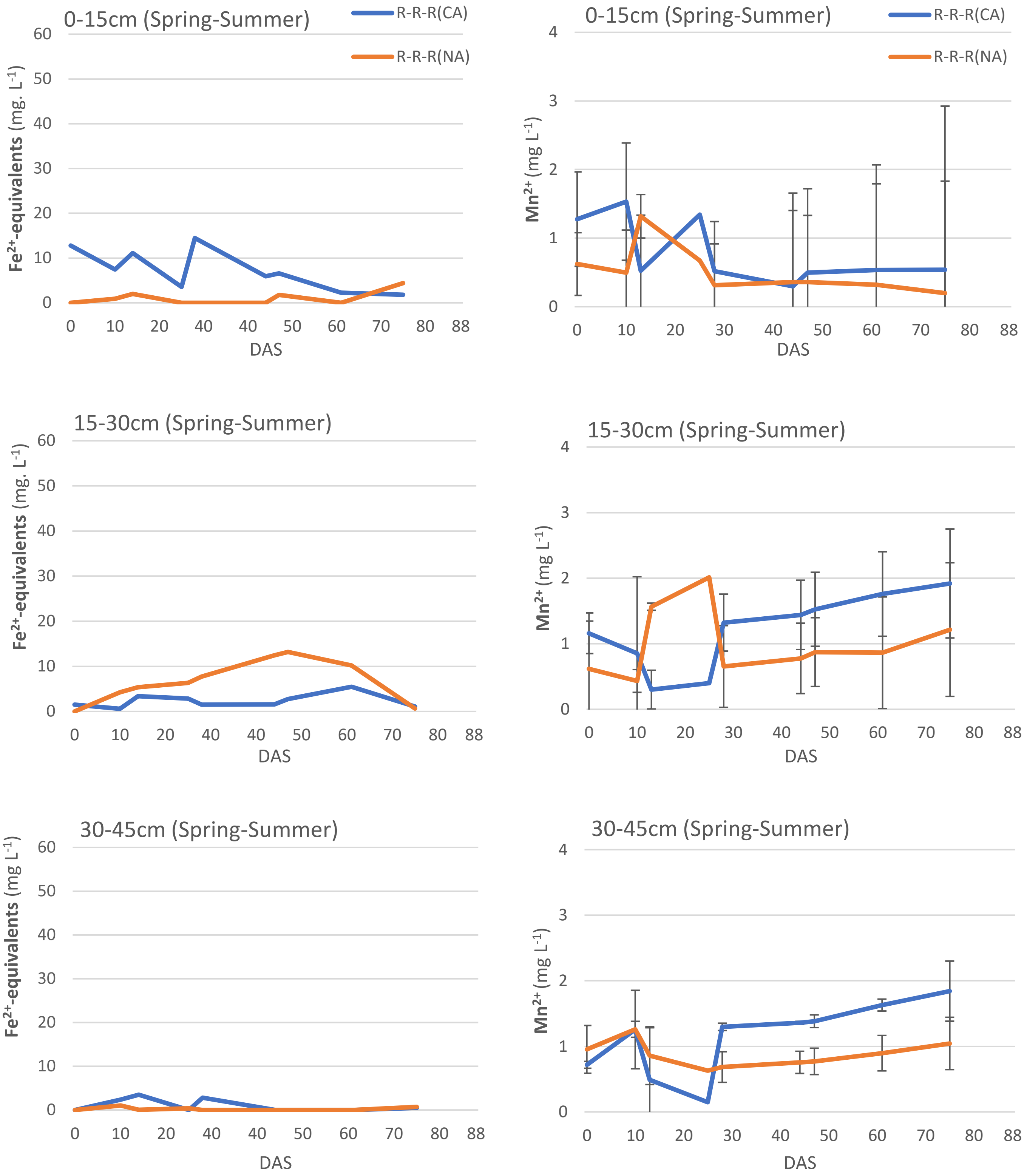

Fig. 20 *Evolution of Fe^{2+}-equivalents concentration (left) and Mn^{2+} concentration (right) in the soil solution at three depths (0-15 cm, 15-30 cm, 30-45 cm) under different cropping and OM amendment treatments during the Spring-Summer season.*

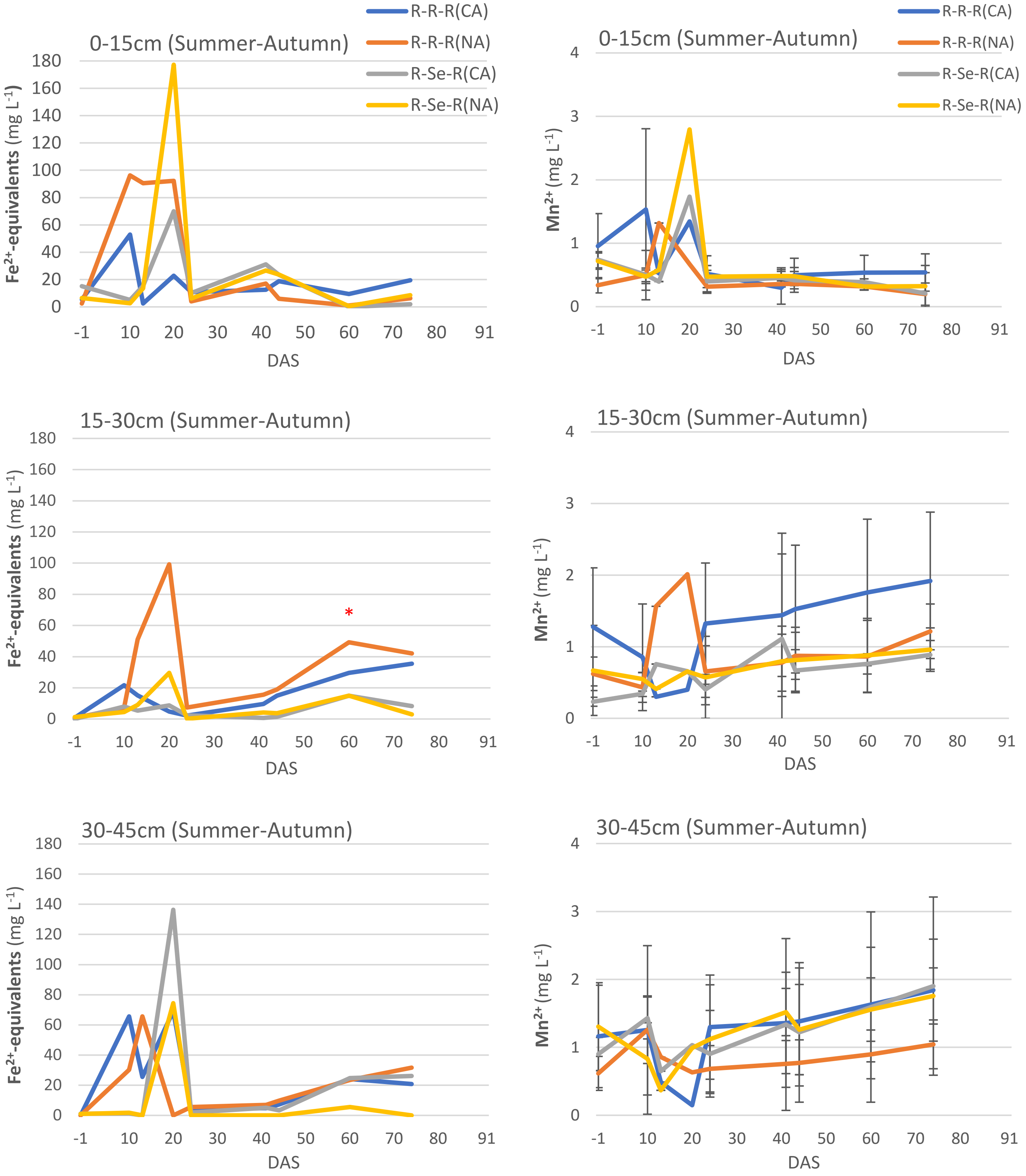

Fig. 21 *Evolution of Fe^{2+}-equivalents concentration (left) and Mn^{2+} concentration (right) in the soil solution at three depths (0-15 cm, 15-30 cm, 30-45 cm) under different cropping and OM amendment treatments during the Summer-Autumn season. (* significant difference between crop treatments ($p<0,05$)).*

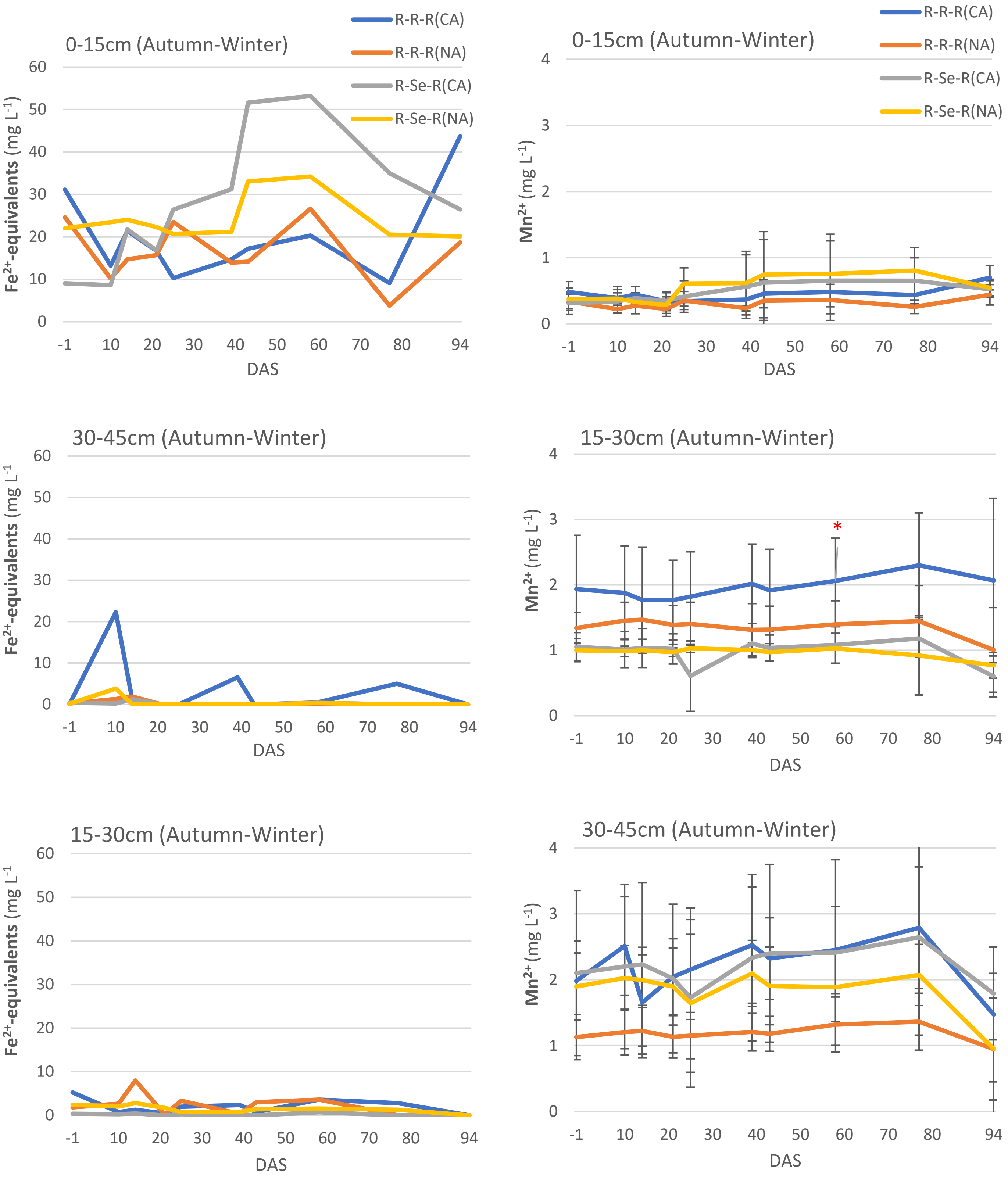

Fig. 22 *Evolution of Fe^{2+}-equivalents concentration (left) and Mn^{2+} concentration (right) in the soil solution at three depths (0-15 cm, 15-30 cm, 30-45 cm) under different cropping and OM amendment treatments during the Autumn-Winter treatments season. (* significant difference between crop treatments (p<0,05)).*

3. GASEOUS SOIL C EMISSION

3.1. Soil CH_4 emission

All treatments, except for the R-Se-R treatments in Spring-Summer, showed clear within season temporal variations ($p<0.05$) for CH_4 emission flux (**Fig**. **23**). Emission fluxes were lowest in the Spring-Summer season, remaining at 0,1 mg CH_4 m^{-2} h^{-1} for both rice treatments in the first 44 DAS, after which they increased to 0,5 mg CH_4 m^{-2} h^{-1}. From 44 DAS, the R-R-R(CA) treatment showed a more rapid flux build-up than the R-R-R(NA) treatment. The emission rate of the R-Se-R crops hovered around 0 mg CH_4 m^{-2} h^{-1}, measuring both slightly positive and negative values. Neither OM amendment nor crop rotation treatment significantly impacted CH_4 efflux for individual point measurements on any point in time.

In the Summer-Autumn season, all treatments followed a similar trend. Slightly faster CH_4 fluxes were observed after the first N-fertilization (10 DAS). The R-R-R(CA) treatment deviated from the overall flux trend after the third N-application (41 DAS): the flux climbed to 1,2 mg CH_4 m^{-2} h^{-1}, while the average flux was 0,3 mg CH_4 m^{-2} h^{-1}. However, again there were no significant differences in CH_4 flux were found between treatments throughout the Summer-Autumn season.

The highest CH_4 emission fluxes were observed in the Autumn-Winter season. The emission again increased immediately after every N-application in all treatments (10, 21 and 39 DAS), but slightly decreased or stagnated afterwards. The R-R-R(CA) treatment clearly showed a larger flux, with a maximum of 1,8 mg CH_4 m^{-2} h^{-1} at 24 DAS. But there were no significant treatment effects on individual CH_4 fluxes in the Autumn-Winter season.

The total seasonal cumulative CH_4 emissions ($CH_{4,CUM}$) are shown in **Table 4** and the evolution of $CH_{4,CUM}$ graphs are presented in Appendix D. The amendment application had no significant effect on $CH_{4,CUM}$ in any season. $CH_{4,CUM}$ was only significantly higher in the R-R-R than in Spring-Summer season, when sesame was growing. In fact soil in the sesame plots acted as net CH_4 sinks, 0.26 g CH_4 ha^{-1} for the R-R-R treatments. Overall CH_4 emissions increased with each consecutive season for all treatments.

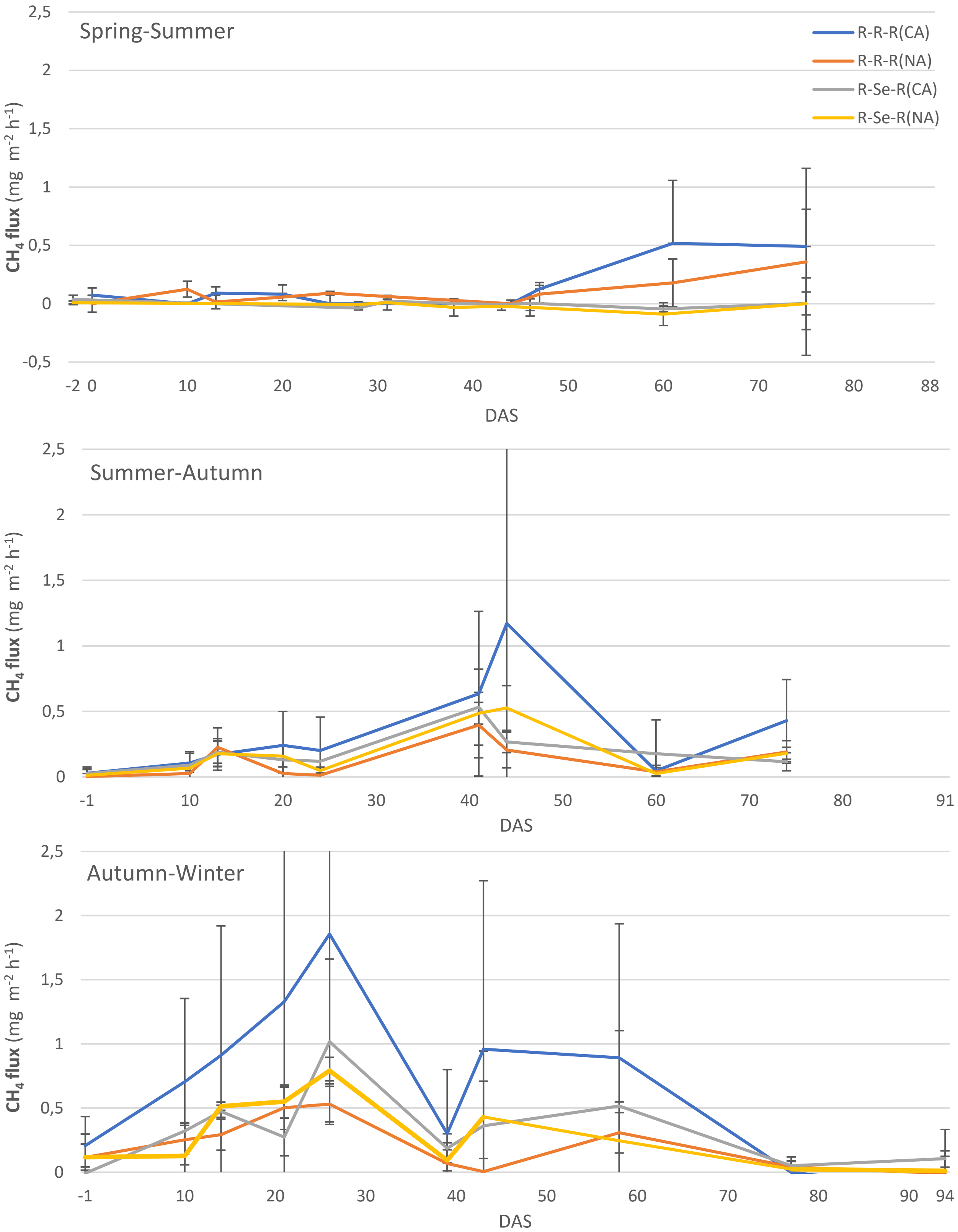

***Fig. 23** Evolution of the CH_4 emission flux from the soils in the Spring-Summer, Summer-Autumn and Autumn-Winter season under different cropping and OM amendment treatments. Error bars denote standard deviations around means (n=3).*

3.2. Soil + plant CO_2 emission

Soil CO_2 emissions (**Fig**. **24**) were measured using dark closed chambers and so are both soil-derived and plant derived. Crop rotation had a significant effect on individual CO_2 fluxes throughout the Spring-Summer season ($p<0.05$). Sesame cultivation clearly led to lower CO_2 emission than rice cultivation. The CO_2 flux remained between 5 and 70 mg CO_2 m^{-2} h^{-1} for the R-Se-R treatments. In the R-R-R treatments, the CO_2 flux increased after 44 DAS (three days after N application) from about 50 mg CO_2 m^{-2} h^{-1} to 165 and 230 mg CO_2 m^{-2} h^{-1} for R-R-R(CA) and R-R-R(NA), respectively. However, there were no significant differences between amendment treatments from neither rice or sesame cultivated plots.

In the Summer-Autumn season all treatments followed a similar trend with increasing CO_2 effluxes up until 60 DAS. At 20 DAS, CO_2 emissions were significantly higher in the R-Se-R than in the R-R-R treatments ($p=0.04$). At 24 DAS, three days after the first N-application, R-Se-R plots and OM amendment treatments both had significantly higher CO_2 effluxes compared to the R-R-R and no-amendment treatments ($p=0.006$ and $p=0.004$, respectively). Throughout the rest of the season there were no further treatment effects on the CO_2 efflux rates. Maximum CO_2 fluxes were found at 60 DAS, with 935 mg CO_2 m^{-2} h^{-1} for both R-Se-R(CA) and R-Se-R(NA), and with 830 and 700 mg CO_2 m^{-2} h^{-1} for R-R-R(CA) and R-R-R(NA), respectively.

Neither crop rotation nor amendment treatment had any significant effect on any of the measured CO_2 efflux rates throughout the Autumn-Winter treatment. A maximum emission rate was found at 43 DAS, three days after the third N-fertilization, with fluxes of 1580, 2330, 2060, 2260 mg CO_2 m^{-2} h^{-1} for R-R-R(CA), R-R-R(NA) R-Se-R(CA) and R-Se-R(NA), respectively. Before 39 DAS and after 58 DAS, CO_2 effluxes were much lower and remained below 600 mg CO_2 m^{-2} h^{-1} .

The total seasonal cumulative CO_2 emissions ($CO_{2,CUM}$) are shown in **Table 4** and the cumulative CO_2 emission plotted vs. time ($CO_{2,CUM}$) is given in Appendix D. OM amendment had no significant impact on $CO_{2,CUM}$ in any season. The effect of crop rotation on $CO_{2,CUM}$ was highly significant in the Spring-Summer season: the soil under sesame cultivation emitted on average 301 kg CO_2 ha^{-1}, while the soil under rice cultivation emitted on average 2199 kg CO_2 ha^{-1}. In contrast, in Summer-Autumn the sesame treatments emitted about 30% more CO_2 than the rice treatments, which is an effect that seems to enlarge in the Autumn-Summer season (however not significant in both seasons).

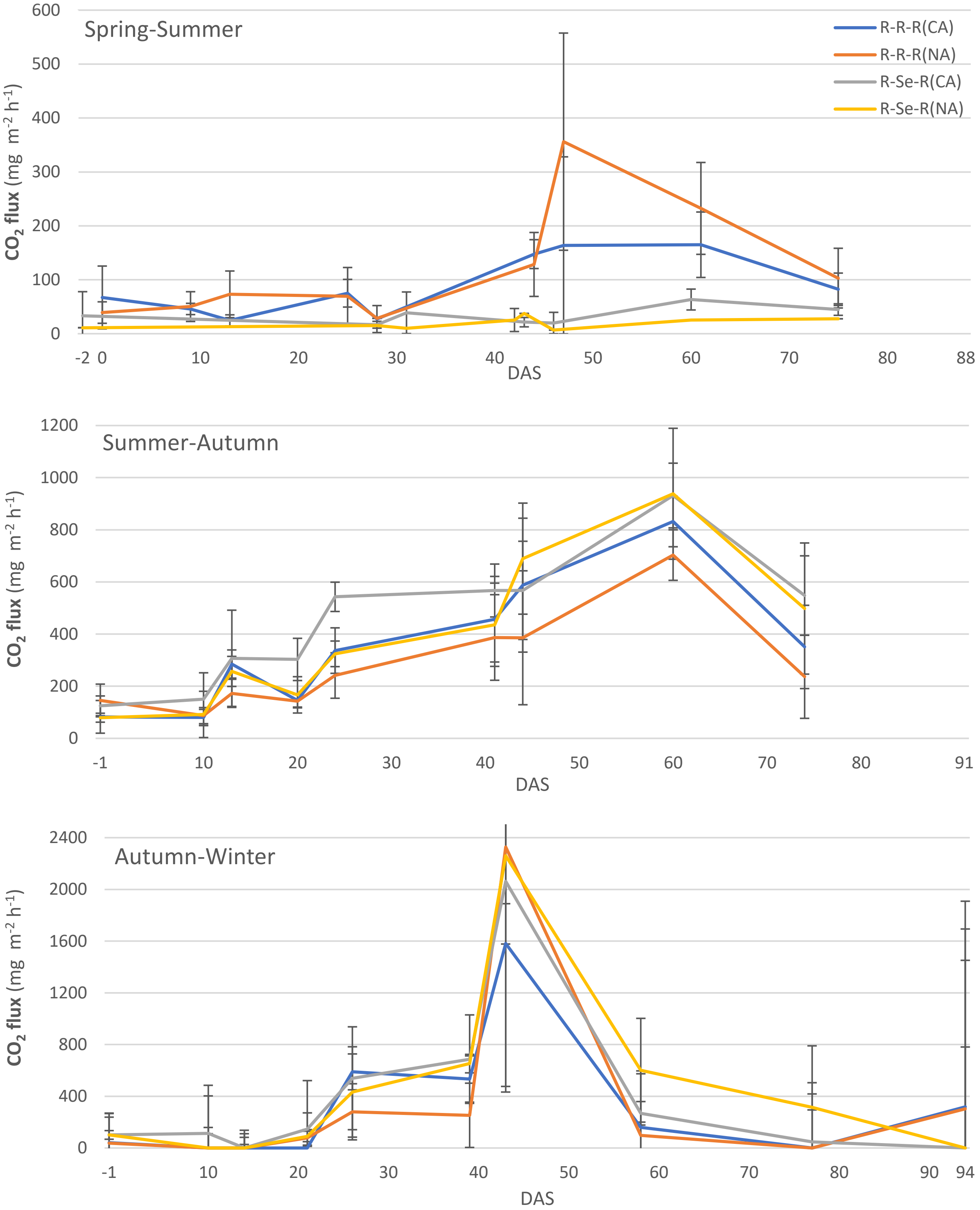

Fig. 24 *Evolution of the CO_2 emission flux from the paddy soils in the Spring-Summer, Summer-Autumn and Autumn-Winter seasons under different cropping and OM amendment treatments. Note that the Y-axis scales are different for each graph, in order to facilitate comparison of treatments. Error bars represent standard deviations around mean values with n=3.*

Table 4 *Cumulative CH_4 and CO_2 emission under different cropping and OM amendment treatments in the Spring-Summer season, Summer-Autumn season and Autumn-Winter season.*

	Spring-Summer		**Summer-Autumn**		**Autumn-Winter**	
Treatment	**CH_4** (kg ha^{-1})	**CO_2** (kg ha^{-1})	**CH_4** (kg ha^{-1})	**CO_2** (kg ha^{-1})	**CH_4** (kg ha^{-1})	**CO_2** (kg ha^{-1})
R-R-R (CA)	3.2 ± 2.4	1817.9 ± 363.8	6.3 ± 7.0	7947.0 ± 1584.6	14.4 ± 14.4	6212.6 ± 641.5
R-R-R (NA)	1.9 ± 1.3	2579.5 ± 794.3	2.3 ± 0.6	6077.6 ± 97.5	3.8 ± 5.0	6584.7 ± 348.4
R-Se-R (CA)	-0.1 ± 0.1	396.0 ± 44.1	3.6 ± 2.2	9482.3 ± 660.8	7.4 ± 1.7	8718.0 ± 644.2
R-Se-R (NA)	-0.3 ± 0.2	233.2 ± 50.5	3.4 ± 0.9	8435.7 ± 1889.1	5.7 ± 2.3	10353.0 ± 539.2
p^{crop}	* [a]	***	ns	*	ns	ns
$p^{amendment}$	ns	ns	ns	ns	ns	ns
$p^{interaction}$	ns	ns	ns	ns	ns	ns

[a] A two-way analysis of variance (ANOVA) was performed with crop rotation and OM-amendment treatment as fixed factors. Treatment effects are presented in the last three rows per cropping season (p^{crop} the crop rotation treatment effect, $p^{amendment}$: concerns the amendment effect, $p^{interaction}$: the interaction effect of both factors; ns: not significant; * $p<0.05$, ** $p<0.01$, *** $p<0.001$)

3.3. Total carbon loss

The sum of CH_4 and CO_2 emitted carbon offers an insight in the amount of carbon that was lost from the soil across the entire cropping season. The SOC concentrations per treatment before the start of this experiment, and the total emitted carbon are given in **Table 5**. The original experiment had been running for three seasons before these SOC values were measured, meaning they could already have been affected by the upland crop season of the previous year (although not significantly).

Table 5 *Cumulative amount of carbon emitted as CO_2 and CH_4 from the soil and crop jointly. These C fluxes are each time also expressed as a relative percentage of the soil organic carbon stock in the topsoil (0-15 cm).*

		Spring-Summer		**Summer-Autumn**		**Autumn-Winter**	
Treatment	**Topsoil SOC stock** (kg C ha^{-1})	**C emission** (kg C ha^{-1})	**C loss** (% of SOC stock)	**C emission** (kg C ha^{-1})	**C loss** (% of SOC)	**C emission** (kg C ha^{-1})	**C loss** (% of SOC)
R-R-R(CA)	91007 ± 11456	1363	1.50	5730	6.30	4662	5.12
R-R-R(NA)	75140 ± 1963	1933	2.57	4552	8.06	4933	6.47
R-Se-R(CA)	81713 ± 3354	296	3.62	7102	8.70	6532	7.99
R-Se-R(NA)	87493 ± 5813	174	0.20	6318	7.22	7755	8.86

3.4. Global warming potential

The global warming potential of the greenhouse gas emissions was calculated by converting seasonal cumulative CH4 emissions into CO2-equivalents (CO2-EQ.) based on the IPCC (2013) GWP values. Conventionally, GWP is presented for a 100 year period. Considering, however, that global warming is happening now already and any action to lower CH4 emission can lead to mitigation of climate change in the coming decades, we instead used GWP values for a 20-year time horizon (**Table 6**). The 100-year GWP values for CH4 are 33% smaller than the 20 year GWP values and these are given in Appendix E.

Table 6 *Table. Global warming potential (GWP) on a 20-year time frame for CH_4, CO_2 and total carbon based emissions (kg CO_2-equivalents ha^{-1}). The relative share of CH_4 and CO_2 to total CO_2-eq emissions is each time presented in the subsequent row. The used IPCC GWP factors in the 20 year time horizon are 84 for CH_4 and 1 for CO_2.*

	Spring-Summer			**Summer-Autumn**			**Autumn-Winter**		
Treatment	**CH_4** (kg CO_2-eq. ha^{-1})	**CO_2** (kg CO_2 ha^{-1})	**Total** (kg CO_2-eq. ha^{-1})	**CH_4** (kg CO_2-eq. ha^{-1})	**CO_2** (kg CO_2 ha^{-1})	**Total** (kg CO_2-eq. ha^{-1})	**CH_4** (kg CO_2-eq. ha^{-1})	**CO_2** (kg CO_2 ha^{-1})	**Total** (kg CO_2-eq. ha^{-1})
R-R-R (CA)	269	1818	2087	532	7647	8179	1212	6213	7425
	12,88%	87,12%		6,51%	93,49%		16,33%	83,67%	
R-R-R (NA)	159	2580	2739	191	6078	6268	361	6585	6945
	5,81%	94,19%		3,04%	96,96%		5,19%	94,81%	
R-Se-R (CA)	-4	396	392	302	9482	9784	619	8718	9337
	-1,14%	101,14%		3,09%	96,91%		6,63%	93,37%	
R-Se-R (NA)	-21	233	212	289	8436	8724	479	10353	10832
	-10,10%	110,10%		3,31%	96,69%		4,42%	95,58%	

4. YIELD AND RICE STRAW

In the Spring-Summer season, rice was only cultivated in the R-R-R treatments, so the effect of crop treatment on harvest parameters, such as rice yield and harvested rice straw, could not be considered in this season. The seed yield and harvested sesame straw are presented in **Table 7**. Rice grain yield was never significantly different between any of the included treatments and in any season. Yields in the Summer-Autumn and Autumn-Winter season were about 5 ton ha-1. In the dry season (Spring-Summer), yields from the R-R-R treatments were lower by 35-50% than those from the Summer-Autumn and Autumn-Winter seasons (**Fig. 25**).

After harvest, rice straw was furthermore collected from the fields and oven-dried. The straw dry matter (DM) is showed in **Fig. 26**. A t-test applied to the Spring-Summer data showed no crop rotation effect on rice straw DM. A two way-ANOVA proved the effect of crop treatment on rice husk DM to be only slightly significant in the Summer-Autumn season with a p-value of 0.04. There was no crop rotation effect in the Autumn-Winter season on rice straw DM. There were no effects of OM amendment either.

Table 7 *Sesame seed yield and harvested sesame straw under different OM amendment treatments in the Spring-Summer season.*

Treatment	Seed yield (t ha^{-1})	Harvested straw (t ha^{-1})
S-S-S(CA)	0,74	6,38
S-S-S(NA)	0,71	5,4

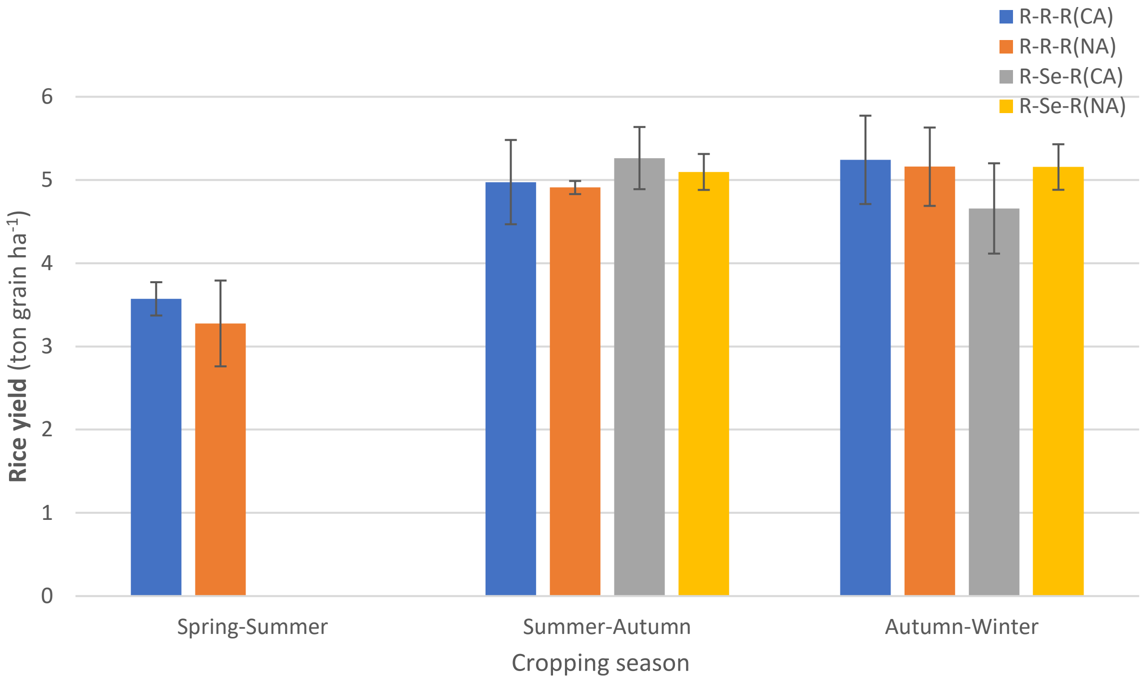

Fig. 25 *Rice yield under different cropping and OM amendment treatments in the Spring-Summer, Summer-Autumn and Autumn-Winter seasons.*

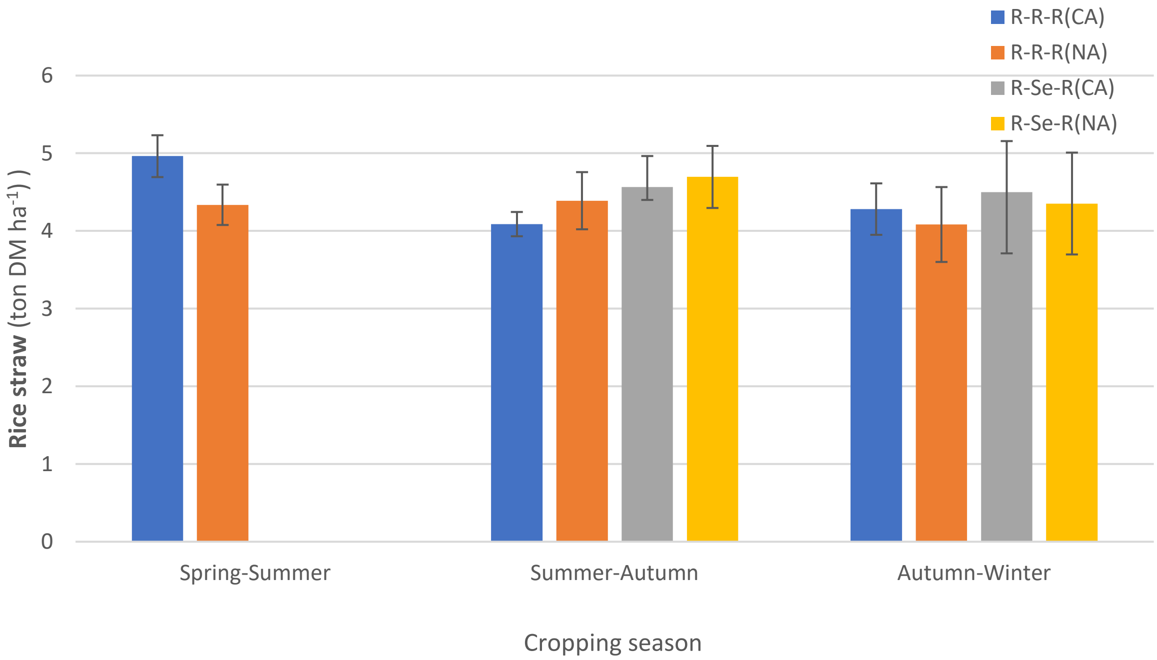

Fig. 26 *Oven-dried Rice straw (dry matter) harvested under different cropping and OM amendment treatments in the Spring-Summer, Summer-Autumn and Autumn-Winter seasons.*

DISCUSSION

1. ENVIRONMENTAL SOIL VARIABLES

1.1. Soil temperature

Crop rotation and OM amendment had no substantial effect on soil temperature. Only in the Spring-Winter season, there was a lower soil temperature in the sesame cultivated topsoil. This could partly explain lower CO_2 emissions in the sesame crop. Theoretically, a change in soil temperature has influence on the emission of GHGs because of a stimulating control on microbial activity. As we did not measure the temperature response of C-mineralization, we estimated with the method of De Neve et al. (1996) that mineralization would be 15% higher at 32°C compared to 27°C. But throughout seasons there did not seem to be a straightforward relation between the evolution of the soil temperature and the CH_4 and CO_2 emission fluxes. The soil temperature, however, remained in a highly suitable range for CH_4 and CO_2 production at all times, which could explain the limited influence on emission fluxes.

1.2. Soil pH

A multitude of studies on paddy soil chemistry confirmed that soil pH increases upon flooding. The soil reductive processes, with Fe^{3+} reduction the main electron accepting process for the oxidation of SOM to proceed, all consume protons, resulting in the neutralization of acidic soils (Sahrawat, 2005). We would have expected a larger increase of the soil pH, evolving towards neutrality, but instead pH values remained between 5 and 6,5. This could be explained by the oxidation that most likely has taken place after removing the soil from the field until measurement in the lab. Hence, pH measurements suffered from an artefact and detected pH trends provide little further insight in the paddy soil biogeochemistry here.

1.3. Soil redox potential

The soil redox potential is an important parameter controlling GHG emissions from rice paddy soils. The soil Eh is also often highly variable in both time and space, so knowledge on soil Eh in different depths and frequent sampling events can be indispensable to explain GHG emission trends. There were no drainage events during the growing period, so oxidation processes would only have occurred at the surface layer of the soil, especially at a low field water level, and around the roots, because the plant aerenchym transports O_2 to the roots for root respiration. The latter can result in sudden high Eh measurements at the sampling depths when the Eh meter is located in the rhizosphere, which can give misleading results because the bulk soil could have a strongly negative Eh. In this research permanent Pt-electrodes were positioned in between plants and so this problem was not encountered. Measurements are then also mainly representative for bulk soil and not rhizosphere. Eh nearly never rose above 0 mV at any observed time, demonstrating the typical anaerobic conditions of a continuously flooded paddy soil. We also observed smaller fluctuations in deeper soil layers, which can be explained by the more limited microbial activity due to the much lower (a factor 4) SOC level compared to the puddle layer. In addition penetration of roots was probably less in subsoil again reducing inputs of C, but also reducing spatial variation, e.g. in O_2 supply and so also in Eh.

As there was no clear variation in Eh between treatments, it becomes difficult to mirror any treatment difference in GHG efflux to the soil Eh. In any case, the soil Eh was sufficiently low to accommodate methanogenesis (<100mV; Hou et al., 2000). Also Eh tended to lower when CH_4 flux was increased, for example at 44 DAS in the Summer-Autumn season and at 25 and 60 DAS in the Autumn-Winter season.

2. CARBON BALANCE

2.1. CO_2 emissions

The monitored CO_2 emission in this study is the result of soil CO_2 emission from root and soil microbial respiration and from the above ground balance of plant respiration and photosynthesis. The latter process may be excluded as closed dark gas flux chambers were used. Sampling was done during the day between 9h and 12h, not taking diurnal and nocturnal emission changes into account, so the measured data are not entirely representative for daily CO_2 emission. Also it is impossible to distinguish the contribution of soil and plants to the total CO_2 emission, so the calculated CO_2 emission fluxes and cumulative CO_2 emission need to be handled with care. Nevertheless, since rice straw yields were statistically equal between all treatments, it seems plausible to assume that the share of plant derived CO_2 emissions was equal for all treatments. Hence, any differences observed in CO_2 emission between treatments are bound to be primarily caused by the different soil microbial activity in the treatments.

Organic matter is decomposed slower in submerged soils than in aerated soils because anaerobic bacteria operate at a much lower energy level (Ponnamperuma 1972). Moreover, aerobic SOM decomposition uses free oxygen as an electron acceptor and in submerged soils, SOM decomposition depends on the availability of electron acceptors such as ferric iron or sulfate (Sahrawat, 2005) as well. In the **Spring-Summer season** however, cumulative CO_2 emissions from the R-Se-R treatments were significantly lower than the R-R-R treatments, which actually contradicts expectations. One possible explanation could be that the sesame plants respired less during sampling in the darkened gas chamber compared to rice pants, but this needs to be verified experimentally.

At 24 DAS **in the Summer-Autumn season**, the R-Se-R treatments showed significantly about CO_2 emission fluxes (about 45% higher) than the R-R-R treatments. In the same season, the $CO_{2,CUM}$ emission of R-Se-R was then also significantly higher than $CO_{2,CUM}$ of R-R-R, namely by approximately 20%. These figures suggest there was a SOM mineralization stimulating effect by the prolonged aerated period of the previous Sesame cultivated season. For instance sesame might have left more or more easily degradable crop residues than rice, but this remains a hypothesis.

The CO_2 flux increased for all treatments in all seasons during the first 40 to 60 DAS and decreased afterwards. Most of the SOM was present in the top soil layer (0-15 cm). This layer contained a rather high amount of organic matter (SOC level 2.2-2.7%). The high organic carbon stocks could explain why CO_2 emissions from all treatments were high, as maily the biodegradable share of SOM is the substrate fueling respiration and growth of aerobes and anaerobes, resulting in CO_2 production and emission. Amending rice straw and cow husk compost had no significant effect on CO_2 emissions, presumably because the dosage (2 ton fresh compost) was simply too small, relative to the present large stock SOM, with then no substantial promotion of microbial activity.

2.2. Soil redox reactions

Iron reduction in paddy soils results in important changes in soil chemical properties: the concentration of soluble iron increases in the soil solution, pH increases, cations are displaced from exchange sites and new minerals are formed. In the Summer-Autumn season, concentration peaks for Fe^{2+}-eq. and Mn^{2+} were observed at all depths in the first 23 DAS. This initial increase in dissolved Fe and Mn is also expected, as most unstable organic material is present at the onset of the growing period. Plant residues from the previous crop and organic amendment can induce a mineralization peak in the first two to three weeks, increasing dissolved reduced iron concentrations. Agreeingly, Ponnamperuma (1976) states that 5 to 50% of the iron oxides in the soil can be reduced within a couple of weeks after submergence. After these few weeks, the soil solution Fe^{2+} and Mn^{2+} concentrations lower again, probably because CO_2 levels in the submerged paddy soil have increased as well and iron carbonate is formed ($FeCO_3$, siderite). Siderite is formed from the onset of submergence, but precipitates slower than Fe^{2+} is produced during the initial phase of flooding, giving Fe^{2+} the opportunity to accumulate in the first few weeks (Jäckel and Schnell 2000; Zhang et al. 2012).

In this study, we did not always observe a clear evolution in Fe^{2+}-eq. and Mn^{2+} concentrations in the soil solution. Concentrations at times remained quite small, with just some peaks at the beginning of the Summer-Autumn season. In the Spring-Summer season, the Fe^{2+}-equivalent concentrations also remained low (<15 mg L^{-1}) in all treatments, while we expected a gradual increase in time, because of further oxygen and NO_3^- depletion after submergence, SOM degrading microorganisms are compelled to use other electron donors, such as Fe^{3+} and $Mn^{3+/4+}$, for their respiration. Therefore, considering the at most times very low Eh, microbial respiration in the paddy soil was expected to have resulted in a larger quantity of Fe^{2+}-equivalents and Mn^{2+} in the soil solution over time. The unexpected observed low soil solution Fe and Mn concentrations demand a more extensive explanation.

Small Fe^{2+}-eq. and Mn^{2+} concentrations could firstly be the result of little Fe^{3+} and $Mn^{3+/4+}$ reduction by micro-organisms. A first explanation would be a possible limited availability of reducible iron, which forces iron-reducing activity to decrease. The restricted Fe^{2+}-eq. concentrations could also be explained by the limited population size of Fe^{3+} and $Mn^{3+/4+}$ reducing micro-organisms in this particular field experiment. Both theories are plausible explanations for low Fe^{2+}-eq. concentrations, knowing methanogenesis occurred in the soil as well, which theoretically can only happen when reducible iron is depleted (Ponnamperuma, 1972). However, in soils rich in organic matter, several reduction processes can coexist because methanogens and iron reducing microorganisms do not have to compete for substrates (Liesack et al., 2000). Moreover, methanogenesis may occur simultaneously with iron reduction, when the overall activity of the iron reducing microbial community is too slow to keep up with electron donation by SOM oxidation. The Mn^{2+} present in soil solution, although in very low concentrations, confirms this logic since $Mn^{3+/4+}$ reduction is a thermodynamically less interesting reduction process, yet here occurring simultaneously with iron reduction. We did not assess inherent reducibility of the Fe^{3+} present in this soil, and this is in fact unstraightforward to assess.

Limited methane emission in all seasons combined (see further) with low Fe reduction and low Eh, suggests that yet another soil reduction process was important for accepting electrons. A large supply in reducible sulfate could thermodynamically support most of the soil microbial activity. When a soil is in a strongly reducing condition and sufficient electrons are available, SO_4^{-2} can be reduced to HS^- and Fe can be precipitated first as FeS and then FeS_2, which is poorly soluble in water. The presence of a substantial amount of sulfate could thus explain why little reduced iron was detected.

The inhibition of methanogenesis might also be attributed to the competition of SO_4^{2-} reducing and methanogenic microorganisms for substrates, such as hydrogen and acetate. Iron and sulfate reducing organisms outcompete methanogens for electron donors when iron and sulfate are available in a readily reduceable form (Van Bodegom et al., 2004; Jäckel and Schnell, 2000; Lovley and Phillips, 1987). As the observed Fe^{2+}-eq. concentrations were low, it is more probable that sulfate reduction is the main methanogenesis inhibiting process. Acid sulfate soils occupy more than 40% of the VMD (Minh et al., 1997). We did not monitor sulfate concentrations, but the region's soil characteristics imply that the presence of high sulfate concentrations in this experiment is expectable. Sulfate redox reactions occur at a Eh of -220 mV, which is lower than the value for the iron reactions (200 mV) (Zhang, 2012). Such low Eh values were observed in all seasons, but further investigations of the progression of soil SO_4^{2-} levels are needed for confirmation of the above forwarded explanation.

Only crop rotation treatment had a significant effect on the Fe^{2+}-equivalent concentration in the Summer-Autumn season in the 15-30 cm soil layer. The concentration was on average 250% higher for R-R-R compared to R-Se-R at 60 DAS. However, since dissolved iron possibly reacted with sulfate to form iron sulfate in all plots, it can be difficult to interpret the observed differences in dissolved iron, because they may not reflect iron reduction, but the net effect of iron reduction and $FeSO_4$ production. Hence, we cannot directly conclude that this higher concentration of dissolved iron in the R-R-R treatments represents more strongly reducing soil conditions, especially given the equalities in Eh between all treatments.

The amendment treatments showed various trends at different depths and in different treatments. It is not immediately apparent that compost amendment had affected the oxidants concentrations. Again the low level of compost added compared to the high SOM stock probably explains the limited impact on soil reductive processes.

2.3. CH_4 emission effluxes

During sesame cultivation, CH_4 emissions were of no relevance, and data even suggested the soil to act as a small net CH_4 sink, by oxidation of atmospheric CH_4 probably by the ambient methanotrophs. High CH_4 emission are the result of continuous flooding condition that enhances growth and activity of the methanogenic population and leads to the low redox potential. During rice cultivation, CH_4 emissions however remained relatively limited in all treatments (<2 mg m^{-1} h^{-1}) even with a sufficiently low soil Eh for methanogenesis. As explained in 2.2 the inhibition of methanogenesis is possibly because of high sulfate concentrations.

Another explanation for the low CH_4 emission flux could have been enhanced methanotrophy. Methanotrophs in the rhizosphere can offset a very substantial part of CH_4 produced and are mostly N-limited to do so. First data on the N-availability in the soil (not presented here) did not indicate enlarged N concentrations (with typical exchangeable levels throughout the growing season of just 20-40 kg NH_4-N ha^{-1}). Thus it is unlikely that methanotrophic activity was particularly substantial in this paddy field, and may well have been limited by low N-availability.

In the Summer-Autumn and Autumn-Winter seasons, CH_4 emission fluxes increased the first half of the growing period, firstly because methanogenesis only occurs after a period of time in which reducible iron and sulfate are being reduced, and secondly, possibly because the amount of SOM and C substrate available for decomposition grew within time because more root exudates were produced and more decaying plant material was present. In the Summer-Autumn and Autumn-Winter seasons, the emission flux decreased again at the end of the rice growing period, probably due to the decreasing supply of exudate C by the rice plants (Jäckel and Schnell, 2000) or by initial depletion of easily degradable SOM.

The introduction of sesame into the rotation system did not lead to any significant differences in CH_4 emission flux. However, the observed fluxes under R-Se-R were smaller than under amended R-R-R(CA) throughout the entire seasons. In the Summer-Autumn season, CH_4 emission flux was reduced by about 10-45% in the R-Se-R(CA). In the Autumn-Winter season, the CH_4 flux in the R-Se-R(CA) treatment was about 50-120% smaller at these sampling events. A comparable study by Weller et al. (2016) reported a similar reduction in CH_4 production of 60% in CH_4 in a rice-maize rotation. The reduction of CH_4 emissions following a prolonged period of soil aeration can be explained by the regeneration of oxidants during this period, such as Fe^{2+} and SO_4^{2-}, renewing the oxidant availability in the next season (Weller et al., 2016). As explained before, the availability of oxidants in the soil has an inhibiting effect of methanogenesis, creating a delay in CH_4 production. Moreover, an extended period of soil aeration could also have a negative effect on the methanogenic micro-organism community. Weller et al. (2016) confirmed a continuous decrease of methanogens in the rice-maize fields as compared to the rice-rice control. The cumulative CH_4 emission of R-Se-R(CA) was 50% than R-R-R(Ca), which shows there was a considerable effect on total CH_4 emission.

As expected, the CA treatments showed higher CH_4 fluxes than the NA treatments, though not significantly. Composted rice straw and cow manure offer new substrate to the soil microbial community, including methanogens. Knowing the soil already contained a large amount of SOM and the amendment quantity was small, the effects of CA may not have been large. The R-R-R(NA) treatment notably emitted less CH_4 than the other treatments. At this point we can only speculate that more crop residues may have been left on the R-Se-R and R-R-R(CA) fields, providing more easily degradable substrate, or that not all compost from the previous seasons was completely degraded, as compost is a more stable than SOM and takes longer to be degraded. This would result in a higher CH_4 emission flux than in the R-R-R(NA) treatment.

Comparing CO_2 , CH_4 emission fluxes and Fe-eq. results in Summer-Autumn at 60 DAS in part also provide some further insight. The CO_2 flux was lower in R-R-R, compared to R-Se-R, so probably more CO_2 was used for methanogenesis, which means less CO_2 was available for $FeCO_3$ formation and this is the reason more Fe remained dissolved in the soil solution. This means the higher Fe^{2+}-eq. concentration could mean more strongly reducing conditions occurred in the R-R-R treatments, promoting CH_4 production. CH_4 fluxes did not show a larger emission flux at 60 DAS in the Summer-Autumn season, but at 43 DAS (before) and 75 DAS (after) we did observe a larger CH_4 flux in R-R-R(CA), which could confirm a more reducing soil environment, which is what we expected because these soils have not undergone a long period of aeration as opposed to the R-Se-R treatments.

2.4. Soil carbon balance

The amount of carbon losses through emission are important to provide insight to the sustainability aspect of a paddy rice soil. from the paddy soils were Weller et al. (2015) described a SOC loss after conversion to rice-maize rotation from monoculture rice of 480 ± 210 kg $ha^{-1}yr^{-1}$, considerably less than the calculated SOC losses due to C-emission in the R-Se-R(CA) and R-Se-R(NA) treatments (13930 and 14247 kg $ha^{-1}yr^{-1}$, respectively). An explanation for the higher SOC losses in this experiments can be the intensity of production, as three crops are grown per year in the VMD compared to two cropping seasons in the experiment by Weller (2016). Moreover, the soil density in the topsoil (0-15 cm in this experiment, 0-20 cm in Weller (2016)) in our experiment was 1360 kg m^{-2} compared to 1000 kg m^{-2} in Weller, and the SOC content was on average 2.47% compared to 1.59%. This means that the soil in our experiment contained about 210% more SOC before the crop diversification than the soil of the Weller (2016) experiment. This greater SOC content is mirrored by larger SOC losses. It is also important to keep in mind that not all measured C-emission represents a loss of SOC. Very importantly though: we measured GHG emissions in dark closed chambers, so CO_2 assimilation by photosynthesis were ruled out, meaning that the real SOC losses will be lower than those measured. Moreover, part of the crop residue will return to the soil, enriching the SOC pool again. Nevertheless we could relatively compare CO_2 emission-derived C-exports from the various treatments.

Higher soil aeration results after shifting from continuously flooded rice monoculture systems to upland crop rotations lead to SOC losses in the topsoil (0-15 cm) (Janz et al. 2019; Weller et al. 2016). Indeed, SOC losses in the Summer- Autumn and Autumn-Winter seasons and were on average 26% higher in the R-Se-R rotation than in the R-R-

R rotation, due to the larger CO_2 emissions, which could be an effect induced by the prolonged soil aeration in the Spring-Summer season. The amendment treatments did not have a clear effect on SOC emission. On the long-term it seems probable that equilibrium SOC stocks would become lower in the R-Se-R rotation compare to R-R-R. Moreover, as the application of OM amendment did not affect GHG emissions during consecutive rice cultivation, amending OM would appear to be beneficial to soil quality with no measurable adverse environmental impact. The added OM could sustain SOC stocks, supporting other soil functions such as fertility on the long term (Janz et al. 2019). However the amount of amendment applicated in this experiment was low (2 ton ha^{-1}), meaning its contribution to the already large SOC pool was probably small as well and the great SOC loss may not have been compensated. More research should be done on higher OM doses to assure that GHG emissions are not highly affected, and soil carbon stock is sufficiently enriched.

2.5. Global warming potential

As CH_4 emission was low and CO_2 emission was high in all seasons, the relative contribution of CH_4 to the total measured GWP was lower than expected (<17%). In comparison Linquist et al. (2015) recorded seasonal CH_4 emissions in a permanently flooded paddy of 100 and 144 kg CH_4-C ha^{-1} in rice-soybean and rice-rice rotations. These emissions correspond to over 2t CO_2-eq ha^{-1}, i.e. double the emission from the Autumn-winter season and a factor 4 and 8 times bigger than the CH_4 emitted in the Summer-Autumn and Spring-Summer seasons, respectively. The result is that in this field experiment CO_2 emission was surprisingly the main controlling factor for GWP in rice production. In fact the R-Se-R actually had a higher GWP than R-R-R owing to large CO_2 emissions in the Summer-Autumn and Autumn-Winter seasons. Two important elements need to be kept in mind when interpreting these results: 1° As explained before CO_2 emissions need to be looked at with care as they were based on both plant and soil derived CO_2 emissions; these total emissions should be corrected for with C assimilated by photosynthesis to yield a net GWP. 2° It should be kept in mind that N_2O is emitted from paddy soils as well and has a GWP of 265. N_2O is mainly emitted during soil aerated periods, thus potentially increases the real total GWP of R-Se-R even more. Many research has been done on the CH_4 and N_2O emissions (B. Linquist et al. 2012), but our study indicates that CO_2 emissions are in any case not negligible contributors of the total GWP of paddy soils. Once more it is crucial to further investigate if the low CH_4 emissions (considering these soil's high SOC level and low Eh throughout) could be linked to high SO_4^{2-} availability.

3. YIELD

OM amendment had no significant effect on sesame yield, although the CA treatment showed a 5% larger seed yield and a 18% increase in sesame straw (DM). Hence, we assume that amending compost mainly affects vegetative growth. Sesame yields in general (about 720 kg ha^{-1}) were smaller than the Vietnamese average seed yield (803 kg/ha), but definitely larger than the global average (554 kg/ha) (FAOSTAT 2017). Moreover, the obtained yields were similar to yields in a field trial by Wacal et al. (2019) in the first sesame cropping season after the conversion of rice paddy fields. As farming in the VMD is strongly rice oriented, a socio-economic evaluation is needed on how a crop rotation with sesame would affect farmer's income. According to FAOSTAT (2017), around 70% of consumed sesame in Vietnam is imported, which means there are definite market opportunities for sesame. A study by Linh (2016) on upland crop rotations with maize and mungbean in the VMD was also very promising. The crop rotation system led not only to more goods for the society, it also generated more income for the farmers' family and more protection of land resources.

The rice yields under different cropping treatments were not significantly different. Weller et al. (2016) observed similar yield results in the Philippines, with no effect of rice system diversification on rice production in a 2.5 year study with maize and/or upland rice in the crop rotation. However, in the ten-year study on rice-upland crop rotation with maize and mungbean by Linh (2016), the yields in the rice-upland cropping system were always significantly higher than in rice monoculture, but the difference between cropping treatments was small in the first years and clearly increased over ten years' time. It is possible that an extension in time of the field trial could eventually display clearer differences between yields under different cropping treatments. Amendment of compost may not have created significant differences because, as mentioned, the amount of compost applied may have been too small to create a sufficiently large pool of organic substrates in a soil with already high SOM levels.

CONCLUSION

The results of this thesis did not support the hypothesis that the introduction of sesame as an upland crop in the crop rotation leads to rice grain yield increase and a reduction in greenhouse gas emissions. Neither did the use of rice straw and cow manure compost significantly increase rice production.

There was only little effect of OM amendment and R-Se-R rotation on the GHG emissions and iron reduction, which can be explained by an already large SOM content, making the applied OM concentration rather unimportant, and by possibly a great deal of sulfate reduction, inhibiting methanogenesis in all treatments. Moreover, to further understand the processes mitigating CH_4 emissions in this experiment in particular, it is imperative to study the sulfate concentrations present in the paddy soil. If the sulfate proves to be abundantly present, this is probably the reason for the observed low CH_4 emissions. CO_2 emissions, however, were unexpectedly high, which we attributed to a large respiration activity of the soil microbial community at the availability of such high SOM levels. The CO_2 emission flux was larger in the R-Se-R rotation, suggesting that emissions from rice production actually were affected by the extended aeration period during sesame cultivation. Moreover, accounting for both CO_2 and CH_4, the R-Se-R rotation emitted more carbon than the rice monoculture, leaving a greater GWP for R-Se-R.

It is clear that, for further research, a shift of focus is appropriate, because CO_2 emission from the monitored paddy soils was clearly the main controlling factor of the SOC losses and total GWP in rice production. Thus, as opposed to many undertaken studies, the CO_2 emissions from paddy soils should not be disregarded, and even more, future research should focus on the overall effect of CH_4, CO_2 and N_2O combined, to research in which processes alternative GHG mitigating activities are most effective.

REFERENCES

Afzaal, M., Mirza, S., Mir, M., Ahmed, S., Rasul, A., Nasir, S., … ud din Umar, U. (2018). Antibiotics and Resistant Genes in Paddy Soil. In *Environmental Pollution of Paddy Soils* (pp. 99–112). Springer.

Anastasi, U., Sortino, O., Tuttobene, R., Gresta, F., Giuffrè, A. M., & Santonoceto, C. (2017). Agronomic performance and grain quality of sesame (Sesamum indicum L.) landraces and improved varieties grown in a Mediterranean environment. *Genetic Resources and Crop Evolution*, *64*(1), 127–137. https://doi.org/10.1007/s10722-015-0338-z

Ashri, A. (1998). Sesame breeding. In J. Janick (Ed.), *Plant breeding reviews* (Vol. 16, pp. 179–228). John Wiley & Sons, Inc.

Ashri, A., & Singh, R. J. (2007). Sesame (Sesamum indicum L.). In *Genetics resources, chromosome Engineering and crop improvement - Oilseed crops* (Vol. 4, pp. 231–289). CRC Press Boca Raton, FL, USA.

Bedigian D. (2004). History and lore of sesame in southwest Asia. *Economic Botany*, *58*(3), 329–353.

Bedigian, D., & Harlan, J. R. (1986). Evidence for cultivation of sesame in the ancient world. *Economic Botany*, *40*(2), 137–154. https://doi.org/10.1007/BF02859136

Bi, L., Zhang, B., Liu, G., Li, Z., Liu, Y., Ye, C., … others. (2009). Long-term effects of organic amendments on the rice yields for double rice cropping systems in subtropical China. *Agriculture, Ecosystems & Environment*, *129*(4), 534–541.

Boivin, P., Favre, F., Hammecker, C., Maeght, J.-L., Delarivière, J., Poussin, J.-C., & Wopereis, M. C. S. (2002). Processes driving soil solution chemistry in a flooded rice-cropped vertisol: analysis of long-time monitoring data. *Geoderma*, *110*(1–2), 87–107.

Boureima, S., Eyletters, M., Diouf, M., Diop, T. A., & Van Damme, P. (2011). Sensitivity of seed germination and seedling radicle growth to drought stress in sesame (Sesamum indicum L.). *Res. J. Environ. Sci*, *5*(6), 557–564.

Breidenbach, B., Blaser, M. B., Klose, M., & Conrad, R. (2016). Crop rotation of flooded rice with upland maize impacts the resident and active methanogenic microbial community. *Environmental Microbiology*, *18*(9), 2868–2885.

Chauhan, B. S. (2012). *Weed management in direct-seeded rice systems*. IRRI.

Chauhan, B. S., Jabran, K., & Mahajan, G. (2017). *Rice Production Worldwide*. Springer.

Conrad, R. (1999). Contribution of hydrogen to methane production and control of hydrogen concentrations in methanogenic soils and sediments. *FEMS Microbiology Ecology*, *28*(3), 193–202.

Conrad, R. (2002). Control of microbial methane production in wetland rice fields. *Nutrient Cycling in Agroecosystems*, *64*(1–2), 59–69.

Conrad, R. (2005). Quantification of methanogenic pathways using stable carbon isotopic signatures: a review and a proposal. *Organic Geochemistry*, *36*(5), 739–752.

Conrad, R. (2009). The global methane cycle: recent advances in understanding the microbial processes involved. *Environmental Microbiology Reports*, *1*(5), 285–292.

Dalal, R. C., Allen, D. E., Livesley, S. J., & Richards, G. (2008). *Magnitude and biophysical regulators of methane emission and consumption in the Australian agricultural, forest, and submerged landscapes: A review*. *Plant and Soil* (Vol. 309). https://doi.org/10.1007/s11104-007-9446-7

Diacono, M., & Montemurro, F. (2011). Long-term effects of organic amendments on soil fertility. In *Sustainable Agriculture Volume 2* (pp. 761–786). Springer.

Dossou-Yovo, E. R., Brüggemann, N., Jesse, N., Huat, J., Ago, E. E., & Agbossou, E. K. (2016). Reducing soil CO2 emission and improving upland rice yield with no-tillage, straw mulch and nitrogen fertilization in northern Benin. *Soil and Tillage Research*, *156*, 44–53. https://doi.org/10.1016/j.still.2015.10.001

FAOSTAT. (2017). Food and agriculture data - Crops. Retrieved May 17, 2019, from http://www.fao.org/faostat/en/#home

Filizadeh, Y., Rezazadeh, A., Younessi, Z., & others. (2007). Effects of crop rotation and tillage depth on weed competition and yield of rice in the paddy fields of Northern Iran. *Journal of Agricultural Science and Technology*, *9*(2), 99–105.

Garcia, J.-L., Patel, B. K. C., & Ollivier, B. (2000). Taxonomic, phylogenetic, and ecological diversity of methanogenic Archaea. *Anaerobe*, *6*(4), 205–226.

Gathala, M. K., Ladha, J. K., Saharawat, Y. S., Kumar, V., Kumar, V., & Sharma, P. K. (2011). Effect of tillage and crop establishment methods on physical properties of a medium-textured soil under a seven-year rice- wheat rotation. *Soil Science Society of America Journal*, *75*(5), 1851–1862.

Holzapfel-Pschorn, A., Conrad, R., & Seiler, W. (1986). Effects of vegetation on the emission of methane from submerged paddy soil. *Plant and Soil*, *92*(2), 223–233.

Hou, A. X., Chen, G. X., Wang, Z. P., Van Cleemput, O., & Patrick, W. H. (2000). Methane and nitrous oxide emissions from a rice field in relation to soil redox and microbiological processes. *Soil Science Society of America Journal*, *64*(6), 2180–2186.

Inglett, P. W., Reddy, K. R., & Corstanje, R. (2004). Anaerobic Soils. *Encyclopedia of Soils in the Environment*, *4*(September 2018), 72–78. https://doi.org/10.1016/B0-12-348530-4/00178-8

IPCC. (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assess- ment Report of the Intergovernmental Panel on Climate Change*. (A. (eds. . Core Writing Team, Pachauri, R.K and Reisinger, Ed.). Geneva, Switserland. https://doi.org/10.1038/446727a

IPCC. (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. (V. B. and P. M. M. (eds. . Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, Ed.). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

IPCC. (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. (R. K. P. and L. A. M. (eds.)]. [Core Writing Team, Ed.). Geneva, Switserland. https://doi.org/10.1016/S0022-0248(00)00575-3

Iqbal, A. (2016). Genetic estimates and diversity study in Sesame(Sesamum indicum L.). *IOSR Journal of Agriculture and Veterinary Science*, *09*(08), 01–05. https://doi.org/10.9790/2380-0908010105

Islam, F., Gill, R. A., Ali, B., Farooq, M. A., Xu, L., Najeeb, U., & Zhou, W. (2016). Sesame. In S. K. Gupta (Ed.), *Breeding Oilseed Crops for Sustainable Production* (pp. 135–147). San Diego: Academic Press. https://doi.org/https://doi.org/10.1016/B978-0-12-801309-0.00006-9

Jäckel, U., & Schnell, S. (2000). Suppression of methane emission from rice paddies by ferric iron fertilization. *Soil Biology and Biochemistry*, *32*(11–12), 1811–1814. https://doi.org/10.1016/S0038-0717(00)00094-8

Janz, B., Weller, S., Kraus, D., Racela, H. S., Wassmann, R., Butterbach-Bahl, K., & Kiese, R. (2019). Greenhouse gas footprint of diversifying rice cropping systems: Impacts of water regime and organic amendments. *Agriculture, Ecosystems and Environment*, *270–271*(June 2018), 41–54. https://doi.org/10.1016/j.agee.2018.10.011

Jeong, S. T., Kim, G. W., Hwang, H. Y., Kim, P. J., & Kim, S. Y. (2018). Beneficial effect of compost utilization on reducing greenhouse gas emissions in a rice cultivation system through the overall management chain. *Science of the Total Environment*, *613–614*, 115–122. https://doi.org/10.1016/j.scitotenv.2017.09.001

Joosten, H., & Clarke, D. (2002). *Wise use of mires and peatlands: background and principles including a framework for decision-making*. International Mire Conservation Group.

Karakurt, I., Aydin, G., & Aydiner, K. (2012). Sources and mitigation of methane emissions by sectors: A critical review. *Renewable Energy*, *39*(1), 40–48. https://doi.org/10.1016/j.renene.2011.09.006

Kimura, M., Murase, J., & Lu, Y. (2004). Carbon cycling in rice field ecosystems in the context of input, decomposition and translocation of organic materials and the fates of their end products (CO2 and CH4). *Soil Biology and Biochemistry*, *36*(9), 1399–1416. https://doi.org/10.1016/j.soilbio.2004.03.006

Kögel-Knabner, I., Amelung, W., Cao, Z., Fiedler, S., Frenzel, P., Jahn, R., … Schloter, M. (2010). Biogeochemistry of paddy soils. *Geoderma*, *157*(1–2), 1–14.

Kontgis, C., Schneider, A., Ozdogan, M., Kucharik, C., Tri, V. P. D., Duc, N. H., & Schatz, J. (2019). Climate change impacts on rice productivity in the Mekong River Delta. *Applied Geography*, *102*(April 2017), 71–83. https://doi.org/10.1016/j.apgeog.2018.12.004

Kuzyakov, Y. (2006). Sources of CO2 efflux from soil and review of partitioning methods. *Soil Biology and Biochemistry*, *38*(3), 425–448. https://doi.org/10.1016/j.soilbio.2005.08.020

Langham, D. R. (2007). Phenology of Sesame. *Issues in New Crops and New Uses, Janick & Whipkey, Eds., ASHS Press, Alexandria, VA*, 144–182.

Langham, D. R. (2008). Growth and development of sesame. *Sesaco Corp*, *329*.

Le, C. B. T. (2018). Agricultural restructuring in Vietnamese Mekong Delta: Economic analysis of rotational sesame production on rice field among small-scale farmers. *International Journal of Environment, Agriculture and Biotechnology (IJEAB)*, (4), 1348–1352. https://doi.org/10.22161/ijeab/3.4.28

Li, X., Liu, J. P., Saito, Y., & Nguyen, V. L. (2017). Recent evolution of the Mekong Delta and the impacts of dams. *Earth-Science Reviews*, *175*(March), 1–17. https://doi.org/10.1016/j.earscirev.2017.10.008

Liesack, W., Schnell, S., & Revsbech, N. P. (2000). Microbiology of flooded rice paddies. *FEMS Microbiology Reviews*, *24*(5), 625–645. https://doi.org/10.1016/S0168-6445(00)00050-4

Lima, A. C. R., Pauletto, E. A., Libardi, P. L., Silva, A. G., & Pinto, L. F. S. (2002). Hydraulic characterization of a lowland soil under long-term management systems. *Sustainable Land Management-Environmental Protection. A Soil Physical Approach. Advances in GeoEcology*, *35*, 247–257.

Linh, T. (2016). *Soil-improving cropping systems for sustainable rice production in the vietnamese Mekong Delta*. Ghent University.

Linh, T., Sleutel, S., Elsacker, S. V, Guong, V. T., Khoa, L. V, & Cornelis, W. M. (2015). Inclusion of upland crops in rice-based rotations affects chemical properties of clay soil. *Soil Use and Management*, *31*(2), 313–320.

Linh, T., Sleutel, S., Thi, G. V., Le Van, K., & Cornelis, W. M. (2015). Deeper tillage and root growth in annual rice-upland cropping systems result in improved rice yield and economic profit relative to rice monoculture. *Soil and Tillage Research*, *154*, 44–52.

Linquist, B., Van Groenigen, K. J., Adviento-Borbe, M. A., Pittelkow, C., & Van Kessel, C. (2012). An agronomic assessment of greenhouse gas emissions from major cereal crops. *Global Change Biology*, *18*(1), 194–209.

Liu, Y., Yang, M., Wu, Y., Wang, H., Chen, Y., & Wu, W. (2011). Reducing CH 4 and CO 2 emissions from waterlogged paddy soil with biochar. *Journal of Soils and Sediments*, *11*(6), 930–939.

Lovley, D. R., & Phillips, E. J. (1987). Competitive mechanisms for inhibition of sulfate reduction and methane production in the zone of ferric iron reduction in sediments. *Applied and Environmental Microbiology*, *53*(11), 2636–2641. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/16347483%0Ahttp://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC204165

Lu, X. X., & Siew, R. Y. (2006). Water discharge and sediment flux changes over the past decades in the Lower Mekong River: possible impacts of the Chinese dams. *Hydrology and Earth System Sciences Discussions, European Geosciences Union*, *10*(2), 181–195. https://doi.org/ffhal-00304834f

Ma, Y. C., Kong, X. W., Yang, B., Zhang, X. L., Yan, X. Y., Yang, J. C., & Xiong, Z. Q. (2013). Net global warming potential and greenhouse gas intensity of annual rice-wheat rotations with integrated soil-crop system management. *Agriculture, Ecosystems and Environment*, *164*, 209–219. https://doi.org/10.1016/j.agee.2012.11.003

Mahapatra, I. C., Behera, U. K., & others. (2011). Rice (Oryza sativa)-based farming systems for livelihood improvement of Indian farmers. *Indian Journal of Agronomy*, *56*(1), 1–19.

Maljanen, M., Sigurdsson, B. D., Gu\dhmundsson, J., Óskarsson, H., Huttunen, J. T., &

Martikainen, P. J. (2010). Greenhouse gas balances of managed peatlands in the Nordic countries--present knowledge and gaps. *Biogeosciences*, *7*(9), 2711–2738.

Mandal, K. G., Kannan, K., Thakur, A. K., Kundu, D. K., Brahmanand, P. S., & Kumar, A. (2014). Performance of rice systems, irrigation and organic carbon storage. *Cereal Research Communications*, *42*(2), 346–358.

Minami, K. (1995). The effect of nitrogen fertilizer use and other practices on methane emission from flooded rice. *Fertilizer Research*, *40*(1), 71–84.

Minh, L. Q., Tuong, T. P., Van Mensvoort, M. E. F., & Bouma, J. (1997). Contamination of surface water as affected by land use in acid sulfate soils in the Mekong River Delta, Vietnam. *Agriculture, Ecosystems and Environment*, *61*(1), 19–27. https://doi.org/10.1016/S0167-8809(96)01084-5

Moormann, F. R., Breemen, N. van, & others. (1978). Rice: soil, water, land. *Rice: Soil, Water, Land.*

Moridis, G. J., & Alagcan, M. (1992). High Frequency Basin Irrigation Design for Upland Crops in Rice Lands. *Journal of Irrigation and Drainage Engineering*, *118*(4), 564–583.

Motschenbacher, J., Brye, K. R., & Anders, M. M. (2011). Long-term rice-based cropping system effects on near-surface soil compaction. *Agricultural Sciences*, *2*(02), 117.

Mousavi, S. F., Yousefi-Moghadam, S., Mostafazadeh-Fard, B., Hemmat, A., & Yazdani, M. R. (2009). Effect of puddling intensity on physical properties of a silty clay soil under laboratory and field conditions. *Paddy and Water Environment*, *7*(1), 45–54.

Nawaz, A., & Farooq, M. (2017). Rice Physiology. In Bhagirath S Chauhan, K. Jabran, & G. Mahajan (Eds.), *Rice Production Worldwide* (pp. 455–485). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-47516-5_17

Neue, H. U., Wassmann, R., Lantin, R. S., Alberto, M. C. R., Aduna, J. B., & Javellana, A. M. (1996). Factors affecting methane emission from rice fields. *Atmospheric Environment*, *30*(10–11), 1751–1754.

Nishimura, S., Yonemura, S., Sawamoto, T., Shirato, Y., Akiyama, H., Sudo, S., & Yagi, K. (2008). Effect of land use change from paddy rice cultivation to upland crop cultivation on soil carbon budget of a cropland in Japan. *Agriculture, Ecosystems & Environment*, *125*(1–4), 9–20.

Oertel, C., Matschullat, J., Zurba, K., Zimmermann, F., & Erasmi, S. (2016). Greenhouse gas emissions from soils—A review. *Chemie Der Erde - Geochemistry*, *76*(3), 327–352. https://doi.org/10.1016/j.chemer.2016.04.002

Pacey, J. G., & DeGier, J. P. (1986). The factors influencing landfill gas production. In *Energy from landfill gas. Proceeding of a conference jointly sponsored by the United Kingdom Department of Energy and the United States Department of Energy (October 1986)* (pp. 51–59).

Pandey, A., Vu, D. Q., Bui, T. P. L., Mai, T. L. A., Jensen, L. S., de Neergaard, A., & others. (2014). Organic matter and water management strategies to reduce methane and nitrous oxide emissions from rice paddies in Vietnam. *Agriculture, Ecosystems & Environment*, *196*, 137–146.

Ponnamperuma, F. N. (1972). The chemistry of submerged soils, *24*, 29–96.

Renaud, F. G., & Kuenzer, C. (2012). *The Mekong Delta system: Interdisciplinary analyses of a river delta*. Springer Science & Business Media.

Roser, H. R. and M. (2019). CO_2 and Greenhouse Gas Emissions. *Our World in Data*. Retrieved from https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

Sahrawat, K. L. (2005). Fertility and organic matter in submerged rice soils. *Current Science*, *88*(5), 735–739. Retrieved from http://www.jstor.org/stable/24111259

Sanchez, P. A. (2019). Soil management in rice cultivation. In *Properties and management of soils in the tropics* (pp. 492–543). Cambridge: Cambridge University Press.

Serrano-Silva, N., Sarria-Guzmán, Y., Dendooven, L., & Luna-Guido, M. (2014). Methanogenesis and Methanotrophy in Soil: A Review. *Pedosphere*, *24*(3), 291–307. https://doi.org/10.1016/S1002-0160(14)60016-3

Sheehy, J. E., Mitchell, P. L., & Hardy, B. (2007). *Charting new pathways to C4 rice*. Int. Rice Res. Inst.

Shine, K. P., Derwent, R. G., Wuebbles, D. J., & Morcrette, J. J. (1990). Radiative Forcing of Climate. Climate Change-The IPCC Scientific Assessment. JT Houghton, GJ Jenkins and JJ Ephraums. Cambridge Cambridge University Press.

Smith, K. A. (1980). A model of the extent of anaerobic zones in aggregated soils, and its potential application to estimates of denitrification. *Journal of Soil Science*, *31*(2), 263–277.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., … others. (2007). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1492), 789–813.

Southern region plans to grow other crops on low-yield rice fields. (2019). Retrieved May 16, 2019, from https://vietnamnews.vn/

Thangarajan, R., Bolan, N. S., Tian, G., Naidu, R., & Kunhikrishnan, A. (2013). Role of organic amendment application on greenhouse gas emission from soil. *Science of the Total Environment*, *465*, 72–96.

Timsina, J., & Connor, D. J. (2001). Productivity and management of rice--wheat cropping systems: issues and challenges. *Field Crops Research*, *69*(2), 93–132.

Timsina, J., Jat, M. L., & Majumdar, K. (2010). Rice-maize systems of South Asia: current status, future prospects and research priorities for nutrient management. *Plant and Soil*, *335*(1–2), 65–82.

Van Bodegom, P. M., Scholten, J. C. M., & Stams, A. J. M. (2004). Direct inhibition of methanogenesis by ferric iron. *FEMS Microbiology Ecology*, *49*(2), 261–268. https://doi.org/10.1016/j.femsec.2004.03.017

Van Nguyen, N., & Ferrero, A. (2006). Meeting the challenges of global rice production. *Paddy and Water Environment*, *4*(1), 1–9. https://doi.org/10.1007/s10333-005-0031-5

Wacal, C., Ogata, N., Sasagawa, D., Handa, T., Basalirwa, D., Acidri, R., … Nishihara, E. (2019). Seed yield, crude protein and mineral nutrient contents of sesame during a two-year continuous cropping on upland field converted from a paddy. *Field Crops Research*, *240*(June), 125–133. https://doi.org/10.1016/j.fcr.2019.06.004

Wassmann, R., Hien, N. X., Hoanh, C. T., & Tuong, T. P. (2004). Sea level rise affecting the Vietnamese Mekong Delta: Water elevation in the flood season and implications for rice production. *Climatic Change*, *66*(1–2), 89–107. https://doi.org/10.1023/B:CLIM.0000043144.69736.b7

Wassmann, R., Lantin, R. S., Neue, H. U., Buendia, L. V., Corton, T. M., & Lu, Y. (2000). Characterization of methane emissions from rice fields in Asia. III. Mitigation options and future research needs. *Nutrient Cycling in Agroecosystems*, *58*(1–3), 23–36. https://doi.org/10.1023/A:1009874014903

Weiss, E. A., & Pereira, H. C. (1983). Sesame. In *Oilseed crops*. Longman Group.

Weller, S., Janz, B., Jörg, L., Kraus, D., Racela, H. S. U., Wassmann, R., … Kiese, R. (2016). Greenhouse gas emissions and global warming potential of traditional and diversified tropical rice rotation systems. *Global Change Biology*, *22*(1), 432–448.

Weller, S., Kraus, D., Ayag, K. R. P., Wassmann, R., Alberto, M. C. R., Butterbach-Bahl, K., & Kiese, R. (2015). Methane and nitrous oxide emissions from rice and maize production in diversified rice cropping systems. *Nutrient Cycling in Agroecosystems*, *101*(1), 37–53.

Witt, C., Cassman, K. G., Olk, D. C., Biker, U., Liboon, S. P., Samson, M. I., & Ottow, J.

C. G. (2000). Crop rotation and residue management effects on carbon sequestration, nitrogen cycling and productivity of irrigated rice systems. *Plant and Soil*, *225*(1–2), 263–278.

Xu, M., Li, D.-C., Li, J.-M., Qin, D.-Z., Kazuyuki, Y., & Hosen, Y. (2008). Effects of organic manure application with chemical fertilizers on nutrient absorption and yield of rice in Hunan of Southern China. *Agricultural Sciences in China*, *7*(10), 1245–1252.

Xu, Y., Chen, W., & Shen, Q. (2007). Soil Organic Carbon and Nitrogen Pools Impacted by Long-Term Tillage and Fertilization Practices. *Communications in Soil Science and Plant Analysis*, *38*(3–4), 347–357.

Xuan, D. T., Guong, V. T., Rosling, A., Alström, S., Chai, B., & Högberg, N. (2012). Different crop rotation systems as drivers of change in soil bacterial community structure and yield of rice, Oryza sativa. *Biology and Fertility of Soils*, *48*(2), 217–225. https://doi.org/10.1007/s00374-011-0618-5

Yagi, K., Tsuruta, H., & Minami, K. (1997). Possible options for mitigating methane emission from rice cultivation. *Nutrient Cycling in Agroecosystems*, *49*(1–3), 213–220.

Yao, H., Conrad, R., Wassmann, R., & Neue, H. U. (1999). Effect of soil characteristics on sequential reduction and methane production in sixteen rice paddy soils from China, the Philippines, and Italy. *Biogeochemistry*, *47*(3), 269–295.

Yoshida, S. (1981). Fundamentals of rice crop science. International Rice Research Institute, 135–147.

Zain, N. A., Mohd, Ismail, M. R., Puteh, A., Mahmood, M., & Islam, M. R. (2014). Impact of cyclic water stress on growth , physiological responses and yield of rice (Oryza sativa L .) grown in tropical environment Impacto do estresse hídrico cíclico sobre o crescimento , as respostas fi siológicas e ABSTRACT. *Ciência Rural*, *44*(12), 2136–2141.

Zeikus, J. G., & Winfrey, M. R. (1976). Temperature limitation of methanogenesis in aquatic sediments. *Appl. Environ. Microbiol.*, *31*(1), 99–107.

Zhang, C., Ge, Y., Yao, H., Chen, X., & Hu, M. (2012). Iron oxidation-reduction and its impacts on cadmium bioavailability in paddy soils : a review, *6*(4), 509–517. https://doi.org/10.1007/s11783-012-0394-y

Zou, J., Huang, Y., Jiang, J., Zheng, X., & Sass, R. L. (2005). A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: Effects of water regime, crop residue, and fertilizer application. *Global Biogeochemical Cycles*, *19*(2).

APPENDICES

5. APPENDIX A

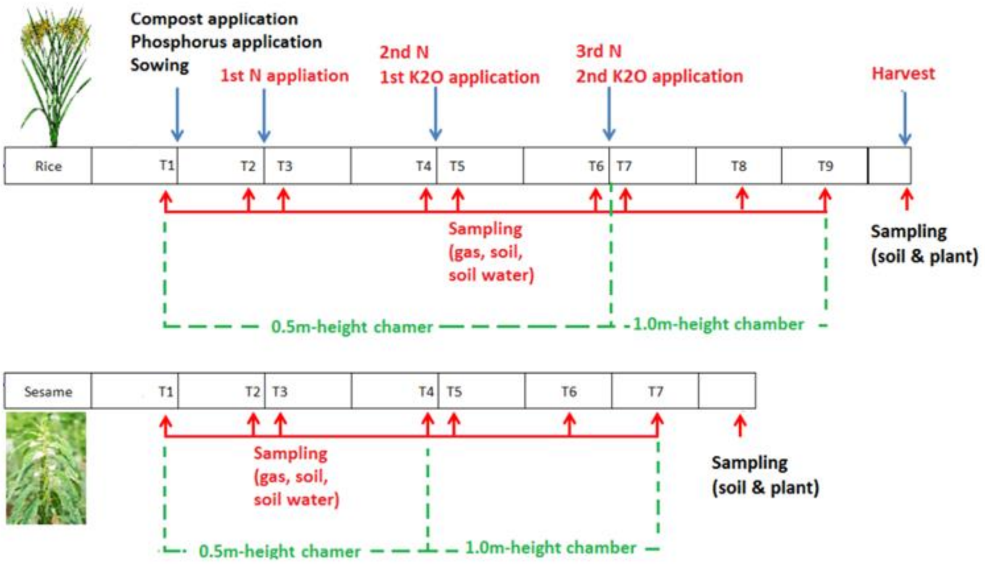

Fig. A.1 *Sampling schedule for the Spring-Summer season.*

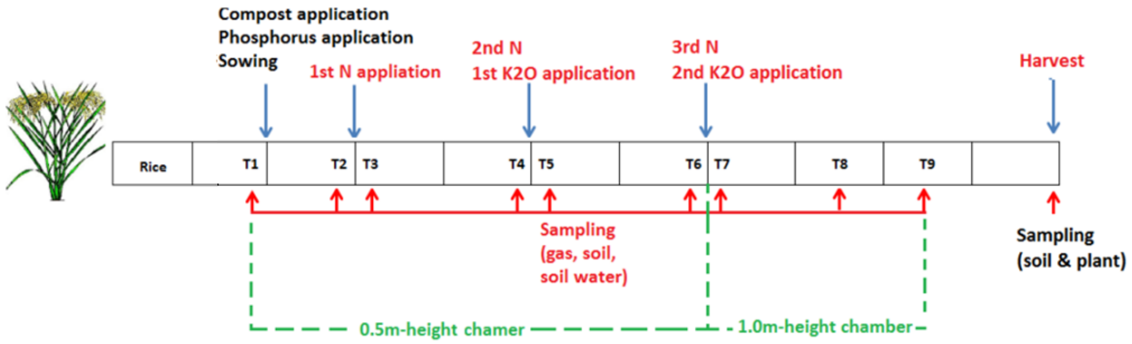

Fig. A.2 *Sampling schedule for the Summer-Autumn season.*

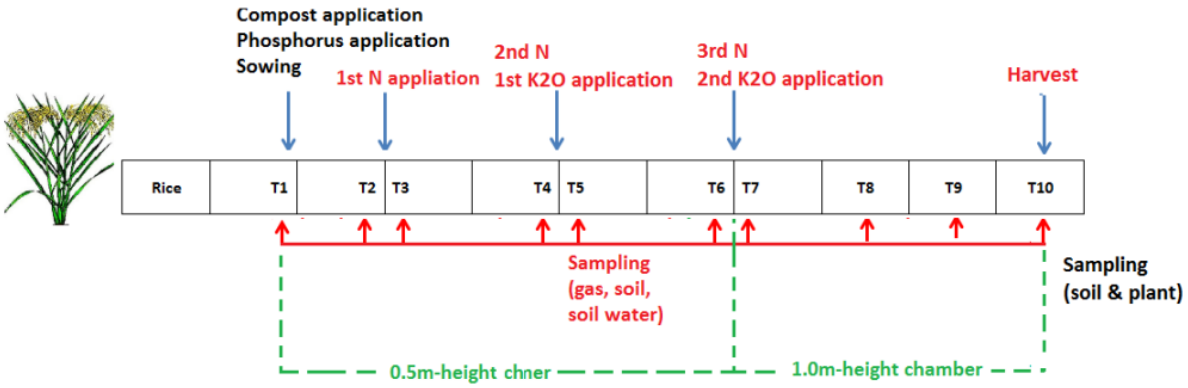

Fig. A.3 *Sampling schedule for the Autumn-Winter season.*

6. APPENDIX B

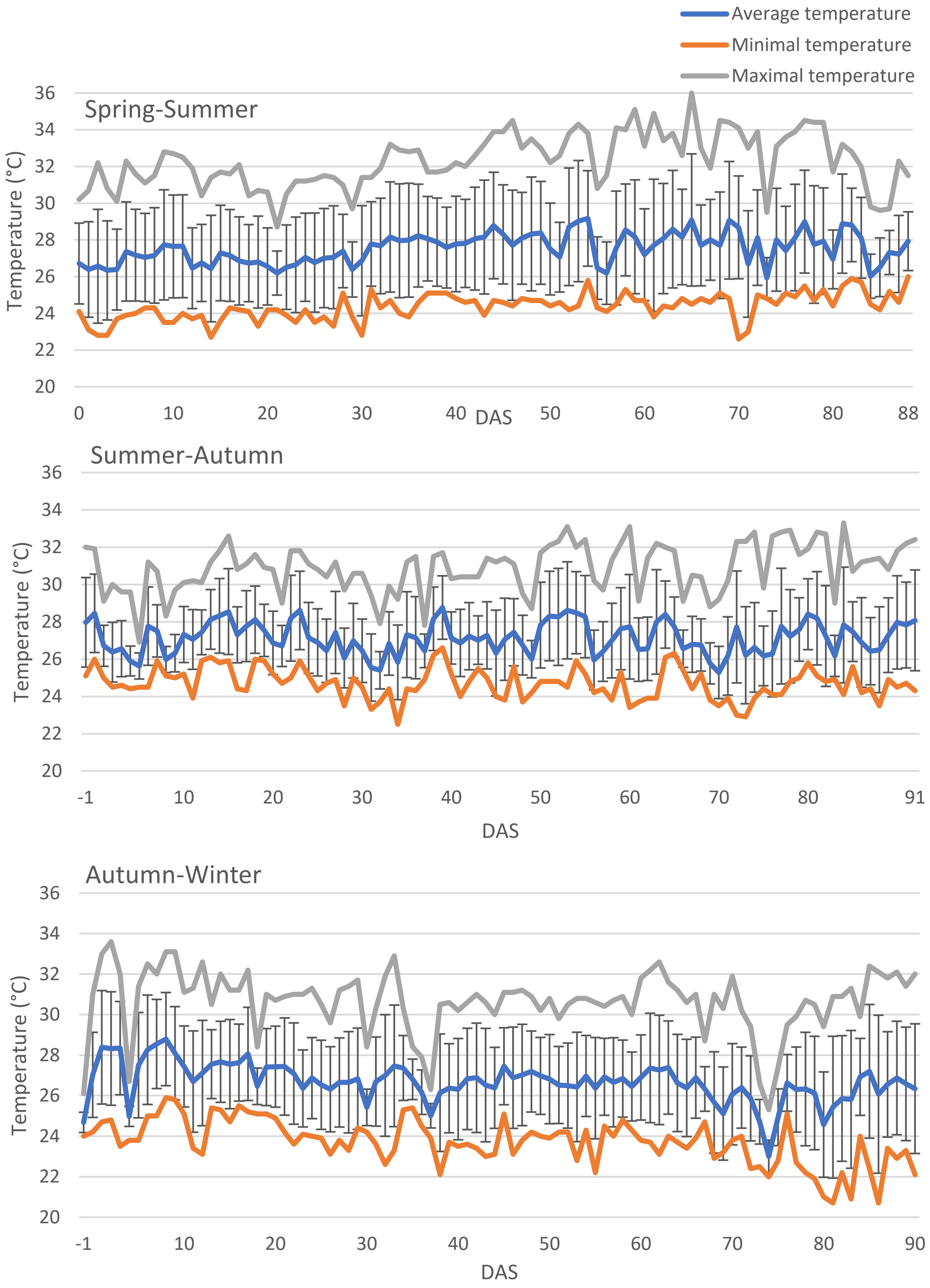

***Fig. B** Average daily air temperature, minimum daily air temperature and maximum daily air temperature at the experimental site during cultivation period in the Spring-Summer, Summer-Autumn and Autumn-Winter season.*

7. APPENDIX C

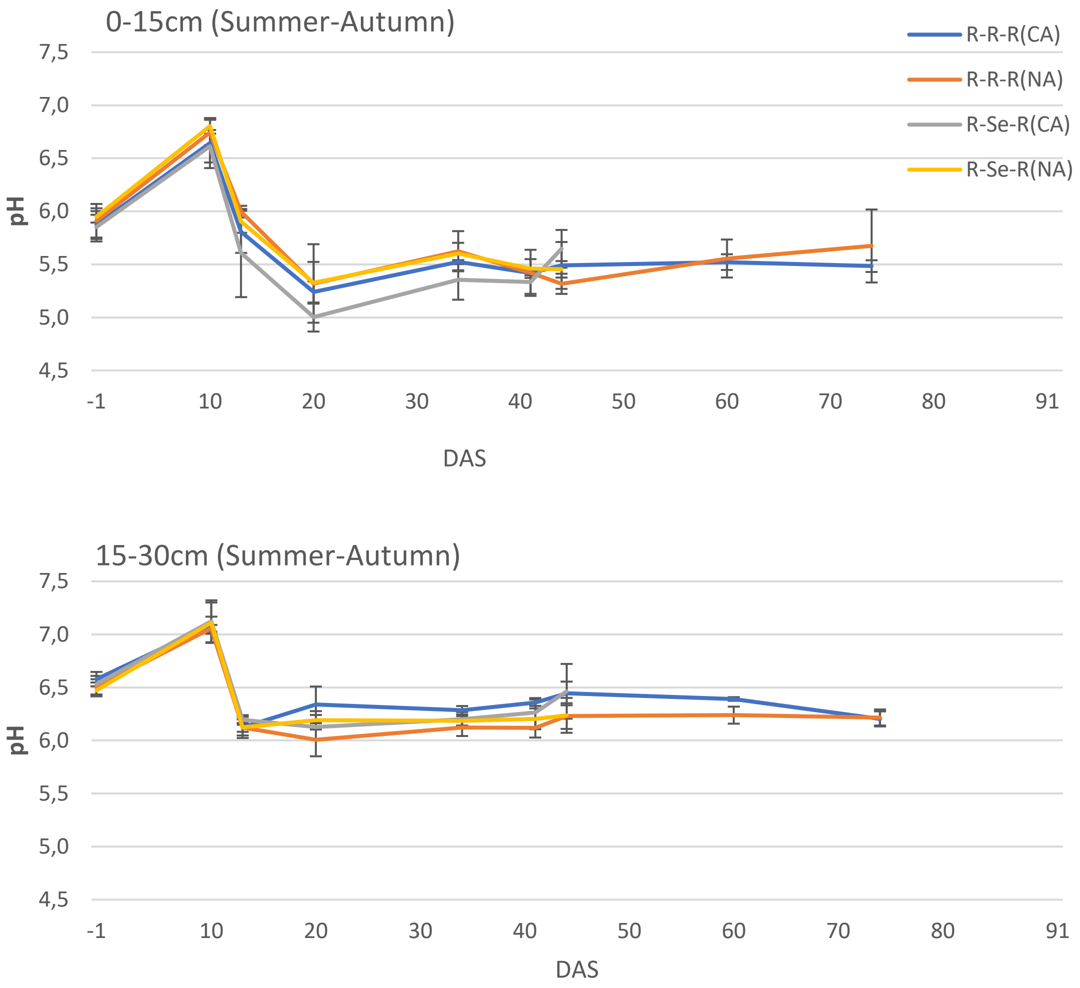

Fig. C.1 *Evolution of the soil pH under different cropping and OM amendment treatments in the Summer-Autumn season in the upper soil layer (0-15cm depth) and lower soil layer (15-30 cm depth).*

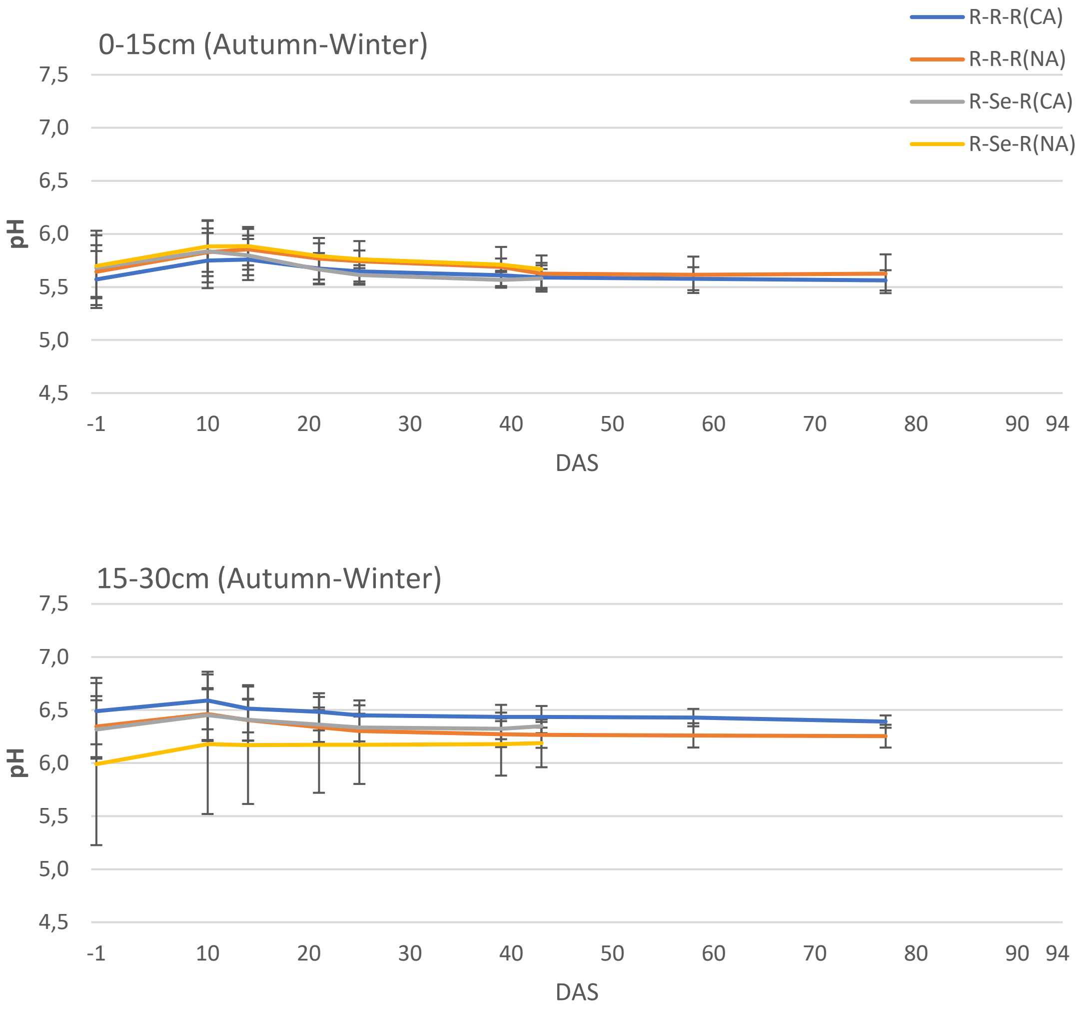

***Fig. C.2** Evolution of the soil pH under different cropping and OM amendment treatments in the Autumn-Winter season in the upper soil layer (0-15cm depth) and lower soil layer (15-30 cm depth).*

8. APPENDIX D

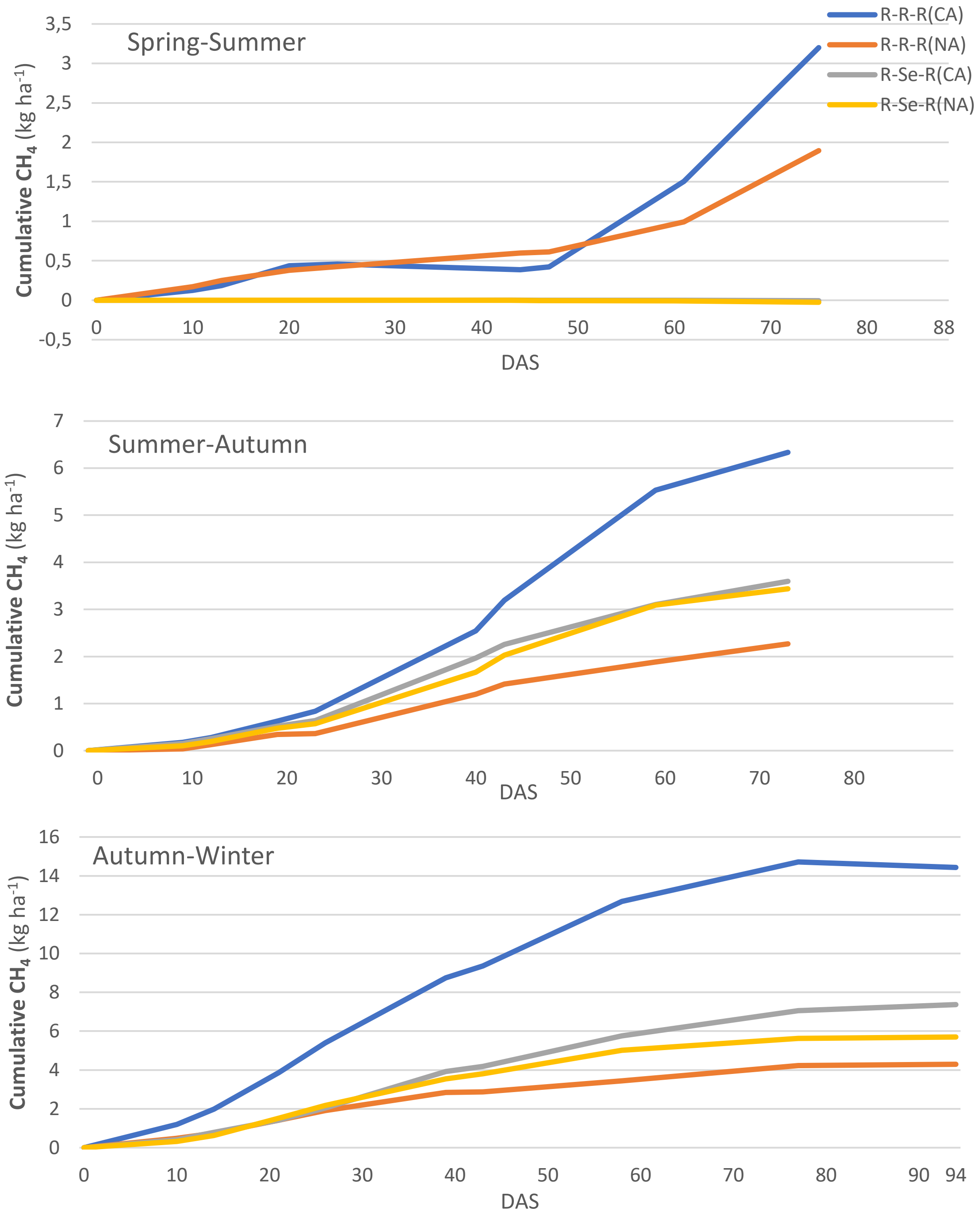

***Fig. D1** Evolution of the cumulative CH_4 emission under different cropping and OM amendment treatments in the Spring-Summer, Summer-Autumn and Autumn-Winter season.* Note that the Y-axis scales are different for each graph, in order to facilitate comparison of treatments.

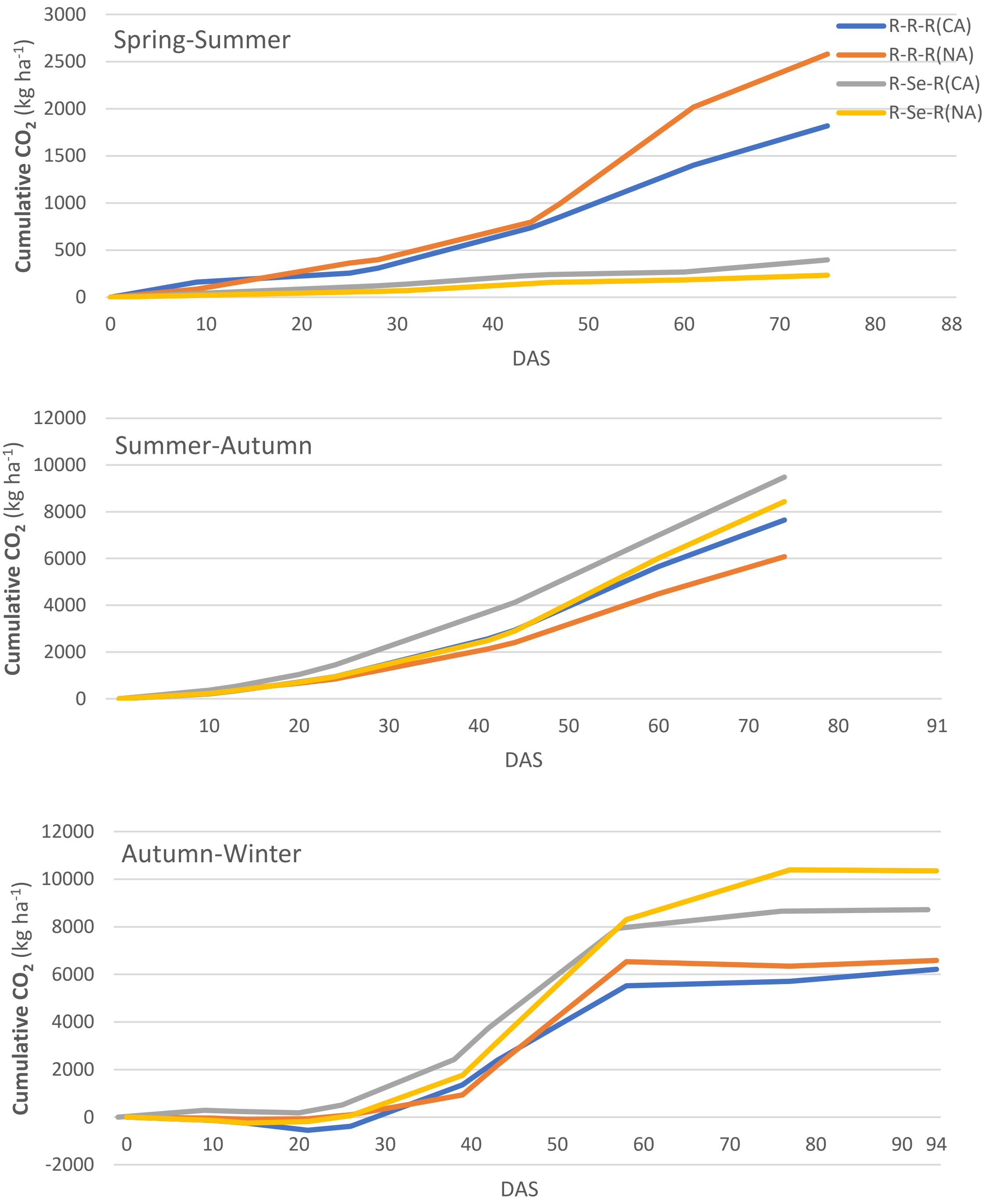

Fig. D2 *Evolution of the cumulative CO_2 emission under different cropping and OM amendment treatments in the Spring-Summer, Summer-Autumn and Autumn-Winter season. (DAS = days after sowing.)* Note that the Y-axis scales are different for each graph, in order to facilitate comparison of treatments.

9. APPENDIX E

Table E *Global warming potential (GWP) of 100 years from CH$_4$, CO$_2$ and total carbon based emissions (kg CO$_2$-equivalents ha^{-1}) and the relative share of CH$_4$ and CO$_2$ in the total carbon based emissions from the rice paddy soil under different treatments in three subsequent seasons. The used IPCC GWP factors in the 100 year time horizon are 28 for CH$_4$ and 1 for CO$_2$.*

	Spring-Summer			**Summer-Autumn**			**Autumn-Winter**		
Treatment	**CH$_4$** (kg CO$_2$-eq. ha^{-1})	**CO$_2$** (kg CO$_2$ ha^{-1})	**Total** (kg CO$_2$-eq. ha^{-1})	**CH$_4$** (kg CO$_2$-eq. ha^{-1})	**CO$_2$** (kg CO$_2$ ha^{-1})	**Total** (kg CO$_2$-eq. ha^{-1})	**CH$_4$** (kg CO$_2$-eq. ha^{-1})	**CO$_2$** (kg CO$_2$ ha^{-1})	**Total** (kg CO$_2$-eq. ha^{-1})
R-R-R (CA)	90	1818	1907	177	7647	7824	404	6213	6617
	4,70%	95,30%		2,27%	97,73%		6,11%	93,89%	
R-R-R (NA)	53	2580	2633	64	6078	6141	120	6585	6705
	2,02%	97,98%		1,03%	98,97%		1,79%	98,21%	
R-Se-R (CA)	-1	396	395	101	9482	9583	206	8718	8924
	-0,38%	100,38%		1,05%	98,95%		2,31%	97,69%	
R-Se-R (NA)	-7	233	226	96	8436	8532	160	10353	10513
	-3,15%	103,15%		1,13%	98,87%		1,52%	98,48%	