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Effect of crop residue management on soil greenhouse gas fluxes in an Austrian long-term experiment

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Declaration of Originality

In lieu of an oath, I declare that the contents of this master thesis are my own work, without any assistance from third parties.

Furthermore, I confirm that no sources have been used other than those acknowledged in the text. The formulations and thoughts taken directly or indirectly from external sources are marked as such. This paper was not previously presented to another examination board and has not been published.

Vienna, 08/08/2022 Nazerke Amangeldy *(manu propria)*

I dedicate this thesis work to Wolfgang Riegler.

The important thing is to never to stop questioning

(Albert Einstein)

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Abstract

Agriculture is the primary source of food and feed production. Greenhouse gas (GHG) emissions from agriculture, forestry, and other land uses contribute to about 25 % of the global anthropogenic GHG emissions. Specifically, agriculture is highly responsible for nitrous oxide (N_2O) and methane (CH_4) emissions. These emissions are strongly influenced by human activity; therefore, management practices play a crucial role in climate change mitigation efforts. Until now, most strategies have tried to increase the amount of soil organic carbon to reduce carbon dioxide (CO_2) in the atmosphere. One of these management strategies is the incorporation of crop residues into the soil (instead of removing them); this way has been proved to be an effective way to enhance soil organic carbon stocks through increased soil organic matter inputs. However, little is known about the effects of crop residue management practice on soil CH_4 and N_2O fluxes, which are essential for the soil GHG balance. In this context, I investigated a long-term research site, Rutzendorf, where crop residue incorporation and removal have been investigated for 40 years. Previous results showed a decrease in C stocks when crop residues are removed. We hypothesized that the incorporation of crop residues leads to an increase in soil N_2O fluxes compared to the removal of crop residues due to the larger substrate availability for microbial activities. We monitored soil CO_2, CH_4 and N_2O fluxes with manual static chambers. Measurements started in July 2021 and are still ongoing. After analysis, the results of the N_2O emissions under both crop residue incorporation and removal management practices had significant variation only during the end of fall and beginning of spring. NO_2 and CO_2 fluxes significantly changed over time compared with CH_4. It was found that crop residue incorporation induced N_2O emissions. At the same time, CO_2 fluxes had no significant difference between the crop residue incorporation and crop residue removal treatments through the investigated time range. Therefore, less evidence was found to explain the variances in CH_4 and CO_2 fluxes.

Zusammenfassung

Die Landwirtschaft ist die Hauptquelle der Nahrungs- und Futtermittelproduktion. Treibhausgasemissionen (THG) aus Land- und Forstwirtschaft und anderen Landnutzungen tragen zu etwa 25 % zu den globalen anthropogenen THG-Emissionen bei. Insbesondere die Landwirtschaft ist in hohem Maße für die Emissionen von Distickstoffoxid (N_2O) und Methan (CH_4) verantwortlich. Diese Emissionen werden stark durch menschliche Aktivitäten beeinflusst; Daher spielen Managementpraktiken eine entscheidende Rolle bei den Bemühungen zur Eindämmung des Klimawandels. Bisher haben die meisten Strategien versucht, die Menge an organischem Kohlenstoff im Boden zu erhöhen, um Kohlendioxid (CO_2) in der Atmosphäre zu reduzieren. Eine dieser Bewirtschaftungsstrategien ist die Einarbeitung von Ernterückständen in den Boden (anstatt sie zu entfernen); Dieser Weg hat sich als wirksames Mittel erwiesen, um die organischen Kohlenstoffvorräte im Boden, durch mehr organisches Material im Boden, zu erhöhen. Es ist jedoch wenig über die Auswirkungen der Praxis der Bewirtschaftung von Ernterückständen auf die CH_4- und N_2O-Flüsse im Boden bekannt, die für die THG-Bilanz des Bodens von wesentlicher Bedeutung sind. In diesem Zusammenhang habe den Langzeitforschungsstandort Rutzendorf untersucht, an dem seit 40 Jahren die Einarbeitung und Entfernung von Pflanzenresten untersucht wird. Bisherige Ergebnisse zeigen die Abnahme der C-Vorräte, wenn Ernterückstände entfernt werden. Wir stellten die Hypothese auf, dass die Einarbeitung von Ernterückständen aufgrund der größeren Verfügbarkeit von Substrat für mikrobielle Aktivitäten zu einem Anstieg der N_2O-Flüsse im Boden im Vergleich zur Entfernung von Ernterückständen führt. Wir haben die CO_2-, CH_4- und N_2O-Flüsse im Boden mit manuellen statischen Kammern überwacht. Die Messungen begannen im Juli 2021 und dauern noch an. Nach der Analyse wiesen die Ergebnisse der N_2O-Emissionen, sowohl bei der Einarbeitung von Ernterückständen als auch bei der Entfernung von Ernterückständen, nur am Ende des Herbstes und am Anfang des Frühlings, signifikante Schwankungen auf. Es wurde festgestellt, dass die Einarbeitung von Ernterückständen zu N2O-Emissionen führte. Gleichzeitig wiesen die CO2-Flüsse über den untersuchten Zeitraum keine signifikanten Unterschiede zwischen den Behandlungen zur Einarbeitung von Ernterückständen und zur Entfernung von Ernterückständen auf. Es wurden jedoch weniger Anhaltspunkte für die Erklärung der Varianzen bei den CH4- und CO2-Flüssen gefunden.

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Introduction

1.1. Greenhouse effect

The greenhouse effect, in simple words, can be described by the energy balance between the incoming radiation from the sun, **"sunlight"** (infrared, ultraviolet, and visible light) and the outgoing radiation to space from the Earth, **"earthlight"** (infrared radiation). Involved in this energy flux, there are "greenhouse gases" such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), water vapor (H_2O), and others in the Earth's atmosphere. Greenhouse gases trap infrared light outgoing to space (Figure 1), and this process is called the **"greenhouse effect"** (Wiley, 2011). Before humans, there were already greenhouse gases in the atmosphere that have kept the temperature and allowed life on earth by preventing the Earth from instant temperature drops as on Mars (Forget and Pierrehumbert 1997; MacCracken 2004).

However, current high levels of CO_2, CH_4, and N_2O in the atmosphere are unprecedented over the last 200,000 years, according to ice records (Raynaud et al. 1993). In 1976, Charles Keeling and his colleagues shared thirteen years of continuous experiment results on atmospheric carbon dioxide (CO_2) measurements ("Long-Term Global Warming Trend Continues", 2013). This research became a highly valuable proof of elevated CO_2 concentration in the atmosphere due to human impact. Similarly, in 1990, the first IPCC Assessment Report stated with confidence that the increase of CO_2 in the atmosphere due to anthropogenic activities is responsible for the greenhouse effect increase ("Climate Change: The IPCC 1990 and 1992 Assessments — IPCC", 1992). Besides, the increase in CH_4 and N_2O amounts in the atmosphere are also harmful to the climate system since these greenhouse gases have a global warming potential of 25-30 and 298, respectively (Zechmeister-Boltenstern et al. 2018).

Today, it is known that certain human activities (use of fossil fuels, agriculture, deforestation, etc.) result in emissions of greenhouse gases (Zechmeister-Boltenstern et al. 2018; "Press Release" 2022.). Ice cores also provided similar evidence for the anthropogenic impact on today's climate change as ice records contain information on the rate of greenhouse gas changes since the beginning of the industrial revolution (Raynaud et al. 1993).

The increasing amount of GHGs (CO_2, CH_4, N_2O) in the atmosphere trap and absorb more infrared radiations, resulting in Earth's temperature increase above precedent levels. Consequently, the temperature increase triggers a cascade of disturbances such as biodiversity extinction, drought, the risk of carbon sinks becoming carbon sources, an increase in fire frequencies and aridity, drastic changes in runoff, and the dieback of forests are expected under the *"business as usual"* human-induced climate change scenario (Scholze et al. 2006; "Projected Distributions of Novel and Disappearing Climates by 2100 AD" 2022), ("Soil Management and Climate Change" 2022). Alternatively, anthropogenic climate change will be reversible (1) by reducing GHG emissions, and (2) in the case of a large net removal of CO_2 from the atmosphere over a sustained period.

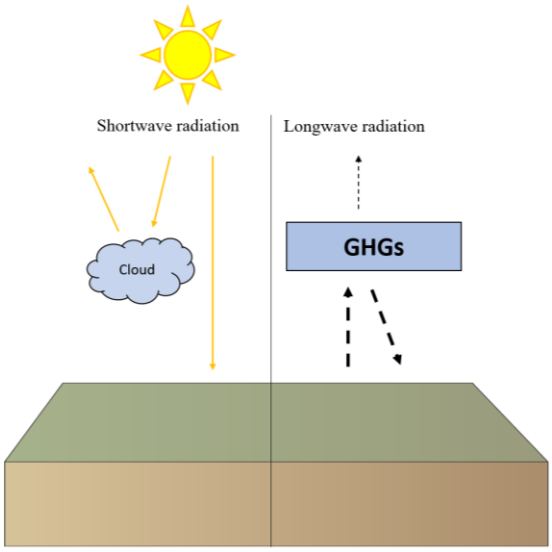


Figure 1. Schematic illustration of the greenhouse effect. A substantial part of the shortwave incoming sunlight can reach the earth surface, while the outgoing longwave radiation (from Earth to space), is reflected by the greenhouse gases back to the earth surface.

1.2. Agriculture and climate change

Holocene, which began about 11,600 B.P., was the *origin epoch* of man's knowledge and technology development ("Mid- to Late Holocene Climate Change: An Overview", 2022). Within it, the evolution of agriculture, about 1600-3600 years later, started *via* domesticating certain plant and animal species (Price and Bar-Yosef, 2011). Today, human activities are widespread globally and humans became a dominant factor altering climate (Principles of Terrestrial Ecosystem Ecology, 2022). As a result, we may have entered a new epoch – an *epoch of man* – Anthropocene (Lewis and Maslin 2015). One fact remains unchanged compared to the beginning of the Holocene: food is the main source of energy for the human body, and agriculture is the primary source of food production. However, there is a strong population growth, (according to "2022 World Population by Countr", today global population is almost 8 billion), which has triggered an increasing food demand. Further, the exposure to changes in climate are also stressing agricultural lands. For instance, an increase in temperature, and increases in extreme weather events (e.g. drought and floodings) may unproportionally affect socio-economic welfareas they may have a strong detrimental effect of crop yields. For a local Austrian farmer, it may not matter if it does not rain today or the day after, but if the farmer has several months without any precipitation, it may ruin his farming business (Wiley, 2011). The IPCC report released in 2022 clearly states that any delay of action may cost an unpayable price for humanity in the future ("Climate Change 2022: Impacts, Adaptation and Vulnerability", 2022). Also, in this report, it was noted that even today, climate change is far widespread globally, and if global warming exceeds 2°C in some parts of the world, it will be almost impossible to cope. This report of IPCC also pointed out the importance of adequate finance and political support in accelerating progress toward sustainable development to adapt to climate change ("Climate Change 2022: Impacts, Adaptation and Vulnerability", 2022).

Agriculture also contributes to the emision of greenhouse gases. FAO (FAO, 2021) describes that the agricultural sector is responsible for non-CO_2 emissions from crops and livestock activities, where CO_2 emissions are caused due to changes in agricultural land-use change . Besides, GHG global emissions due to agriculture in 2018 were 9.3 billion tonnes of CO_2 equivalent (CO_2 eq.). The contribution of CH_4 and N_2O from crop and livestock activities was 5.3 billion tons of CO_2 eq. in 2018 along, a 14% increase since 2000 (FAO 2021). Agriculture has to reduce emissions. Eventually, all of the mitigation options influence at some points the changes in the carbon and/or nitrogen cycle in agricultural soils either by reducing methane (CH_4) and/or nitrous oxide (N_2O), or by increasing carbon (C) storage smith (P. Smith and Olesen 2010). In addition, the production of fertilizers to agriculture is another very energy-intensive process (Hülsbergen et al. 2001), that is why management practices that provide soils with nutrients without relying on synthetic fertilizers (incorporation of crop residue, organic farming, etc.) are also less energy intensive (Pete Smith et al. 2016). Similarly, emissions from agriculture are strongly influenced by human activity; therefore, agricultural management practices play a crucial role in mitigation efforts toward reducing global warming.

That is why **"adaptation and mitigation"** processes are crucial to sustain and improve food production under the rapid changes in climate. Therefore, there are various mitigation and adaptation processes such as nutrient smart activities (precision nutrient application, crop residues, etc.), water smart practices (crop diversification, direct seeded rise, etc.) carbon smart activities (zero tillage, crop residue management, etc.) and so on (Malhi, Kaur, and Kaushik 2021). Until now, most mitigation efforts have tried to increase the amount of organic carbon in agricultural soils, managed ecosystems to increase soil organic carbon (SOC) stocks, to reduce CO_2 in the atmosphere (Guenet, 2021), (Rattan Lal 2008), (R. Lal 2004).

1.3. Carbon and nitrogen cycling in croplands

The definition of soil organic C sequestration given by (Olson et al. 2014) is as follows: "Process of transferring CO2 from the atmosphere into the soil of a land unit through unit plants, plant residues and other organic solids, which are stored or retained in the unit as part of the soil organic matter (humus). Retention time of sequestered carbon in the soil (terrestrial pool) can range from short-term (not immediately released back to atmosphere) to long-term (millennia) storage. The sequestrated SOC process should increase the net SOC storage during and at the end of a study to above the previous pre-treatment baseline." In general terms, increasing soil organic carbon stocks can be done by increasing C inputs and/or decreasing C outputs from the soil.

Increasing soil organic carbon stocks can be done by increasing C inputs and/or decreasing C outputs from the soil. The combination of agricultural practices together and/or practicing them separately (Gomiero, Pimentel, and Paoletti 2011) – both influence soil quality (Bending et al. 2004), (Bai et al. 2018); and as a result type and/or intensity of management practices are expected to influence SOC stocks of cropland soils as well (Tiefenbacher et al. 2021)**.** The authors of (Pete Smith et al. 2005) and (PETE SMITH 2003) mention that there exist promising common approaches for increasing carbon inputs, specifically for European croplands and soils, such as incorporation of crop residue, cultivation of cover crops (Poeplau and Don 2015), biomass conversion to recalcitrant biochar (Pete Smith et al. 2016), (Pete Smith 2016) and agroforestry (Ramachandran Nair, Mohan Kumar, and Nair 2009), (Ramachandran Nair et al. 2010). In addition to this, minimum or no-tillage protects soil from breaking down and less C will be released

(reduced mineralization) to the atmosphere and protects SOC from microbial consumption (Poeplau and Don 2015), but, as a result, there will be less mineralization of N and P, hence, (B. A. Stewart 2019) suggests that additional fertilization might prevent reduction in crop yields. Although, tillage is desirable by farmers since it breaks down aggregates and exposes SOC to soil microorganisms and provides nutrients for plant growth (B. A. Stewart 2019). For that reason, before application, benefits and limits of a certain management system must be considered (Tiefenbacher et al. 2021).

Overall, $\frac{1}{2}$ of CO_2 and $\frac{1}{3}$ of CH_4, and about 9.3 Tg N_2O-N (including indirect emissions e.g. fertilization) gross emissions (globally) are soil-related; which corresponds to about 50% of all the GWP worldwide, including oceanic systems and natural and anthropogenic terrestrial sources (Zechmeister-Boltenstern et al. 2018). Whereas agricultural sector in twenty seven EU countries are already responsible for 55 % CH_4, 80 % N_2O and 0.4 % CO2 emissions ("Eurostat - Data Explorer" 2022). On the other hand, soils are the known largest reservoir of organic carbon (OC) in the terrestrial biosphere, where at one-meter depth, 1.500 – 2.400 Pg C is stored ("AR5 Climate Change 2013: The Physical Science Basis — IPCC"), (Guenet, 2021), (Jobbágy and Jackson 2000). There is a strong interdependence between the soil C and N such as (1) both are stored in organic forms in soils and influenced during the mineralization process; (2) C/N ratio influences the microbial activity and decomposition rate; (3) mineral N transformations depend on C availability; (4) N is needed for photosynthesis processes; etc (Guenet, 2021). In addition, the large amount of soil organic C is desirable in agricultural soils due to their benefits as illustrated below (Figure 2).

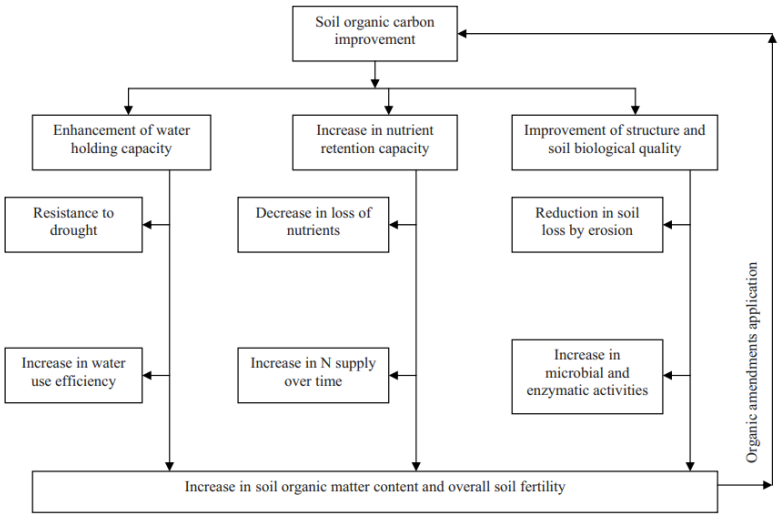


Figure 2. Effects of increasing soil organic matter content and overall soil fertility by soil organic carbon improvement (Diacono and Montemurro 2011).

Similarly, nitrogen (N) is also an essential element for plant growth in both natural and agricultural systems. That is why depletion of N, limitations of N can disrupt internal nitrogen cycle in soils and it is not favourable, especially, in agricultural soils since N plays a key role in agricultural food production and crop growth (Bouwman, Beusen, and Billen 2009). Soil microorganisms are essential for soil N processes as well as in N transformations e.g. mineralization processes carried out by soil microorganisms transforms soil organic N to soil inorganic N forms (NH_4^+ and NO_3^-)

that are good for good crop yield since they are pant available forms of N ("Soil Nitrogen Uses and Environmental Impacts" 2018). On the other hand, NH_4, NO_3 and other soil properties such as soil water content (especially WFPS), pH, high C and N contents (Charles et al. 2017), N cycling enzymes, microbial biomass content and soil temperature (Zechmeister-Boltenstern et al. 2018) also induce N_2O emissions. Also, although the amount of N required by soil microorganisms is twenty times smaller than of C (Diacono and Montemurro 2011), the authors of (Charles et al. 2017) claim that agricultural soils receiving organic amendments that contains N are contributing to N_2O emissions as a result of nitrification and denitrification processes. To be more specific, the organic inputs in agricultural soils contain both C and N which will provide source of energy and nutrients for soil microorganisms. Further, when the water content increases inducing anaerobic condition favourable for denitrifies, the N_2O formation will be optimum around 70 - 80 % WFPS since denitrification rates are stimulated by both the increasing concentration of C as energy source and N substrates (Zechmeister-Boltenstern et al. 2018). In addition, the increasing amount of soil NO_3^- due to C and N substrate availability in organic amendment soils induces N_2O emissions via increasing N_2O:N_2 ratio during denitrification (Charles et al. 2017). However, if the soil becomes fully anaerobic, denitrification process will be completed with its final product N_2. In addition, fungi are also great sources of N2O emissions as final product of fungal denitrification is N2O, whereas N_2O emitted during the nitrification process if mostly negligible (Zechmeister-Boltenstern et al. 2018).

1.4. Climate change mitigation in agriculture

There are significant differences within the countries and continents on their mitigation potential, costs, and applicability. That is why GHGs can be reduced by applying mitigation options and adapting them to local environments. For instance, IPCC (2014) report highlighted the importance of adapting agricultural practices and listed several practices that reduce major GHGs (CO_2, CH_4, and N_2O) and increase C pools in agricultural sector (Pete Smith et al., n.d.). Although, the trade-offs of the certain agricultural management practices should be considered before its adoption (Tiefenbacher et al. 2021).

The "four-per-thousand", proposed by the French Minister of Agriculture at the UN Climate Change Conference (COP21), which aims to reduce atmospheric CO_2 amount via increasing SOC stocks by 0.4% (or 4‰) per year through optimized land and soil management in agricultural soils, (https://4p1000.org/) (Tiefenbacher et al. 2021). Consequently, it would result in a C sequestration potential of 2-3 Pg C per annum (Budiman Minasny 2017), and benefit agricultural soils with positive feedbacks via increasing soil organic matter content (Sophia Hendricks 2020).

Biochar

One of the main influences for biochar application and the use in the context of C sequestration was the Terra Preta, very fertile soils as a result of continuous use of biochar, found in Amazon (Bezerra et al. 2019). Biochar consists of a high proportion of extremely stable C (Bezerra et al. 2019), that is why high recalcitrance of biochar can be a long-term sink of C in soils (Tiefenbacher et al. 2021). The method to make biochar is called "pyrolysis"; where the biomass is decomposed thermally in the absence of oxygen to liquid, gas and solid (charcoal or biochar) biofuels. Thus the biochar is applied to soils instead of being used as a source of energy (Graber et al. 2010). Although, according to (Spokas et al. 2012), there are short-term positive (50 %), neutral (30 %) and some negative (20 %) yield growth impacts. In general, the recalcitrant nature of biochar needs to be studied in the long-term (Tiefenbacher et al. 2021).

Agroforestry

The World Agroforestry Centre describes agroforestry as “a dynamic, ecologically based, natural resources management system that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic and environmental benefits for land users at all levels.” (Ramachandran Nair, Mohan Kumar, and Nair 2009). The SOC sequestration potential of agroforestry is still under debate, with an ongoing debate about the mean C sequestration rate of agroforestry which was assumed to be about 727 $\pm$ 100 kg C per ha per year in (sub)tropical and temperate regions (Tiefenbacher et al. 2021).

Organic farming

The European Union (EU) defines organic farming as follows: organic farming is an agricultural practice that aims to produce food using natural processes and substances (“Organics at a Glance” 2022). There exist agricultural practices such as diverse crop rotation, residue incorporation, usage of organic fertilizers which encourages maintenance of biodiversity, enhancement of soil fertility, responsible use of energy and natural resources, maintenance of water quality and preservation of local ecological balances (“Organics at a Glance” 2022), (Tiefenbacher et al. 2021). In addition, organic farming can sequester more C compared with conventional farming (Tiefenbacher et al. 2021), (Freibauer et al. 2004). In 2000’s Europe had about only 2 % (total area) of agricultural land under certified organic production (Freibauer et al. 2004). Although, the European Green Deal (EGD) pointed out that organic farming area needs to be increased in Europe, and EGD sees organic farming as one of the alternatives for tackling climate and environmental-related challenges (The European Green Deal 2019). Austria has a great share of organic farming (25% in 2022) (Surböck et al. 2022), (“IFOAMEU” 2022). To achieve more sustainable development in the future, increased SOC amount and GHG emissions should be compared under the organic farming (Tiefenbacher et al. 2021). Therefore, there is a need for knowledge and practical experiences in organic farming (Surböck et al. 2022).

Crop residue management

The crop biomass that remains after the harvest is known as crop residue, and these residues are considered a great source of SOM in agricultural soils (Turmel et al. 2015). Incorporation of crop residues to the soil help to prevent soil erosion, reduce surface soil evaporation, enhance water retention/filtration, improve soil structure, provide nutrients and increase SOM (Searle and Bitnere, n.d.). The SOC sequestration via crop residue incorporation is important for both (1) reducing atmospheric CO_2 to mitigate climate change (2) contributing to healthy soil (Searle and Bitnere, n.d.). That is why the incorporation of crop residues into the soil (instead of removing them) is one of the alternatives among different management strategies aiming towards sustainable development through increasing soil organic matter inputs and protecting soils from erosion (Sophia Hendricks 2020). However, according to meta-analysis of twenty one laboratory studies and seven field studies, amendments of crop residue alters substantially availability of soil NH_4^+ and NO_3^- – N that are the major factors controlling , respectively, nitrification and denitrification, and therefore soil N_2O emissions (Chen et al. 2013). Moreover, larger SOC sources are favoured for denitrification processes as a source of energy and as an electron acceptor source for NO_3^-. On the other hand, another meta-analysis (n = 122) concluded that there is no significant impact of crop residue incorporation on N_2O flux (Shan and Yan 2013). However, observation of soil N_2O emissions under crop residue incorporation management system over long-term periods is essential to promote C sequestration *via* this practice as a mitigation

agricultural practice, as well as providing general knowledge about the trade-offs of this management practice. That is why GHG measurements in long-term field experiment (LTFE) are essential to more accurately calculate trade-offs between GHG (CH_4, N_2O) and SOC balance under crop residue incorporation (Lehtinen et al. 2014), (Chen et al. 2013). In this context, a long-term research site, Rutzendorf, was investigated to track the non-CO_2 (N_2O, CH_4) GHG fluxes and their influences under the crop residue incorporation management, where crop residue incorporation and removal have been investigated for 40 years. Additionally, previous LTFE results show increased soil organic C stocks when residues are incorporated compared to when crop residues were removed (De Jong 2021).

Research Objectives:

The research objective of this work is to investigate the soil greenhouse gas fluxes (CO_2, N_2O and CH_4) under the long-term crop residue incorporation and removal of crop residue treatments. Also, to observe N_2O and CH_4 fluxes under the crop residue incorporation since this treatment has more SOC stocks relative to removal of crop residue. Crop residue incorporation maintains SOC stocks compared to removal of crop residue (Spiegel et al. 2018).

Research hypotheses:

It is expected that crop residue incorporation might result in higher N_2O fluxes compared to the removal of crop residues. Incorporation of crop residues increase SOM and result in better soil properties (Turmel et al. 2015), also crop residues increase amount of elements such as C and/or N, where an increase of SOC and N contents in soils may induce larger N_2O emissions compared to removal of crop residue. In addition, the final product of organic C decomposition under anaerobic conditions is CH_4. The methanogens convert the simple compounds such as CO_2, H_2 or acetate to CH_4. However, the increase in SOC content is assumably cannot disrupt CH_4 sink since the methanotrophs and ammonia oxidizers obtain energy and C directly from CH_4 that is being emitted, whereas aerated arable lands have unfavourable conditions for methanogens that release CH_4 into the atmosphere (Zechmeister-Boltenstern et al. 2018), (Conrad 2007).

To investigate N_2O fluxes under the crop residue incorporation management, the following research hypotheses were developed:

1. The incorporation of crop residues leads to an increase in soil N_2O fluxes compared to the removal of crop residues (due to larger C contents under the crop residue incorporation management that provides more substrate and energy sources for microbes that leads in higher decomposition rate during aerobic and anaerobic conditions (De Jong 2021)).
2. Soil CH_4 flux is not influenced by incorporation of crop residue managements.

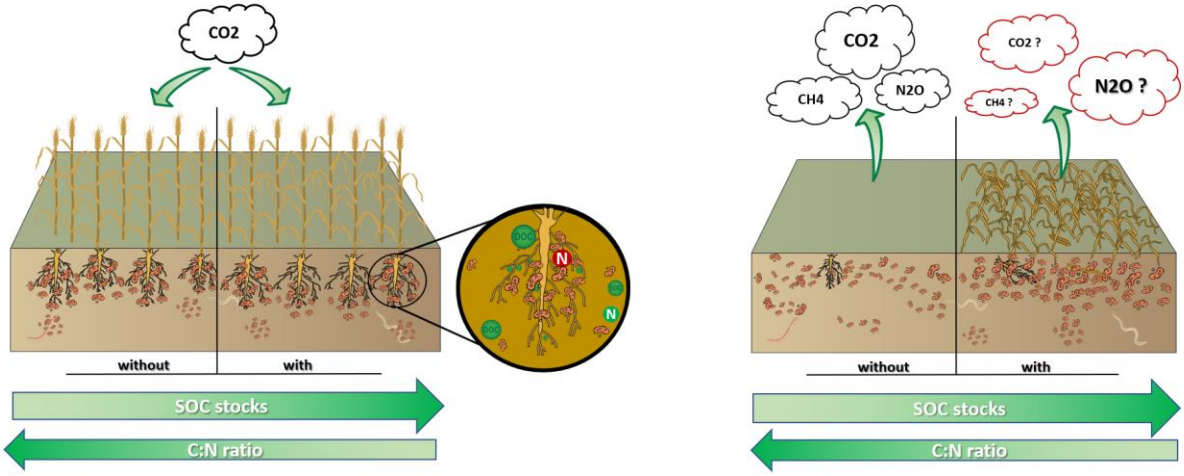


Figure 3. Illustration of the research hypotheses. On the left panel, carbon uptake via photosynthesis is illustrated. Plants store C via photosynthesis in their roots and shoots. Later, these plants will be used as crop residue under the crop residue incorporation management (illustrated on the right side of the panel), and at Rutzendorf, this process is being repeated since 1982 (De Jong 2021).

Methodology

2.1. Study area

Marchfeld region is located in Lower Austria, east of Vienna. The region, flat, is dominated by soils built on calcareous fine sediments that were deposited from the Danube. The region is influenced by Pannonian climate with hot and dry summers and cold winters, and strong winds are common (Dieterich et al. 2014).

To test the above-mentioned hypotheses, the research was carried out in a long-term experimental site, Rutzendorf. The coordinates are 48°13'N 16°37'E, with an altitude of 151 m above sea level (De Jong 2021). Starting from 1982, the area was used for research purposes. According to Philipp de Jong (2021), records of management history before the implementation are missing The soil is a Calcaric Phaeozem (WRB ("World Reference Base | FAO SOILS PORTAL | Food and Agriculture Organization of the United Nations" n.d.)) soil with the soil texture loamy silt to loam (sand 26%, silt 52%, clay 23%), and the pHCaCl2 value is 7.6 (De Jong 2021).

2.1.1. Crop Residue

At Rutzendorf, long term experiments have been conducted since 1982, where incorporation of crop residue on the one part and removal of crop residue on the next part of the field were established. Each management system (with and without crop residue incorporation) site has four replicated with a 32m × 6m (192 metre square) of plot size, and both management systems were designed via randomized block system.

2.2. Chamber sampling and gas analysis

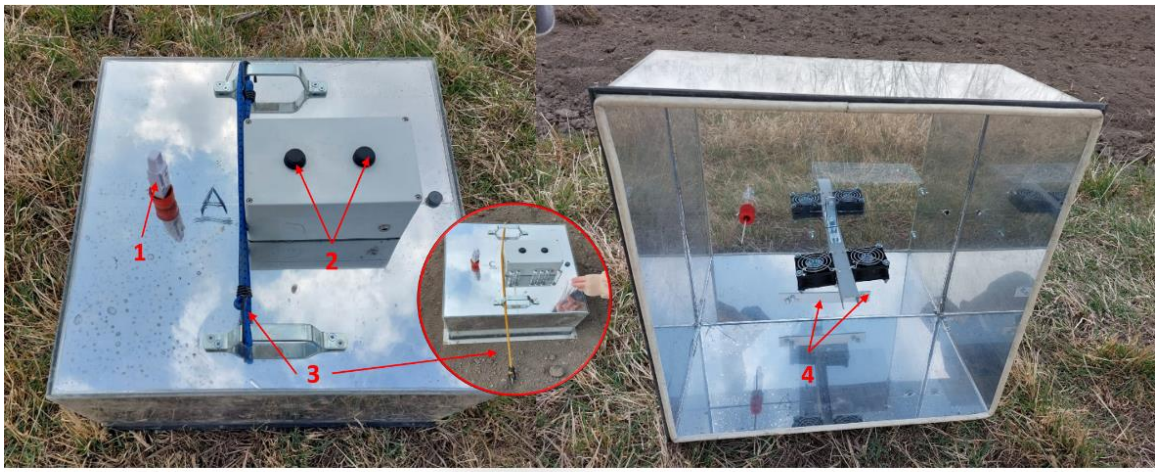
Each half of the study site had eight GHG measurement points, and stainless-steel frames (Figure 5) were installed for all sixteen measurement points (INC = 8, REM = 8). Then, on top of those frames the manual chambers were placed (Figure 4, 5) to provide gas-tightness (Butterbach-Bahl, Kiese, and Liu 2011). After that, GHG fluxes were measured with a plastic syringe (50ml) within each specific time range: 0; 12; 24; 32; 41 minute(s). After each sample measurement with syringe: 15ml of gas sample was injected into a 10 ml glass vial to create overpressure. Further, GHG samples were delivered to Bundesforschungszentrum für Wald (BFW) for Gas Chromatography (GC) analysis of GHG samples. On 4th April and 9th May, LiCor 7810 Analyser portable gas analyser was used for GHG measurements. The soil GHG flux measurements took place in following days:

Table 1. Dates of GHG measurements.

Year								
2021	May 28	July 21	Aug 3	Aug 18	Sept 28	Oct 1	Nov 17	Nov 19
2022	Apr 4	May 9						

The three days that are highlighted on Table 1 were not included in statistical analysis due to analytical performance and liability of the data, and for the same reasons, 3rd August data on only CH_4 flux was discarded from further analysis.

The soil temperature was measured with Thermometer that was installed always into the manual chambers during the GHG measurements (Figure 4). Soil moisture measurements were measured with HydraGo soil moisture sensor: close to frames four times soil moisture measurements were taken after the GHG measurements.



1. **Thermometer** measures headspace temperature
2. **Buttons** to turn on/off fans
3. **Rope** for tightening chamber to the frame; avoids air leak
4. **Two fans** to keep gas homogeneity in the chamber headspace

Figure 4. Manual chambers used during the experiment.

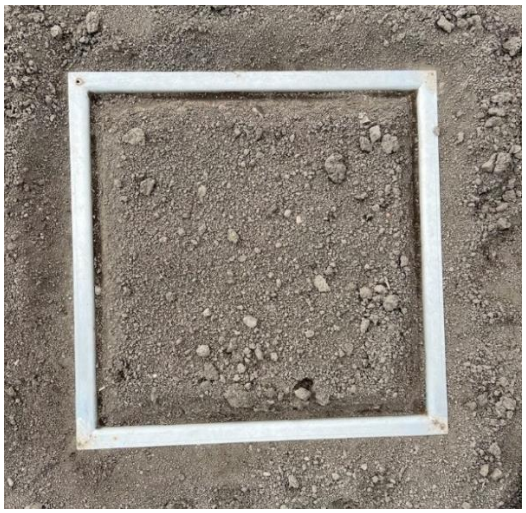


Figure 5. Stainless steel frame prepared for soil GHGs measurement in study field. Frames are used to keep gas-tightness (Butterbach-Bahl, Kiese, and Liu 2011).

2.2.1. Soil GHG flux calculations

Soil GHG flux calculations were calculated according to (Butterbach-Bahl, Kiese, and Liu 2011). For the initial CO_2, CH_4 and N_2O data the following formula was used to calculate the slope (ppmv per min):

$$Slope\ of\ X = \frac{\frac{x \int_1^n flux\ samples\ from\ the\ same\ point\ per\ day}{y \int_0^m time\ of\ each\ measurement}}{\frac{24\ hours}{60\ mins}}$$

After, the slope and mol volume were used in the following formula to calculate the flux rate:

$$f\mathrm{CH_4}\left(\mu g\ \mathrm{C\,m^{-2}\,h^{-1}}\right) = \frac{\text{chamber vol}(\mathrm{m^3})\text{mol weight}\left(\mathrm{g\,mol^{-1}}\right)\text{slope}\left(\mathrm{ppmv\,min^{-1}}\right)}{\text{chamber area}(\mathrm{m^2})\text{mol volume of}\ \mathrm{CH_4}\left(\mathrm{m^3\,mol^{-1}}\right)} 60 \times 10^6$$

2.3. Soil sampling

Soil samples were taken with a gouge auger for lab analysis from 0-25 cm soil depth approximately two meters away from frames, and this process was repeated for four plots (Figure 6). After, soil samples from four plots were pooled together, homogenized, and then sieved (<2 mm). After put inside labelled plastic bags. Soil samples were taken two times, on April the 4th and on May the 9th.

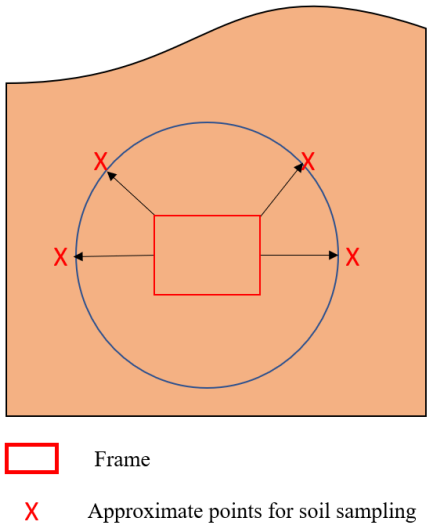


Figure 6. An illustration of approximate points for soil sampling. The soil samples were taken from four points that are about two meters away from installed frames for soil GHGs measurements in the research field (Rutzendorf).

2.4. Soil lab analysis

The following lab procedures were described and conducted strictly following the instruction on (Katharina Keilblinger et al. 2022).

2.4.1. pH

For 2.0 g of soil in 50 ml beaker, 25 ml $CaCl_2$ was added. The solution was stirred with a glass rod and incubated for one hour at a room temperature. After, pH was measured with pH-meter (calibrated to pH 7).

2.4.2. Biomass C and N fumigated-extraction technique

Soils were weighed between 6-7 g to 100 ml beaker. Inside a desiccator moisturized filter papers were put. After, 250 ml beaker with half-filled sodium lime and 250 ml beaker with half-filled chloroform (with zeolites to avoid delay in boiling) were put inside the desiccator together with all beakers with soil sample and closed with a lid. A vacuum pump was connected (and turned on) to desiccator until chloroform started to boil (ac 5 minutes). Then, the desiccator was left inside an incubator (covered outside to avoid light exposure) for 24 hours at 25°C.

Fumigated soil samples and non-fumigated samples were then extracted as follows: 50 ml of 1 *M* KCl solution was added to 5 g of soil and shaken on a horizontal shaker for one hour. Soil solutions were filtrated through 7 µm filter paper (the same process for fumigated samples after fumigation-extraction process). After filtering, all liquid samples, fumigated and non-fumigated, they both were measured in Shimadzu TOC/TN analyser. This device performs simultaneous TOC and TN measurements.

2.4.3. Activity of Leucine-aminopeptidase (LAP) for enzyme activity

For 0.5 g of soil sample 50 ml of 0.1 M Tris buffer (pH=7.4) was added and put into a sonication bath for 1 min (to homogenize and break aggregates). 200 µL of suspended samples under constant stirring were pipetted to 96-well microplates (with four replicates). Next, 50 µL of 1.5 mM aminomethylcoumarin (AMC) substrate (dissolved in buffer) was added. Following, 200 µL of buffer solution was pipetted and 50 µL of AMC-substrate (as substrate control) was added. Wells were covered with cohesive plastic film and shaken horizontally (for 30 seconds to mix sample with substrate and incubated in the dark at 20 ºC for 120 minutes. Then, the fluorescence with Perkin Elmer multiplate-reader (EnSpire 2300 model) with extraction of 365 nm and an emission of 450 nm at 20 flashes were measured. Standard curves for both concentrations (10 µM and 50 µM) were created. Then, all the sample measurements were corrected via subtracting the substrates from the substrate control. After, the means for four replicates of each sample were calculated. The measured fluorescence was converted to nmol activity by using the calculated standard curve, where the best fit curve was used. Later, nmol activity was converted into nmol activity per g dry soil via using original sample weight and dry weight factor. More informtion of LAP procedure can be found on (German et al. 2011), (DeForest 2009), (Marx, Wood, and Jarvis 2001).

2.4.4. Soil extracts for nitrate, ammonium determination

5 g of sieved (< 2 mm) field moist soils were weighed into a 50 ml plastic tubes. After, for all soil samples in plastic tubes, 50 ml of 1 M KCl was added. The solutions were put for 1 hour on a horizontal shaker and then extracts were filtrated.

a) nitrate in 1 M KCl soil extract

For the calculation, the following formula was used:

$$\frac{n * V * 100}{g * \%\, dm} = \mu g\ N - NO3 * g^{-1}\ dm$$

Where, n, V, g, 100/%dm stands for calculated value (µg N, dilution included), extraction volume (ml), soil weight (g), factor for dry matter calculation, respectively.

b) ammonium in 1 M KCl soil extract

Ammonium Chloride stock standard solution (1000 mg N L^{-1}): 0.382 g of NH_4Cl was dissolved in 100 mL MilliQ water. Ammonium Chloride working standard solutions 100 ppm: 5 mL of ammonim stock standard solution was diluted in 50 mL MilliQ water/matrix (KCl) (5mg L^{-1}). Six 10 mL volumetric flasks were prepared, and standards were filled with the same matrix as the samples.

A final volume of 200 µL NH_4 solution was coloured and measured photometrically. After, 200 µL of standards were pipetted twice, then into blanks in microtitre plates. Followingly, 40 µL of (1) sodium salicylate solution, (2) 40 µL oxidation solution. After 30 minutes the process continued to measure the extinction at 660 nm against the reagent blank. Afterwards, calibration curve was plotted from measured absorption versus the concentration. The linear regression was performed; the sample and blank concentrations were determined and the mean of the balnks from the sample values were subtracted to give the corrected solution concentration (c_s).

$$\frac{n * V * 100}{g * \%\, dm} = \ \mu g\ N - NH4 * g^{(-1)}\ dm$$

Where, n, V, g, 100/%dm stands for calculated value (µg N, dilution included), extraction volume (ml), soil weight (g), factor for dry matter calculation, respectively.

2.4.5. Dry matter content

An aliquot amount of field-moist soil samples was weighed into aluminium or porcelain dishes, and dried to constant weight at 105 ºC for at least 3 hours. After, the samples were cooled in a desiccator and weighed again. The dry matter content can be converted into % via following calculation:

$$\frac{soil\ dry\ matter * 100}{initial\ soil\ weight} = \%dry\ matter\ (dm)$$

2.4.6. Soil bulk density (BD), porosity, water content (WC) and water filled pore space (WFPS)

Bulk density and porosity data were taken from (De Jong 2021). After, WFPS and WC were calculated using the formula below:

$$WFPS\ (\%) = \frac{WC(\%)BD}{Porosity\ (\%)} * 100$$

$$WC(\%) = \left(\frac{fresh\ weight - dry\ weight}{dry\ weight}\right) * 100$$

2.4.7. Soil respiration by titration

The method measures the respiration activity of soil microorganisms as CO_2 production per time unit. When soil samples are incubated in a gas tight closed vessel at 25 ºC for 24 hours, the CO_2 produced is absorbed in sodium hydroxide (NaOH), also illustrated below. Thus after adding barium chloride the sodium carbonate is precipitated as the hardly solute barium carbonate and the unused sodium hydroxide is titrated by hydrochloride acid.

$$2NaOH + CO2 \rightarrow Na2CO3 + H2O$$

15 g sieved soil (< 2 mm) was weighed into polyester fabric bags. 10 mL of 0.1 N NaOH was pipetted with dispenser into SCHOTT bottles. After, the polyester fabric bags were inserted into the bottles very carefully without touching the NaOH solution. Then the bottles were closed and the samples were incubated at 25 ºC for 24 hours. In similar way, but without soil, three control bottles were prepared. Later, after the incubation the bottles were taken from incubator and Polyester bags were gently removed. 2 mL of barium chloride solution was added to precipitate the adsorbed CO_2 as barium chloride (milky precipitation). Followingly, few drops of Indicator solution were added, and the rest was titrated with sodium hydroxide with the 0.1 N hydrochloric acid solution until the decolorization of the indicator.

$$\frac{(MVC - MVS) * 2.2 * 100}{SW * \%dm} = mg\ CO2g^{(-1)dm} * 24h^{(-1)}$$

Where: MVC – mean volume of HCl consumed by controls (ml); MVS – mean volume of HCl consumed by samples (ml); SW – initial soil weight (20 g); 2.2. – conversion factor (1 mL 0.1 N HCl corresponds to 2.2 mg CO_2); 100 $\%^{-1}$dm – factor for soil dry matter.

2.4.8. Total organic carbon (TOC), total inorganic C (TIC), total N (TN), total C (Ct)

The procedure consisted of five steps. First, starting of the instrument to make sure that gas supply is opened and then turn on the TOC-unit. (TN-unit always remains turned on). Second, a method, sample table and calibration curves were created for the software. Third, sample run was started. A flask with standard solution was put (between 100 and 10 mg C L-1, depending on the samples) at the ‘0’(offline)- position of the instrument for creation of automatically diluted standard curves. The standard solutions were manually diluted (szintillation flasks for 1:2 dilutions were used) and these standards were put equally and distributed between the samples. The glass vials were covered with aluminium-foil. Before starting a sample run, the followings were checked: (1) container with washing water for ASI is full (big canister); (2) container with dilution water is full; (3) enough hydrochloric acid (very little is needed); (4) water in humifier pot is between ‘low’ and ‘high’; (5) drain pot of dehumidifier is full (water can be filled in using the black valve in the front of TOC-unit); (6) note actual gas pressure (approximately 20 bar are needed for 80 samples). Fourth, after the sample run, the instruments were shut down. Fifth, then the final data was exported. After, the data was calibrated manually by correlating areas and concentrations of standards.

3. Statistical analysis

RStudio 2022.02.3-492.exe version was used for data analysis and data visualization. The repeated measures Anova for comparison of soil GHG measurements and ggplot2(), tidyverse(), ggalt(), GGally(), ggridges(), ggboxplot(), ggplot() and corrplot() packages for data visualization were used.

The two-way repeated measures ANOVA (rmANOVA) was used to check the interactions of two factor variables, time (n=7) and treatment (n=2), on GHG fluxes. In order to perform two-way rmANOVA, the following assumptions about the data were checked: (1) no significant outliers (Appendix 2), (2) normality (Appendix 1), assumption of equality of variances (Appendix 3). The data points were plotted for normality assumption (Appendix 1); all GHGs were assumed to follow normal distribution. For the equality of variances leveneTest was performed (Appendix 3), where the equality of variance assumption was not met only for CO_2 fluxes (p-value = 0.01859). Since there is no best non-parametric alternative for two-way rmANOVA test, for all GHGs (CH_4, CO_2 and N_2O) two-way rmANOVA was performed, including CO_2.

After the rmANOVA, to define which groups were significantly different, pairwise.t.test() with no adjustment method was used for CH_4 and N_2O fluxes. For CO_2 flux, first Kruskal-Wallis test was performed to compare with rmANOVA output. Then, group_by() function was used together with wilcox.test() to check for differences within the groups (alternative to pairwise.t.test()); "none" adjustment method was used. Then, all the GHGs (CH_4, CO_2 and N_2O) were visualised in Excel by using combo charts.

For the statistical analysis of linear correlation between soil moisture or soil temperature versus GHG fluxes (CH_4, CO_2 and N_2O), the "regression" function was used from "Data Analysis" section in Excel.

The correlation matrix was used to visualise the linear correlations between the soil GHGs (CH_4, CO_2 and N_2O) and soil parameters. For the correlation matrix analysis, soil parameters such as bulk density and porosity were not included due to their "zero" standard errors that were impossible for further calculations. Later, the remaining data was visualized via corplot() function, with sig.level = 0.05 that will consider correlations with p-value > 0.05 as insignificant, and all the insignificant correlation coefficient values will be left blank in the final figure (Figure 9; Appendix 7-10) ("Visualize Correlation Matrix Using Correlogram - Easy Guides - Wiki - STHDA" n.d.).

The data from soil lab analysis for 4th April and 9th May were compared using boxplots. The soil properties between the two treatments (INC, REM) were compared using wilcox.test(), and after, the data from May and April were also compared using Kruskal-Wallis test; both tests p-value results were included in boxplot and illustrated (Appendix 11).

The PCA Principal Component Analysis (PCA) was performed to define which soil parameters contribute the strongest to the differences between samples. For this, soil lab analysis data and the principal components (PC) PC1 and PC2 were used. The PCA visualization ("Biplot Using Base Graphic Functions in R" n.d.). The stats, graphics, ellipse packages were used. DOC/SOC, C_{mic}/SOC and total soil N (N_t) were not included for the PCA analysis because of their close to zero values which causes error in the PCA's calculations. For the PCA analysis it is important to have equal values of observation points. However, some of the measurement points contained no data (or NA), they are: (1) from April soil lab analysis data, on INC treatment part one missing

value was found on soil temperature; (2) from May soil lab analysis data, respiration on INC treatment had one missing value. For all these missing values the mean value was taken from other three points. Thus in total four points for INC and four points for REM treatments were included for the PCA analysis (total = 8).

The mean values and standard error (SE) of soil parameters were calculated in Excel by using the formulas in below:

$$mean = \frac{sum\ of\ all\ data\ points}{Number\ of\ data\ points}$$

$$Standard\ Error(SE) = \frac{Standard\ deviation}{\sqrt{the\ number\ of\ data\ points}}$$

For the CO_2-equivalent mean values of N_2O and CH_4 fluxes on Table 2: N_2O and CH_4 fluxes were multiplied by their GWP for over 100 years according to ("AR5 Synthesis Report: Climate Change 2014 — IPCC" n.d.), 265 and 25, respectively. The SOC stock values were obtained from (De Jong 2021), and converted from "mg C ha^{-1}" to "µg C ha^{-1}". Then, two-way ANOVA was performed to check if two treatments (INC, REM) had significantly different N_2O and CH_4 fluxes.

Results

1. Soil GHG flux measurements

The soil moisture content was more in summer compared to fall (Appendix 12). Also, already at the start of spring soil moisture content seemed to increase a bit, but then dropped again to a lesser extent in the second half of sping. Next, the soil temperature had not changed much until the end of first month of fall, although in starting from spring, temperature had been steadily increasing back again (Appendix 12). The average soil moisture and soil temperature on both treatments showed almost the same average values (Table 2).

The highest rates of soil N_2O emissions were observed in the middle of summer (Figure 7). After this peak, N_2O emissions decreased steadily until the end of summer. Although, starting from beginning of mid fall, N_2O emissions increased again close to the end of fall. Then, missing some months in between, from early spring to mid-spring: the least N_2O emissions from both INC and REM were seen (Figure 7). Followingly, there was a steady CO_2 flux until the mid-end of summer, which then started to reduce steadily till the end of fall, and then, remained steady again (Figure 7). However, just after the beginning of spring there is an abrupt increase in CO_2 flux in the second half of spring. Whereas CH_4 fluxes on two treatments (INC, REM) showed mostly contradicting to CO_2 and N_2O flux rates with an inconsistent change in CH_4 flux (Figure 7). For instance, in the mid-summer, REM treatment had CH_4 sink compared to INC, where there were slight CH_4 emissions on INC treatment part. Then, these CH_4 fluxes continuously interchanged within the two treatments. At the same time, CH_4 flux variances within the two treatments started to decrease. Then, from beginning of spring, there was a simultaneous-linear uptake in CH_4 flux.

The repeated measures of ANOVA showed a significant interaction between the investigated time range (from July to May) and two treatments (INC, REM) with p-value = 0.04, and both the time and treatments significantly influenced N_2O fluxes, both p-values were < 0.01 (Appendix 5). Conversely, CO_2 flux was significantly affected by only through the investigated time range (p = 0.0004), and CH_4 had influence of neither time nor treatments (INC, REM). So, there was no significant difference between INC and REM in their CO_2 and CH_4 fluxes, however, CO_2 flux was significantly inconsistent through the investigated time range (from July to May).

The linear correlation between the soil moisture and N_2O emissions on both INC and REM showed significant correlations $r^2(26) = 0.29$, $p = 0.003$ and $r^2(26) = 0.27$, $p = 0.004$, respectively (Figure 8). Similarly, there was a noticeable linear correlation between soil temperature and N_2O emissions on INC and REM, but they were not significant (INC: $r^2(26) = 0.03$, $p = 0.37$; REM: $r^2(26) = 0.01$, $p = 0.61$). Following, the strong linear correlations between the soil temperature and CO_2 fluxes were observed on both INC with $r^2(26) = 0.65$, $p = 1.83E^{-07}$ and REM with $r^2(26) = 0.31$, $p = 0.002$ (Figure 8). However, the soil moisture had very poor correlation with CO_2 fluxes on both management systems (INC, REM). Further, CH_4 fluxes of INC and REM had very weak linear relations in both correlations: CH_4 flux versus soil moisture or soil temperature (Figure 8).

On average, there were lesser CH_4 sinks and more N_2O and CO_2 fluxes on INC in comparison to REM treatment. On the other hand, SOC stocks on REM were overall lesser than INC treatment (Table 2), and according to (Spiegel et al. 2018) this differences are significant between the two treatments (INC, REM). However, the comparison of GHGs (CH_4 and N_2O) and CO_2 fluxes between the two treatments (INC, REM) had no significant difference, p-values are on Appendixes 13, 14 and 15.

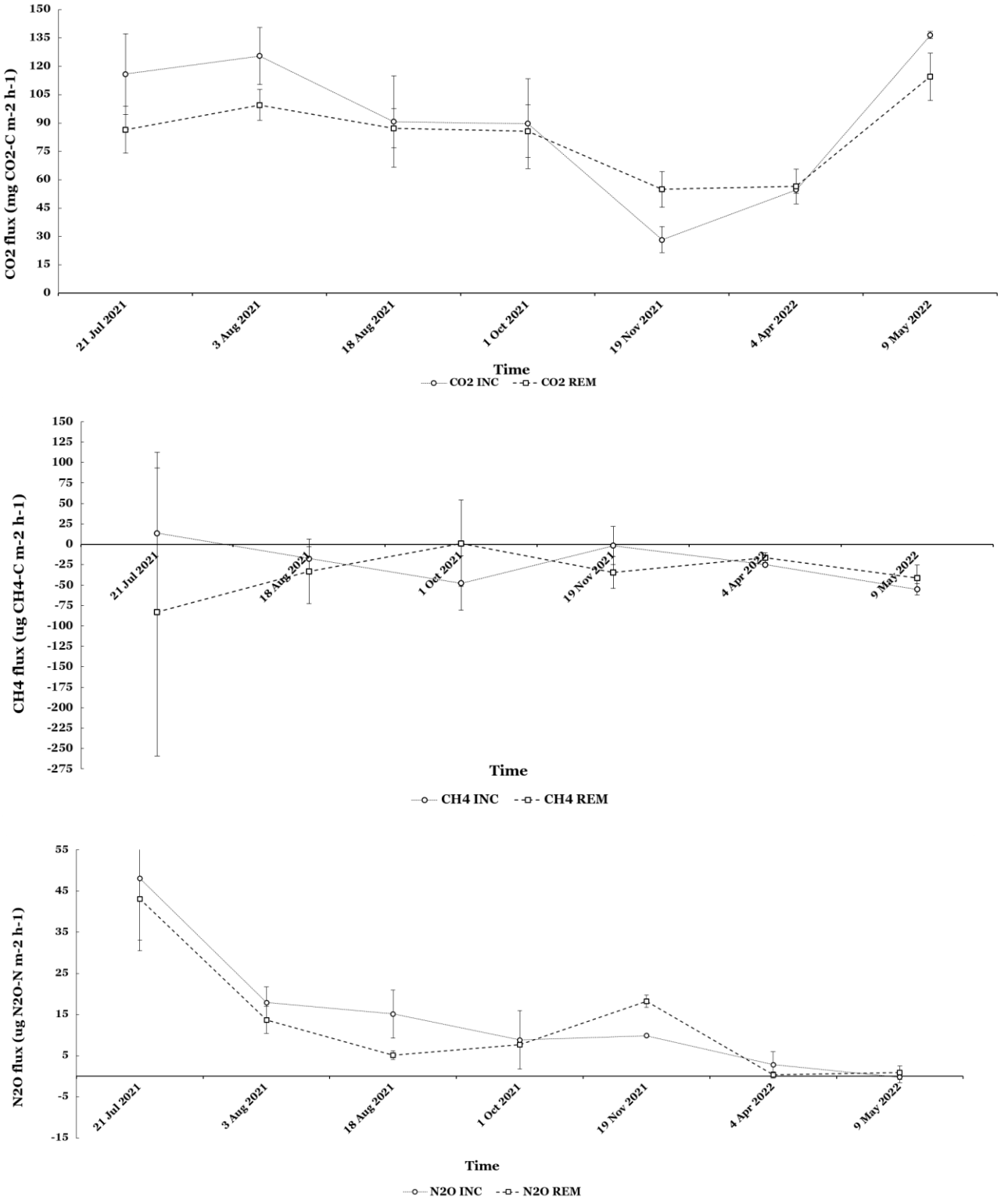


Figure 7. Plots of GHG fluxes over investigated time range.

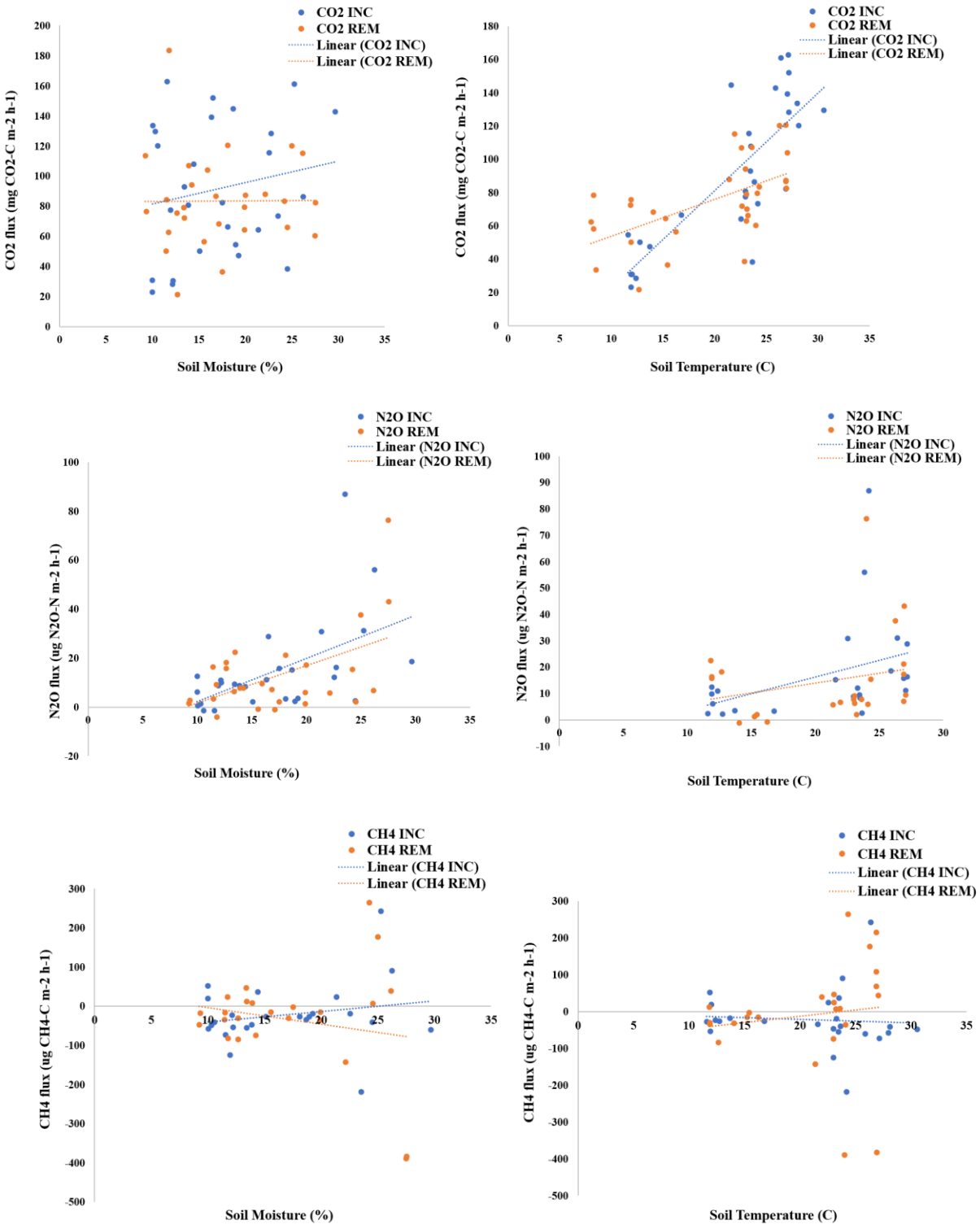


Figure 8. Linear correlation of GHG (CO_2, N_2O, CH_4) fluxes with soil temperature and soil moisture

Table 2. The CO_2-equivalent calculated averages of N_2O and CH_4 fluxes through the investigated time range (from July to May) compared with SOC stocks under two treatments, INC and REM. Additionally, the averages of CO_2 flux rates were also included from July to May on two treatments (INC, REM).

Mean	N_2O (CO_2-eq µg N_2O-N m^{-2} h^{-1})	CH_4 (CO_2-eq µg CH_4-C m^{-2} h^{-1})	CO_2 (mg CO_2-C m^{-2} h^{-1})	Moisture (% (vol))	Soil temp (C)	SOC stocks (µg C ha^{-1})
INC	3882.0 (±3.9)	-620.5 (±29.9)	91.6 (±11.8)	17.0	21.8	63390
REM	3365.5 (±3.1)	-963.2 (±51.6)	83.5 (±12)	17.3	21.8	59440

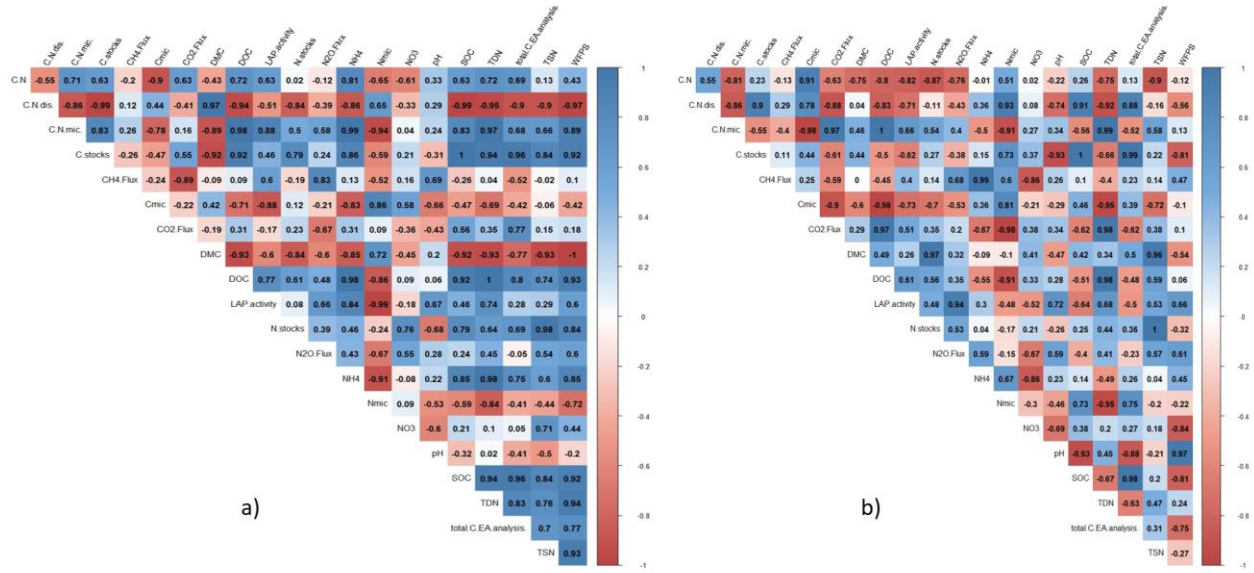


Figure 9. Correlation matrix: soil GHG fluxes (CO_2, N_2O, CH_4) and soil parameters data. The figure order: a. REM in April; b. INC in April.

2. Lab analysis.

The soil parameters that were used for the PCA analysis are pH, gravimetric water content (GWC), dry matter content (DMC), bulk density (BD), porosity, water filled pore space (WFPS), ammonium (NH_4), nitrate (NO_3), dissolved organic C (DOC), total dissolved N (TDN), microbial C (C_{mic}), microbial N (N_{mic}), respiration, LAP activity, total C (C_t, EA analysis), inorganic C (TIC), total soil organic carbon (SOC), soil C stocks, soil N stocks, soil C/N (C/N), microbial C/N (C/N_{mic}), dissolved C/N (C/N_{dis}), and total inorganic carbon.

The PC1 explained 37.8 % of the variation in the soil lab analysis data in April. The PC1 was positively influenced by parameters such as BD > TIC > pH >DMC (Figure 10), whereas porosity > N stocks > NO_3 > C/N_{dis} > C_{mic} > respiration had negative influence on PC1, in data obtained from April. In the same dataset, the PC2 had 34.3 % explanatory power of the variation in data, with positively influenced soil parameters as GWC > DOC > SOC > C/N_{mic} > C stocks > TDN (Figure 10). The parameters with the strongest negative influence on the PC2 were N_{mic} > DMC.

Following, the same PCA analysis were performed for the soil lab analysis data from May (Figure 11). The PC1 (40.1 %) and the PC2 (29.9 %) had overall slightly lesser explanatory power in May relative to April. The soil parameters such as TIC > porosity > pH > TDN and NO_3 > GWC > porosity positively impacted the PC1 and the PC2, respectively (Figure 11). Consequently, C_{mic} > LAP activity > SOC > C/N_{dis} > C stock had strong negative influences on the PC1; NH_4 > DMC > BD impacted strong-negatively the PC2.

The PCA analysis were performed using lab analysis data, separately on 4th April and 9th May, where the first day weather was cloudy (13°C) and the second day was sunny (25°C), respectively. Thus, this can explain the variation in explanatory power of soil components on PCs' that differ within these days. In addition, there is an obvious difference of two separate management system (INC, REM) in both months (Figure 10, 11). Also, in April, data points of INC were very close to each other which formed narrow ellipsoidal shape, but all the other data points were scattered.

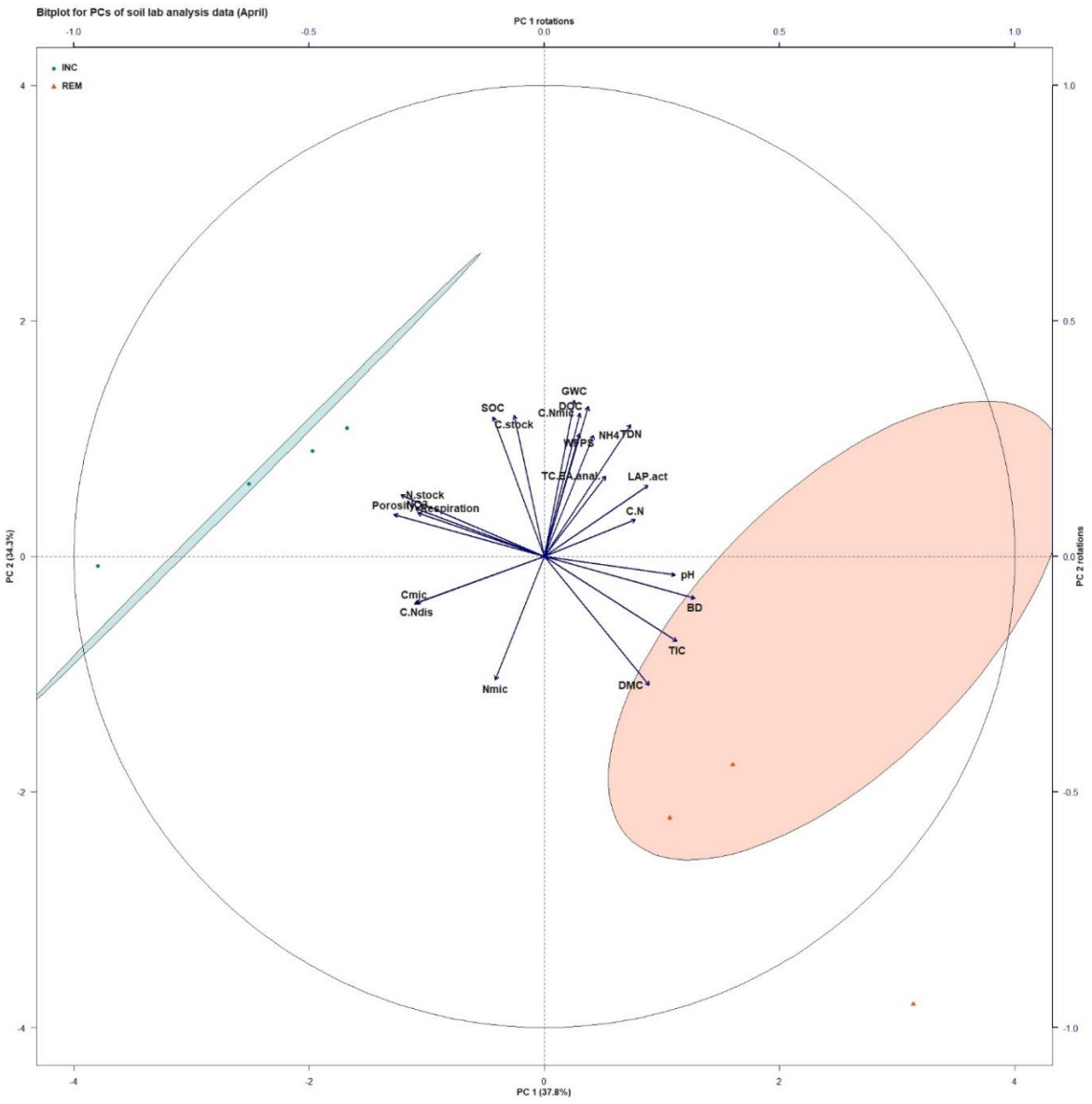


Figure 10. Principal component analysis (PCA) with data of the soil lab analysis from 4th April (2022) in depth 0 - 25 cm using standard soil parameters (pH, OC, N_{mic}, C stocks, etc); different colors represent two treatments: the removal of crop residue and incorporation of crop residue.

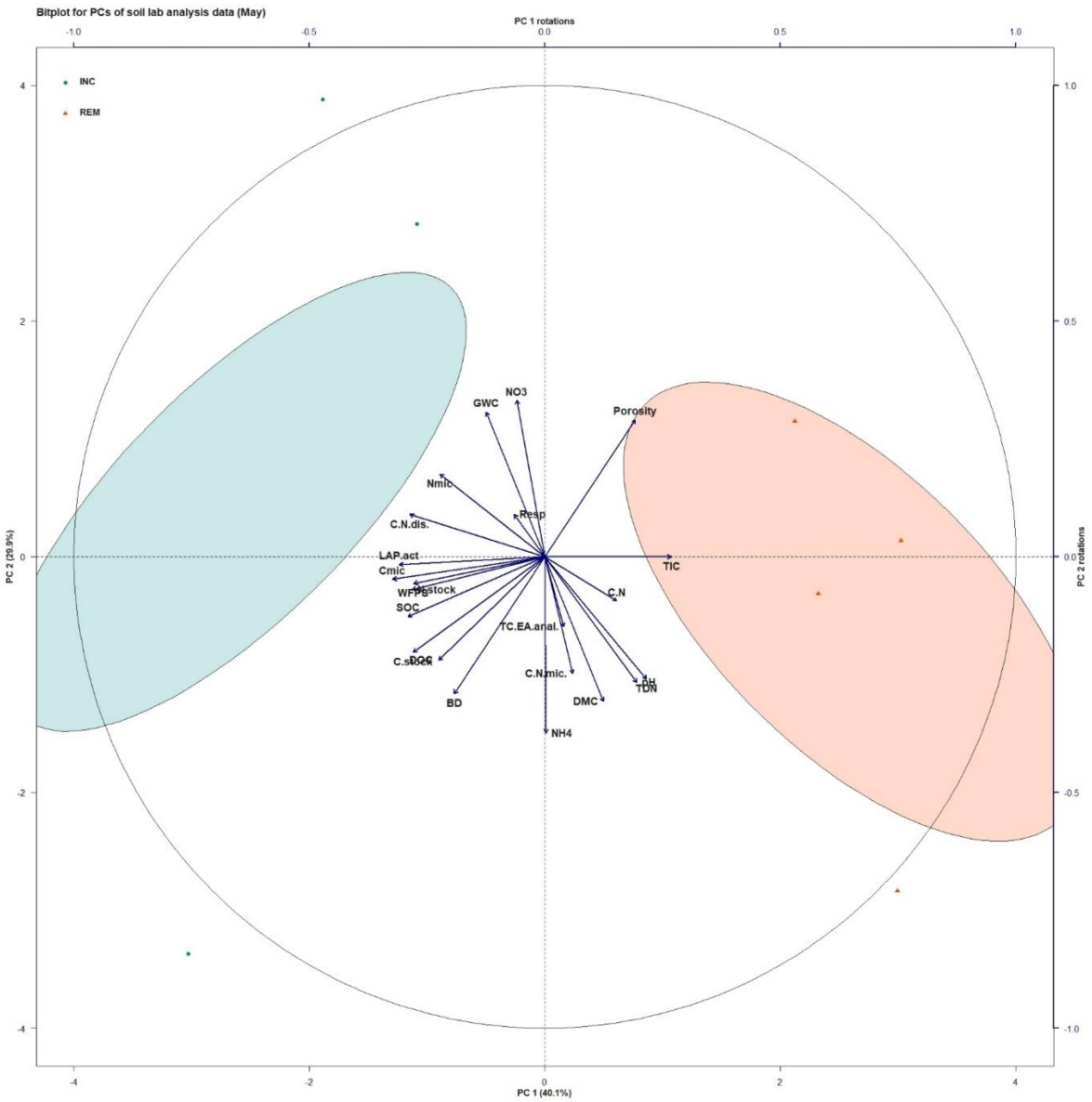


Figure 11. Principal component analysis (PCA) with data of the soil lab analysis from 9th May (2022) in depth 0 - 25 cm using standard soil parameters (pH, OC, Nmic, C stocks, etc); different colors represent two treatments: the removal of crop residue and incorporation of crop residue.

Table 3. The mean values of the soil parameters from May.

	May	SE	May	SE
Soil parameters	REM (0-25 cm)		INC (0-25 cm)	
pH	7.7	0.0	7.4	0.1
GWC (%w/w)	12.0	0.3	12.5	0.3
Dry matter content (%)	89.2	0.2	88.9	0.2
Bulk density (g/cm^3)	1.2	0.0	1.2	0.0
Porosity (% v/v)	55.7	0.0	54.8	1.0
WFPS (%)	25.4	0.6	27.3	0.8
NH_4 (µg NH_4-N/g dw)	4.9	0.7	4.3	1.0
NO_3 (µg NO_3-N/g dw)	7.7	1.5	8.9	1.7
Dissolved organic C (µg DOC/g dw)	42.0	3.1	49.3	2.4
Total Dissolved N (µg tN/g dw)	23.2	1.1	17.7	1.3
Microbial C (µg biomass C/g dw)	127.0	2.8	151.0	4.5
Microbial N (µg biomass N/g dw)	20.4	0.9	26.9	1.9
Respiration (µg CO_2/g dw/d)	294.9	16.5	294.4	13.6
LAP activity (nmol h^{-1} g^{-1} dw)	32.2	1.3	51.9	4.9
Total C (EA analysis) (% w/w)	4.0	0.1	4.0	0.0
Inorganic C (% w/w)	2.0	0.1	1.7	0.0
Total SOC (% w/w)	2.0	0.0	2.2	0.0
Total soil N (%)	0.1	0.0	0.2	0.0
Soil C stocks (Mg C ha^{-1})	59.4	1.2	66.1	2.7
Soil N stocks (Mg N ha^{-1})	4.4	0.2	5.3	0.3
Soil C:N	13.6	0.8	12.4	0.5
Microbial C:N	6.3	0.2	5.7	0.5
Dissolved C:N	1.8	0.1	2.8	0.1
DOC/SOC	0.002	0.0	0.002	0.0
C_{mic}/SOC	0.006	0.0	0.085	0.0

Table 4. The mean values of the soil parameters from April.

	April	SE	April	SE
Soil parameters	REM (0-25 cm)		INC (0-25 cm)	
pH	7.6	0.0	7.5	0.0
GWC (%w/w)	14.9	0.8	14.9	0.1
Dry matter content (%)	87.0	0.6	85.1	0.1
Bulk density (g/cm^3)	1.2	0.0	1.2	0.0
Porosity (% v/v)	55.7	0.0	56.6	0.0
WFPS (%)	31.5	1.6	31.5	1.7
NH_4 (µg NH_4-N/g dw)	7.3	4.9	5.7	3.6
NO_3 (µg NO_3-N/g dw)	6.0	0.7	8.0	0.5
Dissolved organic C (µg DOC/g dw)	66.3	12.3	66.1	6.7
Total Dissolved N (µg tN/g dw)	28.5	7.9	21.7	4.5
Microbial C (µg biomass C/g dw)	116.6	6.2	130.9	5.3
Microbial N (µg biomass N/g dw)	27.2	6.2	21.3	7.0
Respiration (µg CO_2/g dw/d)	276.0	1.8	352.7	25.5
LAP activity (nmol h^{-1} g^{-1} dw)	29.6	2.9	25.4	3.0
Total C (EA analysis) (% w/w)	4.1	0.1	4.0	0.1
Inorganic C (% w/w)	2.0	0.0	1.8	0.0
Total SOC (% w/w)	2.1	0.1	2.2	0.0
Total soil N (%)	0.1	0.0	0.2	0.0
Soil C stocks (Mg C ha^{-1})	61.8	3.2	64.1	1.4
Soil N stocks (Mg N ha^{-1})	4.0	0.2	5.9	0.2
Soil C:N	15.3	0.5	14.3	0.5
Microbial C:N	5.2	1.4	5.4	1.2
Dissolved C:N	2.5	0.2	3.2	0.3
DOC/SOC	0.003	0.0	0.003	0.0
C_{mic}/SOC	0.006	0.0	0.006	0.0

More soil properties from incorporation of crop residue field part showed higher mean values in both May and April compared with REM, and all the significantly different groups are shown in Appendix 11. More specifically, in April, INC had more NO_3, C_{mic}, SOC, total soil N, C stocks, N stocks, C/N_{mic}, C/N_{dis}, porosity and respiration in comparison to REM (Table 4). On the other hand, DMC, NH_4, N_{dis}, enzyme activity (LAP activity), TIC and soil C/N ratio were lesser on INC relative to REM. The other soil parameters such as GWC, BD, WFPS, DOC, total C, SOC and DOC/SOC were almost the same in April within both management systems, INC and REM.

After, in May, there were slight variations in mean values (Table 3); REM treatment had lesser values in soil WFPS, NO_3, DOC, C_{mic}, N_{mic}, LAP activity, SOC, total soil N, soil C and N stocks, C/N_{dis} and C_{mic}/SOC, compared with INC. Although, there were almost the same values of BD, respiration, DMC, total C and DOC/SOC in both treatments (INC, REM). However, REM treatment had also some soil parameters such as soil porosity, NH_4, dissolved N, TIC, C/N ratio and C/N_{mic} with higher mean values than INC treatment.

Discussion

1. *General patterns of GHGs (CO_2, N_2O and CH_4)*

The croplands are known essential GHGs emitters (Terry Barker et al. 2007), that is why good quality research focused on GHG quantifications from various croplands and/or under different agricultural management systems are crucial, especially if the observations are long-term, which provides reliable data to support policies on climate change (Tubiello et al. 2015). At the same time, long term experiments can capture impact of seasonal changes on GHGs that influences soil water content and soil temperature (K. A. Smith et al. 2018), (Martikainen et al. 1993). Also, LTFE represent dynamic changes in soil GHG fluxes that are occurring in the croplands (after or before tillage, fertilization, etc). For instance, different management processes at specific times such as applying varying types of fertilization, tillage intensity, before/after harvest condition (crop residue removal/incorporation) can also alter non-CO_2 GHG fluxes (Sandén et al. 2018), (Syakila and Kroeze 2011), (Powlson et al. 1997), (Zechmeister-Boltenstern et al. 2018).

Further, the higher rates of N_2O flux were observed in this work in mid-summer could be due to the higher N content from previous fertilization application activities e.g., end of March or July. That can explain high rates of N_2O flux under both treatments (INC, REM). This is also supported by (Corre, van Kessel, and Pennock 1996), (Butterbach-Bahl et al. 2013) and (Dobbie, McTaggart, and Smith 1999) findings, where after fertilization N_2O flux increases rapidly, and when some time passes, there are steady decreases of N_2O flux during the next months. Then, during fall and mid-end of spring very small N_2O fluxes were captured.

However, there could be an indirect relation between the N_2O flux, soil temperature and soil respiration. The O_2 concentration in soil volume depletes when there is an increased soil respiration (SR), and this can also lead to denitrification processes with N_2O being a sub-product (K. A. Smith et al. 2018), (K. Smith 1997). At the same time, higher soil temperatures result in higher respiration rates to a certain point that can be explained by a classic Q_{10} function for predicting SR (K. A. Smith et al. 2018), (Janssens and Pilegaard 2003). Consequently, more N_2O and CO_2 fluxes in the mid-summer might be due to high soil temperature (about 25 Cº) and wet conditions, soil moisture content (above 25 % of total soil volume in 0 – 25 cm depth). On the other hand, arable soils are known N_2O sinks in a very minor extent, where specific soil bacteria and archaea that can reduce N_2O to N_2 (Jones et al. 2013). According to (Schlesinger 2013), these known soil microorganism communities can uptake N_2O in the range between <1.0 μg N m^{-2} h^{-1} to 207 μg N m^{-2} h^{-1}, similarly about -0.23 N_2O (μg N2O-N m-2 h-1) sink was also observed in mid-spring (Figure 7). Following, the changes in N_2O fluxes and CO_2 efflux can vary by soil types and amount soil organic C content (Badagliacca et al. 2017), (Lohila et al. 2003), (Butterbach-Bahl et al. 2013), (Chantigny et al. 2017). Also, somewhat similar relations between the soil temperature and N_2O and CO_2 fluxes (Figure 7) were also observed by (Chantigny et al. 2017) during the non-vegetation-growing seasons. In addition, there are numerous studies that highlight the interlink between soil temperature and CO_2 effluxes (Zechmeister-Boltenstern et al. 2018), (K. A. Smith et al. 2018), (Raich and Schlesinger 1992) that was also seen in Figure 8. The CO_2 efflux had significant linear correlation on both treatments (INC, REM). Also, in Figure 7 and in Appendix 12, an increase in soil temperature was followed by an increase in CO_2 efflux on 3rd of August and on 9th of May.

Compared with N_2O and CO_2 fluxes, arable soils are an essential CH_4 sinks. Also, arable soils can be both sources and sinks of CH_4 compared to forests that uptake CH_4 in much larger extent (Dobbie et al. 1996), (Powlson et al. 1997). Following, methanotrophs are known main contributors for CH_4 sink: they are gram-negative aerobic bacteria which are able to meet their need of C and energy through oxidizing CH_4 to CO_2 (Zechmeister-Boltenstern et al. 2018). Thus CH_4 will be converted to CO_2 which has lesser global warming potential ("Methanotrophic Bacteria" n.d.), (Born, Dörr, and Levin 1990). However, CH_4 uptakes might be disrupted due to some causes such as (1) when ammonia monooxygenase and/or methane monooxygenase prefers NH_4^+ over CH_4 if there is a sufficient NH_4^+, (2) various chemical, physical and/or biological conditions of soils e.g. WFPS, pH that influence formation of soil microorganisms communities, (3) and tillage that disrupts the methanotrophic bacteria (Powlson et al. 1997), (Ussiri, Lal, and Jarecki 2009), (Zechmeister-Boltenstern et al. 2018).

2. Crop residue management

Crop residue incorporation improves soil biological, physical and chemical properties via returning OM to the soil (Turmel et al. 2015). That is why leaving crop residues on the field instead of removing them can result in better soil structure, soil moisture retention, microbial activity, nutrient availability, and increases in SOM content that is also linked with cation exchange capacity (Kushwaha, Tripathi, and Singh 2001), (Bending, Turner, and Jones 2002), (Turmel et al. 2015), (Fang et al. 2018), (Sidhu and Beri 1989). At the same time, Spiegel (2018) had found significantly higher SOC content on crop residue incorporation treatment compared to removal of residue in a LTFE at Rutzendorf (Spiegel et al. 2018), similar results were also found by Lehtinen et al. (2014), Sidhu and Beri (1989), Duiker and Lal (1999) and C.A. Campbell et al. (2000).

Although crop residue incorporation has a positive impact on SOC content, it might also increase CO_2 and N_2O fluxes (Frank, Liebig, and Tanaka 2006). According to Li, Frolking, Butterbach-Bahl (2005), Gonzaga et al. (2018) and Jianwen et al. (2004), this might be most possibly because of crop residue incorporation, where (1) increase in amount of available SOC content enhances denitrification and nitrification processes (Patten, Bremner, and Blackmer 1980), (Zou et al. 2005), and (2) crop residue incorporation alters the availability of soil NH_4^+, NO_3^- and N which directly influence nitrification and denitrification processes (Chen et al. 2013). Later, almost in mid-November, N_2O emissions were a lot higher on REM part of field in comparison to INC; and later N_2O emissions started to steadily decrease on both treatments. The most reasonable explanation for this behaviour in N_2O flux could be the low soil temperature during the end of fall and beginning of spring that resulted in less soil microorganisms' activity in both treatments (REM, INC). Moreover, lesser soil microorganisms' activity was also depicted in CO_2 efflux during these periods in comparison to other periods in REM and INC treatments (Figure 7). Similar findings on N_2O fluxes during cold seasons were also found by Wagner-Riddle and Thurtell 1998 (LTFE), where N_2O emissions were small through freezing events (below 0 ºC), < 10 ng m^{-2} s^{-1}.

Later in the beginning of mid-spring, there were instant increase in CO_2 efflux and CH_4 sink due to lesser soil moisture content and increase in soil temperature (Rastogi, Singh, and Pathak 2002), (Conrad 2007). Thus, in this period, the conditions of the water-free pores were more favourable for aerobic soil microorganisms in both treatments (Figure 7). That is why there might be less CO_2, N_2O fluxes and active CH_4 sink. Another possible explanation for reduced N_2O emissions (REM) and minor N_2O sink (INC) during this period could be (1) activity of N_2O

reductase that stimulates N_2O reduction to N_2 (Jones et al. 2013), (2) or it might be that INC part had more water-free pore space and the soil was more aerated compared to REM, (3) or else it could be also the combination of both previous predictions happening simultaneously in a heterogeneous soil volume.

Next, authors of Wegner et al. 2018 found that removal of crop residue can result in higher CH_4 uptake rate compared with incorporation of crop residue; the similar behaviour was observed also in this work (Figure 7).

3. Trade-offs between the GHGs and SOC stocks

There are number of research indicating the benefits of crop residue incorporation on soil properties resulting in higher microbial activities and increased soil productivity compared with the removal of crop residues (Blanco-Canqui and Lal 2009), (Lehman et al. 2014), (Lehman et al. 2015). Also, according to Charles et al. (2017), crop residues incorporation was classified as medium risk emission factor inducing N_2O fluxes. Nonetheless, crop residue incorporation induces N_2O emissions, and this treatment may not be the good option for mitigating GHGs in Rutzendorf. The similar conclusions are made also by Gu et al. (2017). Also, adopting residue incorporation treatment in a long-term may fail to offset N_2O emissions over the SOC stocks. Thus, more practices could be adopted along with residue incorporation instead of relying on only crop residue incorporation.

4. The soil GHGs drivers

It follows that, N_2O is mainly emitted from agricultural soils by denitrification and nitrification processes. Oxygen is an efficient electron acceptor for soil microorganisms than NO_3^-, but under anaerobic soil conditions denitrifying bacteria start to utilise NO_3^- as an energy source. Consequently, under anaerobic conditions N_2O will be emitted when denitrification process is not complete (end-product is not N_2). According to (Davidson et al. 2000), N_2O emissions are expected when WFPS is around 70-80 % (Zechmeister-Boltenstern et al. 2018). In addition to this, other soil biological, physical and chemical properties e.g. pH, WFPS, DOC, NH_4, NO_3^-, enzyme activity, N amount, C content of the soil can also induce more N_2O emissions during denitrification processes on INC site compared to REM (Zechmeister-Boltenstern et al. 2018), (Guenet, 2021), (McKenney et al. 1993), (Kaiser et al. 1996). Whereas for nitrification process it is important that there is an aerobic condition with available and/or available NH_4^+ amount, optimum soil temperature, medium soil moisture and neutral pH (range within 6-7) (Zechmeister-Boltenstern et al. 2018).

In addition, authors of Huang et al. 2004 highlighted heterogeneity of soils and microbial hot spots role in N_2O emission: the high growth of microorganisms under crop residue incorporation reduces the oxygen content and results in air-reduced pore space that may result in N_2O emissions. At the same time, crop residue provides C and N to the soil depending on the C/N ratio of the residues that are being incorporated. Thus low C/N ratio on INC part of the field also stimulates more N_2O emissions (Chen et al. 2013), (Huang et al. 2004) in comparison to REM treatment, depending on environmental conditions such as soil temperature and soil moisture (Zechmeister-Boltenstern et al. 2018), (Pilegaard et al. 2006). Therefore, stronger CC values were observed on INC treatment between the N_2O flux and with total soil N, WFPS, N stocks, C/N ratio in comparison

to removal of crop residue treatment in May with not as strong CC (Appendix 6). Only in May, in a very minor extent, N_2O sink was observed on INC part of the field, and it might be mostly due to N_2O reductase activity. In April, there were higher CC between the enzyme activity (LAP activity), NH_4, total soil N, WFPS, N stocks, C/N ratio, pH and N_2O flux on INC treatment relative to REM. For instance, crop residue decomposition rate is influenced by pH of soils, and N availability for denitrification and nitrification processes will be also linked with pH of the certain soil type (Chen et al. 2013). In the same research by (Chen et al. 2013), C and N contents of soil were found to stimulate N_2O emissions.

The largest terrestrial source of CO_2 to the atmosphere is soil respiration, where CO_2 is being respired by soil aerobic microorganisms, plant roots, etc (Zechmeister-Boltenstern et al. 2018). Hence, available C and N contents will accelerate soil microbial respiration and output larger CO_2 to the atmosphere. However, soil temperature increase until a certain point will lead to higher CO_2 flux (Zechmeister-Boltenstern et al. 2018), it was also depicted in Figure 8, and in mid-spring where CO_2 flux drastically increased on both treatments (Figure 7). Nonetheless, C/Nmic, TDN, LAP activity, pH, DMC and CO_2 flux had higher CC on INC part compared to REM treatment part in April (Figure 9).

Further, it is known that ammonia monooxygenase and methane monooxygenase prefer NH_4^+ over CH_4 if there is a sufficient NH_4^+. In April, higher NH_4 were on REM part of the field compared to INC (Table 4). Accordingly, CC between amount of NH_4 and CH_4 fluxes were only $r^2(4) = 0.13$ compared to INC treatment with $r^2(4) = 0.99$ (Figure 9). Also, the higher content of NH_4 on REM treatment might explain the lesser amount of CH_4 sink relative to INC treatment in April (Figure 7). Later in May, both treatments had less amount of NH_4 compared to April (Table 3). Therefore, there was a lot active CH_4 sink in May in comparison to April (Figure 7). Also in May, REM still had more NH_4 than INC treatment, thus CC between the NH_4 and CH_4 sink were similar to April: REM had $r^2(4) = 0.03$, and INC had $r^2(4) = 0.82$ (Figure 9).

In Figure 9 and Appendix 6, the linear relations between all soil parameters and GHG fluxes (N_2O, CO_2, CH_4) were significant on both treatments. In May, more positive (0 <) CC were found on the INC compared to REM treatment. Nonetheless, small size of sample size was used for correlation matrix (Figure 9) that must be also taken into account. (e.g., correlation coefficients between WFPS and C/N ratio, SOC and Total C, etc.).

In general, all hypotheses of this work were confirmed. First, the incorporation of crop residue resulted in overall higher flux of N_2O, and rmANOVA showed significant interaction between the two treatments (INC, REM) and the measurement periods (p-value = 0.04). Second, no contradictory observations were found to reject the second hypothesis, residue incorporation and removal of residue had no influence on CH_4 fluxes.

Conclusions

In this work, the GHG fluxes under the two treatments, crop residue incorporation and removal of crop residue, were compared during the non-vegetation-growth periods. The crop residue incorporation treatment in the research area was found to maintain SOC stocks in a long term (Spiegel et al. 2018), but as a result, residue incorporation found to induce more N_2O emission. Further, incorporation of crop residue and removal of residues had no difference in their CO_2 and CH_4 fluxes during non-vegetation-growth periods. Instead, increase in soil temperature induced more CO_2 fluxes compared to N_2O and CH_4 on both treatments (INC, REM). Similarly, increase in soil moisture was positively correlated with more N_2O emissions.

On the one hand, crop residue incorporation treatment has positive influences on soil properties (e.g., increase in C and N content) and improves soil quality. Thus, better soil quality is an essential asset to sustain food productivity. At the same time, crop residue incorporation maintains SOC stocks compared to removal of crop residues (Spiegel et al. 2018). On the other hand, according to the results of this work, it is hard to conclude that crop residue incorporation may be the method for mitigating climate change. Further, increase in temperature in near decades ("AR5 Synthesis Report: Climate Change 2014 — IPCC") may increase decomposition rate of residues, and that would shorten the time when soils are being covered by residues. In addition, comparing GHG fluxes (CO_2, N_2O and CH_4) during vegetation-growth periods with non-vegetation-growth periods, and capturing fertilization and tillage events might help to get overall picture of the trade-offs between N_2O emissions and long-term crop residue incorporation treatment. Therefore, quantifying the GHG emissions from croplands are needed for making climate policy, which later will directly influence the mitigation and adaptation actions in real life.

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List of Abbreviations & Acronyms

AMC – aminomethlcoumarin

BFW - Bundesforschungszentrum für Wald

CC – correlation coefficient,

CH_4 – methane,

C_{mic} - microbial C,

CO_2 – carbon dioxide

CO_2 eq. – carbon dioxide (CO_2) equivalent,

COP21 - Conference of the Parties,

CR – crop residue,

C_t - total C (EA analysis),

DOC - dissolved organic carbon,

EGD – European Green Deal,

EU – European Union,

FAO – Food and Agriculture Organization,

GC – Gas Chromatography,

GHG – greenhouse gas,

GWP – global warming potential,

ICR – incorporation of crop residue,

INC – crop residue incorporation,

LTFE – a long-term field experiment,

N_2O – nitrous oxide,

N_2OR – nitrous oxide reductase,

N_{mic} - microbial N,

N_t – total soil N,

PCA– Principal component analysis,

REM – removal of crop residue,

SE – standard error,

SOC – soil organic carbon,

TIC – inorganic carbon,

TIN – total dissolved nitrogen,

UN – United Nations,

WRB – the World Reference Base.

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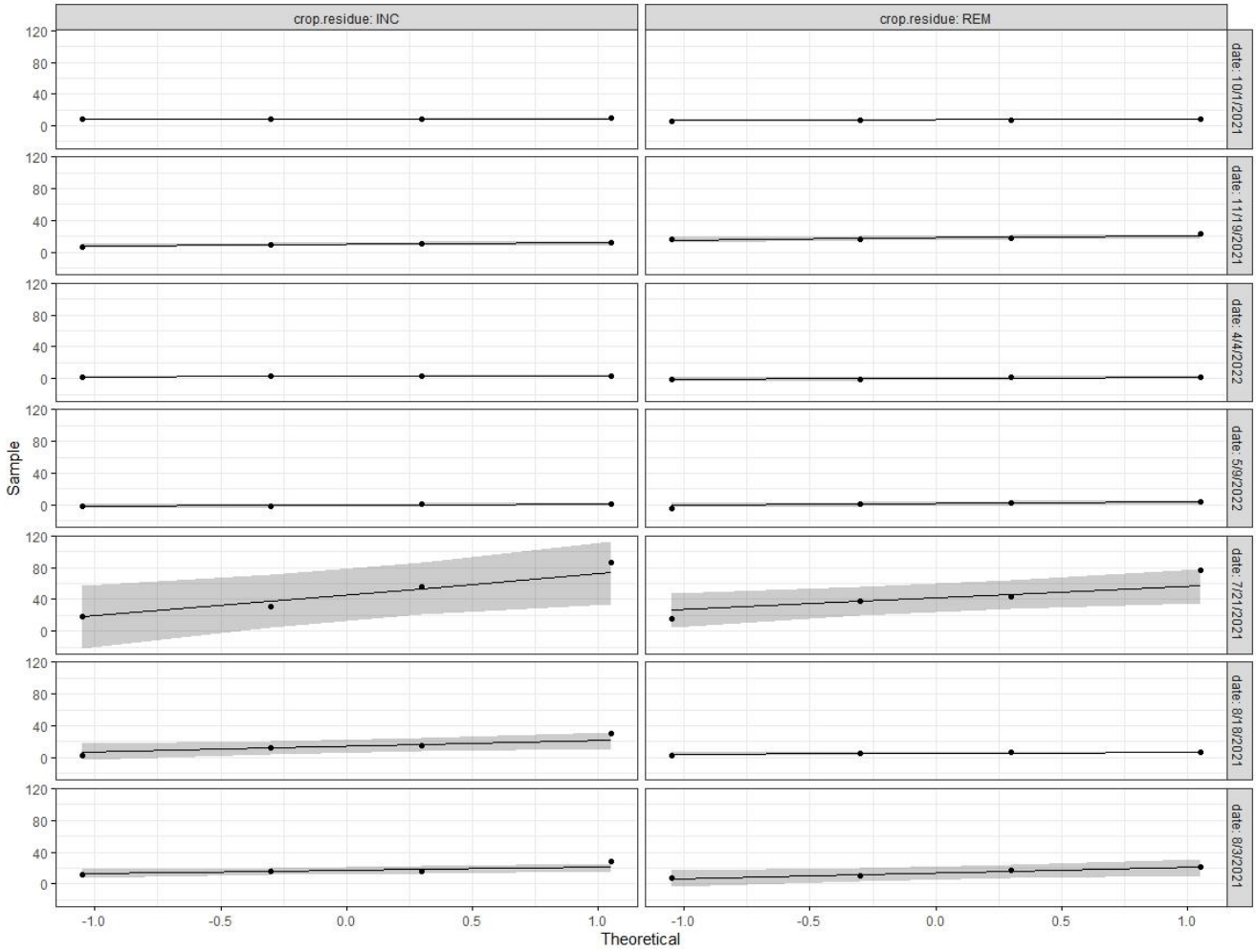
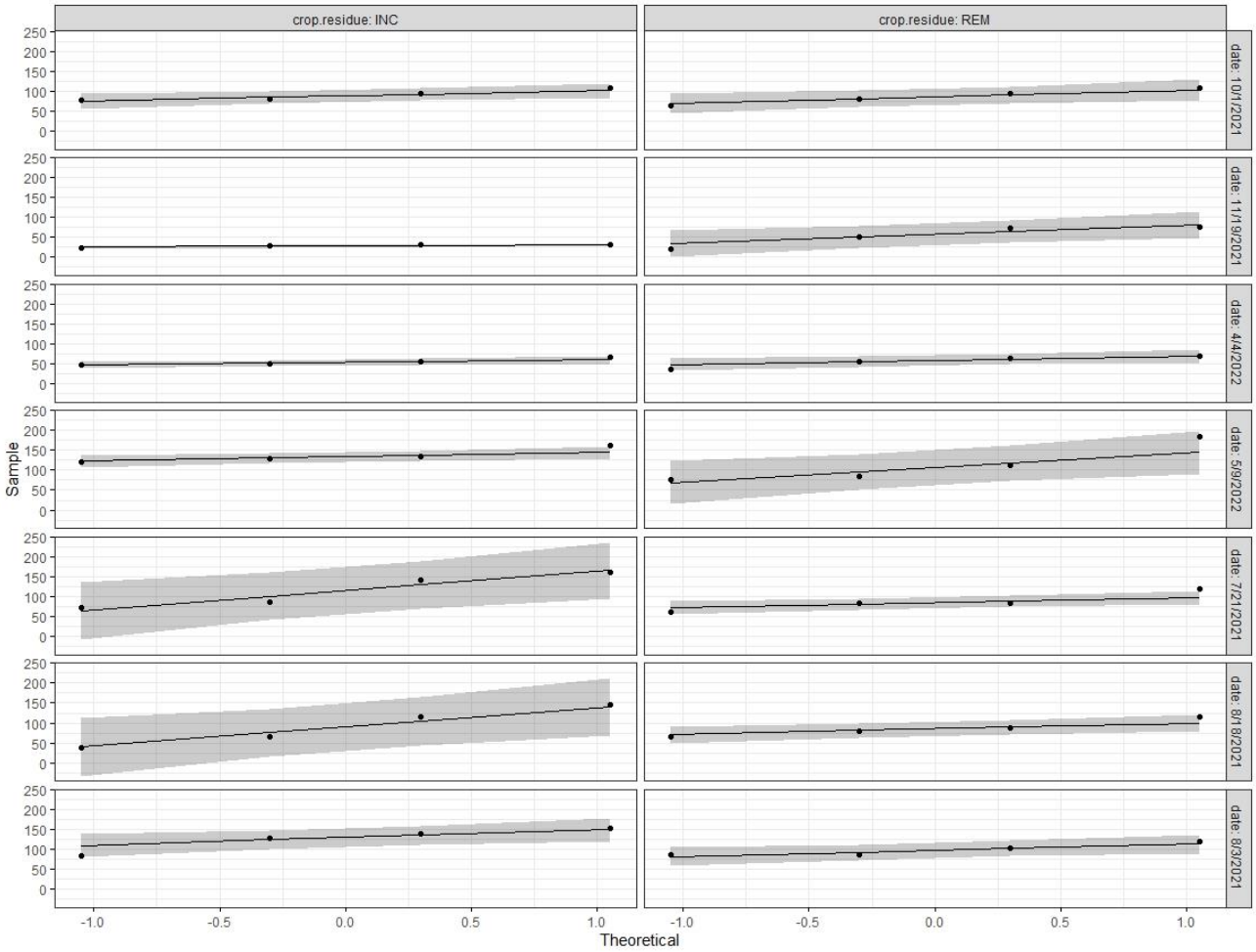
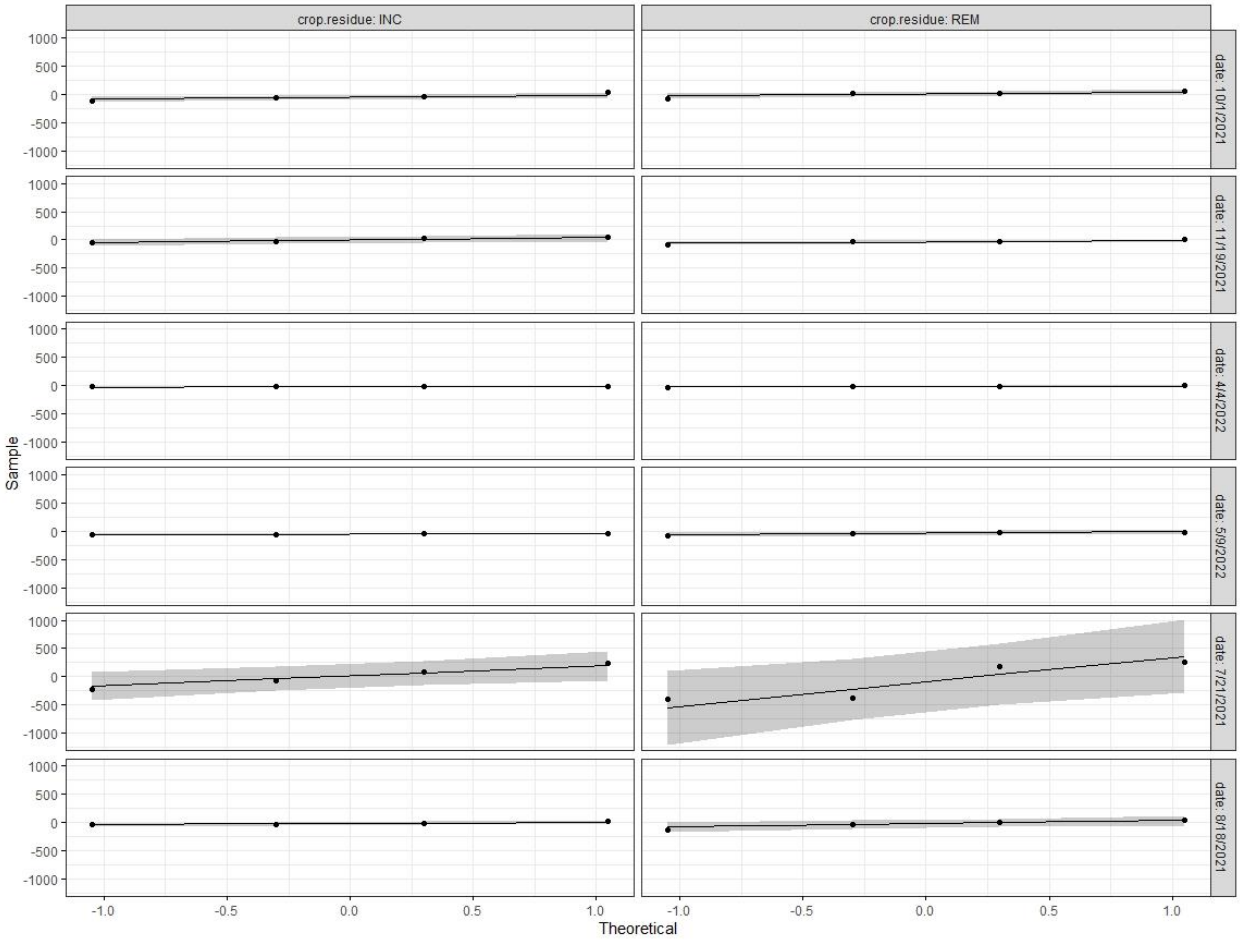
Appendix 1. QQ normal plots of soil GHG measurements.



a) QQ normal plots of N_2O fluxes



b) QQ normal plots of CO_2 fluxes



c) QQ normal plots of CH_4 fluxes

Appendix 2. Outlier data points. All non-extreme outliers are included in the data.

No	Crop residue	Date	Flux	GHG	Is outlier	Is extreme outlier
1	INC	8/3/2021	28.711	N_2O	True	False
2	REM	8/18/2021	2.046	N_2O	True	False
3	INC	10/1/2021	9.047	N_2O	True	False
4	INC	5/9/2022	162.79	CO_2	True	False
5	INC	8/3/2021	354.343	CH_4	True	False
6	INC	4/4/2022	-18.51	CH_4	True	False
7	REM	4/4/2022	-31.114	CH_4	True	False

Appendix 3. Levene Test for equality of variances.

```
> leveneTest(N2O.flux ~ crop.residue, data=flux)
Levene's Test for Homogeneity of Variance (center = median)
      Df F value Pr(>F)
group  1  0.0391  0.844
      54
```

```
> leveneTest(CH4.flux ~ crop.residue, data=flux_ch4)
Levene's Test for Homogeneity of Variance (center = median)
      Df F value Pr(>F)
group  1  1.2411 0.2711
      46
```

```
> leveneTest(CO2.flux ~ crop.residue, data=flux)
Levene's Test for Homogeneity of Variance (center = median)
      Df F value   Pr(>F)
group  1  7.7233 0.007485 **
      54
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

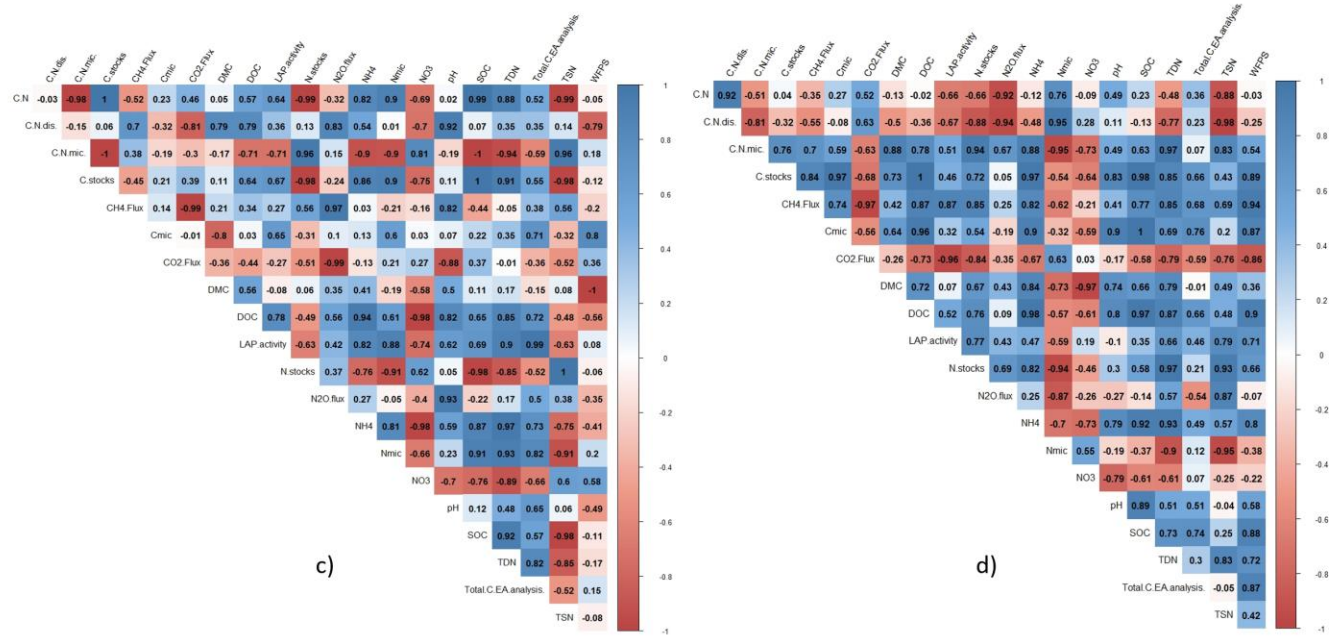
Appendix 4. Pairwise t.test results: CH_4 flux data.

	crop.residue	.y.	group1	group2	n1	n2	p	p.signif	p.adj	p.adj.signif
1	INC	CH4.flux..ug.CH4.C.m.2.h.1.	10/1/2021	11/19/2021	4	4	0.5500	ns	1.000	ns
2	INC	CH4.flux..ug.CH4.C.m.2.h.1.	10/1/2021	4/4/2022	4	4	0.7670	ns	1.000	ns
3	INC	CH4.flux..ug.CH4.C.m.2.h.1.	11/19/2021	4/4/2022	4	4	0.7620	ns	1.000	ns
4	INC	CH4.flux..ug.CH4.C.m.2.h.1.	10/1/2021	7/21/2021	4	4	0.4290	ns	1.000	ns
5	INC	CH4.flux..ug.CH4.C.m.2.h.1.	11/19/2021	7/21/2021	4	4	0.8440	ns	1.000	ns
6	INC	CH4.flux..ug.CH4.C.m.2.h.1.	4/4/2022	7/21/2021	4	4	0.6180	ns	1.000	ns
7	INC	CH4.flux..ug.CH4.C.m.2.h.1.	10/1/2021	8/18/2021	4	4	0.6960	ns	1.000	ns
8	INC	CH4.flux..ug.CH4.C.m.2.h.1.	11/19/2021	8/18/2021	4	4	0.8350	ns	1.000	ns
9	INC	CH4.flux..ug.CH4.C.m.2.h.1.	4/4/2022	8/18/2021	4	4	0.9250	ns	1.000	ns
10	INC	CH4.flux..ug.CH4.C.m.2.h.1.	7/21/2021	8/18/2021	4	4	0.6860	ns	1.000	ns
11	INC	CH4.flux..ug.CH4.C.m.2.h.1.	10/1/2021	8/3/2021	4	4	0.0267	*	0.400	ns
12	INC	CH4.flux..ug.CH4.C.m.2.h.1.	11/19/2021	8/3/2021	4	4	0.0879	ns	1.000	ns
13	INC	CH4.flux..ug.CH4.C.m.2.h.1.	4/4/2022	8/3/2021	4	4	0.0489	*	0.685	ns
14	INC	CH4.flux..ug.CH4.C.m.2.h.1.	7/21/2021	8/3/2021	4	4	0.1260	ns	1.000	ns
15	INC	CH4.flux..ug.CH4.C.m.2.h.1.	8/18/2021	8/3/2021	4	4	0.0589	ns	0.766	ns
16	REM	CH4.flux..ug.CH4.C.m.2.h.1.	10/1/2021	11/19/2021	4	4	0.7470	ns	1.000	ns
17	REM	CH4.flux..ug.CH4.C.m.2.h.1.	10/1/2021	4/4/2022	4	4	0.8750	ns	1.000	ns
18	REM	CH4.flux..ug.CH4.C.m.2.h.1.	11/19/2021	4/4/2022	4	4	0.8690	ns	1.000	ns
19	REM	CH4.flux..ug.CH4.C.m.2.h.1.	10/1/2021	7/21/2021	4	4	0.4490	ns	1.000	ns
20	REM	CH4.flux..ug.CH4.C.m.2.h.1.	11/19/2021	7/21/2021	4	4	0.6600	ns	1.000	ns
21	REM	CH4.flux..ug.CH4.C.m.2.h.1.	4/4/2022	7/21/2021	4	4	0.5470	ns	1.000	ns
22	REM	CH4.flux..ug.CH4.C.m.2.h.1.	10/1/2021	8/18/2021	4	4	0.7550	ns	1.000	ns
23	REM	CH4.flux..ug.CH4.C.m.2.h.1.	11/19/2021	8/18/2021	4	4	0.9930	ns	1.000	ns
24	REM	CH4.flux..ug.CH4.C.m.2.h.1.	4/4/2022	8/18/2021	4	4	0.8770	ns	1.000	ns
25	REM	CH4.flux..ug.CH4.C.m.2.h.1.	7/21/2021	8/18/2021	4	4	0.6530	ns	1.000	ns
26	REM	CH4.flux..ug.CH4.C.m.2.h.1.	10/1/2021	8/3/2021	4	4	0.3340	ns	1.000	ns
27	REM	CH4.flux..ug.CH4.C.m.2.h.1.	11/19/2021	8/3/2021	4	4	0.2030	ns	1.000	ns
28	REM	CH4.flux..ug.CH4.C.m.2.h.1.	4/4/2022	8/3/2021	4	4	0.2640	ns	1.000	ns
29	REM	CH4.flux..ug.CH4.C.m.2.h.1.	7/21/2021	8/3/2021	4	4	0.0940	ns	1.000	ns
30	REM	CH4.flux..ug.CH4.C.m.2.h.1.	8/18/2021	8/3/2021	4	4	0.2060	ns	1.000	ns

Appendix 5. Pairwise t.test results: N_2O flux data.

```
Error: id
          Df Sum Sq Mean Sq F value Pr(>F)
Residuals  1  248.9   248.9

Error: id:crop.residue
             Df Sum Sq Mean Sq
crop.residue  1   6.56    6.56

Error: id:date
     Df Sum Sq Mean Sq
date  6   7254    1209

Error: id:crop.residue:date
                  Df Sum Sq Mean Sq
crop.residue:date  6  344.1   57.35

Error: Within
                  Df Sum Sq Mean Sq F value   Pr(>F)
crop.residue       1    551   550.6   6.245   0.0186 *
date               6   4770   795.0   9.017 1.61e-05 ***
crop.residue:date  6   1379   229.8   2.606   0.0391 *
Residuals         28   2469    88.2
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Appendix 6. Correlation matrix: soil GHG fluxes (CO_2, N_2O, CH_4) and soil parameters data. The figure order: c. REM in May; d. INC in May.



Appendix 7. P-values of correlation coefficient between soil parameters and soil GHGs (CO_2, CH_4 and N_2O) on INC, data from April soil lab analysis.

	pH	DMC	WFPS	NH4	NO3	DOC	TDN	Cmic	Nmic	LAP.activity	total.C.EA.analysis.
pH	0.000000e+00	1.541110e-01	1.008697e-12	7.410088e-01	1.863977e-03	2.088824e-02	2.814263e-03	1.749706e-02	2.616045e-03	2.469171e-06	1.682750e-09
DMC	1.541110e-01	0.000000e+00	3.275762e-02	9.663830e-02	7.780864e-03	1.179270e-02	5.636760e-02	5.264803e-03	1.847854e-01	2.857714e-01	3.106886e-01
WFPS	1.008697e-12	3.275762e-02	0.000000e+00	1.633624e-01	8.598291e-06	2.289375e-01	6.815054e-02	1.846058e-01	7.122320e-02	1.427876e-04	7.864377e-06
NH4	7.410088e-01	9.663830e-02	1.633624e-01	0.000000e+00	8.728647e-06	1.398069e-03	4.546376e-03	8.841084e-03	6.709421e-04	8.239476e-01	1.902086e-01
NO3	1.863977e-03	7.780864e-03	8.598291e-06	8.728647e-06	0.000000e+00	2.496211e-01	5.346199e-01	4.010812e-01	4.078054e-01	8.233415e-02	1.624214e-01
DOC	2.088824e-02	1.179270e-02	2.289375e-01	1.398069e-03	2.496211e-01	0.000000e+00	2.045078e-17	4.910087e-18	3.009823e-12	3.244800e-05	6.605920e-04
TDN	2.814263e-03	5.636760e-02	6.815054e-02	4.546376e-03	5.346199e-01	2.045078e-17	0.000000e+00	9.779392e-15	4.483491e-15	2.637038e-06	3.247620e-05
Cmic	1.749706e-02	5.264803e-03	1.846058e-01	8.841084e-03	4.010812e-01	4.910087e-18	9.779392e-15	0.000000e+00	1.306492e-09	3.406295e-06	1.366556e-03
Nmic	2.616045e-03	1.847854e-01	7.122320e-02	6.709421e-04	4.078054e-01	3.009823e-12	4.483491e-15	1.306492e-09	0.000000e+00	7.641052e-05	3.880927e-06
LAP.activity	2.469171e-06	2.857714e-01	1.427876e-04	8.239476e-01	8.233415e-02	3.244800e-05	2.637038e-06	3.406295e-06	7.641052e-05	0.000000e+00	3.240607e-05
total.C.EA.analysis.	1.682750e-09	3.106886e-01	7.864377e-06	1.902086e-01	1.624214e-01	6.605920e-04	3.247620e-05	1.366556e-03	3.880927e-06	3.240607e-05	0.000000e+00
SOC	3.366013e-11	4.422820e-01	1.514013e-06	3.120262e-01	9.765544e-02	3.978585e-04	1.533177e-05	5.863386e-04	4.683184e-06	1.476323e-06	4.986739e-19
TSN	9.455925e-01	2.777895e-10	5.564568e-01	1.774430e-01	1.511229e-01	2.558983e-04	1.868137e-03	3.183515e-05	2.047604e-02	8.240285e-03	7.930492e-01
C.stocks	3.622198e-11	4.046011e-01	1.468659e-06	3.073010e-01	9.770709e-02	4.928416e-04	2.041506e-05	7.530005e-04	5.588165e-06	2.508156e-06	3.625953e-20
N.stocks	8.258561e-01	6.812974e-12	3.876093e-01	1.829474e-01	1.081561e-01	7.305527e-04	4.746944e-03	1.246194e-04	3.865735e-02	1.976046e-02	9.845867e-01
C.N	2.993428e-02	7.107501e-04	1.811317e-01	1.361982e-01	7.753673e-01	9.490349e-09	4.873993e-08	9.292966e-12	1.922528e-05	3.458461e-07	1.553736e-02
C.N.mic.	1.068573e-02	1.880876e-02	1.511564e-01	2.767016e-03	3.558577e-01	1.093245e-25	1.262737e-20	1.470561e-18	8.641981e-13	9.397838e-06	2.852650e-04
C.N.dis.	7.966855e-06	5.084530e-01	1.889158e-03	3.730879e-02	6.894295e-01	1.912374e-08	1.341422e-11	6.441103e-08	6.291291e-12	1.387990e-07	1.859716e-09
CH4.Flux	4.883757e-01	1.997794e-01	8.674534e-02	1.638457e-17	2.130199e-06	1.200053e-02	2.793299e-02	5.038096e-02	5.343570e-03	7.240166e-01	3.325426e-01
CO2.Flux	1.185461e-02	5.209363e-02	1.746662e-01	3.652460e-04	2.401081e-01	3.357937e-17	2.360559e-17	3.337261e-12	8.006235e-18	1.057708e-04	9.878378e-05
N2O.Flux	5.565891e-05	3.160626e-01	1.473486e-04	2.770077e-01	7.209119e-03	6.758492e-03	2.286188e-03	1.184775e-03	1.860110e-02	7.673746e-11	4.574930e-03

Appendix 8. P-values of correlation coefficient between soil parameters and soil GHGs (CO_2, CH_4 and N_2O) on REM, data from April soil lab analysis.

	pH	DMC	WFPS	NH4	NO3	DOC	TDN	Cmic	Nmic	LAP.activity	total.C.EA.analysis.
pH	0.000000e+00	1.541110e-01	1.008697e-12	7.410088e-01	1.863977e-03	2.088824e-02	2.814263e-03	1.749706e-02	2.616045e-03	2.469171e-06	1.682750e-09
DMC	1.541110e-01	0.000000e+00	3.275762e-02	9.663830e-02	7.780864e-03	1.179270e-02	5.636760e-02	5.264803e-03	1.847854e-01	2.857714e-01	3.106886e-01
WFPS	1.008697e-12	3.275762e-02	0.000000e+00	1.633624e-01	8.598291e-06	2.289375e-01	6.815054e-02	1.846058e-01	7.122320e-02	1.427876e-04	7.864377e-06
NH4	7.410088e-01	9.663830e-02	1.633624e-01	0.000000e+00	8.728647e-06	1.398069e-03	4.546376e-03	8.841084e-03	6.709421e-04	8.239476e-01	1.902086e-01
NO3	1.863977e-03	7.780864e-03	8.598291e-06	8.728647e-06	0.000000e+00	2.496211e-01	5.346199e-01	4.010812e-01	4.078054e-01	8.233415e-02	1.624214e-01
DOC	2.088824e-02	1.179270e-02	2.289375e-01	1.398069e-03	2.496211e-01	0.000000e+00	2.045078e-17	4.910087e-18	3.009823e-12	3.244800e-05	6.605920e-04
TDN	2.814263e-03	5.636760e-02	6.815054e-02	4.546376e-03	5.346199e-01	2.045078e-17	0.000000e+00	9.779392e-15	4.483491e-15	2.637038e-06	3.247620e-05
Cmic	1.749706e-02	5.264803e-03	1.846058e-01	8.841084e-03	4.010812e-01	4.910087e-18	9.779392e-15	0.000000e+00	1.306492e-09	3.406295e-06	1.366556e-03
Nmic	2.616045e-03	1.847854e-01	7.122320e-02	6.709421e-04	4.078054e-01	3.009823e-12	4.483491e-15	1.306492e-09	0.000000e+00	7.641052e-05	3.880927e-06
LAP.activity	2.469171e-06	2.857714e-01	1.427876e-04	8.239476e-01	8.233415e-02	3.244800e-05	2.637038e-06	3.406295e-06	7.641052e-05	0.000000e+00	3.240607e-05
total.C.EA.analysis.	1.682750e-09	3.106886e-01	7.864377e-06	1.902086e-01	1.624214e-01	6.605920e-04	3.247620e-05	1.366556e-03	3.880927e-06	3.240607e-05	0.000000e+00
SOC	3.366013e-11	4.422820e-01	1.514013e-06	3.120262e-01	9.765544e-02	3.978585e-04	1.533177e-05	5.863386e-04	4.683184e-06	1.476323e-06	4.986739e-19
TSN	9.455925e-01	2.777895e-10	5.564568e-01	1.774430e-01	1.511229e-01	2.558983e-04	1.868137e-03	3.183515e-05	2.047604e-02	8.240285e-03	7.930492e-01
C.stocks	3.622198e-11	4.046011e-01	1.468659e-06	3.073010e-01	9.770709e-02	4.928416e-04	2.041506e-05	7.530005e-04	5.588165e-06	2.508156e-06	3.625953e-20
N.stocks	8.258561e-01	6.812974e-12	3.876093e-01	1.829474e-01	1.081561e-01	7.305527e-04	4.746944e-03	1.246194e-04	3.865735e-02	1.976046e-02	9.845867e-01
C.N	2.993428e-02	7.107501e-04	1.811317e-01	1.361982e-01	7.753673e-01	9.490349e-09	4.873993e-08	9.292966e-12	1.922528e-05	3.458461e-07	1.553736e-02
C.N.mic.	1.068573e-02	1.880876e-02	1.511564e-01	2.767016e-03	3.558577e-01	1.093245e-25	1.262737e-20	1.470561e-18	8.641981e-13	9.397838e-06	2.852650e-04
C.N.dis.	7.966855e-06	5.084530e-01	1.889158e-03	3.730879e-02	6.894295e-01	1.912374e-08	1.341422e-11	6.441103e-08	6.291291e-12	1.387990e-07	1.859716e-09
CH4.Flux	4.883757e-01	1.997794e-01	8.674534e-02	1.638457e-17	2.130199e-06	1.200053e-02	2.793299e-02	5.038096e-02	5.343570e-03	7.240166e-01	3.325426e-01

	SOC	TSN	C.stocks	N.stocks	C.N	C.N.mic.	C.N.dis.	CH4.Flux	CO2.Flux	N2O.Flux
pH	3.366013e-11	9.455925e-01	3.622198e-11	8.258561e-01	2.993428e-02	1.068573e-02	7.966855e-06	4.883757e-01	1.185461e-02	5.565891e-05
DMC	4.422820e-01	2.777895e-10	4.046011e-01	6.812974e-12	7.107501e-04	1.880876e-02	5.084530e-01	1.997794e-01	5.209363e-02	3.160626e-01
WFPS	1.514013e-06	5.564568e-01	1.468659e-06	3.876093e-01	1.811317e-01	1.511564e-01	1.889158e-03	8.674534e-02	1.746662e-01	1.473486e-04
NH4	3.120262e-01	1.774430e-01	3.073010e-01	1.829474e-01	1.361982e-01	2.767016e-03	3.730879e-02	1.638457e-17	3.652460e-04	2.770077e-01
NO3	9.765544e-02	1.511229e-01	9.770709e-02	1.081561e-01	7.753673e-01	3.558577e-01	6.894295e-01	2.130199e-06	2.401081e-01	7.209119e-03
DOC	3.978585e-04	2.558983e-04	4.928416e-04	7.305527e-04	9.490349e-09	1.093245e-25	1.912374e-08	1.200053e-02	3.357937e-17	6.758492e-03
TDN	1.533177e-05	1.868137e-03	2.041506e-05	4.746944e-03	4.873993e-08	1.262737e-20	1.341422e-11	2.793299e-02	2.360559e-17	2.286188e-03
Cmic	5.863386e-04	3.183515e-05	7.530005e-04	1.246194e-04	9.292966e-12	1.470561e-18	6.441103e-08	5.038096e-02	3.337261e-12	1.184775e-03
Nmic	4.683184e-06	2.047604e-02	5.588165e-06	3.865735e-02	1.922528e-05	8.641981e-13	6.291291e-12	5.343570e-03	8.006235e-18	1.860110e-02
LAP.activity	1.476323e-06	8.240285e-03	2.508156e-06	1.976046e-02	3.458461e-07	9.397838e-06	1.387990e-07	7.240166e-01	1.057708e-04	7.673746e-11
total.C.EA.analysis.	4.986739e-19	7.930492e-01	3.625953e-20	9.845867e-01	1.553736e-02	2.852650e-04	1.859716e-09	3.325426e-01	9.878378e-05	4.574930e-03
SOC	0.000000e+00	5.618406e-01	1.139250e-34	7.701581e-01	5.214160e-03	1.498696e-04	3.149943e-10	5.324441e-01	8.743471e-05	6.123255e-04
TSN	5.618406e-01	0.000000e+00	6.104102e-01	1.043084e-23	1.347099e-07	3.936387e-04	5.473443e-02	4.105217e-01	3.402931e-03	1.154081e-02
C.stocks	1.139250e-34	6.104102e-01	0.000000e+00	8.242258e-01	6.646332e-03	1.912257e-04	5.545330e-10	5.202913e-01	1.049924e-04	8.211396e-04
N.stocks	7.701581e-01	1.043084e-23	8.242258e-01	0.000000e+00	1.261867e-06	1.128959e-03	1.021809e-01	4.057923e-01	7.385915e-03	2.370679e-02
C.N	5.214160e-03	1.347099e-07	6.646332e-03	1.261867e-06	0.000000e+00	5.981664e-09	2.013021e-05	3.887231e-01	1.473511e-06	2.774600e-05
C.N.mic.	1.498696e-04	3.936387e-04	1.912257e-04	1.128959e-03	5.981664e-09	0.000000e+00	2.489033e-09	2.003068e-02	4.497186e-17	3.561537e-03
C.N.dis.	3.149943e-10	5.473443e-02	5.545330e-10	1.021809e-01	2.013021e-05	2.489033e-09	0.000000e+00	1.198325e-01	1.194075e-09	6.286480e-04
CH4.Flux	5.324441e-01	4.105217e-01	5.202913e-01	4.057923e-01	3.887231e-01	2.003068e-02	1.198325e-01	0.000000e+00	3.879321e-03	8.895444e-02
CO2.Flux	8.743471e-05	3.402931e-03	1.049924e-04	7.385915e-03	1.473511e-06	4.497186e-17	1.194075e-09	3.879321e-03	0.000000e+00	1.864874e-02
N2O.Flux	6.123255e-04	1.154081e-02	8.211396e-04	2.370679e-02	2.774600e-05	3.561537e-03	6.286480e-04	8.895444e-02	1.864874e-02	0.000000e+00

Appendix 9. P-values of correlation coefficient between soil parameters and soil GHGs (CO_2, CH_4 and N_2O) on INC, data from May soil lab analysis.

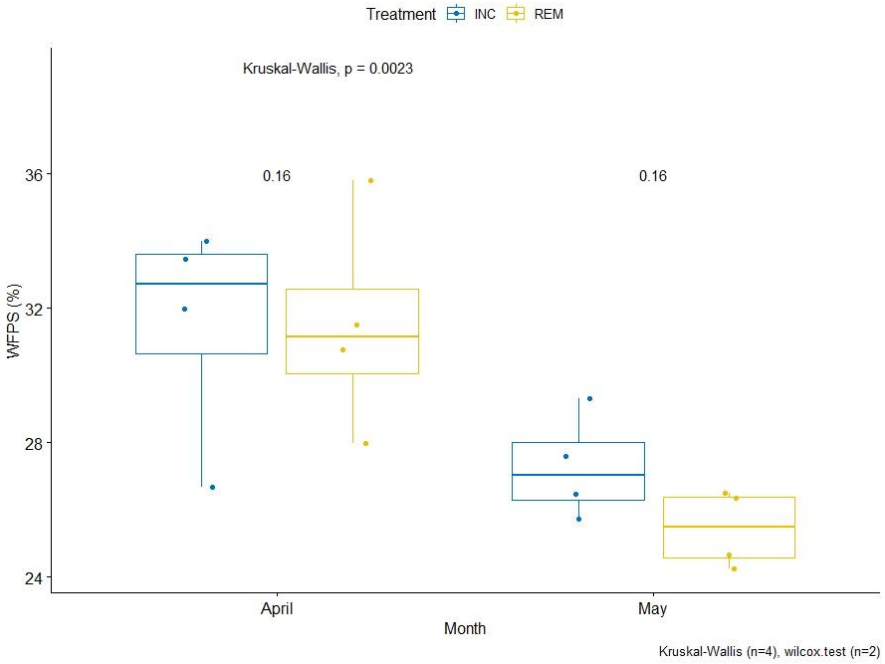
	pH	DMC	WFPS	NH4	NO3	DOC	TDN	Cmic	Nmic	LAP.activity	Total.C.EA.analysis.
pH	0.000000e+00	2.503036e-04	2.663777e-04	5.068929e-03	3.734994e-04	1.294506e-05	3.032368e-02	0.7684834538	2.766395e-01	5.842368e-03	2.651218e-03
DMC	2.503036e-04	0.000000e+00	1.098745e-48	4.617569e-02	5.146348e-03	2.348806e-03	2.367358e-01	0.0007951165	9.798303e-01	4.339972e-01	5.200340e-01
WFPS	2.663777e-04	1.098745e-48	0.000000e+00	4.631947e-02	5.187016e-03	2.391118e-03	2.371175e-01	0.0007695274	9.797307e-01	4.369036e-01	5.242908e-01
NH4	5.068929e-03	4.617569e-02	4.631947e-02	0.000000e+00	1.674983e-15	2.590921e-11	1.577388e-15	0.2054117646	5.235899e-08	8.833199e-10	9.240224e-08
NO3	3.734994e-04	5.146348e-03	5.187016e-03	1.674983e-15	0.000000e+00	4.135711e-17	5.781729e-10	0.5158281439	1.545111e-05	8.274738e-08	1.250631e-06
DOC	1.294506e-05	2.348806e-03	2.391118e-03	2.590921e-11	4.135711e-17	0.000000e+00	5.897329e-08	0.5575363191	1.573819e-04	1.543114e-07	7.464172e-07
TDN	3.032368e-02	2.367358e-01	2.371175e-01	1.577388e-15	5.781729e-10	5.897329e-08	0.000000e+00	0.0473412699	6.326425e-12	1.227127e-11	8.755577e-09
Cmic	7.684835e-01	7.951165e-04	7.695274e-04	2.054118e-01	5.158281e-01	5.575363e-01	4.734127e-02	0.0000000000	2.430004e-03	5.223641e-03	2.395130e-03
Nmic	2.766395e-01	9.798303e-01	9.797307e-01	5.235899e-08	1.545111e-05	1.573819e-04	6.326425e-12	0.0024300036	0.000000e+00	2.203564e-09	1.452548e-07
LAP.activity	5.842368e-03	4.339972e-01	4.369036e-01	8.833199e-10	8.274738e-08	1.543114e-07	1.227127e-11	0.0052236409	2.203564e-09	0.000000e+00	1.882917e-18
Total.C.EA.analysis.	2.651218e-03	5.200340e-01	5.242908e-01	9.240224e-08	1.250631e-06	7.464172e-07	8.755577e-09	0.0023951304	1.452548e-07	1.882917e-18	0.000000e+00
SOC	3.234802e-01	5.409117e-01	5.392318e-01	3.826021e-09	2.118603e-06	6.978541e-05	3.319767e-12	0.0490477174	2.560484e-13	4.821119e-07	1.756553e-05
TSN	7.564867e-01	9.506100e-01	9.533255e-01	1.635029e-06	1.461372e-04	1.762515e-03	8.126400e-09	0.0178124478	7.217998e-13	8.818066e-06	1.343658e-04
C.stocks	3.485711e-01	5.469334e-01	5.451121e-01	6.051378e-09	2.759221e-06	8.777572e-05	8.021580e-12	0.0524435194	5.569244e-13	7.675364e-07	2.514306e-05
N.stocks	7.223637e-01	9.892198e-01	9.919023e-01	1.155947e-06	1.138495e-04	1.455839e-03	5.211106e-09	0.0193469140	5.548020e-13	7.325976e-06	1.181389e-04
C.N	5.149345e-01	7.218118e-01	7.193936e-01	8.912917e-08	1.737019e-05	3.606165e-04	2.706545e-10	0.0399627785	8.442688e-13	2.997737e-06	6.742912e-05
C.N.mic.	2.147491e-01	3.955039e-01	3.942988e-01	2.060550e-10	3.043561e-07	1.635476e-05	9.290285e-14	0.0675556340	1.077785e-12	1.700048e-07	8.424958e-06
C.N.dis.	1.370622e-11	1.277872e-07	1.434045e-07	2.026972e-02	1.492296e-03	1.349680e-04	1.176508e-01	0.1159975808	7.088582e-01	7.368706e-02	5.808362e-02
CH4.Flux	3.455468e-04	5.901856e-02	6.077207e-02	5.131489e-01	9.788503e-01	5.383924e-01	2.496646e-01	0.3014459073	4.623375e-02	7.851877e-01	8.803457e-01
CO2.Flux	2.268800e-05	9.579315e-03	9.970650e-03	8.778813e-01	6.046560e-01	2.492225e-01	4.753192e-01	0.1808839665	9.609184e-02	9.758099e-01	6.898999e-01
N2O.flux	5.056604e-08	4.489625e-03	4.711091e-03	4.776057e-01	1.729652e-01	4.263071e-02	8.630278e-01	0.3994106459	4.502864e-01	3.575161e-01	2.003962e-01

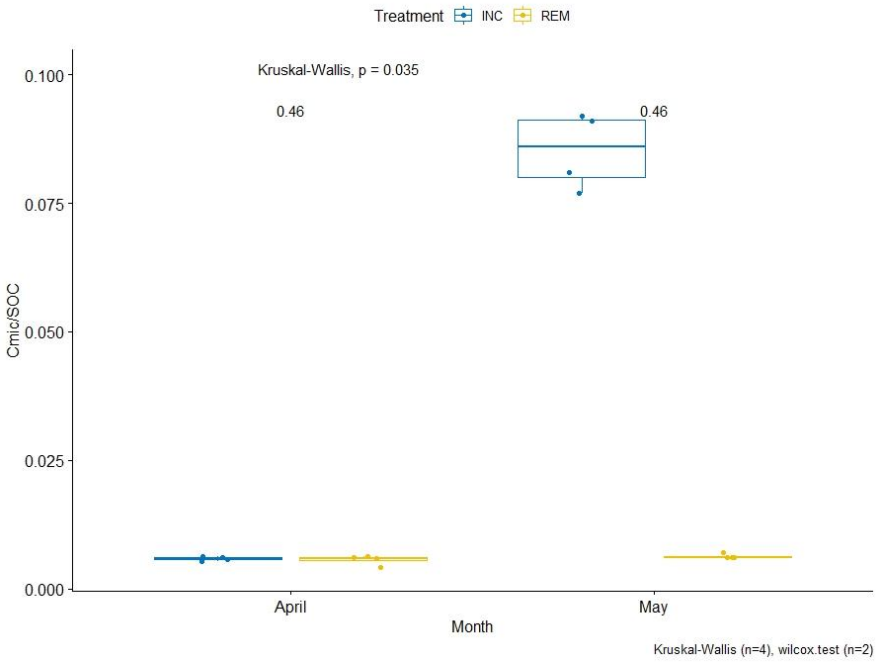
Appendix 10. P-values of correlation coefficient between soil parameters and soil GHGs (CO_2, CH_4 and N_2O) on REM, data from May soil lab analysis.

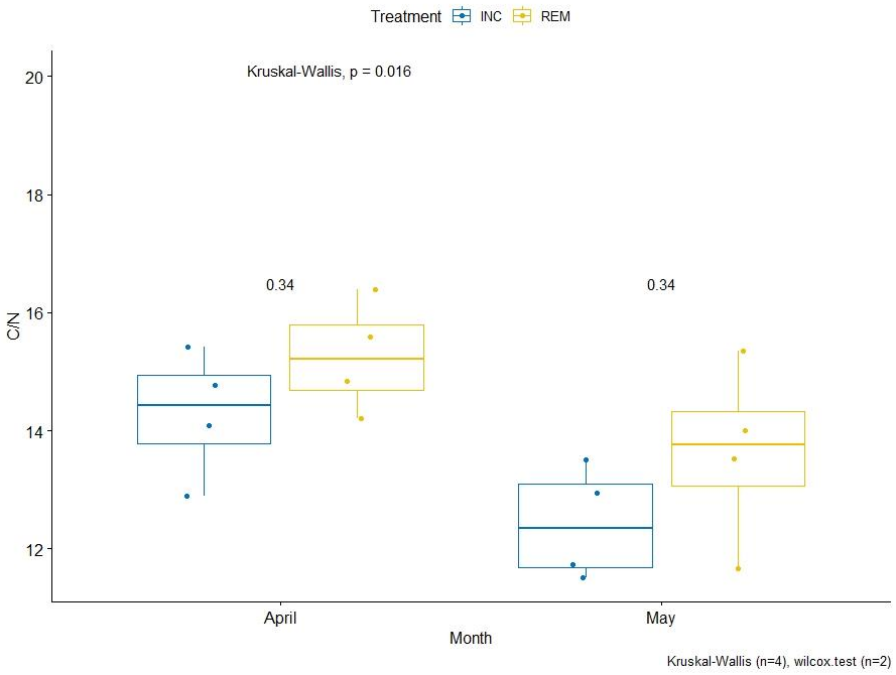
	pH	DMC	WFPS	NH4	NO3	DOC	TDN	Cmic	Nmic	LAP.activity	Total.C.EA.analysis.
pH	0.000000e+00	2.503036e-04	2.663777e-04	5.068929e-03	3.734994e-04	1.294506e-05	3.032368e-02	0.7684834538	2.766395e-01	5.842368e-03	2.651218e-03
DMC	2.503036e-04	0.000000e+00	1.098745e-48	4.617569e-02	5.146348e-03	2.348806e-03	2.367358e-01	0.0007951165	9.798303e-01	4.339972e-01	5.200340e-01
WFPS	2.663777e-04	1.098745e-48	0.000000e+00	4.631947e-02	5.187016e-03	2.391118e-03	2.371175e-01	0.0007695274	9.797307e-01	4.369036e-01	5.242908e-01
NH4	5.068929e-03	4.617569e-02	4.631947e-02	0.000000e+00	1.674983e-15	2.590921e-11	1.577388e-15	0.2054117646	5.235899e-08	8.833199e-10	9.240224e-08
NO3	3.734994e-04	5.146348e-03	5.187016e-03	1.674983e-15	0.000000e+00	4.135711e-17	5.781729e-10	0.5158281439	1.545111e-05	8.274738e-08	1.250631e-06
DOC	1.294506e-05	2.348806e-03	2.391118e-03	2.590921e-11	4.135711e-17	0.000000e+00	5.897329e-08	0.5575363191	1.573819e-04	1.543114e-07	7.464172e-07
TDN	3.032368e-02	2.367358e-01	2.371175e-01	1.577388e-15	5.781729e-10	5.897329e-08	0.000000e+00	0.0473412699	6.326425e-12	1.227127e-11	8.755577e-09
Cmic	7.684835e-01	7.951165e-04	7.695274e-04	2.054118e-01	5.158281e-01	5.575363e-01	4.734127e-02	0.0000000000	2.430004e-03	5.223641e-03	2.395130e-03
Nmic	2.766395e-01	9.798303e-01	9.797307e-01	5.235899e-08	1.545111e-05	1.573819e-04	6.326425e-12	0.0024300036	0.000000e+00	2.203564e-09	1.452548e-07
LAP.activity	5.842368e-03	4.339972e-01	4.369036e-01	8.833199e-10	8.274738e-08	1.543114e-07	1.227127e-11	0.0052236409	2.203564e-09	0.000000e+00	1.882917e-18
Total.C.EA.analysis.	2.651218e-03	5.200340e-01	5.242908e-01	9.240224e-08	1.250631e-06	7.464172e-07	8.755577e-09	0.0023951304	1.452548e-07	1.882917e-18	0.000000e+00
SOC	3.234802e-01	5.409117e-01	5.392318e-01	3.826021e-09	2.118603e-06	6.978541e-05	3.319767e-12	0.0490477174	2.560484e-13	4.821119e-07	1.756553e-05
TSN	7.564867e-01	9.506100e-01	9.533255e-01	1.635029e-06	1.461372e-04	1.762515e-03	8.126400e-09	0.0178124478	7.217998e-13	8.818066e-06	1.343658e-04
C.stocks	3.485711e-01	5.469334e-01	5.451121e-01	6.051378e-09	2.759221e-06	8.777572e-05	8.021580e-12	0.0524435194	5.569244e-13	7.675364e-07	2.514306e-05
N.stocks	7.223637e-01	9.892198e-01	9.919023e-01	1.155947e-06	1.138495e-04	1.455839e-03	5.211106e-09	0.0193469140	5.548020e-13	7.325976e-06	1.181389e-04
C.N	5.149345e-01	7.218118e-01	7.193936e-01	8.912917e-08	1.737019e-05	3.606165e-04	2.706545e-10	0.0399627785	8.442688e-13	2.997737e-06	6.742912e-05
C.N.mic.	2.147491e-01	3.955039e-01	3.942988e-01	2.060550e-10	3.043561e-07	1.635476e-05	9.290285e-14	0.0675556340	1.077785e-12	1.700048e-07	8.424958e-06
C.N.dis.	1.370622e-11	1.277872e-07	1.434045e-07	2.026972e-02	1.492296e-03	1.349680e-04	1.176508e-01	0.1159975808	7.088582e-01	7.368706e-02	5.808362e-02
CH4.Flux	3.455468e-04	5.901856e-02	6.077207e-02	5.131489e-01	9.788503e-01	5.383924e-01	2.496646e-01	0.3014459073	4.623375e-02	7.851877e-01	8.803457e-01

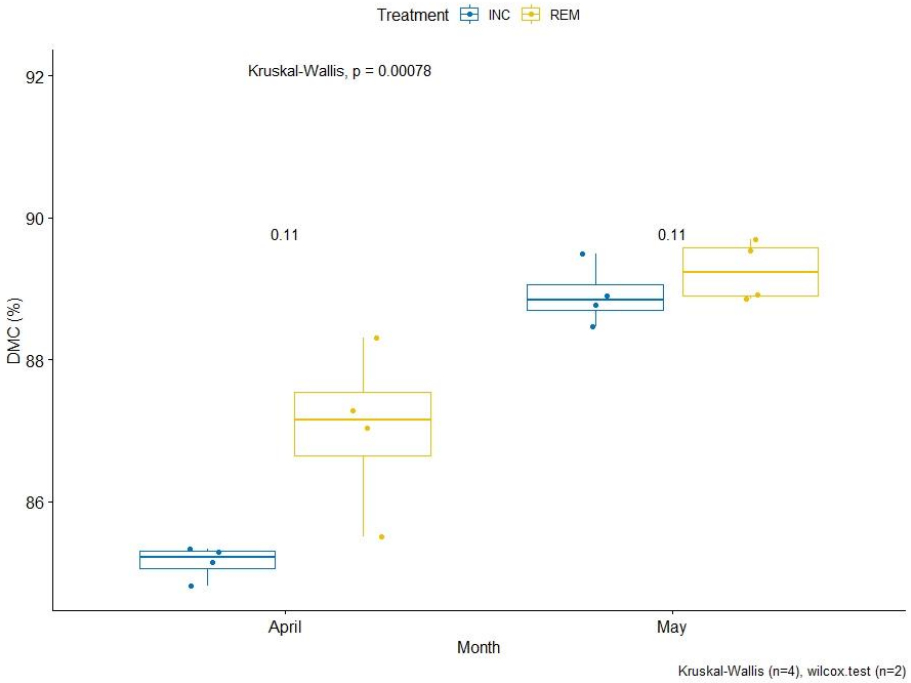
	SOC	TSN	C.stocks	N.stocks	C.N	C.N.mic.	C.N.dis.	CH4.Flux	CO2.Flux	N2O.flux
pH	3.234802e-01	7.564867e-01	3.485711e-01	7.223637e-01	5.149345e-01	2.147491e-01	1.370622e-11	3.455468e-04	2.268800e-05	5.056604e-08
DMC	5.409117e-01	9.506100e-01	5.469334e-01	9.892198e-01	7.218118e-01	3.955039e-01	1.277872e-07	5.901856e-02	9.579315e-03	4.489625e-03
WFPS	5.392318e-01	9.533255e-01	5.451121e-01	9.919023e-01	7.193936e-01	3.942988e-01	1.434045e-07	6.077207e-02	9.970650e-03	4.711091e-03
NH4	3.826021e-09	1.635029e-06	6.051378e-09	1.155947e-06	8.912917e-08	2.060550e-10	2.026972e-02	5.131489e-01	8.778813e-01	4.776057e-01
NO3	2.118603e-06	1.461372e-04	2.759221e-06	1.138495e-04	1.737019e-05	3.043561e-07	1.492296e-03	9.788503e-01	6.046560e-01	1.729652e-01
DOC	6.978541e-05	1.762515e-03	8.777572e-05	1.455839e-03	3.606165e-04	1.635476e-05	1.349680e-04	5.383924e-01	2.492225e-01	4.263071e-02
TDN	3.319767e-12	8.126400e-09	8.021580e-12	5.211106e-09	2.706545e-10	9.290285e-14	1.176508e-01	2.496646e-01	4.753192e-01	8.630278e-01
Cmic	4.904772e-02	1.781245e-02	5.244352e-02	1.934691e-02	3.996278e-02	6.755563e-02	1.159976e-01	3.014459e-01	1.808840e-01	3.994106e-01
Nmic	2.560484e-13	7.217998e-13	5.569244e-13	5.548020e-13	8.442688e-13	1.077785e-12	7.088582e-01	4.623375e-02	9.609184e-02	4.502864e-01
LAP.activity	4.821119e-07	8.818066e-06	7.675364e-07	7.325976e-06	2.997737e-06	1.700048e-07	7.368706e-02	7.851877e-01	9.758099e-01	3.575161e-01
Total.C.EA.analysis.	1.756553e-05	1.343658e-04	2.514306e-05	1.181389e-04	6.742912e-05	8.424958e-06	5.808362e-02	8.803457e-01	6.898999e-01	2.003962e-01
SOC	0.000000e+00	3.477597e-16	1.704691e-36	8.951836e-17	1.442057e-22	1.577673e-24	5.814003e-01	1.709454e-02	5.749081e-02	3.192422e-01
TSN	3.477597e-16	0.000000e+00	1.591733e-16	3.991028e-38	1.203341e-20	1.153351e-13	8.638990e-01	2.271967e-03	9.299904e-03	9.801634e-02
C.stocks	1.704691e-36	1.591733e-16	0.000000e+00	3.832661e-17	1.013115e-23	2.180111e-23	6.070836e-01	1.451458e-02	5.081651e-02	2.942034e-01
N.stocks	8.951836e-17	3.991028e-38	3.832661e-17	0.000000e+00	1.105920e-21	4.335825e-14	9.031185e-01	2.623899e-03	1.065596e-02	1.072267e-01
C.N	1.442057e-22	1.203341e-20	1.013115e-23	1.105920e-21	0.000000e+00	7.472825e-18	8.226922e-01	6.157406e-03	2.433992e-02	1.828468e-01
C.N.mic.	1.577673e-24	1.153351e-13	2.180111e-23	4.335825e-14	7.472825e-18	0.000000e+00	4.145031e-01	3.270684e-02	1.004200e-01	4.521287e-01
C.N.dis.	5.814003e-01	8.638990e-01	6.070836e-01	9.031185e-01	8.226922e-01	4.145031e-01	0.000000e+00	4.426235e-04	1.442034e-05	2.590015e-07
CH4.Flux	1.709454e-02	2.271967e-03	1.451458e-02	2.623899e-03	6.157406e-03	3.270684e-02	4.426235e-04	0.000000e+00	8.655714e-17	5.649445e-11
CO2.Flux	5.749081e-02	9.299904e-03	5.081651e-02	1.065596e-02	2.433992e-02	1.004200e-01	1.442034e-05	8.655714e-17	0.000000e+00	1.669741e-14
N2O.flux	3.192422e-01	9.801634e-02	2.942034e-01	1.072267e-01	1.828468e-01	4.521287e-01	2.590015e-07	5.649445e-11	1.669741e-14	0.000000e+00

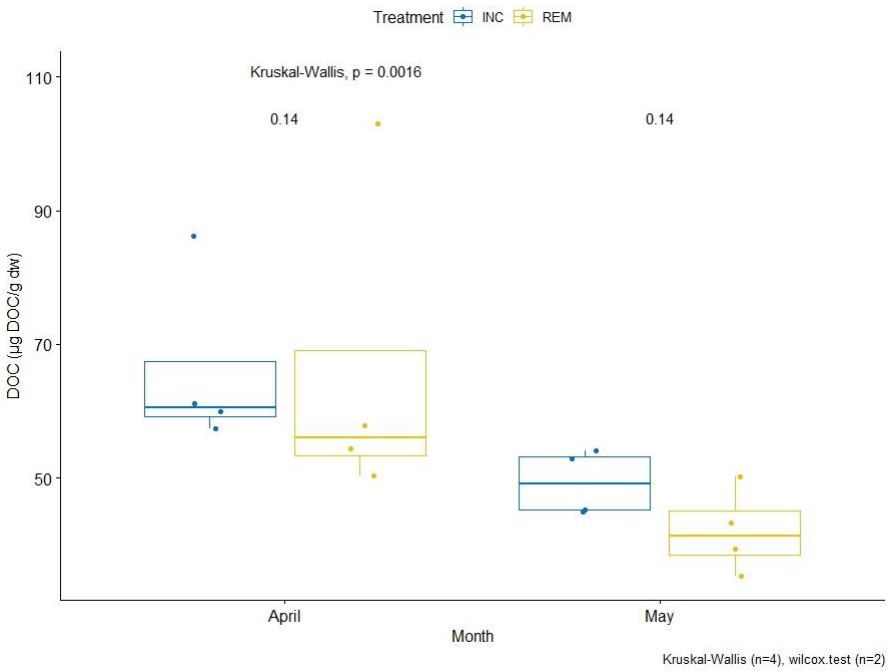
Appendix 11. Boxplots of selected soil properties from 0 – 25 depth, May and April soil lab analysis data.

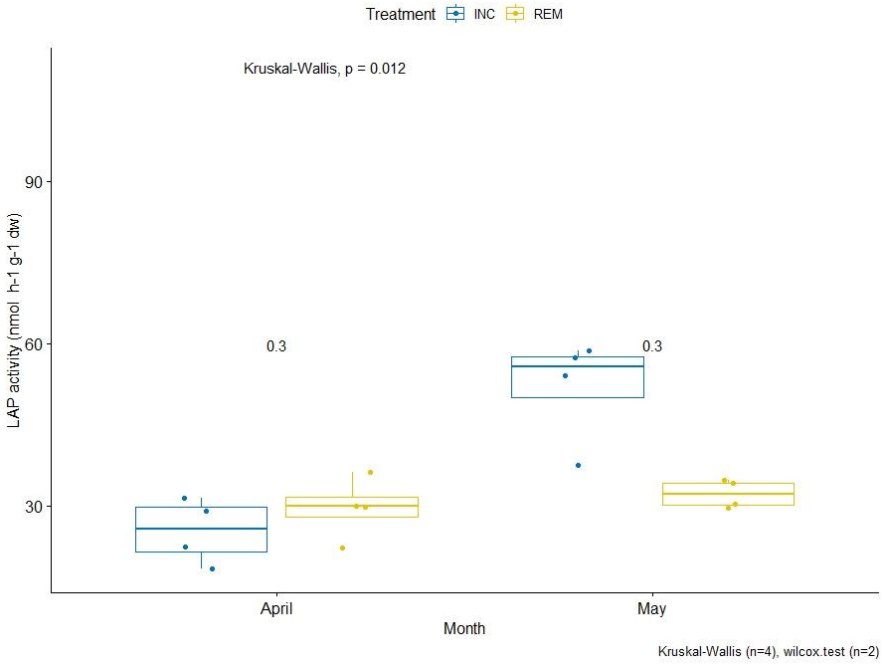


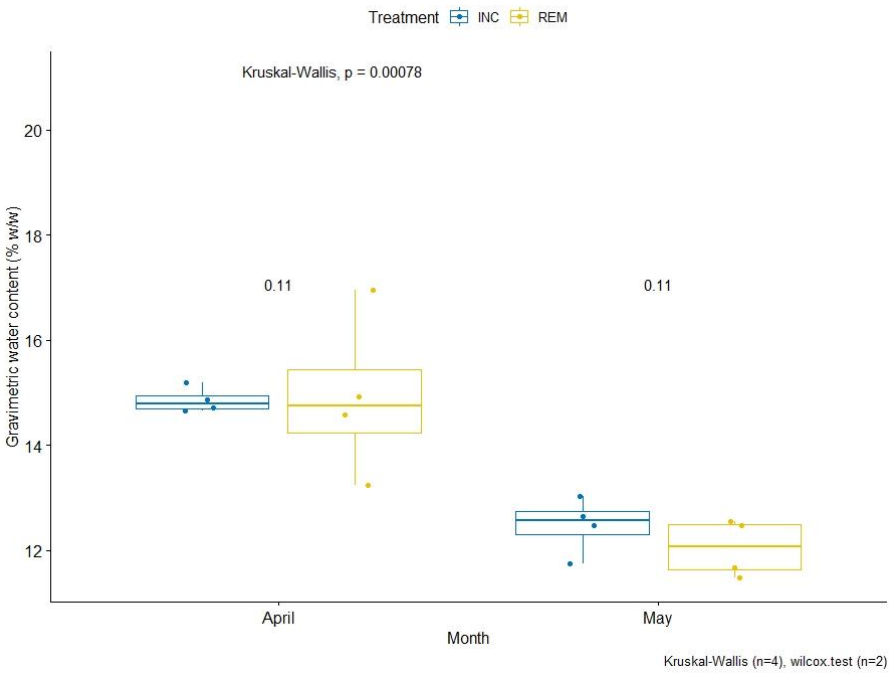



Treatment INC REM
Kruskal-Wallis, p = 0.016
20
18
16
14
12
C/N
0.34
0.34
April
May
Month
Kruskal-Wallis (n=4), wilcox.test (n=2)

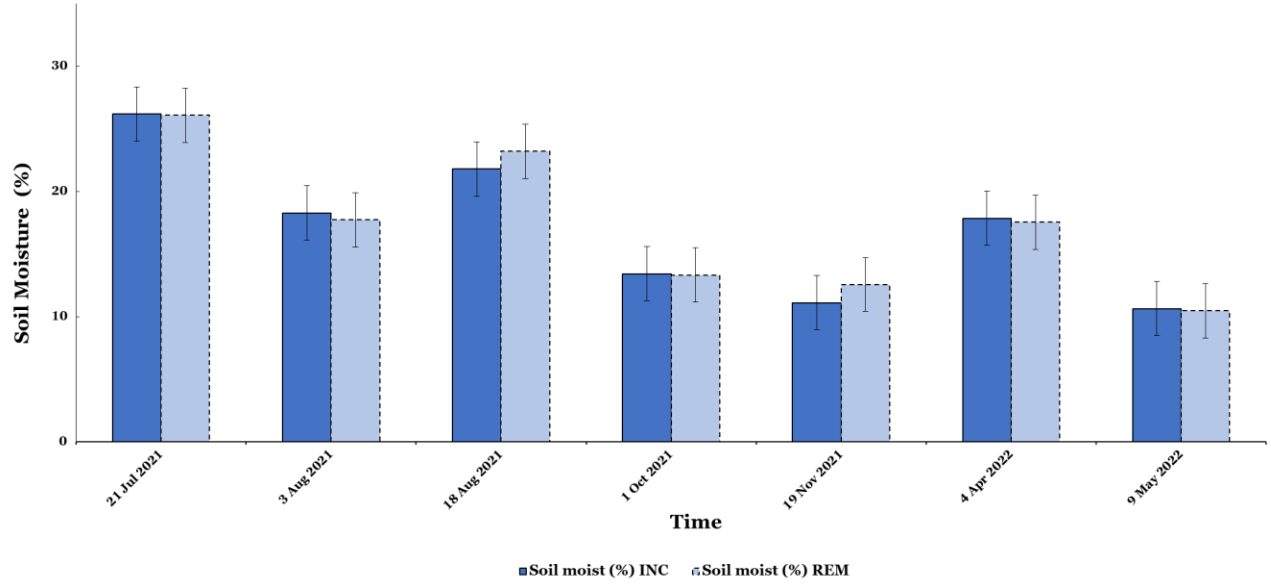

Treatment INC REM
Kruskal-Wallis, p = 0.00078
92
90
88
86
DMC (%)
0.11
0.11
April
May
Month
Kruskal-Wallis (n=4), wilcox.test (n=2)

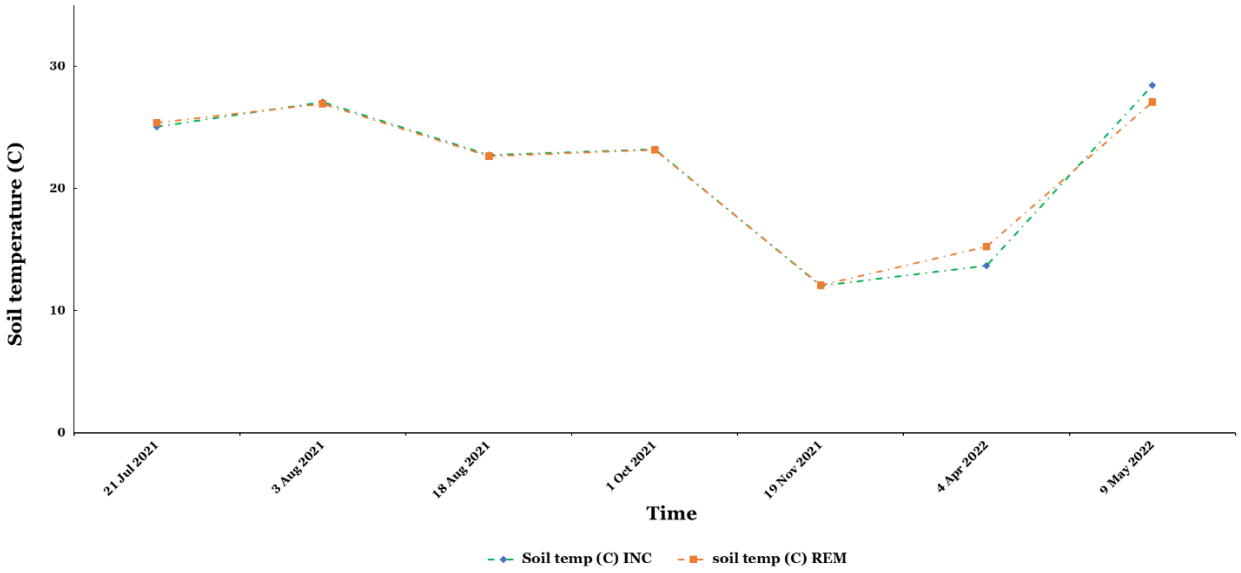

Treatment INC REM
Kruskal-Wallis, p = 0.0016
0.14
0.14
110
90
70
50
DOC (µg DOC/g dw)
April
May
Month
Kruskal-Wallis (n=4), wilcox.test (n=2)


Treatment INC REM
Kruskal-Wallis, p = 0.012
0.3
0.3
90
60
30
LAP activity (nmol h-1 g-1 dw)
April
May
Month
Kruskal-Wallis (n=4), wilcox.test (n=2)


Treatment INC REM
Kruskal-Wallis, p = 0.00078
20
18
16
14
12
Gravimetric water content (% w/w)
0.11
0.11
April
May
Month
Kruskal-Wallis (n=4), wilcox.test (n=2)

Appendix 12. Soil moisture and soil temperature measurements from two treatments.





Appendix 13. Two-way ANOVA results of the N_2O fluxes under two treatments (INC, REM)

```
# ----       Two way ANOVA       -----
 res.aov <- anova_test(data = flux, dv = N2O.flux, between = c(date, crop.residue))
Coefficient covariances computed by hccm()
> res.aov
ANOVA Table (type II tests)

             Effect DFn DFd      F        p p<.05   ges
1              date   6  42 14.256 8.82e-09     * 0.671
2      crop.residue   1  42  0.403 5.29e-01       0.010
3 date:crop.residue   6  42  0.503 8.03e-01       0.067
```

Appendix 14. Two-way ANOVA results of the CH_4 fluxes under two treatments (INC, REM)

```
 res_aov_ch4 <- anova_test(data = flux_ch4, dv = CH4.flux, between = c(date, crop.residue))
Coefficient covariances computed by hccm()
> res_aov_ch4
ANOVA Table (type II tests)

             Effect DFn DFd     F     p p<.05   ges
1              date   5  36 0.066 0.997       0.009
2      crop.residue   1  36 0.118 0.733       0.003
3 date:crop.residue   5  36 0.323 0.896       0.043
```

Appendix 15. Two-way ANOVA results of the CO_2 fluxes under two treatments (INC, REM)

```
> pairwise.wilcox.test(flux$CO2.flux, flux$crop.residue, p.adjust.method = "none")

        Pairwise comparisons using Wilcoxon rank sum exact test

data:  flux$CO2.flux and flux$crop.residue

    INC
REM 0.52

P value adjustment method: none
```