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THESIS TITLE: NITROUS OXIDE AND SOIL CARBONDIOXIDE FLUX DYNAMICS IN ARABLE LANDS.

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ABBREVIATIONS AND ACRONYMNS

LAI	Leaf Area Index
SWC	Soil Water Content
N_2O	Nitrous Oxide
CO_2	Carbon dioxide
GHG	Green House Gas
CH_4	Methane
PPB	Parts Per Billion
WMO	World Meteorological Organization
Ts	Temperature
Masl	Meters Above Sea Level
$NaNO_3$	Sodium Nitrate
VI	Vegetative Index
NUE	Nitrogen Use Efficiency
Ni	Nitrogen Inhibitors
NEE	Net Ecosystem Exchange
IPCC	Intergovernmental Panel on Climate Change
AFOLU	Agriculture Forestry and Other Land Use
LULUF	Land Use, Land-use Change and Forestry

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CHAPTER ONE: INTRODUCTION.

1.1 Background to the study.

The global climate has undergone substantial changes that are defined by warming during the past century due to the growth of the global economy and energy consumption (Lui et al., 2019). The primary driver of the observed global warming is human-induced GHG emissions (Yang et al., 2014; Mohammed et. 2021; Wang et al. 2021; Smith, 2017). GHGs are primarily composed of Nitrous Oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4), all of which are steadily rising in the atmosphere and contributing to the change in the planet's climate. In 2019, the level of CO_2 in the atmosphere reached 410 ppm, while CH_4 levels were 1866 ppb and N_2O levels at 332 ppb. Halogenated gases and tropospheric ozone (O_3) are other two more significant causes of warming (IPCC, 2023).

According to reports, N_2O has a 300-fold larger potential for global warming than CO_2 and can stay in the atmosphere for an average of 120 years. making it the most destructive of these gases in terms of its impact on ozone depletion (Davison et al., 2014; Bouteldja et al. 2021). In 2020, the quantity of N_2O in the atmosphere was 333.2 ppb, which is 123% more than pre-industrial levels (WMO, 2020). Recent estimates also indicate that more than 60% of N_2O emissions originate from fertilized agricultural soils, with waste management and agricultural soils accounting for the remaining portion (Bouteldja et al., 2021). Fertilizer use is predicted to rise based on global population growth rates, with close to 20% expected increase in N_2O emissions by 2030 (Bouteldja et al., 2021) and a predicted doubling of human-induced N_2O emissions by 2050 (Davidson et al., 2014).

In comparison to earlier 50-year periods over the past 2000 years, the global surface temperature has risen more quickly since 1970. The total rise in global surface temperature due to human activities is predicted to be 0.8°C between 1850 and 1900 and 1.3°C between 2010 and 2019. (IPCC, 2023). For the last 20 years, it is likely that GHGs contributed to a warming of 1.0°C to 2.0°C, other human drivers (mostly aerosols) to a cooling of 0.0°C to 0.8°C, and natural (solar and volcanic) drivers to a change of 0.1°C in the global surface temperature (IPCC, 2023).

In 2019, the energy sector accounted for approximately 34% of net worldwide GHG emissions, followed by industry (24%), Agriculture, Forestry, and Other Land Use (AFOLU) (22%), transportation (15%), and buildings (6%) (IPCC, 2023). The largest portion of CO_2 emissions from

AFOLU are attributed to LULUCF especially deforestation according to Pradhan et al. (2019) and Oertel et al. (2016). Nevertheless, in contrast to the previous ten years, the average yearly GHG emission rate between 2010 and 2019 reduced in the energy sector (from 2.3% to 1.0%) and industry (from 3.4% to 1.4%) but remained approximately the same (2% per year) in the transportation industry (IPCC, 2023). East Asian nations were responsible for 27% of the world's net anthropogenic emissions over the past 20 years. North America came in second place with 16% of emissions, followed by South America and the Caribbean region with 10%. European, western central Asian countries contributed 14% of the total emissions during the aforementioned period (IPCC, 2023).

Impacts of climate change are more severe and widespread than previously predicted (IPCC, 2023). In terrestrial, aquatic, cryospheric, coastal, and open ocean habitats, climate change has significantly impacted these ecosystems and resulted in rising irreversible losses according to Muhammed et al. (2021). Because of warming, shifting rainfall patterns, and increased occurrence and intensity of climatic extremes, climate change has hampered efforts to achieve the Sustainable Development Goals by reducing food security and affecting water security (Huang et al., 2020). Climate change has had negative effects on human health, way of life, and essential infrastructure in urban areas (Leal Filho et al., 2018). Globally, climate change has an adverse effect on people's physical and mental health, and it is causing humanitarian catastrophe where climate risks interact with greater vulnerability (Muhammed et al., 2021). Thus, climate change's effects are having an increasingly negative influence on people's livelihoods as well as social and economic impacts that transcend national boundaries.

In order to combat climate change, anthropogenic greenhouse gas emissions must be decreased or atmospheric greenhouse gas absorption must be increased (IPCC, 2023). In order to reduce or stabilize GHG emissions globally, a number of initiatives have been implemented, including the Kyoto Protocol in 2002, the Paris Agreement in 2015, and the United Nations Framework Convention on Climate Change 1992, also known as UNFCC-1992 (Muhammed et al., 2021).

The European Commission adopted the latest EU climate change plan on February 24, 2021 (EU Commission, 2021). The new strategy outlines how by 2050, the European Union can become climate resilient and adapt to the inescapable effects of climate change. The four main goals of the

Strategy are to enhance climate change adaptation in a smarter, systematic and swifter way and to establish global actions on climate change adaptation.

Many scientists have sought to monitor and categorize GHG emissions at national and global scales. In Hungary, CO_2 monitoring began in 1981, and numerous initiatives to track the GHG budget in various ecosystems were undertaken in the 1990s (Haszpra, 2011). A number of studies have been conducted to monitor CO_2 emissions in the country (Major et al. 2018; Bouteldja et al. 2021; Fóti et al. 2018; Farkas et al. 2011; Horváth et al. 2010).

Hungary's total CO_2 in 2019 were 64.4 million tonnes of carbon dioxide equivalent. In comparison to the base year (average of 1985-87), 1990, and 2005, the current emissions are less by 42%, 32%, and 16%, respectively (Hungarian Meteorological service). Emissions of CH_4 are 39% lower compared to their level in the base year. 8% of all GHG emissions originate from N_2O. The primary sources of N_2O emissions are manure management and agricultural soils and however, when compared to the base year, N_2O emissions are 56% lower (Hungarian Meteorological service).

There have been numerous measures attempted to reduce GHG emissions across all sectors in the Hungary. It recently launched key components of a new framework for the energy industry that gave the greatest priority to low carbon emissions across all sectors, including supply and consumption chains, methods for producing heat, the electrical industry, and transportation (Fogarassy and Kovacs, 2016).

In terms of CC mitigation, Hungary's adoption of environmental policies has had favorable effects. Between 1985 and 2018, total emissions dramatically decreased by 81.5%, 69%, and 145.6% for CO_2, CH_4, and N_2O, respectively (Mohammed et al. 2021). Both the biomass and transportation industries have seen a considerable positive rise in CO_2 emissions. They also noted that there was a large decline in CO_2 emissions from the industrial sector, the energy sector, and the household sector. In most key sectors, except for soil in terms of N_2O emissions, CO_2, CH_4, and N2O emissions all saw considerable decreases (Mohammed et al., 2021). They also highlighted that while economic growth can lead to environmental improvement in Hungary, in order to reduce CO_2 and N_2O emissions, agricultural systems urgently need a plan for reducing GHGs in the country.

1.2 Problem Statement

Reliable quantification of GHG emissions from agricultural soils is critical for developing plans to reduce GHG emissions from soils, developing models to predict emissions, and developing global, regional, national, and local GHG emission inventory lists.

GHG emissions exhibit inherent spatial and temporal variations as a result of the variable nature of environmental conditions, crop management, and measurement procedures that are used to measure emissions. The temperature of soil and SWC are two crucial environmental parameters that affect GHG emissions. It is recognized that these environmental elements change with time and place. Compared to the effects of slow-onset weather changes, information and quantitative data coverage on the impacts of extreme weather occurrences on emissions are quite limited.

The degree of uncertainty in GHG quantification is additionally increased by the limitations of the typical or standard methodologies for quantifying GHG emissions. Inconsistent data collection, modeling, and reporting techniques and uneven data availability make it difficult to compare and combine the results of different studies. The measurement procedure must adhere to stringent standards of accuracy, precision, and stability in order to measure and monitor global emissions accurately. Despite the widespread use of static and dynamic chamber techniques, it is vital to take into account their drawbacks, including the fact that they are only applicable to crops with short heights and that the air flow through the chamber may be excessive, leading to inaccurate measurements. Research and monitoring of trace gases has gained a fresh perspective with the use of LI-COR Trace Gas Analyzers. The device's ability to perform high-resolution sampling with minimal uncertainty is made possible by the dense grid created by the fixed cavity resonance modes in conjunction with tightly controlled cavity temperature and pressure (Li-COR, 2023). Modern technology and signal processing also enable extremely quick and sensitive measurements hence improving reliability of measurements (Li-COR, 2023).

The physical and biological characteristics of soil, such as its pH, C and N contents, microbial population, and texture, change with time and space. It is also acknowledged that these factors have an impact on emissions of greenhouse gases from agricultural soils.

Furthermore, different agricultural practices such as irrigation, crop residue management, tillage, fertilization, and timing of these practices all have an impact on greenhouse gas emissions and tend to vary among farms. Interestingly, Bouteldja et al. (2021) observed that few investigations or trials of this nature have been conducted in a normal farming environment. The majority of the studies that we examined were conducted at experimental stations, which can have different management practices than a regular farm setup.

The aforementioned factors thus imply that more extensive and ongoing studies must be conducted while taking into account the environmental, crop management, and measurement procedures in order to obtain reliable inferences, have a greater comprehension of the fundamental causes of the spatio-temporal variation, and reduce unpredictability in GHG emissions.

Consequently, the goal of our study was to measure N_2O and CO_2 emissions in wheat in a typical farming setting using the most recent N_2O and CO_2 measurement technology (LI-COR) and to determine the relationship between the emissions with SWC and soil temperature.

1.3 General Objective

To determine the patterns of N_2O and soil CO_2 fluxes in wheat in a farming system.

1.4 Specific Objectives

a. To determine the effect of soil temperature on N_2O and soil CO_2 emissions.
b. To determine the effect of SMC on N_2O and soil CO_2 emissions.

1.5 Research Hypothesis

i. Soil temperature has a significant effect on N_2O and soil CO_2 emissions.
ii. SMC has a significant effect on N_2O and soil CO_2 emissions.

1.6 Significance of the Study

The field experiment's findings might demonstrate the intricacy of N_2O and CO_2 emissions and the substantial roles that the studied environmental factors play in determining the emissions patterns. When designing management plans to lower N_2O and CO_2 emissions from agricultural soils, as well as in modelling studies and developing GHG inventories, these correlations might be a useful resource.

CHAPTER TWO: LITERATURE REVIEW

2.1 The Nitrogen Cycle

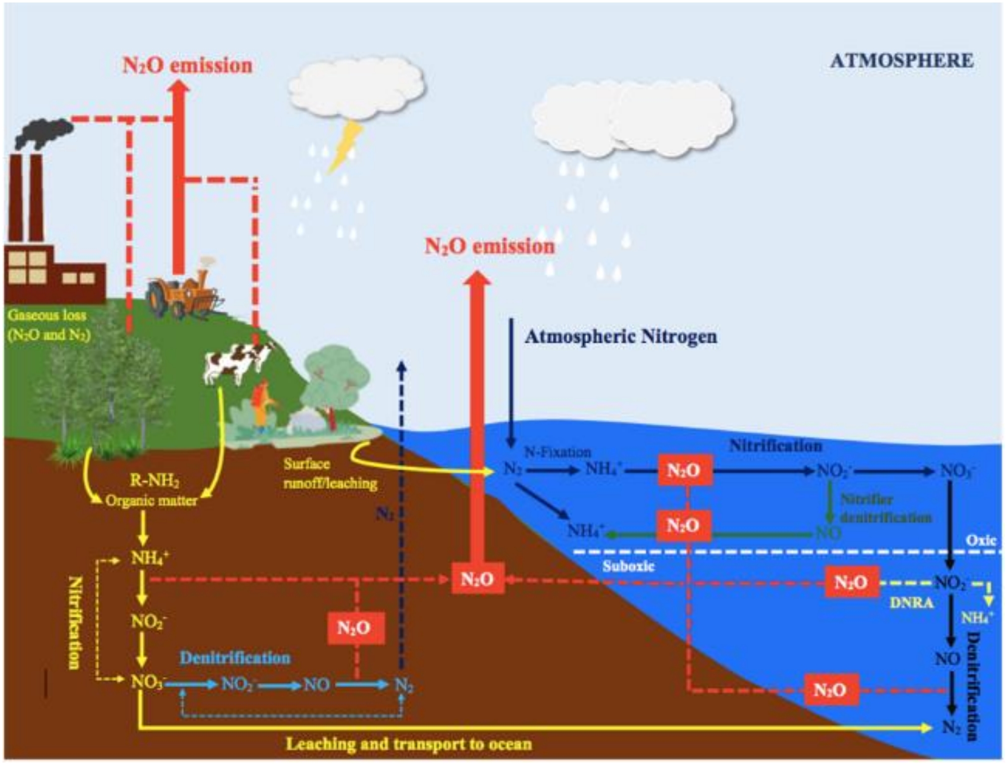
Nitrogen gas (N_2) is the most prevalent gas in the atmosphere, accounting for approximately 78% of the total composition of the atmosphere (Yu & Zhuang, 2019). It is one of the fundamental biological components for all living forms in marine, terrestrial, and freshwater ecosystems. This is because many crucial chemicals for life, such as DNA and chlorophyll, are composed of nitrogen (Marcarelli et al., 2022). However, because a variety of creatures and plants cannot access gaseous nitrogen, the productivity of many ecosystem components is constrained (Aryal et al., 2022).

2.2 Discovery of the Conventional Nitrogen Cycle (CNC)

The biogeochemical and microbiological processes that contribute to the evolution of the N cycle date back over 3 billion years. Its comprehension, however, is still a young one (Aryal et al., 2022). N was formally added to the periodic table as the seventh element by Jean Antoine Claude Chaptal, according to Galloway et al. (2004). Atmospheric depositions, lightning, and geologically natural processes were among the major factors governing the original N-cycle**.**

Boussingault noted in 1838 that legumes can store nitrogen in the roots (Aryal et al., 20229. With the microbiological study of Herman Hellriegel and Hermann Wilfarth, this phenomenon was further understood 50 years later (Galloway et al., 2004; Galloway et al., 2013). They discovered that legumes can fix atmospheric N in the soil by interacting with live bacteria in symbiotic relationships. Key elements of the N-cycle, such as nitrification and denitrification, were identified and restructured in the late 20th century (Xu et al., 2013). The fundamental understanding of how atmospheric N transforms into a variety of distinct oxidation level molecules is still insufficient (Aryal et al., 2022).

The conventional nitrogen cycle (CNC) is one of the recognized biogeochemical cycles. Through this process, large quantities of atmospheric nitrogen are transferred to soil and aquatic habitats (Fowler et al., 2013). N_2 is eventually returned to the atmosphere as a result of the microbial denitrification that takes place in soils and aquatic habitats (Aryal et al., 2022). Thus, nitrification, denitrification, and ammonification are the major steps in the nitrogen cycle as seen in Figure 1.



(Figure 1): The Nitrogen Cycle.
Source: Aryal et al., (2022)

2.3 Latest Discoveries in N Cycle.

The biological processes in terrestrial and aquatic ecosystems have been documented to be greatly influenced by the initial N fixation by soil microbes and the presence of N compounds such as NH_3, NH_4^+, NO, NO_2, HNO_3, N_2O, and other Organic N compounds (Aryal et al., 2022).

The CNC phases have been linked to a variety of microorganisms. But nonetheless due to recent breakthroughs in sequencing and isolation techniques (Aryal et al., 2022), researchers have recently discovered new functional and phylogenic N cycling microorganisms. The identification of *Nitrosopumilus maritimus*, a chemoautotrophic Ammonia-Oxidizing Archaeon (AOA), in 2005 has reportedly caused a paradigm change in the diversity of microbes involved in the CNC, according to Monterio et al. (2014) and Sanjuan et al. (2020). Most recent studies continue to show that a variety of microorganisms carry out denitrification (Aryal et al., 2022). This has led researchers to the conclusion that a variety of constantly evolving microorganisms, including bacteria and archaea, can contribute to the biogeochemical N cycle.

2.4 N_2O Emission

According to Monterio et al. (2014) and Sanjuan et al. (2020), Joseph Priestly discovered oxygen and N_2O in 1722, with N_2O gaining prominence due to its usage in medical aesthetics from the 18th century to the present time. However, the existence of N_2O in the atmosphere was discovered the late 1930s by Adel (Aryal et al., 2022).

Tables 1 shows that over the past 40 years. The use of synthetic ammoniacal fertilizers and the burning of petroleum and coal have contributed to remarkably high levels of N_2O buildup in the atmosphere (Norton & Ouyang, 2019). Around 30% more N2O has been released into the atmosphere over the past 20 years. Global N2O emissions are expected to reach 8.16 Tg N2O-N/yr by 2050. (Tian et al., 2020).

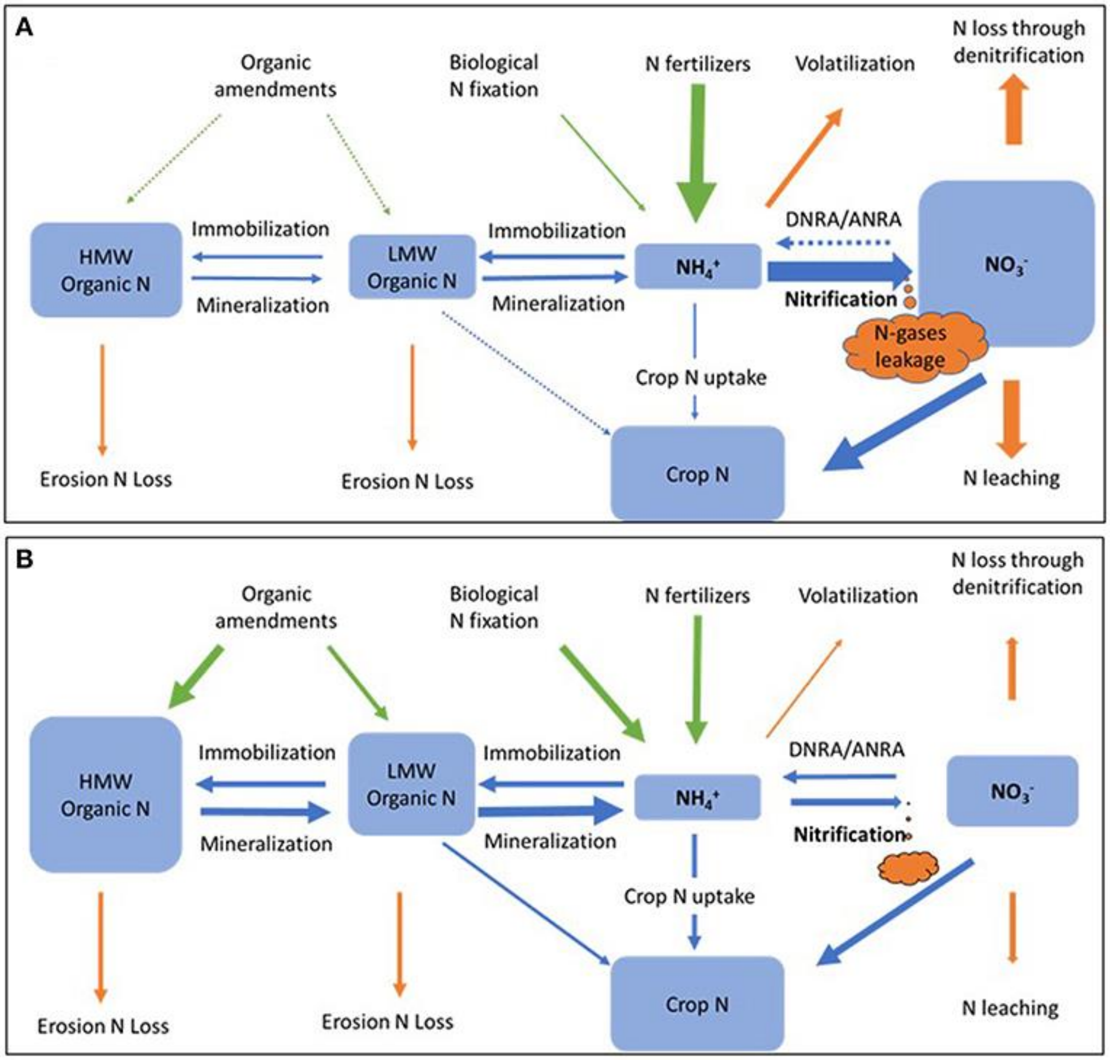
(Table 1): Anthropogenic causes of global N_2O emissions (1980s, 1990s, 2000s, and 2007-2016).

		1980s			1990s			2000s			2007–2016		
Anthropogenic sources		**Mean**	**Min.**	**Max.**	**Mean**	**Min.**	**Max.**	**Mean**	**Min.**	**Max.**	**Mean**	**Min.**	**Max.**
Direct emissions from nitrogen additions in the agricultural sector (Agriculture)	Direct soil emissions	1.5	0.9	2.6	1.7	1.1	3.1	2.0	1.3	3.4	2.3	1.4	3.8
	Manure left on pasture	0.9	0.7	1.0	1.0	0.7	1.1	1.1	0.8	1.2	1.2	0.9	1.3
	Manure management	0.3	0.2	0.4	0.3	0.2	0.4	0.3	0.2	0.5	0.3	0.2	0.5
	Aquaculture	0.01	0.00	0.03	0.03	0.01	0.1	0.1	0.02	0.2	0.1	0.02	0.2
	Subtotal	**2.6**	**1.8**	**4.1**	**3.0**	**2.1**	**4.8**	**3.4**	**2.3**	**5.2**	**3.8**	**2.5**	**5.8**
Other direct anthropogenic sources	Fossil fuels and industry	0.9	0.8	1.1	0.9	0.9	1.0	0.9	0.8	1.0	1.0	0.8	1.1
	Waste and waste water	0.2	0.1	0.3	0.3	0.2	0.4	0.3	0.2	0.4	0.3	0.2	0.5
	Biomass burning	0.7	0.7	0.7	0.7	0.6	0.8	0.6	0.6	0.6	0.6	0.5	0.8
	Subtotal	**1.8**	**1.6**	**2.1**	**1.9**	**1.7**	**2.1**	**1.8**	**1.6**	**2.1**	**1.9**	**1.6**	**2.3**
Indirect emissions from anthropogenic nitrogen additions	Inland waters, estuaries, coastal zones	0.4	0.2	0.5	0.4	0.2	0.5	0.4	0.2	0.6	0.5	0.2	0.7
	Atmospheric nitrogen deposition on land	0.6	0.3	1.2	0.7	0.4	1.4	0.7	0.4	1.3	0.8	0.4	1.4
	Atmospheric nitrogen deposition on ocean	0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.2	0.1	0.1	0.2
	Subtotal	**1.1**	**0.6**	**1.9**	**1.2**	**0.7**	**2.1**	**1.2**	**0.6**	**2.1**	**1.3**	**0.7**	**2.2**
Perturbed fluxes from climate/CO_2/land cover change	CO_2 effect	−0.2	−0.3	0.0	−0.2	−0.4	0.0	−0.3	−0.5	0.1	−0.3	−0.6	0.1
	Climate effect	0.4	0.0	0.8	0.5	0.1	0.9	0.7	0.3	1.2	0.8	0.3	1.3
	Post-deforestation pulse effect	0.7	0.6	0.8	0.7	0.6	0.8	0.7	0.7	0.8	0.8	0.7	0.8
	Long-term effect of reduced mature forest area	−0.8	−0.8	−0.9	−0.9	−0.8	−1.0	−1.0	−0.9	−1.1	−1.1	−1.0	−1.1
	Subtotal	**0.1**	**−0.4**	**0.7**	**0.1**	**−0.5**	**0.7**	**0.2**	**−0.4**	**0.9**	**0.2**	**−0.6**	**1.1**
Anthropogenic total		**5.6**	**3.6**	**8.7**	**6.2**	**3.9**	**9.7**	**6.7**	**4.1**	**10.3**	**7.3**	**4.2**	**11.4**

Source: Norton & Ouyang (2019)

2.5 N_2O Emission Pathways in Agricultural Soils.

Figure 2 shows various pathways of N_2O emission through the N cycle. These processes are highlighted in the subsequent sections.



(Figure 2): Nitrogen stores and fluxes in high-nitrifying (A) and low-nitrifying (B) cropping systems.Green arrows reflect N inputs. Orange N losses and Blue N transformations. HMW stands for High Molecular Weight; LMW for Low Molecular Weight, DNRA means Dissimilatory Nitrate Reduction to Ammonium and ANRA Assimilatory Nitrate Reduction to Ammonium.
Source: Norton & Ouyang (2019)

2.5.1 Nitrification

Nitrification is a two-step process in which specific microbes perform the biological oxidation of ammonium to nitrite and the subsequent conversion of nitrite to nitrate. According to Equations 1, 2, and 3, nitrification leads to the emission of N_2O because Hydroxylamine Reductase (HAO) converts NH_2OH to NO_2. Then, NO is reduced to N_2O by cytochrome C554. 2022) (Aryal et al. 2022)

$NH_4^+ + O_2 + 2e \rightarrow NH_2OH + H_2O$…………………………………………………...……Equation 1

$NH_2OH+H_2O \rightarrow NO_2+5H^+ +4e$……………………………………………….....……. Equation 2

$2NH_2OH + 2NO \rightarrow N_2O + N_2 + 3H_2O$…………………………………………...... Equation 3

Ammonia oxidizers carry out the first stage, the oxidation of ammonium to nitrite, under aerobic circumstances. Bernhard (2010) claims that an intermediary substance named hydroxylamine is involved in this process. *Nitrosomonas*, *Nitrosospira*, and *Nitrosococcus* are examples of Ammonia Oxidizing Bacteria (AOB) that perform this stage of nitrification. Some microorganisms that can oxidize ammonium, however, have been found such as Ammonia Oxidizing Archaea (AOA) found in soil and marine ecosystems (Norton and Ouyang, 2019). However, Zhou et al. (2014); Kozlowski et al. (2016); Hink et al. (2017, 2018) all found that they emit less N_2O than AOB. The second step involves nitrite-oxidizing bacteria such as Nitobacter and Nitrospira, that oxidize nitrite to nitrate. (Aryal et al., 2022)

2.5.2 Denitrification

Denitrification is the gradual conversion of nitrates and nitrites into gaseous nitrogen, with the generation of NO and N_2O as intermediate products, as illustrated in Equation 4 (Aryal et al., 2022). It is an anaerobic process that occurs largely in soils and oxygen-deficient zones such as lakes and oceans and is carried out by facultative anaerobic bacteria from the genera Bacillus, Pseudomonas, and Paracoccus. Denitrifier microorganisms depend on organic material as a source of energy (Groffman, 2012; Thamdrup, 2012).

$NO_3^- \rightarrow NO_2^- \rightarrow NO + N_2O \rightarrow N_2$ ………………………………………….............. Equation 4

Two periplasmic enzymes discovered in the genome of denitrifying bacteria, as shown below, carry out denitrification in terrestrial ecosystems. The majority of microorganisms, according to Aryal et al., (2022), do not have all of the aforementioned enzymes, which are necessary for denitrification to take place.

a. $NO_2 \rightarrow NO$ by Cu-containing Nitrite Reductase (encoded by nirK) and a haem-containing cd1 Nitrite Reductase (encoded by nirS). (Aryal et al., 2022)
b. $NO \rightarrow N_2O$ by Nitric Oxide Reductases cNOR (a Cytochrome c-dependent Complex) and qNOR (a Quinol-dependent Complex) (Pajares and Ramiro, 2019).

c. $N_2O \rightarrow N_2$ by Nitrous Oxide Reductase (NOS), encoded as the nosZ gene (Hinojosa et al., 2017).

Denitrification takes place in marine ecosystems via the Nitrifier Denitrification Pathway (Pajares and Ramiro, 2019). The partial process is characterized by the conversion of NO_2 to N_2O in anoxic or suboxic environments. Tallec et al. (2008) observaed that more N_2O is released as oxygen levels drop in the marine ecosystem served as further confirmation of this mechanism.

2.5.3 Dissimilatory Nitrate Reduction to Ammonium (DNRA)

As illustrated in equation 5, DNRA is characterized by the conversion of NO_3^- to NO_2 and NH_4^+ and subsequent release of N_2O. In anaerobic environments, fungus and bacteria carry out this activity. The nrfA gene in bacteria codes for the enzyme that catalyzes the DNRA pathway (Yoon et al., 2019).

$NO_3^- \rightarrow NO_2^- \rightarrow N_2O + NH_4^+$ …………..……………...……………………………. Equation 5

2.5.4 Mineralization and Immobilization

Heterotrophic soil bacteria carry out the biological process of mineralization, which transforms organic nitrogen in the soil into inorganic molecules like NH_4^+ and NH_3 (Ramm et al., 2021). These microorganisms get their energy from the nitrogen in organic materials. The rate of mineralization is influenced by a number of variables, including temperature, rainfall, soil characteristics, crop residue chemical composition, microbial community structure and composition, and the C:N ratio in the soil following the incorporation of plant residues (Grzyb et al., 2020). According to their study, any modification to the values of these variables impacts the rate and direction of the mineralization of crop residues in soil.

Nevertheless, bacteria that transform inorganic substances like NH_4^+, NH_3, NO_3^-, and NO_2 into organic substances that are responsible for the immobilization of N (Poffenbarger et al., 2018). Because they rely on soil nutrients for survival, soil microbes actively compete with plants for such resources. As these microorganisms consume nutrients in the soil and outcompete plants, the plants get immobilized since the nutrients are no longer available to them. Aryal et al. (2022) claim that raising carbon bioavailability can improve microbial nitrogen (N) immobilization in soil. The processes of immobilization and mineralization coexist in soils and compete with one another.

According to Aryal et al. (2022), if the rate of mineralization is faster than the rate of immobilization, the amount of inorganic N formed in the soil will increase.

2.6 Drivers of N_2O Emissions Temporal Variability in Agricultural Soils.

Table 2 lists the subcategories of environmental elements, managerial factors, and measurement factors that affect the amount of N_2O emitted from agricultural soils. Because of the environmental variation in both location and time, the limits at which nitrification and denitrification take place in different contexts are highly variable (Wang et al., 2021). The effect of each factor on emissions of N_2O from agricultural soils is thoroughly explained in the subsequent sections, and generalized correlations between each factor and N_2O emissions are also provided. A schematic representation among the variables is also shown in Figure 3.

(Table 2): Drivers of N2O emissions in agricultural soils.

Environmental Factors	**Management Factors**	**Measurement Factors**
Microbial community	Fertilizer application	Length of measurement period
Soil available Carbon	Soil tillage system	Types of measurements.
Soil N content	Harvest and crop residues	
Soil Water Content	Irrigation	
Soil texture		
Soil temperature		
Soil pH		
Soil salinity		

Source: Wang et al., (2021)

2.1.1 Environmental Variables.

Conditions in the environment must be favorable for the populations of soil microbes that are in responsible of the nitrification and denitrification processes that result in N_2O emission. According to studies, these circumstances have a direct impact on some microorganisms' activities and can instantly modify the rates of nitrification and denitrification as well as the ratio of N_2O to N_2 (Wang et al., 2021). The subsequent section describes the environmental conditions that affect nitrification, denitrification, and the N_2/N_2O ratio, which in turn affects N_2O emissions

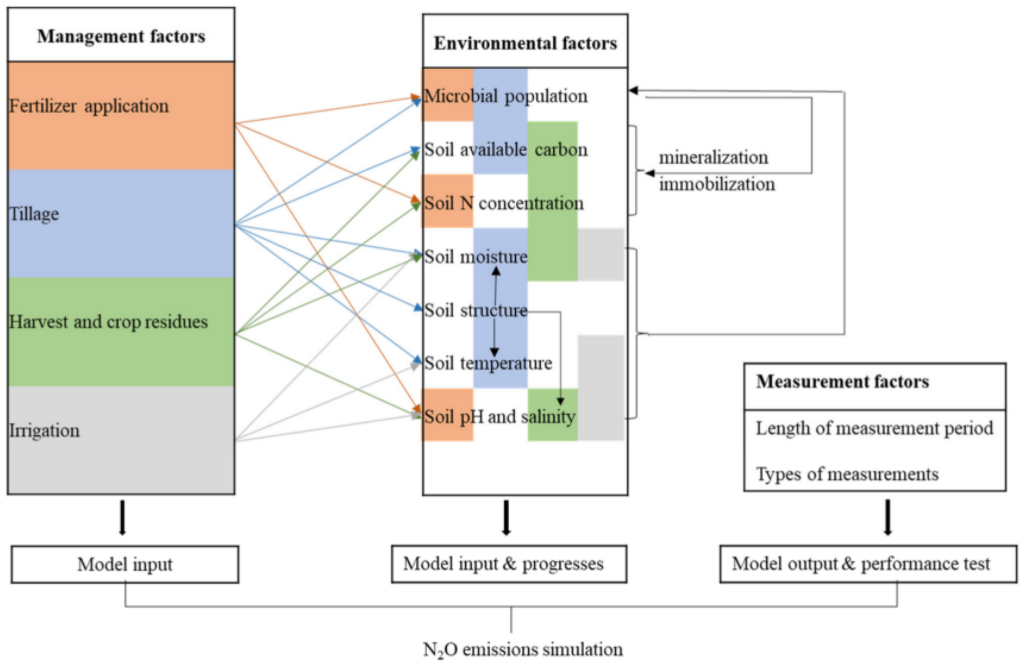


Figure 3: Schematic illustration of the factors affecting N_2O emissions and their interactions
Source: Wang et al. (2021)

2.1.2 Environmental Variables.

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2.1.2.1 Soil Microbial Population

A variety of soil microorganisms are involved in the denitrification and nitrification processes. According to Wang et al. (2021), autotrophic bacteria like *Nitrosomonas* and *Nitrobacter* are predominantly responsible for nitrification. Microorganisms that use light, inorganic nitrate, and organic carbon as sources of energy, such as phototrophs, lithotrophs, and organotrophs, carryout denitrification. Examples include heterotrophic microbes (such as *Pseudonomas denitrificans, Pseudomonas stutzeri, Pseudomonas aeruginosa*), autotrophic bacteria such as *Thiobacillus denitificans*, Fungi such as *Fusarium oxysporum, F. solani* and *Trichosporoncutaneum* (Aryal et al., 2022).

The range of soil microorganisms and microbial activity is impacted by environmental impact variables as well. For example, a C/N ratio of 5-22, oxygen concentration of 0-4.68 mg/L, soil salt of 0-30 g NaCl/L, and a pH range of 7-9.5 are required for denitrification by Pseudomonas denitrificans (Wang et al., 2021). Therefore, the myriad and the activities of such organisms in the soil at a specific time determines the rate of denitrification in soils.

2.1.2.2 Soil Oxygen Concentration

Oxygen plays an important function in the global N-cycle because its concentration levels have direct impacts on the rates of nitrification and denitrification that determine the quantity of N_2O emitted (Song et al., 2019). Diffusion is widely acknowledged as the primary mechanism for gas movement in the soil pore system. O_2 movement from the surface into the soil to a large extent control its availability in the soil matrix. Aerobic respiration and biological nitrification can rapidly use O_2 and cause depletion of O_2 in the soil when diffusion is constrained (Aryal et al., 2022).

The rate of gas exchange depends on soil structural characteristics including the size distribution, continuity, and interconnectedness of the macropores ((Song et al., 2019). Because gas diffusion occurs more slowly in water than it does in air, water saturation is the principal effective barrier to soil O_2 transport. Soil oxygen deficiency is frequently caused by excessive rainfall, irrigation, soil tillage, soil compaction, and straw return to the soil (Song et al., 2019). Under such conditions denitrification process is favored.

2.1.2.3 Soil Temperature

Temperature affects a number of N cycle biogeochemical processes in marine, aquatic and terrestrial ecosystems. By directly altering the response and the proliferation of microbial communities (like *Pseudomonas*), soil temperature has an impact on N*2*O emissions (Wang et al. 2021). Furthermore, by affecting microbial community growth, soil temperature regulates biological oxygen consumption, which lowers soil oxygen concentrations and promotes anaerobic condition (Oertel et al., 2016).

A number of studies show that increasing soil temperature leads to higher N_2O emissions in agricultural soils. Geng et al. (2017) noted that the growth and responses of soil microbes in terrestrial ecosystems is influenced by temperature. Avrahami et al. (2003) noted a positive correlation between the rates of nitrification and denitrification and soil temperature up to $30^{o}C$

with a resultant increase in the rate of N_2O emissions. Wang et al. (2021) also found out that highest rates of N_2O occur at 35°C. The increase in N_2O emission is associated to enhanced soil nitrogen mineralization, proliferation of N_2O producing microbes and availability soil carbon (an energy source for soil microbes) due to photodegradation of organic matter (Qiu et al., 2018).

Additionally, soil temperature impacts on freeze-thaw events, which increase the quantity of N that is available and accessible in the soil and also lead to oxygen deficient conditions that affect the release of N_2O and N_2 (Wang et al., 2021). In some areas (such as temperate regions), the upper soil layer is frequently frozen for a portion of the winter, and these soils can also experience repeated cycles of freezing and thawing. A significant portion of the annual N_2O emissions may happen shortly after thawing, according to research (Wang et al., 2021). The main factor that is attributed to the increase in emission is the formation of anaerobic conditions that favor the activities and proliferation of denitrifies and the high soil-water content's ability to promote the release of labile C and N molecules from dead microbial biomass (Smith, 2017).

2.1.2.4 Soil Salt Content (Salinity)

Anthropogenic activities such as irrigation, excessive groundwater pumping and salt additions through soil fertilization have resulted in elevated levels of salts in the soil (Aryal et al., 2022). Other factors such as increase in global temperatures as a result of climate change can increase the rate of soil salinization (Sanchez et al., 2020).

The generation and of N_2O is affected by soil salinity (Wang et al., 2021). According to Wei et al., 2018), salinity of irrigation water was observed to cause an increase in N_2O emissions. In order to reduce soil N_2O emissions, their findings imply that desalinating water to a low salinity level before using it for irrigation may be beneficial.

Soil salinization can increase N_2O emissions by altering microbial processes in the soil. Guo et al. (2020) noted that at average salinity (10–20 ppm), there is enhanced nitrification because of the proliferation of AOA. Increase in soil salinity according to Hu et al. (2012a, b) and Wang et al. (2018) can also lead to an increase in N_2O emissions through the inhibition of the activities of N_2O Reductase. Akhtar et al. (2012) also noted that increase in soil salinity enhances DNRA by limiting the much-needed microbial activity responsible for perpetuating the ammonia and nitrate ratios in the soil. The findings of Yu et al. (2020) also demonstrate the critical role soil salinity plays in regulating the temperature sensitivity of soil N_2O emissions.

2.1.2.5 Soil pH

Environmental factors and human activities such as intensification of agriculture, increased use of synthetic N fertilizers, accelerated leaching and accumulation of organic matter in the soil have led to decrease in soil pH. (Kissel et al., 2020). Soil pH is among the significant soil parameter that determines the rate of denitrification by having effect on the growth and survival of denitrifying microbes.

When addressing how soil pH affects nitrification and denitrification, various studies show inconsistent conclusions. Clough et al. (2003) investigated the impact of liming the soil on the N_2O emissions from a silt loam. They discovered that autotrophic nitrification is restricted at pH levels below 4.5. It has been demonstrated that liming of acidic soils can alter both the nitrification rate and the N_2O flux and can stimulate nitrification (Wang et al., 2021). With a drop in soil pH, denitrification rates decline (Wang et al.,2021). Kessik et al. (2006) reported that increase in soil pH to neutral level (pH 7) increases the rate of denitrification with the maximum emission occurring at pH 7 to 7.5. This is also confirmed by Qingxian et al. (2019) who found out that there is a significant emission of N_2O at soil pH range of 6.5 to 8. Increase in pH beyond this limit decreased the emission of N_2O. However, Sun et al. (2012) reported that peak denitrification occurs at pH 4.3 to 5.9 in forest soils and soil pH ranges of 6.1 to 7.8 in grasslands. Therefore, soil pH is a good indicator of denitrification and determines the proportion of Nitrogen and N_2O emitted from soils into the atmosphere.

The ratio of N_2/N_2O emissions is also influenced by soil pH. It is generally accepted that soil pH affects the activity of nitrifying and denitrifying bacteria in the soil, which in turn controls N_2O emissions (Wang et al., 2021). The pH of the soil controls whether NO_2^- and NO_3^- chemically break down into N_2O or N_2. Denitrifier bacteria like *Pseudomonas* release N_2O in acidic conditions, according to Wang et al (2021). Acidic soils produce more N_2O than N_2, whereas soils with a pH of 6.0 emit approximately equal quantities of N_2O and N_2 (Wang et al., 2021), which is supported by the findings of Šimek et al. (2002), who discovered that at pH 6.0, the only denitrification product was N_2O, while at higher pH, more N_2 was emitted.

However, it is impossible to generalize the relationship between pH and denitrification in soils, according to Wang et al (2021)'s review of the of studies on the topic.

2.1.2.6 Atmospheric CO_2 Content

The primary mechanism and the relationship between atmospheric CO_2 and nitrogen cycle has not been fully studied (Aryal et al., 2022). However, atmospheric carbon concentration has been noted to affect the assemblage and functioning of soil microbes that involved in the global biogeochemical N cycle (Xu et al., 2013). Increase in Carbon dioxide in the atmosphere also affects the global N cycle by enhancing the immobilization of Nitrogen and the decrease in soil nitrification (Chang, 2019) and retard the activity of Nitrate Reductase, hence reduction in the emissions of N_2O (Chang, 2019; Jiang et al., 2020).

2.1.2.7 Soil Water Content

Most of investigations have noted an increase in N_2O emissions following the application of N fertilizer, particularly in conditions of high soil moisture, which is texture dependent (Wang et al. 2021; Oertel et al. 2016; schauffer et al. 2010; Aryal et al. 2020; Smith, 2017; Norton & Ouyang, 2019). In addition, the said studies show that N_2O is often released most quickly when the soil has more than 60% of its pore space filled with water.

The amount of accessible oxygen in the soil pores is reduced when WFPS is higher than 60%. This creates anaerobic conditions that are conducive to facultative anaerobic bacteria producing N_2O (Smith, 2017, Wang et al., 2021). N_2O is utilized by soil microbes in anaerobic circumstances when soil moisture is above 90% (Wang et al., 2021). Hence the proportion of N_2 gas is released (higher N_2/N_2O ratio) during denitrification is higher at these levels.

2.1.2.8 Available Soil Carbon.

Menhaz et al. (2018) claim that soil C availability typically serves as an energy source for soil microbes and hence boosts microbial activity. According to Wang et al. (2021), nitrifiers and denitrifiers need a readily accessible C supply to oxidize ammonia (NH_4^+) and reduce NO_3^-. Water-soluble C is the source of energy that microbes may access most easily and promotes microbial activity. Hence the capacity for soil nitrification and denitrification increases with an increase in SOC concentration, specifically the water-soluble C content (Wang et al., 2021).

2.1.2.9 Soil N Content

The primary component needed for denitrification is the molecule of nitrate (Wang et al., 2021). Any source of nitrogen (N) input into agricultural soils, including manures, slurry, legumes, and post-harvest crop residues, is a potential source of N substrates for N_2O emissions (Smith, 2017 & Norton & Ouyang, 2019). The rate of microbial immobilization, plant uptake of nitrogen, leaching and lateral flow of NO_3^-, as well as its concentration in the soil, all play a role in how much NO_3^- is present in the soil at any given time (Wang et al., 2021).

It is well acknowledged in the literature that nitrification and N input have a positive relationship. The ratio of nitrified N to N_2O emitted, however, varies depending on the soil type and climate. A review of literature by Wang et al. (2021) revealed that elevated soil NO_3^- concentrations limit the reduction of N_2O to N_2.

2.1.2.10 Soil Texture

The possibility of aerobic or anaerobic conditions prevailing in the soil is the principal way how soil texture influences N_2O emissions (Wang et al., 2021). As a result of variations in SOC, N availability, and microbial population, Xu et al. (2013) also claim that soil texture also influences N_2O emissions.

According to Wang et al. (2021), soils with finer textures can emit more N_2O than soils with sand. Compared to fine textured soils, such soil types contain larger capillary pores inside aggregates, which helps them hold soil water more firmly (Oertel et al., 2016). As a result, compared to sandy soils, finer textured soils may make it possible for anaerobic conditions to be attained and sustained for longer within aggregates (Smith, 2017).

2.1.2.11 Site Exposure

Soil temperature and moisture can also be affected by site exposure factors such elevation, morphological location, and plant cover. Due to the higher soil moisture content found mostly in low-lying lands, N_2O emissions in depressions are higher than those on sloped land and hills according to Wang et al. (2021). Yet, the lower air pressure at higher elevations favors N_2O emissions because there is less counterpressure on soils (Oertel et al., 2016).

(Table 3): Summary of the correlations of nitrification and denitrification with main environmental variables

Processes	Soil N	SOC	SWC (WFPS)	Soil Temperature	Soil pH
Nitrification	+	+	~60%: +	+	Need more research
Denitrification	+	+	60–80%: +	+	Need more research
N2/N2O ratio	−	+ depends on N	>90%: +	+	<6.0: more N2
					=6.0: equivalent;
					>6.0: more N2

Source: Wang et al. (2021)

2.1.3 Management Factors

Field management practices have a big impact on N_2O emissions because they control how much nitrogen is added to the soil, which could alter the environmental and microbiological conditions in the soil. Examples of management elements include the types and amounts of fertilizer applied, the crops grown, and the tillage practices used, all of which have an impact on how much crop residue is left in the soil.

2.1.3.1 Application of Fertilizers

Synthetic (mineral) fertilizers, such as urea, ammonium nitrate, ammonium sulfate, and NPK, solid organic fertilizers, such as organic manure, composted municipal soil waste, composted animal manure, and crop residues, and liquid organic fertilizers such as raw or digested animal slurries are types of nitrogen fertilizers used in agricultural fields (Wang et al., 2021).

The type, amount, and timing of fertilizer application affect the amount of N_2O emitted (Wang et al., 2021). The varying concentrations of NH_4^+, NO_3^-, and organic C in fertilizers have a significant impact on the quantity of N_2O emissions (Smith, 2017). The amount of fertilizer applied, which supplies the soil with a source of nitrogen, contributes to N_2O emissions (Smith, 2014). The efficiency of fertilizer use and crop yields are influenced by the timing of fertilizer application. The large pool of soil nitrogen in the early stages of crop growth that cannot be assimilated by the crop can cause N_2O emissions to increase when mineral fertilizer or manure is applied before or at sowing as per the findings of Wang et al. (2021).

2.1.3.2 Soil Tillage Practices.

Changes in soil structure, soil aeration, microbial activity, rate of residue breakdown and loss of soil organic matter from the system, as well as variations in soil temperature and moisture, are all driven by soil tillage (Yuan et al., 2018). In a study by Grave et al. (2018), it was discovered that cumulative N_2O emissions were 107% greater in no-till soil as compared to tilled soil when N was applied. According to their study, larger N_2O emissions that were recorded from no-till soil is as a result of enhanced WFPS (greater than 60%) and higher N availability (C/N approximately 1.58) compared to tilled soil.

2.1.3.3 Crop Harvest and Plant Residue Management

According to research by Duan et al. (2018) and Yuan et al. (2018), adding crop residues to the soil generally boosts N_2O production because the more organic C that is available and can be utilized in the N mineralization processes. In addition, the aerobic conditions necessary for agricultural residue breakdown may activate denitrification when soil oxygen levels are reduced (Wang et al., 2021).

2.1.3.4 Irrigation

Rain-fed irrigation systems, high-watered systems (furrow, sprinkler, and micro-sprinkler irrigation), and low-watered irrigation systems (surface and subsurface drip irrigation techniques) are all categories of irrigation. By modifying soil moisture, temperature, and anaerobic conditions, irrigation affects the denitrification process. It also modifies soil salinity (Wang et al., 2021). As WFPS rises, soil aeration may be impaired, resulting in low oxygen levels and anaerobic conditions that encourage denitrification.

The changing environmental conditions as a result of irrigation may collectively influence the processes of dissolution/crystallization, oxidation/reduction, adsorption/desorption, and other reactions, which will ultimately affect the generation and utilization of N_2O in the soil (Aguilera et al., 2013).

2.1.3.5 Environmental Contaminants,

The environment is becoming more contaminated as a result of massive economic expansion and rapid growth in agriculture and industry (Aryal et al., 2022). Environmental contaminants are hazardous compounds that infiltrate the environment from both manmade and natural sources. Certain human activities, such as synthetic industries, coal conversion, and trash burning, cause severe constraints for water, air, and soil animals, plants, and humans. Environmental toxicants are typically heavy metals and pesticides that harm the entire ecosystem, severely affecting its functioning and composition (Aryal et al., 2022)

Agrochemicals used to increase crop production such as herbicides, insecticides, pesticides, and fungicides also indirect impact the global N cycle by affecting the constitution of vegetation and the soil-vegetation interaction which contribute to determining moisture and temperature variability (Aryal et al., 2022).

Besides, accumulation of pesticide residues can alter the soil denitrification rates from agricultural soils. For example, a study conducted by Hu et al. (2021a, b) showed that the persistence of Tetracycline and Fluoroquinolone antibiotics in the soil can enhance or retard the oxidation and reduction of Nitrogen in soils by altering microbial communities.

2.1.4 Measurement Factors

N_2O emissions are not directly impacted by the measuring factors. But nonetheless, the measurements are significant information because they have an impact on the precision and accuracy of the observed N_2O level and are helpful in highlighting the measurement errors. Inadequate spatial or temporal N_2O sample measurements from the soil might result in either an overestimation or an underestimating the emissions (Wang et al., 2021). They also found that the methodologies used to quantify N_2O emissions as well as the measurement's temporal and spatial scales are the key contributors to measurement discrepancies.

2.1.4.1 Duration of Measurement

The measurement of an entire year's N_2O emissions is essential to obtain reliable data (Wang et al., 2021). Out of the 21 studies examined by Shang et al. (2020), including measurements of N_2O emissions throughout the year and throughout the growing season, the Emission Factor (EF) for the entire year was much higher than for the growing season. The highest EF difference was seen in vegetables (0.19%), followed by paddy rice (0.11%), for all crops combined (0.07%).

Similarly, in a study by Smith (2017), who examined the relationship between the length (days) of N_2O being sampled and N_2O emissions from agricultural land, he found out that N_2O emissions (as a function of % of N fertilizer applied) during three different lengths of measurement periods (>30, >100, and >200 days) were 0.6, 1.1, and 1.6, respectively. This study brought focus on the duration of measurement as a factor that affects the amount of N_2O emitted.

2.1.4.2 Measurement Type.

Many approaches, such as chamber techniques, static core techniques, and micrometeorological techniques, are utilized to detect N_2O emissions in terrestrial and aquatic environments (Wang et al., 2021). To examine N_2O flows spatially at various scales, chambers are frequently utilized. The static core approach is employed primarily to predict possible N_2O emissions from managed soils, while the best techniques for determining N_2O fluxes from landscape (field) scale are micrometeorological methods (Wang et al., 2021).

Wang et al. (2021) reported that each measuring method has benefits and drawbacks, even at smaller landscape levels, because of the great geographical and temporal variability of N_2O emissions. When chambers are put on the soil surface for brief periods of time, chamber methods represent the most practical ways for detecting N_2O fluxes (Wang et al., 2021). However, the closed chamber is only suited for short-height crops and because the air flow velocity through the open chamber can be too high, it can give erroneous measurements. N_2O emissions from the soil have also been measured using micrometeorological techniques, which have the benefit over chambers in terms of their spatial and temporal integration (Wang et al., 2021).

2.2 Modelling N_2O Emissions

A variety of mathematical models can be used to simulate nitrification and denitrification to varied degrees. These models take into account the previously mentioned variables that affect N_2O emissions. Since they can easily replicate environmental variables, crop development, and N_2O fluxes under various management options on a daily time and temporal scales, the majority of these models are process-based as opposed to empirical models. (Wang et al., 2021). Examples of such models include eco-hydrological model SWAT and biogeochemical models such as DAYCENT and DNDC (Wang et al.,2021). The three models are summarized in Table 4.

(Table 4): Process-based models for modelling N2O emissions

Model	Input Data	Physical Processes and Products Partitioning	Considered Environmental Factors
DAYCENT	Daily weather variables, site-specific soil properties, and land use.	Nitrification	Soil N, temperature, WFPS and pH
		Denitrification	Soil N, SOC and WFPS
		N_2/N_2O	Soil N, SOC and WFPS
		NO_x/N_2O	Soil WFPS
DNDC	Daily weather variables, soil properties, and management practices.	Nitrification	Nitrifiers, soil N, WFPS, temperature, and pH
		Denitrification	De-nitrifiers, SOC, soil N, temperature, and pH
		NO_x, N_2	Soil pH
SWAT	DEM, soil properties, daily weather variables, and management practices.	Nitrification	Soil N, WFPS, temperature and pH
		Denitrification	Soil N, SOC, moisture, temperature and pH

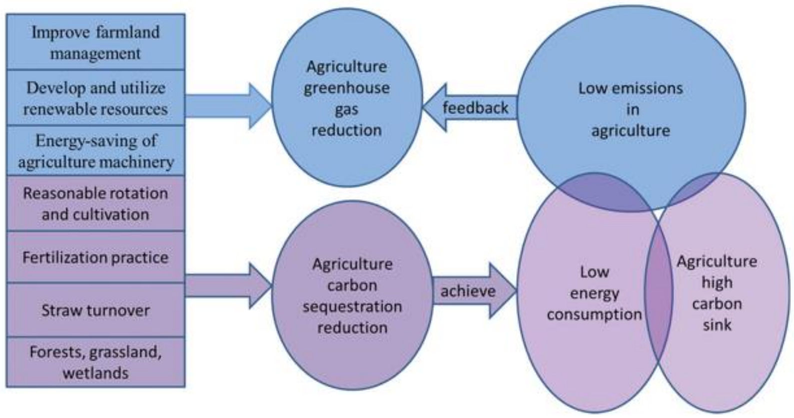
Source: Wang et al., (2021)

2.3 Agricultural Management Options for Mitigating Nitrification in Soils

Since increasing N availability is the primary agrotechnique required to boost crop yields, more than 50% of nitrogen in terrestrial ecosystems come from agriculture (Norton & Ouyang, 2019). As was previously said, the conversion of ammonium to nitrate during the nitrification process improves the flow of nitrogen in the soil, having an impact on how much nitrogen is left in the soil. In order to lower the rate of nitrification in agricultural soils, soil management measures should be directed at regulating N substrate supply and interfering with the operations of denitrification. A number of options are available to reduce N_2O emissions in agricultural soils as discussed below and shown hypothetically in Figure 4.

2.3.1 Strategies for Decreasing N Losses

Agricultural management options that decease N losses in agricultural soils are aimed at enhancing soil fertility. These include minimum tillage, having a greater diversity of crops through crop rotation and as diverse mixtures of crops and keeping the soil covered with mulches at all times (Norton & Ouyang, 2019). Such practices add organic matter to the system, and hence decreases nitrate accumulation and potential leaching (Abdalla et al., 2019). However, cover crops must be managed carefully especially in drier climates to avoid decreases in the productivity of the primary crop due to water or nutrient uptake while promoting soil nitrate recycling.



(Figure 4): Schematic representation of the methods of reducing N_2O emissions

Source: Wang et al., (2021)

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2.3.3 Strategies for controlling Nitrate substrate availability

In order to achieve optimum crop yields, it is imperative to apply the N fertilizer in the right dosage, time and type. Such approaches improve NUE, which is the difference between the amount of N supplied by the soil and N requirements of the crop. such strategies include the following.

2.3.3.1 Timing of Fertilizer Application

As opposed to basal application before planting, N must be applied during the crop growth season right before the period of maximum plant uptake in order to ensure efficient utilization (Norton & Ouyang, 2019) and ensure high NUE, which can lower denitrification rates. The time of N application is determined by crop growth stages, in addition to other plant and soil testing methods (Ma et al., 2010)

2.3.3.2 Controlled or Slow-Release Fertilizers.

The most widely used nitrogen fertilizers, including urea, are easily hydrolyzed and susceptible to nitrification (Norton & Ouyang, 2019). However, by coating such fertilizers with both organic and inorganic polymers, such as sulfur, such drawbacks can be lessened. These fertilizers effectively match the time of nutrient release to plants and are known as Slow or Controlled Release Fertilizers. As a result, these fertilizers significantly lower the rates of nitrification in agricultural soils.

2.3.4 Integrated N Management

According to Paustain et al. (2016), nitrification rates are decreased with a noticeably improved NUE when soil nitrate fixation and mineralization rates are higher than nitrate supplied by inorganic fertilizers. The direct enhancement of N fixation and mineralization as well as the increase in N cycling variety all contribute to the retention of N in the soil. By incorporating soil organic amendments with a high carbon content, such as compost, manure, and biochar, this strategy can be realized (Hu and He, 2018).

2.3.5 Direct Nitrification Inhibition

Nitrification Inhibitors (NIs) raise the NUE of fertilizers by slowing the microbial conversion during the denitrification, thus lowering the risk of loss due to leaching and denitrification (Norton & Ouyang, 2019). Both synthetic and organic forms of NIs exist.

In order to lower the rates of nitrification in soils while reducing the activity of the enzyme ammonia monooxygenase, synthetic Nis such as 2-chloro-6-(trichloromethyl) pyridine (nitrapyrin), Dicyandiamide (DCD), and 3,4-dimethylepyrazole Phosphate (DMPP) have been used. Other forms of Nis used to reduce urea hydrolysis and volatilization include urease inhibitors like N-(n-butyl) thiophosphoric triamide (NBPT) (Norton & Ouyang, 2019).

It has been demonstrated that some plant species' roots such as *Brachiaria spp*. and *Sorghum bicolor* have the capacity to prevent soil nitrification by producing biological inhibitors, (Subbarao et al., 2015; Coskun et al., 2017). As a result, including these crops in crop rotations and mixtures for agriculture can aid in lowering the rate of nitrogen losses from nitrification.

2.4 CO_2 Emissions

With an average global CO_2 flow value of 6 g m^2 d^{-1}, natural soil CO_2 emissions account for a significant fraction of the carbon emitted to the atmosphere Camarda et al. (2019). Three categories of CO_2 fluxes have known to exist, namely root, microbial and ecosystem respirations. Root and microbial respiration all occur in soil. The average contribution of root respiration to soil respiration is around 50%, however depending on the season and vegetation species, this amount might range from 10% to 95% according to Oertel et al. (2016). Ecosystem respiration additionally includes aboveground plant respiration. The distinction between ecosystem respiration and photosynthesis is known as net ecosystem exchange (NEE). A CO_2 sink is revealed by a negative NEE, whereas a positive NEE shows a CO_2 source according to Oertel et al. (2016).

According to Zhang et al. (2016), terrestrial CO_2 emissions also include the release of CO_2 from the crust and mantle as a result of Earth's degassing, in addition to CO_2 produced by plant, microbial and root respirations. Other processes such as biogenic degradation of organic molecules, and/or oxidative decay of organic materials also contribute to the emission of CO_2 from soils (Oertel et al., 2016).

2.4.1 Measurements of Soil CO_2 emissions

Several approaches, which may be divided into two main classes: in situ measurement methods and remote sensing methods, can be used to measure CO_2 emissions depending on the research's objectives (Camarda et al., 2019).

Remote sensing techniques include Optical Remote Sensing (using ground, air and space borne techniques), Passive Remote Sensing (through the use of Grating Spectrometers, Gas Correlation Radiometers. Open Path Fourier Transformation Infrared Spectometry) and finally Active Remote Sensing through the use of differential absorption lidars, Raman Lidars and optical correlation lidars (Queißer et al., 2019). The major advantages of remote sensing are a safe measuring distance, inclusive spatial probing, and quick measurements, whereas the main drawbacks are a generally lower measurement precision and the lack of commercially accessible systems (Camarda et al., 2019).

Single point measurements and measurements on a broad spatial scale are the two categories of in situ measurements. According to Camarda et al. (2019), Eddy Covariance analysis is the technique most frequently utilized for measurements at broad spatial scales. This method relies on the covariance between changes in the vertical component of the wind and changes in the gas concentration in the atmosphere to calculate the flux at the surface.

Single point measurements may be performed directly by observing concentration gradients in the soil. The dynamic concentration method and the accumulation chamber method are the two indirect single point techniques that are applied more extensively (Camarda et al., 2019). The basis for the accumulation chamber method is the measurement of the increase in CO_2 concentration within a known volume, open-bottomed container that is placed inverted on the soil surface. According to the volume, pressure, and temperature values of the chamber, the flux value is determined using a theoretical equation. The dynamic concentration method is based on a measurement of the CO_2 concentration in an air and soil gas combination produced by a specially constructed probe that is placed into the soil at a depth of 50 cm (Camarda et al., 2019).

However, because soil CO_2 emissions are controlled by a number of activities, choosing the approach that is most appropriate isn't the key concern; rather, it's the understanding of the mechanisms that led to the observed values (Camarda et al., 2019). Soil CO_2 emission is a complex process that is influenced by soil characteristics (mainly air permeability and bulk diffusion coefficient) and the dominant CO_2 transport modes, such as advection, diffusion, and their interaction. Additionally, meteorological factors including atmospheric pressure, air temperature, and precipitation have a big impact on the gas emission, which results in big measurement variances (Oertel et al., 2016).

2.4.2 Factors affecting CO_2 Emission from Agricultural Soils.

We present a thorough examination of both abiotic and geological factors that affect soil CO_2 emissions in the sections that follow as reported in literature**.**

2.4.2.1 Abiotic Factors

Environmental factors, such as air temperature, atmospheric pressure, and precipitation, are discovered to be the main exogenous variables that can affect the release of gases from the soil (Smith, 2017). These characteristics can alter the qualities of soil in addition to directly affecting the soil CO_2 level (Camarda et al., 2017). A discussion of some of these factors is provided below.

2.4.2.1.1 Atmospheric Pressure Variations

According to Camarda et al. (2019), soil CO_2 time series are characterized by low values and changes during the summer season and significantly larger values and variations throughout the winter seasons. They also noted that there is a significant variation in air pressure variability during the winter, when strong atmospheric perturbations are more common, and a small variation during the summer. The fact that soil CO_2 flow values rise as air pressure drops is indicated by the negative connection between soil CO_2 flux and atmospheric pressure.

A physical process associated with pressure change that can cause these variations is known as "Barometric Pumping" (Camarda et al., 2019), which states that a decrease in atmospheric pressure causes a gas to migrate from deep soil layers to the surface, hence a rapid decrease in barometric pressure causes a sharp increase in the soil CO_2 flux. Diffusion and advection are two distinct processes that can transport gas in soils. The flow of matter from a high-concentration area to a low-concentration area is called diffusion. The movement of matter brought on by a pressure gradient is called advection. Gas transport occurs as a result of a combination of advection and diffusion processes because pressure and concentration gradients frequently coexist in natural soil (Camarda et al., 2019). The flux of a generic gas species can therefore be expressed as the sum of its diffusive and advective components.

According to Camarda et al. (2019), the effect of atmospheric pressure variation relies entirely on the magnitude of the change in atmospheric pressure and the magnitude of the pressure difference between the atmosphere and the gas source. It is independent of the depth of the gas source, the permeability of the soil, or the viscosity of CO_2.

2.4.2.1.2 Air temperature and SWC

It is typical to find a strong relationship between soil CO2 flow and temperature in literature (Zhan et al. 2016; Hicks Piers et al. 2017; Oertel. 2016; Camarda et al. 2012, 2016, 2017, 2019). The variation in air temperature has a number of consequences that can alter the transport of soil CO_2 through the soils in addition to influencing biogenic and CO_2 productivity (Hicks Pries et al. 2017 & Camarda et al. 2017).

The soil temperature, which directly affects the molecular diffusion coefficient of CO_2 in soil, is often regulated by seasonal variations in air temperature. CO_2 diffusion coefficient varies with a 1.5 power of the air temperature (Camarda et al., 2019). Oertel et. (2016) also observed that temperature has a positive relationship with CO_2 emissions. They associated this to increased microbial metabolism resulting in higher soil respiration rates. They also observed that at soil temperatures below 7°C, bacteria were shown to be slower in respiring.

The volumetric water content of the soil (VWC), which is the percentage of the entire volume of the soil that is occupied by water, is regulated by the level of evapotranspiration that is dependent on air temperature (Camarda et al. 2019). Both the bulk diffusion coefficient and the air permeability of the soil are significantly influenced by its volumetric water content. As the soil's VWC declines, these two transport parameters both increase (Smith, 2017).

2.4.2.1.3 Soil pH

Soil pH has an impact on microbial activity as noted by Smith (2017). Oertel et al. (2016) highlighted that management techniques such as liming have impacts on soil emissions, for example the application of more carbonates in the soil led to the release more CO2. They also noted that the largest CO_2 emissions were observed in neutral soil pH levels.

2.4.2.1.4 Nutrient Availability

In order to support microbial and plant activities, nutrients must be readily available in soils. Soil's natural N and C content, atmospheric deposition, application of manure, and fertilizer all play a significant role in influencing nutrient availability in soils (Wang et al., 2021). Oertel el al. (2016) noted that the C/N-ratio of organic matter and CO_2 emissions have a positive correlation. They attributed this to the microbial activity that can be enhanced by the high levels of C, which is a source of energy for soil microbes.

2.4.2.2 Geological Factors

Endogenous activities linked to the volcano or/and hydrothermal system and tectonic activity can also have a significant impact on the soil CO_2 flux in addition to exogenous processes and variables (Camarda et al., 2019). Although CO_2 emissions are significant in the majority of volcanic and hydrothermal systems, very few instrument networks are installed in such locations to regularly monitoring such a crucial parameter, according to Camarda et al. (2012, 2019). Among the endogenous variables that affect CO_2 emissions include.

2.10.2.1 Volcanic Activities

Both deeper tectonic structures and crater conduits are used to dispose of stored gases, and the process is visible in the discharges of peristaltic fluids. In addition to changing geochemical indications, the large fluid release increases the fluid pore pressure that causes high-frequency seismicity (Camarda et al., 2019). In line with this occurrence, data from Gaudin et al. (2017) clearly demonstrated that the commencement of seismic activity follows the onset of geochemical anomalies, demonstrating that the seismicity is driven by an increase in pore pressure due to an increase in fluid release. Significant increase in CO_2 emission is observed during such times.

2.10.2.1.1 Tectonic Factors

The stress that causes seismogenic processes in tectonically active regions also results in noticeable alterations in the shallower layers of the crust, such as surface deformation, changes in pore pressure, and adjustments to fluid circulation (Camarda et al. 2019). Recent research has shown that fluid circulation can be affected by the deformation brought on by tectonic crustal stress (Camarda et al., 2012, 2016, 2019).

It is unclear how these processes are caused by their underlying mechanisms. Nonetheless, it is commonly believed that tectonic stress modifies rock qualities like porosity, permeability, and pore fluid pressure (Camarda et al., 2019). They did, however, demonstrate that the dynamics of the local stress field connected to the seismogenetic process can affect the rates of volcanic fluid discharge in volcanic locations by using stress-induced permeability changes.

CHAPTER 3: MATERIALS AND METHODS

3.1 Study Site

A field experiment was carried out at Kartal from February 2021 to December 2022 under conventional farming system involving soil tillage, sowing, weed, pest and disease and mineral fertilizer application. the site's three-year rotation and crop management information is are shown in table 5.

The site is located in the central part of Hungary, 153 Masl with geographic coordinates 47.658° N, 19.532° E. The soil type at the site is chernozem brown forest soil (WRB, 2015 chernozem) with a continental climate.

(Table 5): Management data and agronomic practices at the experimental site from 2017 to 2021

Season	Crop Grown	Date of Sowing	Date of Harvest	Fertilizer	N Input kg	Application Date
2017-2018	Winter Wheat	3/10/2017	14/07/2018	CAN 27%	100	1/10/2017
				Nikrol 30%	140	15/03/2018
2018	Oil Seed Rape	10/9/2018	No Harvest	NPK 15-15-15	200	29/08/2018
2019	Sorghum	3/5/2019	30/09/2019	MAS 27%	200	3/5/2019
2019-2020	Winter Wheat	14/10/2019	16/07/2020	MAS 27%	100	10/4/2019
2020-2021	Sun Flower	3/4/2021	3/9/2021	Nitrosol 30%	475 L	3/10/2020
				KCl	84	24/11/2020
				MAP	122	25/11/2020

Source: Field Data

3.2 Land Preparation and Sowing.

Mowing and ploughing were carried out on 3rd September 2021, followed by seedbed preparation on 14th October 2021. During seed preparation, MAP (12% N and 52% P) was applied at a rate of 100kg /ha. Winter wheat was sown on 15th October 2021 at a rate of 200kg/ha.

3.3 Experimental Setup

24 PVC collars of 10 cm in height with a diameter of 20 cm were immediately inserted into the soil after the winter wheat was sown, leaving a height of exactly 4 cm above the soil surface for the smart chamber to be placed for the flux measurements and were left in the experimental field throughout the course of the study. The geographic coordinates of each collar are shown in Table 6, while the pattern of placement is shown in Figure 5.

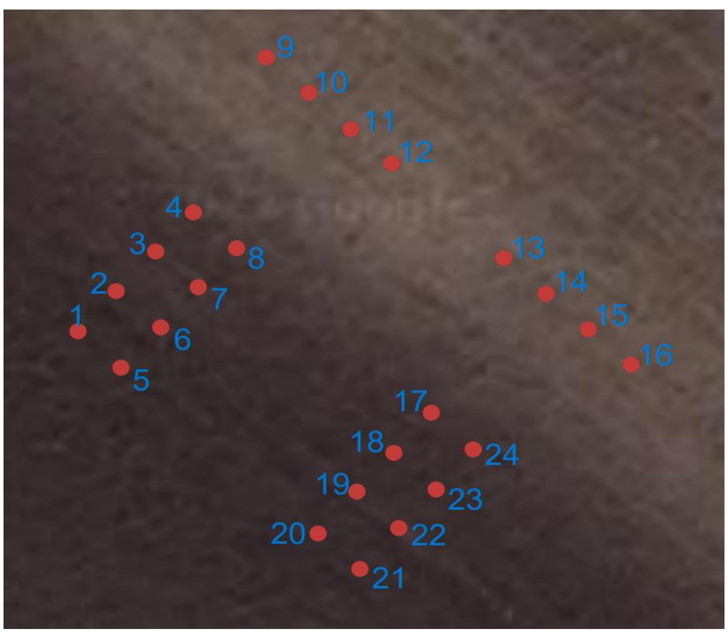
3.4 Application of Treatment

$NaNO_3$ was applied at a rate of 185 kg/ha on 30th April 2022 to collars 1, 2, 3, 4, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19 and 20, while collars 5, 6, 7, 8, 21, 22, 23 and 24 were covered with foil and did not receive the fertilizer.

(Table 6): Coordinates of the location of the collars in the experimental site

Collar	UTMy	UTMx	z	Longitude	Latitude	Collar	UTMy	UTMx	z	Longitude	Latitude
1	5279734	389446	201.529	19.5275	47.6616	13	5279739	389469	201.365	19.5278	47.6616
2	5279737	389448	201.515	19.5276	47.6616	14	5279737	389471	201.36	19.5279	47.6616
3	5279739	389450	201.551	19.5276	47.6616	15	5279734	389473	201.336	19.5279	47.6616
4	5279741	389452	201.492	19.5276	47.6616	16	5279733	389475	201.327	19.5279	47.6615
5	5279732	389449	201.541	19.5276	47.6615	17	5279730	389465	201.406	19.5278	47.6615
6	5279735	389451	201.492	19.5276	47.6616	18	5279728	389463	201.456	19.5278	47.6615
7	5279737	389453	201.557	19.5276	47.6616	19	5279725	389461	201.478	19.5277	47.6615
8	5279739	389455	201.522	19.5277	47.6616	20	5279723	389459	201.504	19.5277	47.6615
9	5279750	389456	201.48	19.5277	47.6617	21	5279721	389461	201.544	19.5277	47.6614
10	5279748	389458	201.458	19.5277	47.6617	22	5279723	389463	201.527	19.5278	47.6615
11	5279746	389461	201.44	19.5277	47.6617	23	5279725	389465	201.495	19.5278	47.6615
12	5279744	389463	201.409	19.5278	47.6616	24	5279728	389467	201.535	19.5278	47.6615

Source: Field Data



(Figure 5): Numbering and pattern of collars
Source: Field Data

3.5 Soil N_2O and CO_2 Emissions Measurements

The N_2O and CO_2 emissions were measured using Li-Cor Smart Gas Analyser (LI-870 CO_2/H_2O Analyser and LI-7820 N_2O/H_2O Trace Gas Analyser) connected to the 8200-01S Smart Chamber.

The fluxes were measured weekly at noon throughout the study period and the data was remotely transferred to a file created on our mobile phones. This was made possible by the Wi-Fi connection of the device. The dates of measurement are shown in Table 7.

(Table 7): Dates of measurement during the study period.

	Feb	Marc	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Week 1	4th	3rd	5th	3rd	2nd	×××	×××	7th	4th	×××	7th
Week 2	×××	8th	13th	12th	×××	×××	×××	15th	12th	×××	12th
Week 3	×××	17th	21st	18th	×××	×××	×××	20th	×××	×××	×××
Week 4	×××	24th	28th	26th	×××	×××	×××	28th	×××	×××	×××

Source: Field data
××× means no measurements were conducted because of a faulty in the device (Li-COR)

3.6 Measurement Principles

The Smart Chamber was linked to our mobile devices via wireless WIFI. On the first date of measurement, we generated a new file on our device and named it Kartal. Because we were using homemade collars during the study, we had to configure the measurement by setting the Constants (Collar Offset in cm and Soil Area cm2, which is the area inside the collar) on the first date of measurement. When the smart chamber was powered on and the files button was pressed during subsequent measurements, it immediately opened the previous files. We had to ensure that the gas analyzer cables and tubing were properly installed.

When taking measurements, we placed the Smart Chamber on a collar and inserted the soil probes into the soil. We then returned to the home screen of our phone devices and tapped the Start button to begin the measurement. The measurement was carried out automatically and lasted 2 minutes per collar. We could observe and save data values we selected in the right-hand part of the Home screen. We picked up the chamber and soil probes after each measurement (once per collar) and moved on to the next collar. We performed the above steps for all of the collars.

3.7 Drawbacks during the study.

The most difficult challenges we faced during the study was a flaw in the device at specific points. This was due to a technical defect in the device. However, we sought technical support from the manufacturers.

The weather patterns during the study period were characterized by extremely dry soil conditions. This may have influenced the performance of the soil probes, as we got seemingly unreliable soil temperature and SWC data. During data analysis, we used the measurements (soil temperature and SWC) from the Eddy Covariance Station and did not consider the data collected in December because of the continued fault in the measurement device.

3.8 Evaluation of the LI-COR device.

Each location has its own set of conditions. A gas analyzer should also be able to work in a variety of environments. Based on the data we collected, the LI-COR smart gas analyzer appears to be reliable in determining fluxes. The unreliability we noticed with soil temperature and SWC could be attributable to a technical defect in the equipment. The evaluation of the device can further be revisited in future studies.

3.9 Additional Measurements.

An Eddy Covariance (EC) station located at a distance of approximately 50m from the site, measured environmental variables, namely air temperature, relative humidity, soil moisture content (7cm), soil water content (30 cm), soil temperature, photosynthetically active radiation, net global radiation, soil CO2 levels and precipitation.

Regardless, we also measured soil temperature and SWC near each ring. The former was measured with a LI-Cor thermometer attached to the Smart Chamber and the latter was determined by Time Domain Reflectometry (FieldScout, TDR300 Soil Moisture Meter, Spectrum Technologies, IL-USA) in the top 0-5 cm layer of the soil. However, the data collected seemed not to be reliable. Therefore, environmental data, namely soil temperature and SWC at 30cm were used in the analysis.

3.10 Data Analysis.

We calculated the Pearson correlation coefficient using Microsoft Excel (2019 version) to measure the association between the fluxes (covered and treated) and a particular environmental variable (SWC and soil temperature).

We calculated the t-score and p-value for each correlation coefficient to determine if it was statistically significant. The t-score of a correlation coefficient (r) was calculated using the formula (Statology, 2023).

$$t\ score = r\sqrt{(n-2)} / \sqrt{(1-r^2)}$$

The p-value was determined as the corresponding two-tailed p-value for the t-distribution with n-2 degrees of freedom. To evaluate if the correlation is statistically significant, we used a significance level of $\alpha = 0.05$.

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4.1 Environmental Variables during the Research Period

During the study period, the experimental site's average SWC (30 cm), as recorded by the Eddy Covariance Station was 30.66%. The maximum SWC value of 39.13% was recorded on 10th April, while the minimum value (24.92%) was observed on 28th September (Figure. 6). The mean soil temperature recorded was 14.16°C, with the highest value of 27.35°C and lowest of 0.31°C recorded on the 23rd of July and 25th of January respectively (Figure 6)

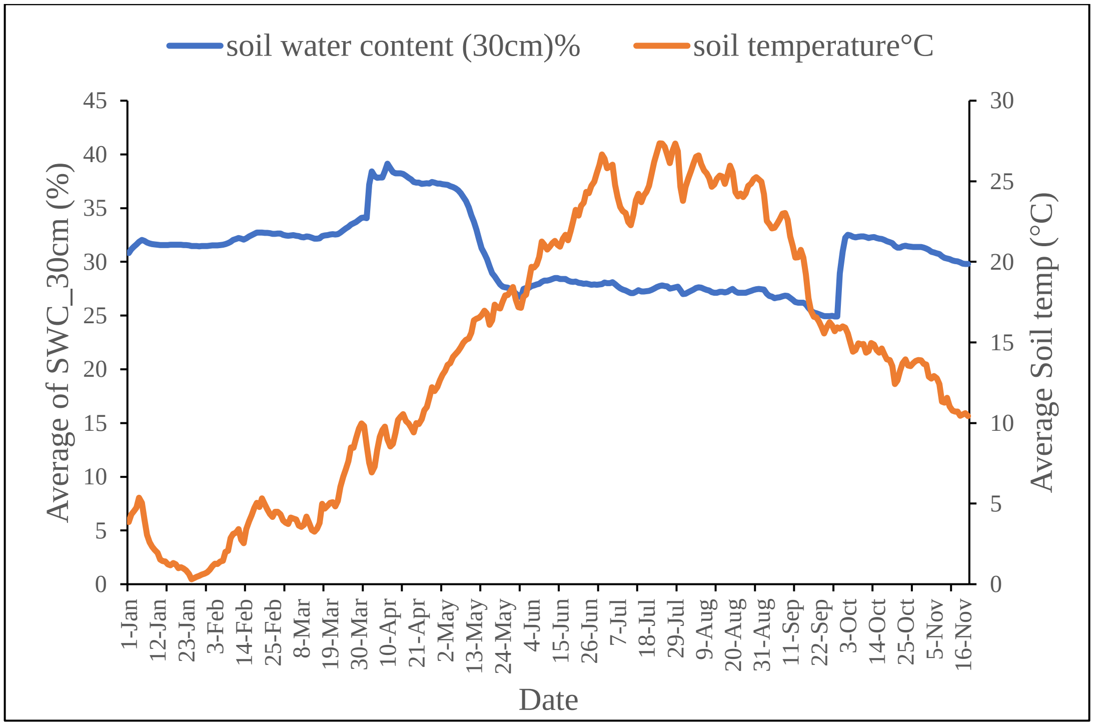
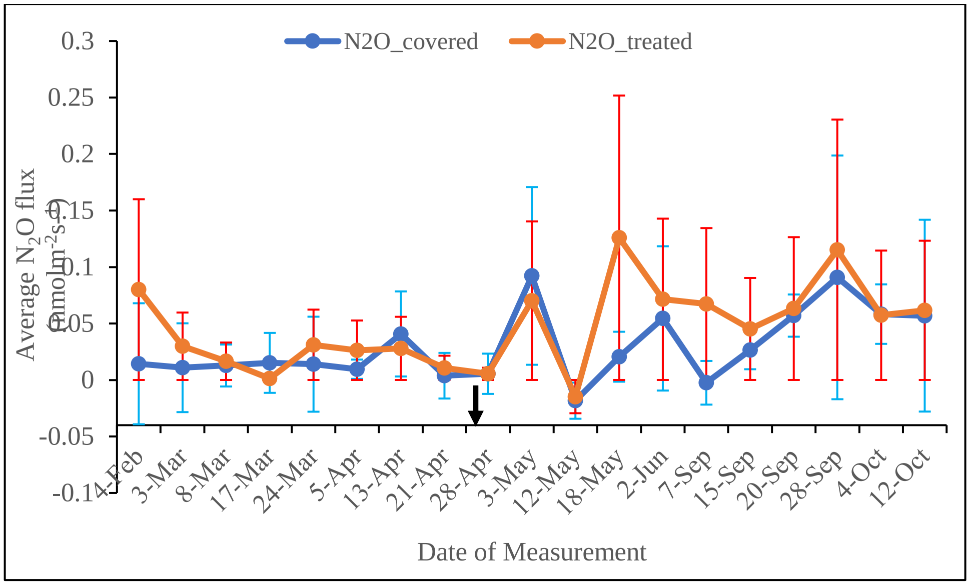


Figure 6: Average SWC_30cm and average soil temperature of the experimental site.

4.2 N_2O Emission Variations

Figure 2 shows the variability of N_2O emissions during the time of the study. The mean N_2O emissions showed significant variations in time throughout the study period. The average emission from the covered collars was 0.0296 nmolm^{-2}s^{-1} and attained a maximum of 0.092 nmolm^{-2}s^{-1} and a minimum of -0.018 nmolm^{2}s^{-1} on 3rd May and 12th of May respectively.

The average N_2O flux from the treated collars was 0.0469 nmolm^{2}s^{-1}. The maximum value was 0.126 nmolm^{-2}s^{-1}, reached on 18th May and minimum of -0.015 nmolm^{-2}s^{-1} was recorded on 12th of May (Figure 7).

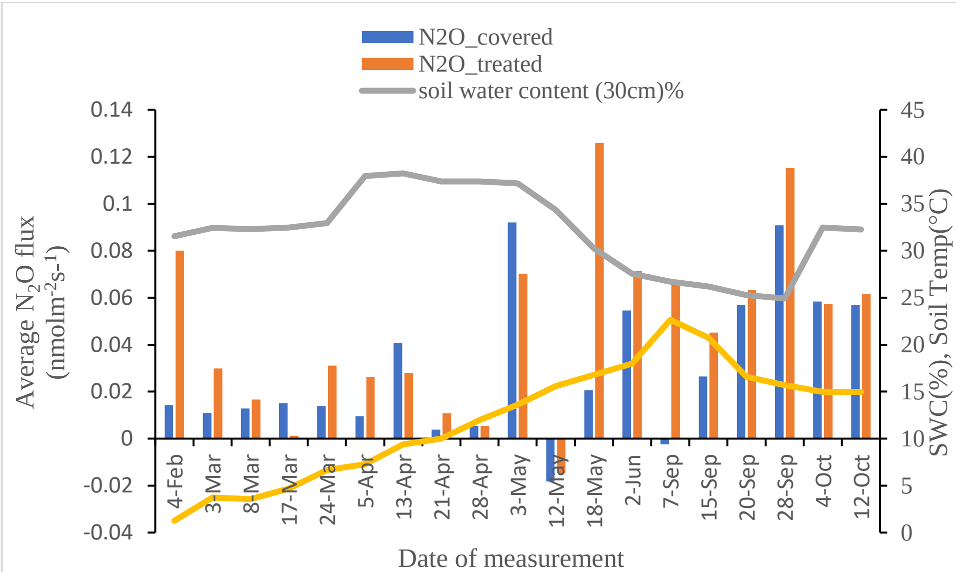


(Figure 7): Variability of N_2O emissions during the study period. Black arrow indicates time of 185kg/ha $NaNO_3$ application.

Typically, the covered and treated collars' temporal emission pattern displayed a clear pattern during the study period as seen in Figures 7 and 8.

The slightly higher-than-average N_2O emission that was observed from 4th February to 13th April for the covered and treated collars might have been attributed to low soil temperature and high SWC as seen in figure 7. Our results are comparable to the findings of Kurganova and Lopes (2010), who found out an accelerated N_2O release from soils with a substantial amount of water at low soil temperatures. This pattern may also be explained by the oxygen deficiency circumstances brought on by the relatively SWC, which might have sparked denitrification and N_2O generation. This emission might also be associated with the residual N present in the soil following application of MAP and Nitrosol on 3rd October 2021 and 5th February 2022 respectively. The observed emission might have been linked to the soils having with a high level of labile carbon following the incorporation of the pre crop (sunflower) residues. The C might have acted as a source of energy for the soil microbes during the denitrification process. Since N_2O emission have been noted to be positively correlated with soil carbon content (Bouteldja et al., 2019).

There was an observed increase in emissions for the both the treated and covered collars on 3rd May (Figures 7 & 8). This occurred at a relatively SWC and relatively low soil temperatures. These environmental conditions might have accelerated the denitrification process, with a subsequent increase in the emissions, as noted in many studies such as Schauffer et al. (2010); Soulski et al. (2014); Bouteldja et al. (2020); Wang et al. (2021).



(Figure 8): N_2O flux emission time series with soil temperature and SWC

The physiological growth of the wheat might also be responsible for the noted emission on the said date. However, there seems to be no consensus as to whether plants increase or decrease N_2O fluxes. Some researchers, for instance, Ciampitti & Vyn (2012) and Wang et al. (2019), argue that since plants use a lot of N from the soil to grow, there is a decrease in N that is accessible in the soil, which might decrease N_2O emissions. On the contrary, others, such as Hayashi et al. (2015) argue that the presence of plants may generally enhance N_2O release, because plant roots influence rhizosphere biogeochemical parameters. These include oxygen availability (as plants growth, the plant roots reduce the oxygen content of the soil, which in turn increases the soils sensitivity to denitrification), increase in labile organic carbon and inorganic nitrogen. Zou et al. (2005) also noted an increase in emissions during the heading stage of wheat than during the tillering stage. This finding is consistent with our finding since the head formation of the wheat started in early May. In addition, Bouteldja et al. (2020) also observed that the presence of plants can stimulate emissions of N_2O since they observed a significant correlation between N_2O emission and VI green Index.

The minimum average N_2O emissions for the covered and treated collars were recorded on the 12th of May (-0.018 $nmolm^{-2}s^{-1}$ and -0.015 $nmolm^{-2}s^{-1}$, respectively). This occurred at a slightly lower

SWC of 34.34% and at soil temperature of 15.60°C (Figures 7 & 8). According to a study by Shurpali et al. (2016), N_2O is slowly released and denitrification rates are lowered in conditions where there is limited soil N availability or after the effect of applied N has subsided. This study suggests that the lowest emission was likely caused by a limited N content in the soil. The increasing soil temperature and a slight reduction in SWC might have also contributed to a reduction in the denitrification process during the said period.

The peak N_2O emission peak for the treated collars was 0.126 nmolm^{-2}s^{-1} occurred on the 18th of May, 18 days after the application of the N fertilizer and corresponded with a SWC of 30.25% and increased soil temperature of 20.84°C (Figure 8). This was likely triggered by the application of $NaNO_3$ fertilizer (185 kg/ha) to the treated collars on April 30 (197 days after planting). This occurred through the process of denitrification due to the availability of nitrate for the soil microbes. Our findings are in line with recent studies by Putz et al. (2018) and Nan et al. (2016) who also noted increased emissions following nitrate fertilizer applications.

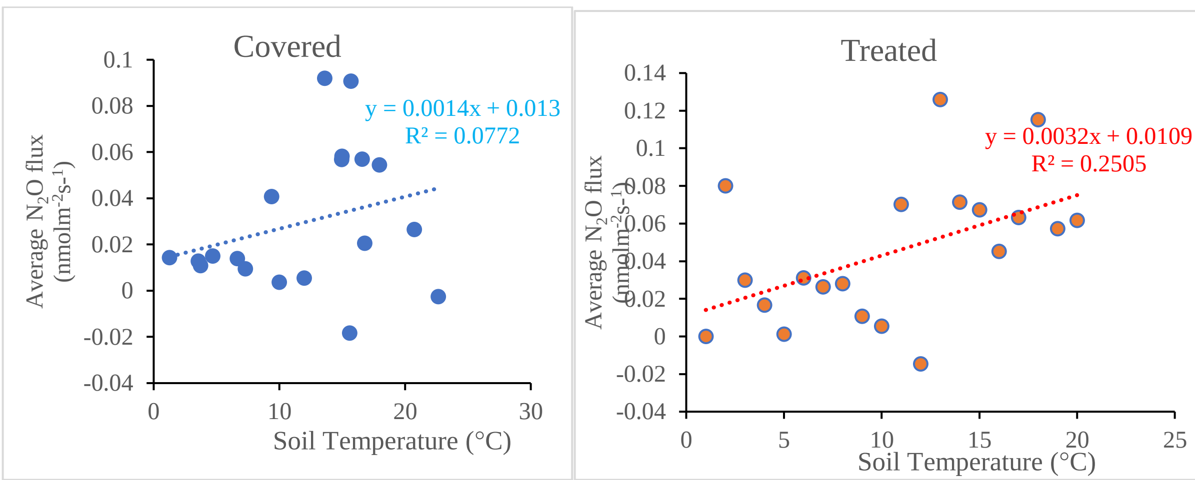
For the case of the covered collars, the observed increase in the fluxes observed on the 18th May (though not greater than for the treated) might be triggered by the nitrate fertilizer that was applied to the treated collars through the processes of nitrate dissolution and movement in the soil. It has been reported that nitrate fertilizers are moderately soluble in water and can easily move within the soil (Galal et al., 2015).

The emissions seemed to be higher from May to October for both the covered and treated collars (fig. 7 & 8). This might be attributed to the presence of residual N in the soil following plant uptake. N uptake by wheat is estimated to be 35% to 40% (Omara et al., 2019). This meant that the residual nitrate content in the soil was high (approximately 65%) and favourable for N_2O release under prevailing environmental conditions. In support of this, according to studies by Nan et al. (2016) and Schils et al. (2008), the key factor determining soil N_2O emissions may be the nitrogen concentration of the soil. Based on their studies, in the weeks following fertilizer application, N_2O emissions driven by N-fertilizers were concentrated. Besides, the incorporation of wheat residues after harvest might have increased the concentration of easily decomposable carbon in the soil. N_2O release has been noted to be significantly correlated with soil carbon content (Bouteldja et al., 2019) because the organic carbon is used a source of energy to consume the nitrates in the soil.

4.3 Correlation between N_2O Emission and Different Driving Variables.

4.3.1 Correlation between N_2O Emission and Soil Temperature

We used soil temperature data measured by the Eddy Covariance tower since soil temperature recorded by the Li-COR seemed to be unreliable. We observed no significant relationship between soil temperature and the fluxes for both the covered and treated collars (p value of 0.25 and 0.10 respectively) but a positive relationship between the variables for the two types of collars (Figure 9 and Table 8).



(Figure 9): Scatter plots of average N_2O (Covered and Treated) Vs Soil Temperature

However, most researchers such as Sulzman et al. (2005) and Soulski et al. (2014), noted a significant positive association between soil temperature and N_2O emissions from the soils. This because increase in soil temperature favours the activities and proliferation of soil microbes.

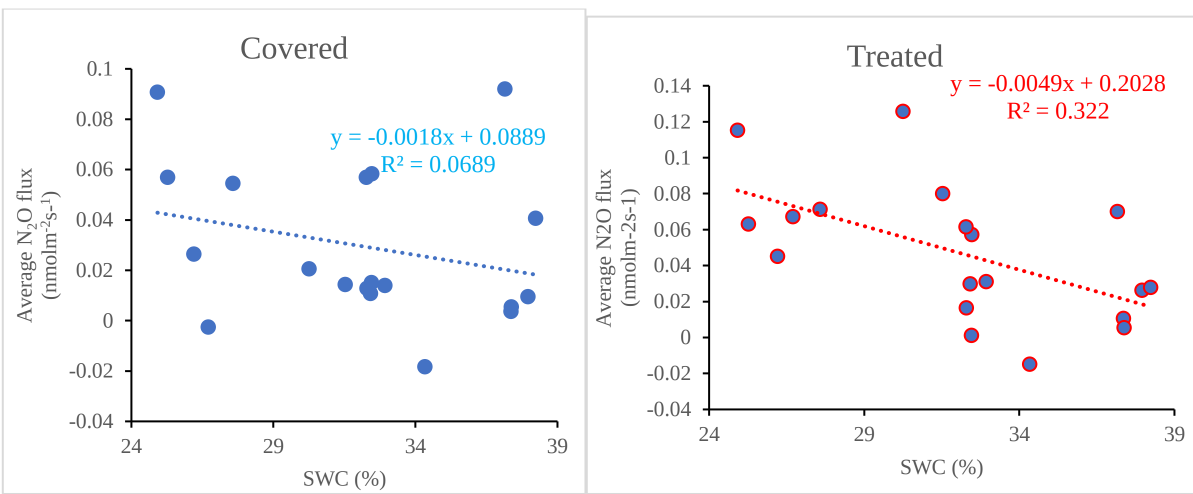
4.3.2 Correlation between N_2O Emission and SWC.

We observed an insignificant negative correlation between N_2O emission and SWC for the covered collars (p value 0.28) and a significant correlation for the treated collars (p value 0.01) as seen in Figure 10 and Table 8. Our findings seem not to be in line to be in line with a number of studies that evaluated the relationship between N_2O emissions and soil water content.

We anticipated enhanced emissions with increase in SWC. This could anomaly be linked to very dry conditions experienced during the study period (Figure 8). Higher N_2O emissions have been reported following the application of N fertilizer, particularly when there is significant soil moisture (Wang et al., 2021). The available O2 in the soil pores is displaced by soil water, resulting in anaerobic conditions favorable to the generation of N2O, according to Wang et al. (2021). As a result, N_2O is typically emitted significantly when the soil has more than 60% water-filled-pore space (WFPS) as per their finding.

(Table 8): N_2O Correlation Matrix between variables.

	N2O_covered	*N2O_treated*	*SWC (30cm)%*	*Soil Temp°C*
N2O_covered	1			
N2O_treated	0.593879834	1		
SWC (30cm)%	-0.262561569	-0.567411426	1	
Soil Temp°C	0.277898293	0.389696707	-0.502040899	1



(Figure 10): Scatter plots of average N_2O (Covered and Treated) Vs SWC

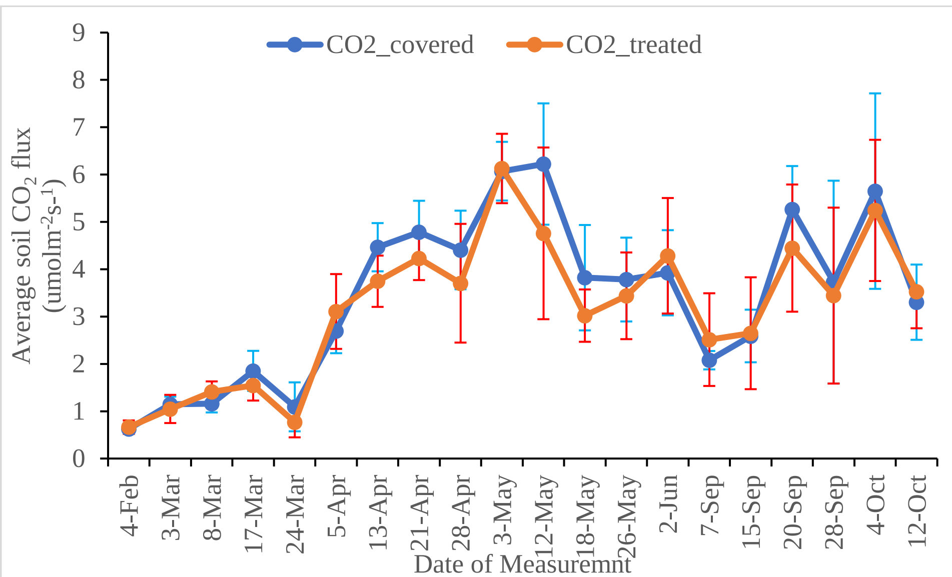
Under such circumstances, facultatively anaerobic bacteria (such as *Pseudomonas citronellolis*) convert soil NO_3^- to NO2, N_2O, and then N_2 according to Oertel et al. (2016) and Butterbach-Bahl and Dannenmann (2011). The optimal WFPS, though, depends on the soil's texture for both nitrification and denitrification processes to actually occur (Wang et al.,2021). In contrast to nitrification, which was the primary mechanism leading to the release of N_2O at 35–60% WFPS according to Bateman and Baggs (2005), Soulski et al., (2014) and Bouteldja et al., 2019**.**

4.4 Soil CO_2 Emission Variations.

Figure 11 shows the variability of soil CO_2 emissions during the time of the study. The average CO_2 emission for the covered collars was 3.433 umolm^{-2}s-^{1} and 3.184 umolm^{-2}s-^{1} for the treated collars.

The maximum CO_2 emission for the covered and treated collars were 6.223umolm^{-2}s-^{1} and 6.129 umolm^{-2}s-^{1} and occurred on 12th of May and 3rd of May respectively. These peak emissions were characterised by a SWC of 34.34% and 37.16% for the covered and treated collars respectively. The soil temperature for the covered collars and treated collars during the peak flux were 15.60°C and 13.62°C respectively (Figure 12)

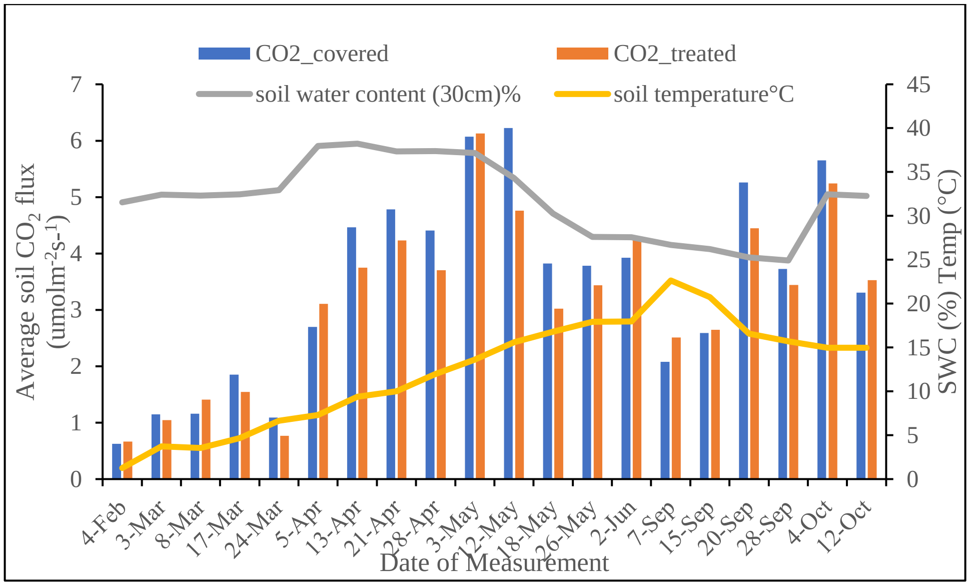
The lowest CO_2 emissions occurred on the 4th of February for both the covered and treated collars (0.624 umolm^{-2}s-^{1} and 0.663 umolm^{-2}s-^{1} respectively). These emissions occurred at SWC of 31.53% and soil temperature of 1.26°C. (Figure 12)



(Figure 11): Soil CO_2 variability during the study period

As illustrated in Figures 11 and 12, the soil CO_2 flux patterns for both collars (covered and treated) seemed to be similar throughout the study period.

The fluxes were low and stable for both the treated and covered collars from the start of February till the end of March. This period was characterized by low soil temperatures (figure 12) and relatively high SWC. This emission trend is in line with the study of Schauffer et al., (2010) who noted a reduction in CO_2 emissions under high SWC. This is because high SWC limits soil respiration because of a reduction in soil aeration and hence diffusion from the soil.



(Figure 12): Soil CO_2 flux emission time series with soil temperature and SWC

Later, there was an exponential increase in the emissions from the start of April, attaining a peak on 3rd and 12th May for the treated and covered collars respectively (Figure 11). The peak fluxes occurred at increased soil temperatures and relatively high SWC (Figure 12). This could be related to soil conditions that fostered the development and action of various soil microorganisms. A number of studies point to this fact, such as Schauffer et al. (2010); Melillo et al. (2017); Oertel et al. (2016); Nottingham et al. (2020); Barnard et al. (2020). Warming might also increase the likelihood that soil carbon becoming mineralized (Graham et al., 2014). It might also stimulate the production of litterfall, aboveground biomass, and root biomass, increasing the quantity of carbon that is added to the soil and promoting the proliferation and activity of the microbial population in the soil (Wang et al., 2014; Li et al., 2016).

The fluxes later slightly reduced and remained fairly stable from May to mid-September (Figure 11). This occurred at high soil temperatures and lower SWC (Fig, 12). The decline in the emissions might be associated to the depletion of microbially accessible carbon sources, decreases in microbiological biomass, a change in microbial carbon use efficiency, and modifications to composition of microbial communities due to the warming. This observation is in line with the studies for Melillo et al., (2017) and Nottinghham et al., (2020) who observed a reduction in CO_2 emissions at high temperatures.

There was again an increase in emissions from 20th September to 4th October and a decline on 12th October (Figures 11 & 12). This pattern was characterized by elevated SWC and a reduction in soil temperature and might be linked to the wetting of the soil after prolonged dry soil conditions (Figure 12). During rewetting, the CO_2 emissions typically showed a pattern of very high rates at the start of wetting and later declined with time according to a study by Barnard et al., (2020), which is consistent with our findings. Oertel et al. (2016) also noted that after a few minutes or hours of the start of precipitation following precipitation after lengthy drier times, CO_2 emissions increased and within a few days, they returned to previous levels. This is called the pulsating or Birch effect (Oertel et al., 2016). According to them, this phenomenon is caused by the resumption of mineralization and the availability of easily decomposable materials for the metabolism of reactivated microorganisms and with more frequent wet-dry cycles, the Birch effect declines (Oertel et al., 2016).

The CO_2 increase due to the Birch effect may also be associated to biotic or abiotic factors in the soil. Abiotic processes include the solubilization of carbonates, which depends on the amount of carbonate in the soil, the displacement of CO_2 from the pore spaces to the atmosphere by water and degassing of CO_2 dissolved in rain according to Barnard et al. (2020). They noted that abiotic processes are the primary causes of the soil CO_2 emissions upon rewetting in non-carbonate-rich soils.

The biotic factors include compatible solute accumulation such as proline, glutamine, glycine, betaine in the soil by microbes in response to the dry conditions (Barnard et al., 2020). These solutes are rapidly disposed upon wetting and can be assimilated and mineralized by other soil microbes. Secondly, the rapid microbial death due to drying and subsequent wetting (Blazewicz et al., 2020) and bacteriophage predation (Williamson et al., 2017) might enhance C substrate in the soil. These can be used by the soil microbes hence increasing CO_2 emissions. Evans et al. (2016) also noted a proliferation of soil microbes upon wetting due to the soil regaining its water film connectivity. Day et al. (2018) also suggests that photo degradation of surface litter increases the breakdown of carbon into substrates that can easily be metabolized by microbes upon wetting.

Finally, the disruption of organic matter occlusion due to wetting as suggested by Barnard et al. (2020) can increase substrate availability for soil microbes in the soil.

In order to determine the causes of variability during the study period, we carried out correlation tests between the CO_2 fluxes and environmental variables recorded during the study, namely SWC and soil temperature.

4.5 Correlation between Soil CO_2 Emission and Different Driving Variables.

4.5.1 Correlation between Soil CO_2 Emission and Soil Temperature

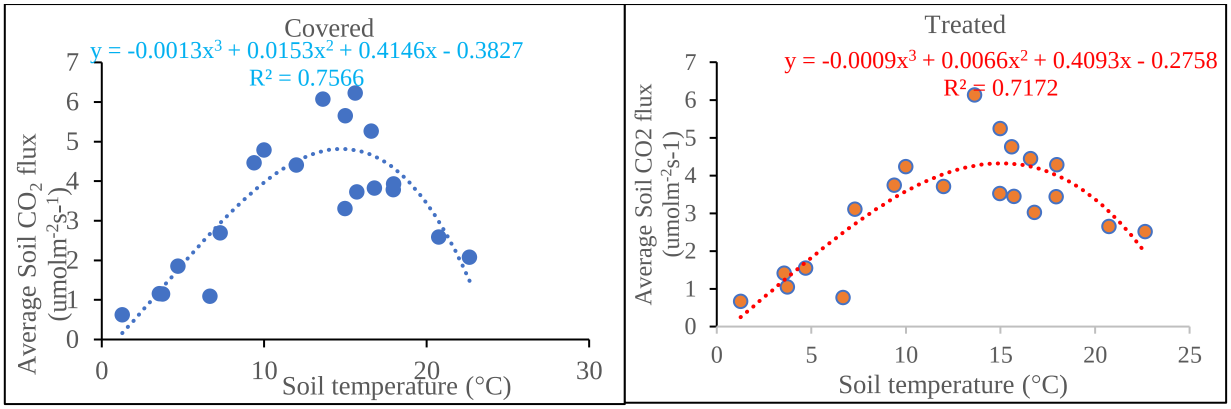
CO_2 flux and soil temperature were shown to be significantly correlated for both the covered and treated collars (p value of 0.02 and 0.01 respectively at $P < 0.05$). The scatter plot and correlation coefficient for the variables are shown in Figure 13 and Table 9 respectively. Our results are in line with a number of studies that have established the role of soil temperature as a key environmental factor affecting CO_2 variability. (Li et al., 2016;2019; Oertel et al., 2016; Graham et al., 2014; Wang et al., 2014; Maucieri et al., 2016; Cardoso et al., 2020).

(Table 9): Soil CO_2 Correlation Matrix for the variables**.**

	CO2_covered	*CO2_treated*	*SWC (30cm)%*	*Soil temp°C*
CO2_covered	1			
CO2_treated	0.961625321	1		
SWC (30cm)%	0.178773197	0.14905805	1	
Soil temp°C	0.521480695	0.5719338	-0.526578758	1

Maucieri et al. (2016) suggested that the observed relationship could be explained by the accelerated aerobic soil microbial breakdown of soil organic matter at high soil temperatures.

In addition, Oertel et al. (2016) found that at low soil temperatures, bacterial soil respiration was perhaps inhibited. It has been reported that soil microbial respiration is more sensitive to temperature rises in colder regions than it is in warmer ones according to the findings of Li et al. (2019). Several explanations have been put forth to account for the rise in soil respiration brought about by warming. First, warming increases the likelihood that soil carbon store may become mineralized (Graham et al., 2014). Second, warming might stimulate the production of litterfall, aboveground biomass, and root biomass, increasing the quantity of carbon that is added to the soil and promoting the proliferation and activity of the microbial population in the soil (Wang et al., 2014; Li et al., 2016).



(Figure 13): Scatter plots between Soil CO_2 fluxes (covered and treated) with soil temperature.

4.5.2 Correlation between Soil CO_2 Emission and SWC

CO_2 and SWC showed no significant association for both the covered and treated collars (p value of 0.45 and 0.53 respectively, at $P< 0.05$). However, from Figure 14 and table 8, we can observe a positive correlation between CO_2 fluxes and SWC for both the treated and covered collars. This finding concurs with the investigations of most researchers who studied the effect of SWC on CO_2 fluxes for instance Oertel et al. (2016), Schauffer et al. (2010) and Buragienė et al. (2019).

They found a substantial negative link between soil respiration and total soil porosity as well as a high positive correlation with soil porosity and CO_2 emissions. This means that increase in SWC reduces soil porosity. As a result, when the soil is overly hydrated, permeability and, consequently, the air diffusion coefficient, may be hampered and thus affecting microbial respiration. On the other hand, osmotic stress on the soil's microbiota and a reduction in CO_2 release can occur when the soil is overly dry (Schauffer et al., 2010).

It is also important to note that the effects of moisture and temperature may often overlap in the field, which may make it challenging to see distinct associations and soil water content must therefore be nearly at saturation in order to lower CO_2 emissions in the soil (Oertel et al., 2016).

The texture of the soil may also have an impact on the composition of the microbial population and the respiration rates (Camarda et al., 2017). They further claim that the soil's physical properties probably are the main reasons for the soil CO_2 flux's relatively low dependence on SWC. For instance, whereas soil organisms in clay loam soils tended to respire more in drier soil conditions, they tended to do so in wetter soil conditions in sand and sandy loam soils. (Oertel et al., 2016).

Since soil moisture is influenced by soil texture. large-pored soils tend to hold less water and, as a result, encourage the release of gases generated by aerobic conditions. (Oertel et al., 2016). Fine textured soils produced more CO_2 emissions than sandy soils, particularly during warm, dry periods because C and N are less readily available to soil microbiota and an increase in gas diffusion coefficient (Oertel et al., 2016). Therefore, the soil texture at the study site might be responsible the observed trend in CO_2 emission.

The visualisation of Figures 11 and 12 show similarity. Therefore, the SWC might be the primary factor responsible for the emission patterns observed. This is in line with a number of studies that point out that the main environmental variable responsible for CO_2 emissions is SWC such as Oertel et al. (2016); Schauffer et al. (2010); Buragienė et al. (2019).

On the contrary, Lou et al. (2003) also noted a negative relationship between CO2 flux and SWC. However, the fact that moisture-related elements were not taken into account in their study may be the cause of the anomaly observed. The soil moisture used in this study was only measured down to a depth of 10 cm, which is far too shallow to account for the potential deep penetration of plant roots and microbial respiration.

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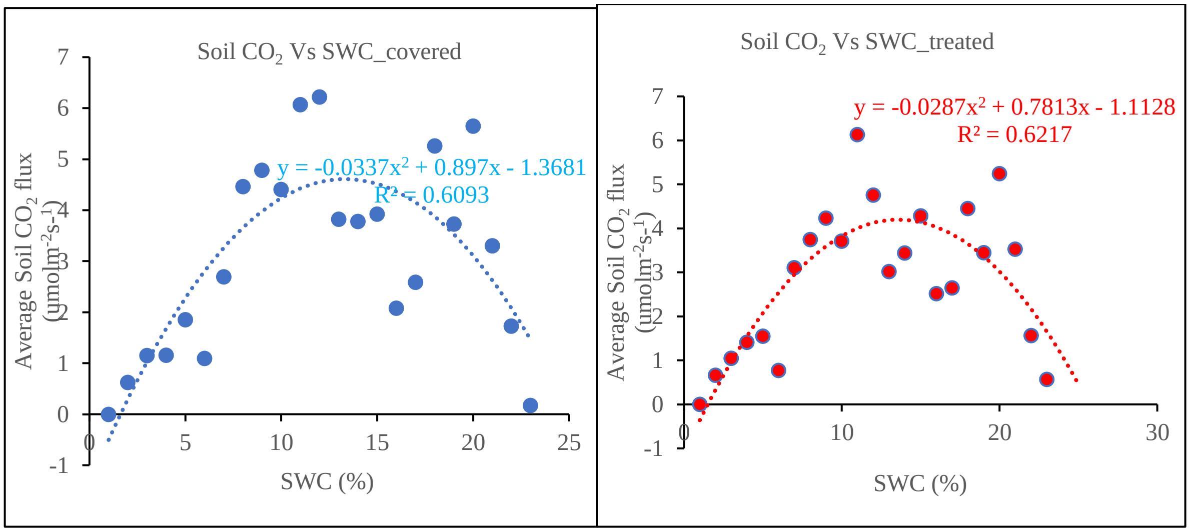

(Figure 14): Scatter plots between Soil CO_2 fluxes (covered and treated) with SWC.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS.

Climate change is mainly caused by human-induced GHG emissions and halogenated gases, leading to irreversible losses in ecosystems, hampered efforts to achieve Sustainable Development Goals, and negative effects on human health. Hungary's adoption of environmental policies has had positive effects on CO_2, CH_4, and N_2O emissions. The Economic growth in the country has led to environmental improvement, but agricultural systems need a plan to reduce GHGs.

Reliable quantification of GHG emissions from agricultural soils essential for development of plans to mitigate GHG emissions. However, GHG emissions vary due to variables in environmental conditions, crop management, and measurement procedures. Studies must therefore be conducted to understand causes of spatio-temporal variation and reduce GHG emissions. The goal of our study was to measure N_2O and CO_2 emissions in winter wheat in a typical farming setting and to determine the relationship between the emissions with SWC and soil temperature.

A field experiment was conducted at Kartal from February 2021 to December 2022. 24 PVC collars of 20 cm diameter were inserted into the soil in the field sown with winter wheat, leaving a height of 4 cm above the soil surface for the flux measurements. $NaNO_3$ was applied to collars at a rate of 185 kg/ha, with collars 5, 6, 7, 8, 21, 22, 23 and 24 covered with foil and did not receive the fertilizer. Li-Cor Smart Gas Analyzer was used to measure the fluxes weekly at noon. An Eddy Covariance (EC) station measured environmental variables. The Pearson correlation coefficient was used to measure the correlation between fluxes and environmental variables ($\alpha = 0.05$).

We observed varying connections between the emissions and the environmental factors under study (SWC and soil temperature). For both the covered and treated collars, we found a positive but insignificant connection between N2O emission and soil temperature. For the covered collars, there was an insignificant negative correlation between N2O and SWC, but a significant negative correlation for the treated collars. We expected a positive association based on previous research. This inconsistency is most likely related to the weather extremes characterized by high temperatures experienced during the study. We also found a significant positive correlation between CO2 and soil temperature in both the covered and treated collars, as well as a positive but insignificant relationship between CO2 fluxes and SWC in both types of collars. The field experiment's findings therefore demonstrated the intricacy of N_2O and CO_2 emissions and the substantial roles that the studied environmental factors played in determining the emissions. When designing management plans to lower N_2O and CO_2 emissions from agricultural soils, as well as for modelling studies and GHG inventories, these correlations might be a useful resource.

During the course of our study, we noted that environmental and management factors interact to determine how much N and C are present in soils. While measurement factors do not have a direct impact on N_2O and CO_2 emissions, they may impact on the accuracy (and uncertainty) of measured data, which is crucial for validation. With regards to our study, the SWC and temperature data measured by the Li-COR seemed erroneous and we had to resort to data recorded by the Eddy Covariance tower.

However, the general consensus on how major environmental variables (namely SWC and soil temperature) correlate with N_2O and CO_2 emissions seems to vary with the soil types and weather conditions during the course of study as shown by our findings. For example, we observed negative correlations between N_2O emissions and SWC for both the covered and treated collars, yet we anticipated enhanced N_2O emissions with increase in SWC in line with literature. This could be linked to very dry conditions experienced during the study period. It is therefore suggested to consider such weather extremities in determining and modelling N_2O emissions from agricultural soils.

The depth of measurement of both SWC and soil temperature is crucial for drawing conclusions about the correlations between the variables (SWC and soil temperature) and emissions. For instance, unlike Lou et al. (2003) who measured SWC at 10 cm and found a negative correlation between SWC and soil CO_2 flux, we measured SWC at 30 cm depth and observed a positive association between the two variables. Thus, it is recommended that the depth of measuring SWC in such research be standardized.

It is may also be feasible to carry out a study on the effects of environmental and management factors on the ratio of N_2O and N emissions resulting from nitrate fertilization, which may vary depending on the type of soil and climate. Another aspect that has not been fully addressed and that can be further researched is the impact of soil pH, site elevation, and air pressure on N_2O and CO_2 emissions. Additionally, it is recommended to do more research to discover how the entire soil profile would react to warming and to quantify emissions from the various soil profiles.

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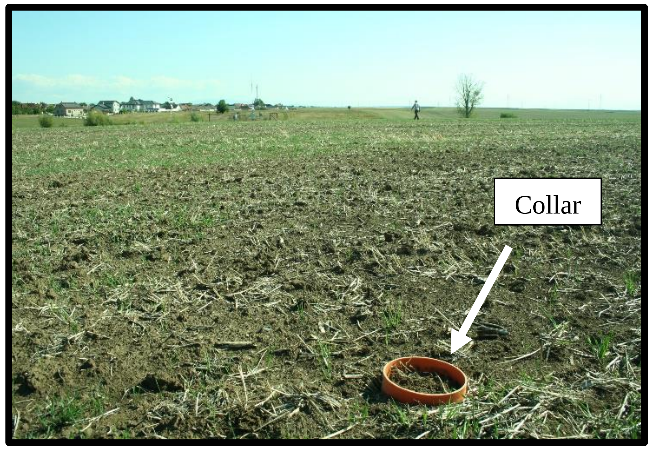
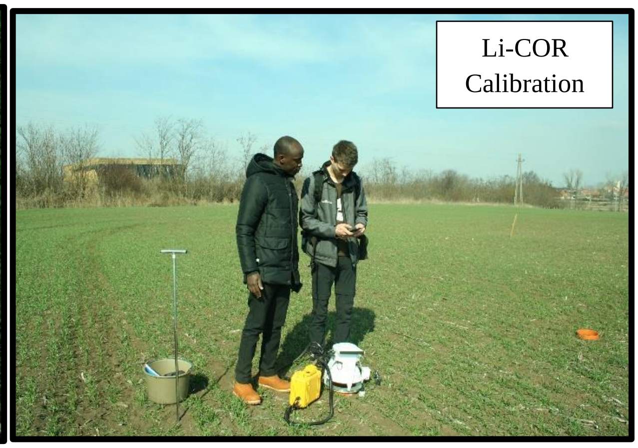
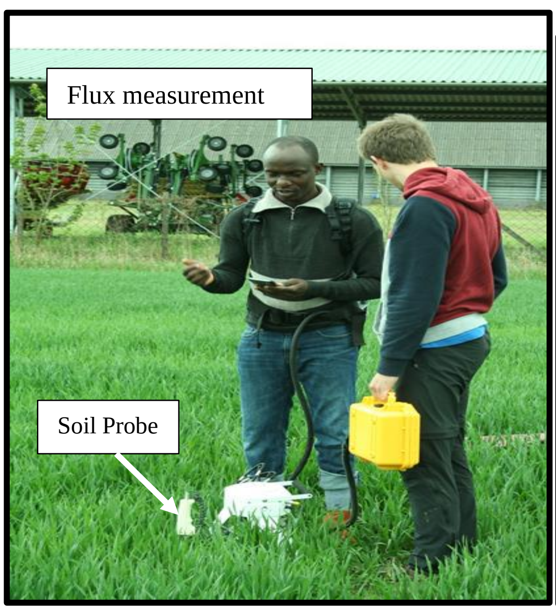
APPENDICES

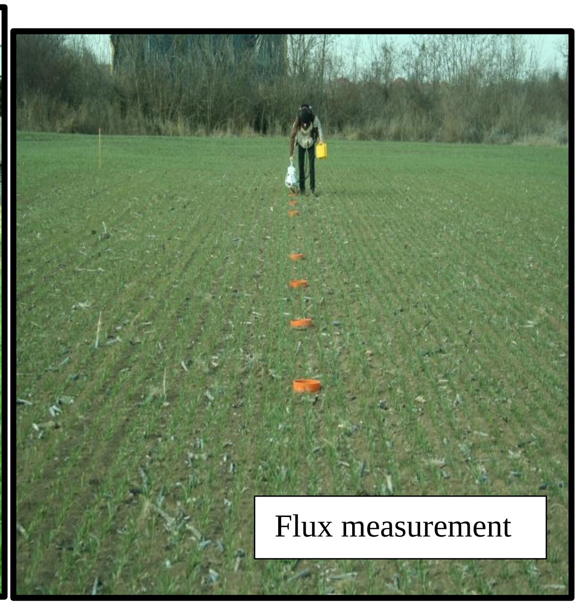

Pattern of collars

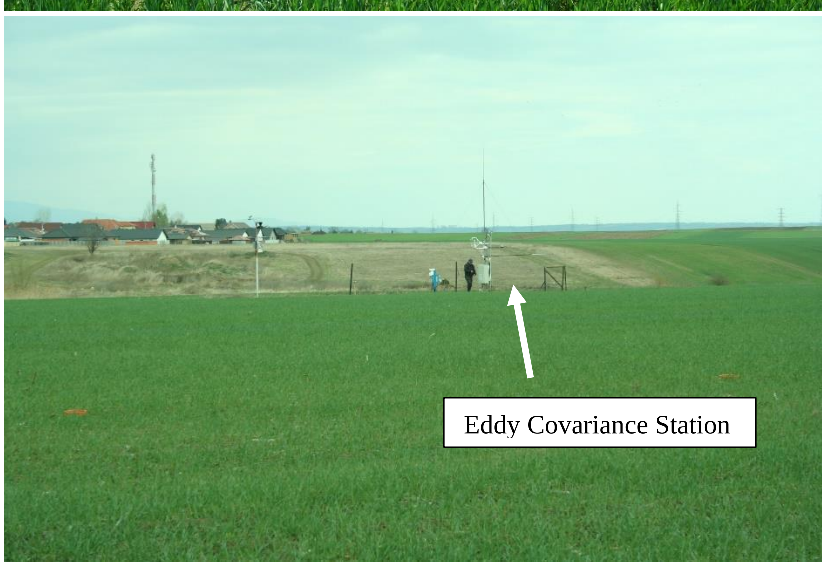

Collar


Li-COR Smart Gas Analyzer


Li-COR Calibration


Flux measurement
Soil Probe


Flux measurement



Source: Personal Photos taken during the study period

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STUDENT DECLARATION

Signed below, **Omoding Nicholas**, student of the Szent István Campus of the Hungarian University of Agriculture and Life Science, at the **MSc Course of Crop Production Engineering** declare that the present Thesis is my own work and I have used the cited and quoted literature in accordance with the relevant legal and ethical rules. I understand that the one-page-summary of my thesis will be uploaded on the website of the Campus/Institute/Course and my Thesis will be available at the Host Department/Institute and in the repository of the University in accordance with the relevant legal and ethical rules.

Confidential data are presented in the thesis: yes no*

Date: 2023/MAY/ 02

Student

SUPERVISOR'S DECLARATION

As primary supervisor of the author of this thesis, I hereby declare that review of the thesis was done thoroughly; student was informed and guided on the method of citing literature sources in the dissertation, attention was drawn on the importance of using literature data in accordance with the relevant legal and ethical rules.

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Approval of thesis for oral defense on Final Examination: approved not approved *

Date: 2023 /MAY/03 Signature