EFFECTS OF ENVIRONMENTAL DRIVERS AND AGRICULTURAL PRACTICES ON THE CARBON AND NITROGEN CYCLE OF CHERNOZEM SOILS

THESIS OF PhD DISSERTATION

by

DENCSŐ MÁRTON

Supervisors:

Barcza Zoltán, PhD
associate professor

Hubainé Tóth Eszter, PhD
senior research fellow

Program of Environmental Chemistry, Doctoral School of Environmental Sciences
Eötvös Loránd University

Director: Turányi Tamás, DSc

Program leader: Turányi Tamás, DSc

Department of Meteorology, Institute of Geography and Earth Sciences, Faculty of Science
Eötvös Loránd University

Department of Soil Physics and Water Management, Institute for Soil Sciences
Centre for Agricultural Research

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1. Introduction

The atmospheric concentrations of greenhouse gases (GHG) such as carbon dioxide (CO_2), methane (CH_4), or nitrous oxide (N_2O) have increasing trends due to anthropogenic perturbation of the global biogeochemical cycles since the industrial revolution, causing climate change and weather extremes (Ciais et al., 2013).

Numerous articles have been published in the scientific literature on carbon and nitrogen balance of the land surface, sources and sinks of GHGs, and consequences of elevated concentrations or possible mitigation options (Balogh et al., 2022; Barcza et al., 2020; Friedlingstein et al., 2020; Haszpra et al., 2018).

Carbon and nitrogen balance of soils are an important part of the global biogeochemical cycles, which can be influenced by anthropogenic activities such as land use change, tillage techniques, fertilization and other factors (Francioni et al., 2019; Post & Kwon, 2000). There are large uncertainties in the estimations of carbon and nitrogen balances and GHG emissions of soils due to the diverse soil types and climatic zones around the world, thus long-term field experiments and biogeochemical models are essential to improve our knowledge (Hidy et al., 2022).

Focusing specifically on croplands, several techniques like soil cultivation method or fertilizer doses/types influence biotic and abiotic factors that affect the GHG emissions, thus affecting the carbon and nitrogen balance of croplands. Emissions associated with different types of tillage operations and organic or mineral fertilization treatments can be different in the short and even long-term (Dencső et al., 2021; Gelybó et al., 2022; Herr et al., 2019).

2. Objectives

In this thesis, the effects of soil cultivation techniques (one conventional and two conservational tillages) on soil respiration and N_2O emission of chernozem soil were investigated in a long-term tillage experiment. In addition, the effects of manure and NPK fertilizer on soil derived emissions were also monitored in another long-term field experiment. Primary environmental drivers of GHG emissions such as soil temperature and soil water content were studied at each experimental site.

3. Materials and Methods

3.1. Introduction of the Field Experiments

Józsefmajor Experimental and Training Farm is a long-term tillage experiment established in 2002 by Professor Márta Birkás. The soil type of the area is Haplic Kastanozem (Aric, Pantoloamic, Pachic, Bathycalcic) according to the WRB database. Investigation of conventional mouldboard **ploughing**, and two conservational treatments of **shallow cultivation** and **no-tillage** (with 28-30, 18-20, and 0 cm tillage depths respectively), started in 2015. Crop rotation and adaptive fertilization management are typical of the experiment. The sown crops from the year 2015 to 2021 were winter wheat, maize, winter oat, soybean, winter wheat, winter oat, and sunflower, respectively.

The long-term fertilization experiment (labeled 1.6) of Martonvásár was established in 1955. Investigation of GHG emissions and related drivers started including the **manure**, NPK **fertilizer**, **combined** manure and fertilizer, and unfertilized **control** parcels in 2020. The soil type of the experiment is Endocalcic Chernozem (Aric, Pantoloamic, Pachic, Bathygleyic) according to WRB. The doses of NPK fertilizer application were 160 kgN ha^{-1}, 80 kgP ha^{-1}, and 80 kgK ha^{-1}, while the dose of manure was 35 kg ha^{-1}. The sown crop was maize in both of the investigation years.

3.2. Measurements

Soil temperature (Ts) and soil water content (SWC) monitoring was installed in one location at 4 depths (in the range of 5-45 cm) in each tillage treatment of Józsefmajor during the experimental time (2015-2021). In addition, Ts and SWC measurements with more spatial replicates were carried out with portable instruments at 0-10 cm depth, during the in situ operations (gas sampling). The dry weight of straw mulch was measured to examine the onground mulch layer after harvest and tillage in 2020. Soil chemical parameters related to carbon and nitrogen cycles, such as soil organic carbon, total nitrogen, ammonium nitrogen, and nitrate nitrogen were measured regularly at 0-10 cm depth, in addition occasional sampling was done to determine soil pH and $CaCO_3$ content of the soil. Vertical heterogeneity of the chemical parameters in 0-20 cm was also examined. Soil respiration and N_2O emission measurements were carried out typically weekly and biweekly, respectively. Additional targeted measurements were also implemented after precipitation events. Several laboratory experiments were set up examining the effects of tillage practices, fertilizer doses, straw mulching, and environmental drivers under a controlled environment. In such setups, undisturbed soil columns under field SWC (different for each treatment) were utilized. A microcosm experiment was also initiated with sieved soil samples under the same SWC.

Ts and SWC were measured by portable devices at 0-10 cm in parallel with gas measurements in the Martonvásár 1.6 experiment as well. Soil organic carbon, $CaCO_3$, and nitrogen contents were also determined at 0-10 cm. Soil respiration and N_2O emission were measured on a biweekly basis, with additional occasions related to precipitation events.

4. Results and Discussion

4.1. Environmental Drivers of GHG Emissions

The annual course of soil respiration correlated with Ts ($r^2 \geq 0.37$; exponential model) in both experimental sites, and this relationship was stronger under controlled laboratory experiments ($r^2 > 0.92$). The correlation of these parameters was stronger after harvest ($r^2 \geq 0.67$) than in the growing season ($r^2 \geq 0.20$), because vegetation (and other environmental drivers) affected the soil temperature dependency (so-called apparent response) of soil respiration. Soil respiration peaks occurred shortly after the harvest of winter crops, due to the positive effects of straw mulching on Ts, SWC, and microbial activity. There were no relationship between soil respiration and SWC under field conditions, due to the confounding effect of other biotic and abiotic drivers, although strong exponential and quadratic correlations were found ($r^2 > 0.96$; depending on treatment type) under laboratory conditions. Similarly, there was no correlation between Ts and N_2O emission in the case of field measurements, but linear and quadratic dependencies were detectable in the laboratory ($r^2 = 0.42$-0.99). Exponential and quadratic relationships were observed between SWC and N_2O emission under both field and controlled environments ($r^2 \geq 0.38$; $r^2 \geq 0.87$). The Józsefmajor site had particularly high N_2O emissions above 40% SWC conditions, which highlights the importance of denitrification processes. Besides SWC, the timing of fertilizer application, including total nitrogen and nitrate nitrogen contents, was also an important factor in the emissions.

4.2. Effect of tillage on GHG emissions

The average soil respiration and N_2O emission of the chernozem soil were higher in no-tillage than in ploughing. These differences were more pronounced under laboratory experiments (Dencső et al., 2021; Gelybó et al., 2022). Similar soil respiration was measured in shallow cultivation as in no-tillage, while the N_2O emission of shallow cultivation was the same as in ploughing (*Figure 1*).

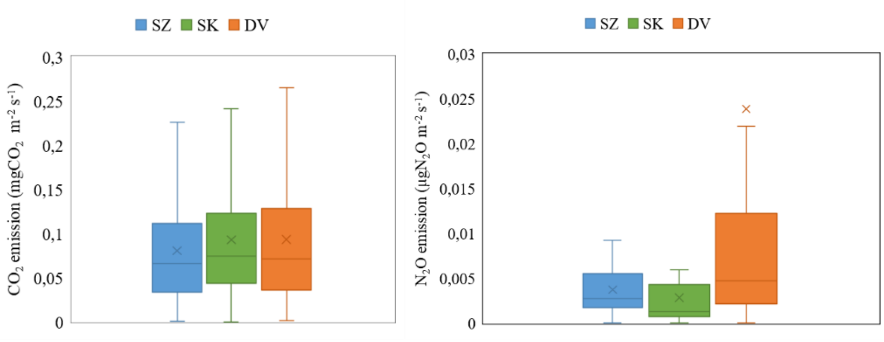

Figure 1. Average soil respiration and N_2O emission measured under mouldboard ploughing (SZ), shallow cultivation (SK), and no-tillage (DV) treatments of Józsefmajor Experimental and Training Farm's long-term tillage experiment

The greater soil respiration associated with shallow cultivation and no-tillage treatments can be explained by the higher soil organic carbon content in these treatments, which provides substrate for the microbial activity responsible for CO_2 production. The greater mulch layers present in conservational treatments (relative to ploughing) can also be an explanation for the higher soil respiration, which may influence the microbial community. Higher soil respiration measured in shallow cultivation could also be explained by the highest plant productivity (that is indicated by yield measurements; detailed data not included in the thesis), which might have caused elevated root respiration. Major differences between tillage treatments were predominantly observed in the case of spring crops, which suggests that an appropriate choice of investigation length is essential for such experiments (Gelybó et al., 2022).

Elevated N_2O emission measured under no-tillage can be explained by the high SWC, total nitrogen, and nitrate nitrogen contents of the soil, which is associated with occasional anoxic and nutrient rich environment for denitrification processes, especially above 40% SWC. The lowest pH value among the three treatments in no-tillage is also an explanatory factor for the highest N_2O emissions. According to the microcosm experiment, the pattern of mean N_2O emissions in the treatments was the same as the pattern of total nitrogen and nitrate nitrogen contents (ploughing<shallow cultivation<no-tillage, respectively), which highlights the importance of soil chemistry in soil emissions.

4.3. Effect of Fertilization on GHG Emissions

Manure application was associated with higher mean soil respiration compared to mineral fertilizer application, although this difference varied by experimental year. In the case of N_2O, emissions were higher in the fertilized and combined treatments than in the manured or control treatments during the whole experimental and in the two years separately as well (*Figure 2*).

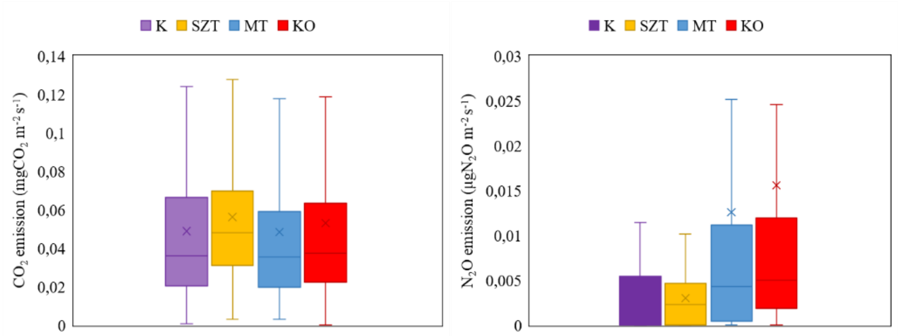

Figure 2. Average soil respiration and N_2O emission of control (K), manure (SZT), NPK fertilizer (MT), and combined manure and fertilizer (KO) treatments of Martonvásár's 1.6 long-term fertilization experiment

The higher soil respiration of manured parceles can not be explained by the differences between the soil organic carbon contents, thus further investigations are required on this topic. Reduced pH of the soil due to NPK fertilization could have caused reduced emissions in the fertilized treatment.

Higher total nitrogen and nitrate nitrogen, reduced pH and C/N ratio via nitrification and denitrification processes caused higher N_2O emissions in the fertilized and combined treatments.

5. Thesis points

Effects of conventional and conservational tillages on GHG emissions:

1. Based on 18 site-year soil respiration measurements focusing on two kinds of conversational tillage and one conventional ploughing practice, I found that both conservational tillage practices are associated with higher mean soil respiration than mouldboard ploughing (0.093 vs. 0.081 mgCO_2 m^{-2} s^{-1}) on a chernozem soil. The 20% extra soil respiration is mainly caused by the higher soil organic carbon content in shallow cultivation and no-tillage treatments.
2. According to the field measurements, 6 times higher N_2O emission can be observed in no-tillage than in the other treatments (0.024 vs. 0.003 or 0.004 μgN_2O m^{-2} s^{-1} long term mean), due to elevated soil water, total nitrogen, nitrate nitrogen contents, and reduced pH.

3. The results of the laboratory experiments corroborate the *in situ* results. In controlled environment the differences between the treatments were even greater. In the case of soil respiration the ratio between the conversational tillage and the conventional ploughing was 1.9-2.5 (in the field it was 1.2). In the case of N_2O emission the same ratio was between 14 and 26 (that was 6 in field conditions).
4. Based on the findings, shallow cultivation is the proposed soil cultivation method in Józsefmajor as it is associated with higher soil organic carbon content relative to ploughing, and lower N_2O emission relative to the no-tillage treatment.

Effect of different fertilization managements on GHG emissions:

5. N_2O emissions were four times higher in the NPK fertilized treatments than in the manured or control parceles (0.014 or 0.017 vs. 0.003 μgN_2O m^{-2} s^{-1}) likely due to higher total nitrogen and nitrate nitrogen contents, lower pH and C/N ratio.
6. N_2O emission was lower in the case of manure application than in the NPK fertilization treatment, thus usage of organic fertilizers can be considered on the cropland from the point of view of total GHG emission.

Effects of environmental drivers on GHG emissions:

7. Soil respiration was mainly governed by soil temperature, while N_2O emissions depended more on soil water content and fertilization. Measured environmental variables suggest the dominance of denitrification in the soil N_2O emission.

6. Related publications

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