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Environmental Assessment of Methane (CH_4) Emissions From Different Land Management Systems. A Case of the Central Chernozem State Biosphere Nature Reserve Named After Professor V.V. Alyokhin

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***Abstract*— This study investigates methane (CH_4) emissions from various land management systems in the Central Chernozem State Biosphere Nature Reserve of the Russian Federation. Land management systems considered in this study include: Non-Mowed Virgin Steppe (NMVS), Forest Ecosystem (FE), Meadow Land Ecosystem (MLE), Clean Fallow Ecosystem (CFE), 5-Year Rotational Mowed Steppe (5RMS), and 10-Year Rotational Mowed Steppe (10RMS). Using the static-closed gas chamber method, and gas chromatography, the study reveals that FE, NMVS, 5RMS and 10RMS acted as CH4 sinks with negative fluxes, indicating CH_4 oxidation surpassing production. MLE and CFE exhibit positive CH_4 emissions, considerably attributed to anaerobic conditions favouring methanogenesis due to soil disturbance. Soil temperature shows moderate positive correlation (0.6) with CH_4 emissions, demonstrating temperature sensitivity of methanogenic microbial activity. Soil moisture displays a weaker correlation (0.2), but remains significant in influencing CH_4 dynamics. The study recommends promoting Non-Mowed and Rotational Mowed Steppes for their CH_4 sink potential, and implementing soil aeration strategies in MLE and CFE ecosystems to mitigate emissions. Continuous monitoring and adaptive management are essential for optimizing land management to reduce greenhouse gas emissions. This research provides a foundation for developing effective CH_4 mitigation strategies, contributing to broader climate change mitigation efforts.**

***Keywords*— chernozem, greenhouse gas emission, land use management system, methane, Russia**

I. Introduction

Methane (CH_4) is a potent greenhouse gas that significantly influences the Earth's climate system [1]. It is the second most important anthropogenic greenhouse gas after carbon dioxide (CO_2), with a global warming potential (GWP) of 84 - 87 times that of CO_2 over a 20-year period [2]. The emissions of CH_4 from soil, predominantly those associated with different land management systems, are of great importance in understanding and mitigating the impacts of climate change. CH_4 contributes to the greenhouse effect by trapping heat in the atmosphere, thereby increasing global temperatures. The radiative forcing mechanism of CH_4 is primarily due to its ability to absorb and re-emit infrared radiation, which is a critical factor in global warming [3]. In addition, CH_4 plays a significant role in atmospheric chemistry, leading to the formation of tropospheric ozone and influencing the stratospheric water vapour content, both of which have further climatic implications [4].

CH_4 emissions from soils are a result of complex interactions between biological, chemical, and physical processes. Microbial activities, particularly those of methanogenic archaea, play a very important role in the production of CH_4 under anaerobic conditions [5]. Conversely, CH_4 oxidation by methanotrophic bacteria in aerobic soils can reduce CH_4 emissions, thereby making such soils a sink for CH_4 [6]. These microbial processes are influenced by various environmental factors such as soil temperature, moisture, pH, and organic matter content [7]. Further, land management practices have a great effect on CH_4 emissions from soils. Different land management systems such as agriculture, forests, fallow, and wetlands exhibit varying capacities to emit or absorb CH_4 [8]. For instance, wetlands are known to be significant sources of CH_4 due to their waterlogged conditions that favor methanogenesis [9]. On the other hand, well-drained upland soils typically act as CH_4 sinks because of higher rates of CH_4 oxidation [10].

In the context of the Russian Central Chernozem Biosphere Reserve, the Streletsky Steppe represents a unique ecosystem where various land management systems are implemented. These land management systems include: non-mowed steppe, rotational mowed steppe, meadow land, forest, and clean fallow. This reserve is characterized by rich black soil (chernozem), known for its high fertility and organic matter content. The diversity in this ecosystem provides an excellent opportunity to study and compare CH_4 emissions under different land management practices [11].

Several studies have highlighted the variability of CH_4 emissions across different land management systems. For example, Mosier et al. [12] found that agricultural practices, such as tillage and fertilization, can significantly influence CH_4 emissions. In forested areas, factors such as tree species composition and soil moisture regimes play a critical role in determining CH_4 dynamics [13]. In addition, grazing and mowing practices in grasslands and meadows can alter soil structure and microbial activity, thereby impacting CH_4 emissions. Grazing, and associated livestock traffic can increase soil compaction. This can result in reduced gas exchange and potentially lead to higher CH_4 emissions under certain conditions [14]. Equally, mowing can enhance CH_4 oxidation by promoting aerobic soil conditions [15].

The primary objective of this study was to assess CH_4 emissions from different land management systems within the Central Chernozem Biosphere Reserve. The specific land management systems studied included: Non-Mowed Virgin Steppe (NMVS), Forest Ecosystem (FE), Meadow Land Ecosystem (MLE), Clean Fallow Ecosystem (CFE) - which is held under regular ploughing for over 70 years now to control weed growth, 5-Year Rotational Mowed Steppe (5RMS), and 10-Year Rotational Mowed Steppe (10RMS) - which are mowed once every after five and ten years, respectively for insemination (Fig. 1). These different land management systems can have an impact on soil conditions, which, in turn, may influence CH_4 emissions. It is important to note, that CH_4 production and consumption in soils are highly sensitive to temperature and moisture levels, making these factors essential for consideration in this study. By measuring CH_4 emissions, soil temperature, and soil moisture, the study aimed to identify key factors influencing these emissions and to determine the relative contributions of different land management practices to overall CH_4 fluxes.

II. Materials And Methods

A. Sudy Site

This study was conducted in the Central Chernozem State Biosphere Nature Reserve named after Professor V.V. Alyokhin, in the Russian Federation. The reserve is located within the Streletsky steppe in the Kursk region of the Russian Federation, spanning the geographic coordinates of 50° 54' to 52° 26' N and 34° 05' to 38° 31' E (Fig. 1) [16]. The Central Chernozem State Biosphere Nature Reserve is ecologically significant and is characterized by its typical and leached chernozem soils, along with an erosive relief [11, 17].

The climate in this region is classified as temperate continental, with an average annual air temperature of +5.4°C and a total annual precipitation of 570 mm. The coldest month is January, with an average temperature of -7.9°C, while the warmest month is July, with an average temperature of +18.9°C [18, 19]. During the winter months, periodic thaws occur when air temperatures rise above 0°C. The warm season, spanning from April to October, receives approximately 65-70% of the annual precipitation. On average, the region experiences 190 days of precipitation per year, and there are approximately 1800 hours of sunshine annually. The longest season is winter, lasting 130 days, while the shortest is spring, with a duration of 63 days. The average length of the growing season is 185 days, and the thermal regime remains relatively stable. Precipitation is unevenly distributed both from year to year and throughout the year. Typically, snow cover forms in the first ten days of December and melts by the first ten days of April [17].

The soils in the Russian Central Chernozem State Biosphere Nature Reserve have evolved under the influence of meadow steppe vegetation. These soils are characterized by a high humus content, resulting in their dark color. Over thousands of years, the fertile chernozem soil layer was formed by natural processes in the steppe environment, maintaining a specific hydrothermal regime. The upper dark-colored humus layer of chernozem can reach a thickness of 1.5 meters, with a humus content in the upper 10 cm of soil ranging from 9% to 13%. The humus reserve in a one-meter layer is approximately 540 tonnes per hectare (t/ha) [11]. The rich chernozem on non-mowed virgin soil of the reserve closely resemble the conditions of prehistoric steppes [17].

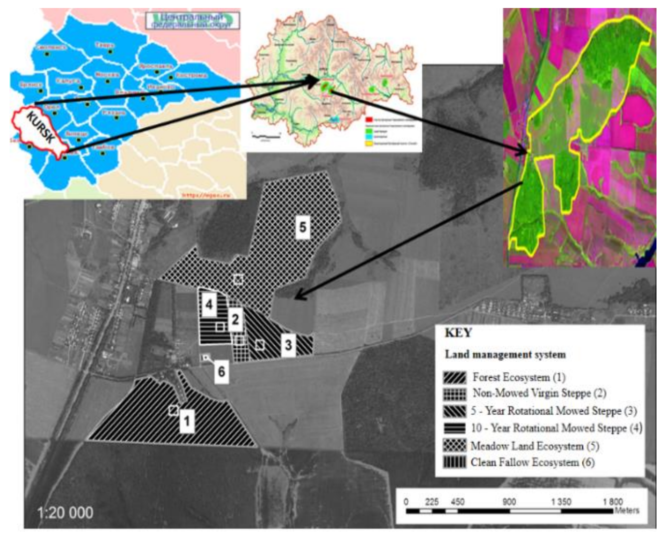

Fig. 1. Representative Land Management Systems

B. Methodology

The measurements of CH_4 emissions were conducted by means of static-closed gas chamber method, modified by the Laboratory of Agroecological Monitoring and Prediction - LAMP (RF patent # 2518979), and gas chromatograph (Chromatek Kristal 5000.2). The static-closed gas chamber method is a pivotal technique in the measurement of greenhouse gas (GHG) emissions, and operates on the fundamental principle of confining the volume of air in which gas exchange transpires, thereby enhancing the sensitivity to variations in gas concentrations within the headspace [20, 21, 22].

In order to collect air samples for the measurement of CH_4 emissions, PVC collars (Fig. 2) were set up to a depth of about 3-5cm in five replicas on each representative site. Then the static-closed gas chamber (Fig. 3) of 10 cm in diameter and 15cm-height was mounted on PVC collars, which were inserted in the soil. The gas chamber was clipped to the collars with pegs in order to prevent air from escaping the chamber and also entering it from the surrounding environment.

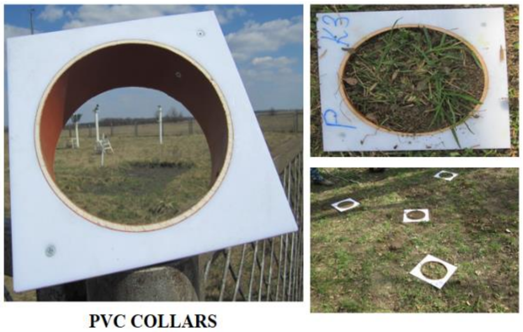

Fig. 2. Experimental Set Up

Air sampling was done by using 60 ml plastic syringes (Fig. 3). The air samples were collected three times at intervals of 30 minutes, to measure concentration changes inside the chambers on an hourly basis (0min, 30min, 60min). This is because, in the context of static-closed chambers, there is usually minimal air exchange within the headspace, leading to an accumulation of gas concentrations over time. This temporal increase in gas concentration is regarded as the actual flux originating from the soil [21, 23]. The research was conducted for a period of two years.

Fig. 3. Air Sampling

After collection, air samples were consequently transferred into 10 ml glass vials for further analysis by gas chromatograph (Chromatek Kristal 5000.2). Soils CH_4 emissions were expressed in milligrams of CH_4 per square meter in a day (mg CH_4 m^{-2} day^{-1}). Soil temperature (°C) and moisture (%) were simultaneously recorded using digital soil temperature and moisture probes (Fig. 4) at every interval of air sample collection in order to understand their correlations with CH_4 fluxes.

Fig. 4. Soil temperature and moisture digital probes

III. Results And Discussions

A. *CH_4 emission across different land management systems*

The findings presented in Table I and Fig. 5 below provide, a detailed summary of CH_4 emission, soil temperature, and soil moisture across various land management systems within the Central Chernozem State Biosphere Nature Reserve, an important ecological zone in the Russian Federation. These results show the significant influence of different land management systems on CH_4 emissions, and the relationship between environmental factors (soil temperature and soil moisture) and CH_4 emissions.

TABLE I. Mean CH4 Emission, Soil Temperature, And Soil Moisture Across Different Land Management Systems

Land Management System	**CH_4 fluxes (mg CH_4 m^{-2} day^{-1})**	**Average Soil Temperature (°C)**	**Average Soil Moisture (%)**
NMVS	-0.16±0.15	17.00±0.62	21.15±2.34
10RMS	-0.14±0.13	18.40±0.50	24.44±2.61
5RMS	-0.15±0.11	18.45±0.81	22.77±2.46
MLE	0.60±0.20	18.91±0.56	28.18±2.25
FE	-0.11±0.11	17.78±0.59	18.67±1.62
CFE	0.38±0.29	22.82±0.46	25.72±3.73
Correlation Coefficient		0.6	0.2

As clearly demonstrated in Table I and Fig. 5 above, there is a notable variation in CH_4 emission across the different land management systems. NMVS, 10RMS, 5RMS, and FE all exhibit negative CH_4 fluxes, indicating that these land management systems act as CH_4 sinks. Specifically, the NMVS shows the highest CH_4 uptake (-0.16 mg CH_4 m^{-2} day^{-1}), closely followed by the 5RMS and 10RMS (-0.15 and -0.14 mg CH_4 m^{-2} day^{-1}, respectively), while the FE had the lowest sink of CH_4 (-0.11 mg CH_4 m^{-2} day^{-1}).

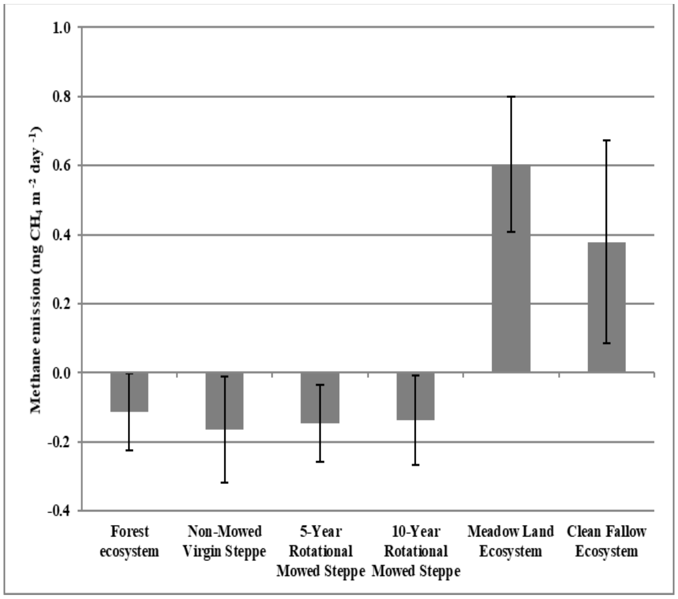

Fig. 5. Graphical representation of CH_4 emission across different land management practices

Findings on FE align with those of Wanyama et al. [24], who indicated that forest soils favor the activities and growth of methanotrophs, leading to domination of CH_4 oxidation over production, and therefore, making forest soils CH_4 sinks. In addition, the high organic matter content in the forest soils, non-mowed steppe, and rotational mowed steppe results in well-drained aerobic conditions, promoting the activities of CH_4 oxidizing bacteria and contributing to their role as CH_4 sinks [25]. This finding is also consistent with studies by Dutaur and Verchot [10], which found that well-drained upland soils typically act as CH_4 sinks due to higher CH_4 oxidation rates.

MLE and CFE on the contrary show positive CH_4 fluxes, with the meadow land having the highest emission rate of 0.60±0.20 mg CH_4 m^{-2} day^{-1}. The clean fallow also shows substantial CH_4 emissions at 0.38±0.29 mg CH_4 m^{-2} day^{-1}. This land management system (CFE), which is under frequent cultivation, has reduced soil particle sizes and increased surface area for temperature, leading to increased microbial activities and CH_4 emissions. This is because frequent soil cultivation disturbs soil structure and texture, aligning with the findings of Bayer et al. [26] who reported a dramatic increase in CH_4 emissions from soils due to soil disturbance. Moreover, Increased land tillage frequency leads to loss of soil organic matter due to the mixing of soil and crop residues, disruption of aggregates, and increased aeration [27]. These results reflect the influence of land management practices on CH_4 fluxes.

B. *Impact of Soil Temperature and Moisture on CH_4 fluxes*

Soil temperature showed a moderate positive correlation of 0.6 with CH_4 emissions, with Clean Fallow (22.82±0.46°C), and Meadow Land (18.91±0.56) exhibiting the highest temperatures and CH_4 emissions, respectively. This is because warmer soils generally promote methanogenic microbial activities, increasing CH_4 emissions [28]. However, the higher CH_4 emissions from Meadow Land compared to Clean Fallow, despite the latter having higher temperatures, could be attributed to accumulated cow dung on Meadow Land [29]. On the other hand, the non-mowed steppe, with a lower average soil temperature (17.00±0.62°C), exhibits negative CH_4 fluxes. This pattern aligns with the findings of Conrad [7], who highlighted that microbial activities involved in CH_4 production and oxidation are temperature-sensitive, with higher temperatures generally promoting methanogenesis, which leads to CH_4 emissions.

Soil moisture also plays a significant role in soil CH_4 fluxes. The meadow land management system, with the highest soil moisture content (28.18±2.25%), shows the highest CH_4 emissions, while the forest, with the lowest soil moisture (18.67±1.62%), shows the lowest CH_4 uptake by the soil. This is consistent with Le Mer and Roger [6] who emphasized that soil moisture impacts the balance between methanogenic and methanotrophic microbial activities. Higher moisture levels tend to favor methanogenesis due to anaerobic conditions, while lower moisture levels enhance methane oxidation due to aerobic conditions. This could have contributed to higher CH_4 emissions from meadow land than from any other land management system [30]. Moreover, livestock grazing on meadow land could modify CH_4 exchange, production, and oxidation by affecting soil temperature, plant productivity, and nutrient inputs [31].

The correlation coefficient between CH_4 fluxes and soil moisture was 0.2, indicating a weak positive correlation. This suggests that, while soil moisture is crucial for methanogenic activity, its influence on CH_4 emissions appears less pronounced than that of soil temperature in this study. This may be due to the fact that optimal soil moisture levels for methanogenesis vary and can be influenced by other factors such as soil texture and organic matter content [6, 32]. Therefore, moisture content alone may not be the primary driver of CH_4 emissions. In addition, soil temperature appears to be a more significant factor influencing CH_4 emissions compared to soil moisture. These findings emphasize the importance of temperature in driving CH_4 fluxes.

Generally, the observed CH_4 fluxes in this study are consistent with findings from other regions with similar land management practices. Mosier et al. [12] found that agricultural practices, including tillage and fertilization, significantly influence CH_4 fluxes, often leading to increased emissions. The positive CH_4 emissions from the clean fallow land management system in our study support this, likely due to soil disturbance and subsequent anaerobic conditions promoting methanogenesis. In forested areas, CH_4 dynamics may be influenced by factors such as tree species composition and soil moisture regimes [13]. The forest plot in this study, with relatively low methane emissions (-0.11±0.11 mg CH4 m^{-2} day^{-1}) and moderate soil moisture, likely benefits from CH_4 oxidation processes in its aerobic soil environment.

C. *Environmental and climate implications*

The Streletsky Steppe`s diverse land management systems provide a unique opportunity to understand $CH_4$ dynamics under different ecological conditions. The negative $CH_4$ fluxes from non-mowed and rotationally mowed steppes indicate these systems` potential as CH_4 sinks, which is crucial for mitigating greenhouse gas emissions. These findings align with the observations by Dutaur and Verchot [10] regarding the role of well-drained upland soils as CH_4 sinks. Conversely, the positive CH_4 emissions from meadow land and clean fallow land management systems highlight the need for careful land management to minimize greenhouse gas emissions. The significant CH_4 emissions from these land management systems suggest that changes in land management practices, such as reduced tillage or enhanced soil aeration, could mitigate CH_4 emissions.

IV. Conclusion

This study provides valuable understandings into CH_4 emissions from soils under different land management systems in the Streletsky Steppe. The findings highlight the significant influence of land management practices on CH4 fluxes and the potential of certain systems, such as non-mowed and rotationally mowed steppes, to act as CH_4 sinks. These insights are key for developing effective strategies to mitigate greenhouse gas emissions and address climate change impacts. Future research should focus on long-term monitoring and the exploration of additional land management practices that can further enhance CH_4 mitigation in this ecologically significant region, and other areas globally.

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