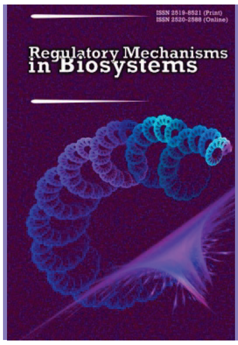
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Modelling of the impact of climate change on the transformation of nitrogen forms in the soil and N_2O emissions from the agroecosystems of Eastern Ukraine

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The moisture-temperature regime influences the nitrogen status of the soil and the microbiological processes of the transformation of nitrogen forms. Therefore, we assumed that ongoing climate change may affect the emission of nitrous oxide N_2O, which is formed in the course of the transformation of nitrogen forms in the soil and is one of the most aggressive greenhouse gases that determine the global warming potential. To test this hypothesis and make a quantitative assessment of the impact of climate change on the transformation of nitrogen forms in the soil and N_2O emissions from the agroecosystem soils, we used a complex model of greenhouse gas emissions from an agroecosystem soil that we developed and the RCP4.5 climate change scenario. The research was performed for the chernozem soils of Eastern Ukraine, with winter wheat being the cultivated crop. 'Dry' and 'wet' years typical for the period of 2021–2050 were selected among climate conditions in accordance with the climate change scenario. A 'dry' year was considered to be a year with a precipitation of 60% or less of the long-term average, a 'wet' year was a year with a precipitation of 130% or more of the long-term average for the studied period. The level of ammonification during the growing season for both 'dry' and partially 'wet' years was mainly controlled by temperature. At the beginning of the period, at negative temperatures below –3 °C ammonification and nitrification almost stopped, and at temperatures above –2 °C they slightly increased. Indices for the intensity of these processes increased with a rise in temperature from 0 °C to 10–11 °C. In the conditions of a 'dry' year an increment in temperature to the level of 22.4–27.8 °C caused a sharp increase in the rate of ammonification and caused a high level of the rate of nitrification. For the conditions of a 'wet' year with a sufficiently low (compared to a 'dry' year) temperature regime, a relatively significant rise in temperature with still quite good humidification increased the intensity of the ammonification process. The dependence of the intensity of the ammonification and nitrification processes on the moisture reserves in the soil is traced. The high level of moisture reserves in the arable layer at the beginning of the growing season in both 'dry' and 'wet' years formed anaerobic conditions in the upper layer of the soil. Against the background of rising temperatures, this called forth the denitrification process. N_2O emission was 0.03–0.29 g N-N_2O/ha•day due to the denitrification process in a 'dry' year, and 0.7–5.2 g N-N_2O/ha•day in a 'wet' year. The highest level of N_2O emission due to nitrification was observed in a 'dry' year in the middle of the vegetation period at high temperatures (22.7–27.8 °C) and amounted to 8.2–11.2 g N-N_2O/ha•day. A decrease in soil moisture reserves during the second half of the growing season reduced the level of N_2O emissions. Nitrification was the main process producing N_2O. The emissions of N_2O with moisture reserves greater than 55 mm in the arable layer occurred due to denitrification. A rise in temperature increases the level of N_2O emissions. The peculiarities of the influence of moisture and temperature conditions of 'dry' and 'wet' years on the processes of ammonification, nitrification, denitrification, and N_2O emissions from chernozem soils according to the RCP4.5 climate change scenario in Eastern Ukraine were assessed.

Keywords: temperature; precipitation; moisture reserves; ammonification; nitrification; denitrification; nitrous oxide; agroecosystem.

Introduction

Agricultural activity contributes to global warming owing to methane and nitrous oxide emissions. The latter is a particularly important component because it accounts for a significant share of total nitrogen emissions from agroecosystems. It is formed as a result of anaerobic microbiological changes in nitrogen introduced into the soil together with mineral fertilizers. Changing weather conditions in response to climate change can significantly affect the efficiency of nitrogen fertilizer application in agriculture and, consequently, cause undesirable environmental consequences (Avtaeva et al., 2021; Langraf et al., 2021).

Environmental factors stipulate the intensity of complex biochemical and biophysical processes that occur in the soil of an agroecosystem and determine the processes of greenhouse gas emission from the soil. The transformation of nitrogen compounds in the soil proceeds mainly under the influence of microorganisms. Humidity and temperature are the most important environmental factors affecting microbial processes in soils (Sharma & Kumar, 2021; Huang et al., 2022; Li et al., 2022). A fundamental review (Ayiti & Babalola, 2022) provides an analysis of the factors influencing the process of soil nitrification; the patterns and factors of the global gross mineralization of nitrogen in soils are considered in the paper (Elrys et al., 2022). There are many publications on laboratory experiments studying the influence of moisture and temperature on microbial processes in the soil – decomposition of organic matter, nitrogen mineralization, and nitrification (Richard et al., 1964; Myers, 1975; Macduff & White, 1985; Butler et al., 2012; Guntiñas et al., 2012).

In incubation experiments (Wei et al., 2022) using typical cornfield soil in the Wujiang River Basin in southwest China, the effects of soil moisture and fertilizers on N_2O emissions were studied. At the same time, the experimental soil was more sensitive to moisture than the soils of other regions, in which the microbial processes of N_2O formation at various levels of humidity differed significantly. Nitrifier denitrification was the critical process dominating N_2O production at high soil moisture levels (70% WFPS). Lage Filho et al. (2022) assessed the impact of land use, temperature, and nitrogen on N_2O emissions in Amazon soils. To this end, three randomized, five-replication treatments were conducted to quantify N_2O emissions: (1) three different land uses (tropical rainforest, grassland, and agriculture); (2) different temperatures (25, 30, 35 and 40 °C); and (3) different soil nitrogen application (0, 90, 180 and 270 kg N/ha). The results show that land use modifies N_2O flux, with the highest emissions occurring in agricultural soils compared to forest and pasture lands. A change in soil temperature up to 30 °C increased N_2O emission during land use, in which N_2O emission was higher in pasture and agricultural soils.

In laboratory experiments, the impact of various scenarios of future rainfall regimes on nitrogen mineralization in the soil and nitrogen oxide emissions, along with the impact of climate warming and hazardous phenomena (drought, intense precipitation) on NO and N_2O emissions, are modelled (Song et al., 2020). By means of the factorial combination of soil temperature and moisture (Gonçalves & Carlyle, 1994), the influence of soil temperature or moisture on net nitrogen mineralization was studied, the results were presented in the form of simple exponential and logistic functions, which were combined in a simple linear model of nitrogen mineralization. Various mathematical functions have been proposed to describe the influence of temperature and water content on nitrogen mineralization in the soil, and an analysis of these functions in nine models is given (Rodrigo et al., 1997).

Various agroecosystem models have been widely used to conduct numerical experiments in which the amount of precipitation and the level of air temperature were changed for the purpose of assessment of the impact on the dynamics of nitrogen in the soil (Medinets et al., 2021). In order to quantify the influence of climatic factors on N_2O emissions, the SWAT model and a modified SWAT-N_2O coupler were used (Huang et al., 2022) to study the impact of climatic factors on the migration and transformation of non-point sources of nitrogen and N_2O emissions in an agricultural catchment from 2009 to 2018, as well as according to climate scenarios RCP2.6, RCP4.5 and RCP8.5 for the period from 2021 to 2080.

The impact of climate change on crop production and nitrate-nitrogen (NO_3-N) pollution from subsurface drained fields was studied (Wang et al., 2015) using the calibrated and validated RZWQM2 (combined with CERES-Maize and CROPGRO in DSSAT), potential implications of climate change and increased atmospheric CO_2 concentrations (CO_2) for a maize-soybean crop rotation system near Gilmore City, Iowa, the USA. The results of RZWQM2 simulations are obtained for 20 years of observed historical weather data (1990–2009) and predicted future meteorological data for 20 years (2045–2064). An assessment of the impact of future climate change and nitrogen deposition on the nitrogen cycle in the ecosystem was implemented (Dirnböck et al., 2017) using the Landscape DNDC model, supplemented with historical data from eight long-term forest ecosystem monitoring stations in Austria, and downscaling future nitrogen deposition and climate scenarios. Transformations of nitrogen compounds in the soil, caused mainly by climatic conditions, are considered Wiśniewski (2019) and Gworek et al. (2021).

Thus, the moisture-temperature regime influences the nitrogen status of the soil and the microbiological processes of the transformation of nitrogen forms. Therefore, we assumed that ongoing climate change may affect the emission of nitrous oxide N_2O, which is formed in the course of the transformation of nitrogen forms in the soil and is one of the most aggressive greenhouse gases that determine the global warming potential. The testing of this hypothesis was based on the achievement of the following research objectives, which are: 1) to study the influence of temperature and moisture conditions on the intensity of ammonification, nitrification and denitrification processes in chernozem soils; 2) to assess the potential for N_2O emission from the winter wheat agroecosystem; 3) to identify the factors influencing N_2O emissions.

Materials and methods

The research is based on the RCP 4.5 climate change scenario (Stepanenko & Polevoy, 2018) for the period of 2021–2050 and a complex model of greenhouse gas emissions from the agroecosystem soils (Polevoy & Bozhko, 2021), which allows for a quantitative assessment of the impact of agrometeorological conditions on transformation processes of nitrogen compounds in the agroecosystem soil and the dynamics of N_2O emissions from the agroecosystem soil in specific scenarios of land use and crop rotation.

To perform numerical experiments with the complex mode, the observation materials from the Bilovodsk hydrometeorological station, which is located in Eastern Ukraine (coordinates: 49º13" N, 39 º35" E, the height above sea level is 75 m), were used, as well as climate scenario RCP 4.5. The soils are ordinary chernozems, light clay and heavy loam.

The soils are characterized by the high content of particles smaller than 0.01 mm (53.3–64.1%), carbon content (44.5–69.2 t/ha), humus (3.0–4.93%), pH of soil (7.2–8.1), easily hydrolyzable nitrogen content (114–137 mg/kg) and volume density of soil (1.21–1.28 g/cm^3).

'Dry' and 'wet' years typical for the period of 2021–2050 were selected among climate conditions in accordance with the climate change scenario. A 'dry' year was considered to be a year with a precipitation of 60% or less of the long-term average, a 'wet' year was a year with a precipitation of 130% or more of the long-term average for the studied period.

Results

The years studied differed significantly in terms of air humidity and temperature conditions and productive moisture supplies in the layer of 0–20 cm. The calendar period of spring-summer-autumn was considered. The data, shown in Figure 1, make it possible to assess the discrepancy in the dynamics of air temperature, precipitation and productive moisture supplies in the soil in the layer of 0–20 cm.

According to the air temperature variation in March–April, 'dry' and 'wet' years differ significantly. The former is notable for a lower temperature regime, with the average air temperature for these two months of 1.7 °C, while the 'wet' year is characterized by a higher temperature regime, and the average temperature of the two months is 17.2 °C. From May to August, the air temperature for the 'dry' year remains at a much higher level compared to the air temperature for the 'wet' year. At the beginning of the autumn period, this trend continues.

In these years, there is a significant difference in precipitation during the spring months. Thus, for the period of March–May, the amount of precipitation in the 'dry' year is 82 mm, while for the 'wet' year it amounts to 242 mm, which accordingly determines the soil moisture regime in these months. It is also possible to notice a common parameter of summer precipitation – the lowest amount of precipitation falls in the period from June to the second 10-day period of September. At the same time, 56 mm falls during this period in a 'wet' year, and 35 mm – in a 'dry' year. During a 'dry' year, most of the precipitation falls in late October and November, and during a 'wet' year – in March, April, and November.

Such dynamics of the moisture and temperature regime caused the formation of diverse reserves of productive moisture in the soil layer of 0–20 cm. Thus, in a 'dry' year, critical reserves of productive moisture were formed starting from the first ten-day period of June and had not changed until late October. In a 'wet' year, depending on the amount of precipitation, the productive moisture supplies in the 0–20 cm soil layer began to gradually decrease from the second ten-day period of May, reached critical values in the first ten days of July, and were low until the second ten days of September. In general, the duration of the drought period in a 'dry' year comprised 15 ten-day periods from 1 June to 1 November, and the duration of the drought period in a 'wet' year made up 7 ten-day periods – from the 1st ten days of July to the 2nd ten days of September.

Climate models predict a change in the moisture and temperature regime under global climate change. By the instrumentality of numerical experiments with the complex model, a quantitative assessment of the impact of possible agrometeorological conditions according to the climate scenario on the processes of ammonification, nitrification and denitrification, and emissions of nitrous oxide due to nitrification and denitrification was performed. As already indicated, we studied 'dry' and 'wet' years.

A 'dry' year. Ammonification. In a 'dry' year, with rather low negative temperatures in the first ten-day period of March (–7.8 °C), ammonification (Fig. 2a) stopped, and with some temperature rise in the second ten days of March (up to –1.8 °C), it increased to 0.082 mg N-NH_4/kg per a ten-day period.

Later, when the temperature rose from 0.4 to 11.0 °C, the rate of ammonification increased significantly from 0.116 in the third ten days of March to 0.265 mg N-NH_4/kg per day in the third ten days of April. In view of a rather low temperature level (15.5–19.3 °C) from the second ten days of May to the second ten days of June, the intensity of the ammonification process decreased slightly (up to 0.161–0.211 mg N-NH_4/kg per day. Significant temperature rise in the period from the third ten days of June to the third ten days of August to the level of 22.4–27.8 °C caused a sharp increase in the rate of ammonification to the level of 0.244–0.372 mg N-NH_4/kg per day. Lowering of the air temperature from the first 10 days of September led to a decrease in the intensity of the ammonification process, which in October and November comprised 0.060–0.082 mg N-NH_4/kg per day.

Nitrification. Similarly to the ammonification process, at low temperatures in the first ten days of March, the nitrification process was not observed (Fig. 2b). A rise in temperature and a sufficiently high level of moistening (the productive moisture supplies in the 0–20 cm layer are close to the lowest moisture content) determined a high level of nitrification rate (0.116–0.240 mg N-NO_3/kg per day) in the period from the second ten days of March to the first ten days of April. A decrease in productive moisture supplies in the 0–20 cm layer from 54 to 29 mm reduced the nitrification rate from 0.067 to 0.017 mg N-NO_3/kg per day in the period from the second ten days of April to the second ten days of May. The following drought period, which was characterized by a small amount of precipitation and minimal moisture reserves in the soil, called forth a rather low nitrification rate (0.01–0.057 mg N-NO_3/kg per day) until the third ten days of October. Precipitation in November improved moistening, and moisture reserves rose to 21–25 mm in the arable layer of the soil. This resulted in an increase in the nitrification rate compared to the rate in October. It should be noticed that in the second ten days of November, when the air temperature dropped to 0.7 °C, the speed of the process decreased to the minimum value (0.007 mg N-NO_3/kg per day). A rise in the temperature to 4.0 °C led to an increase in the nitrification rate to 0.028 mg N-NO_3/kg per day).

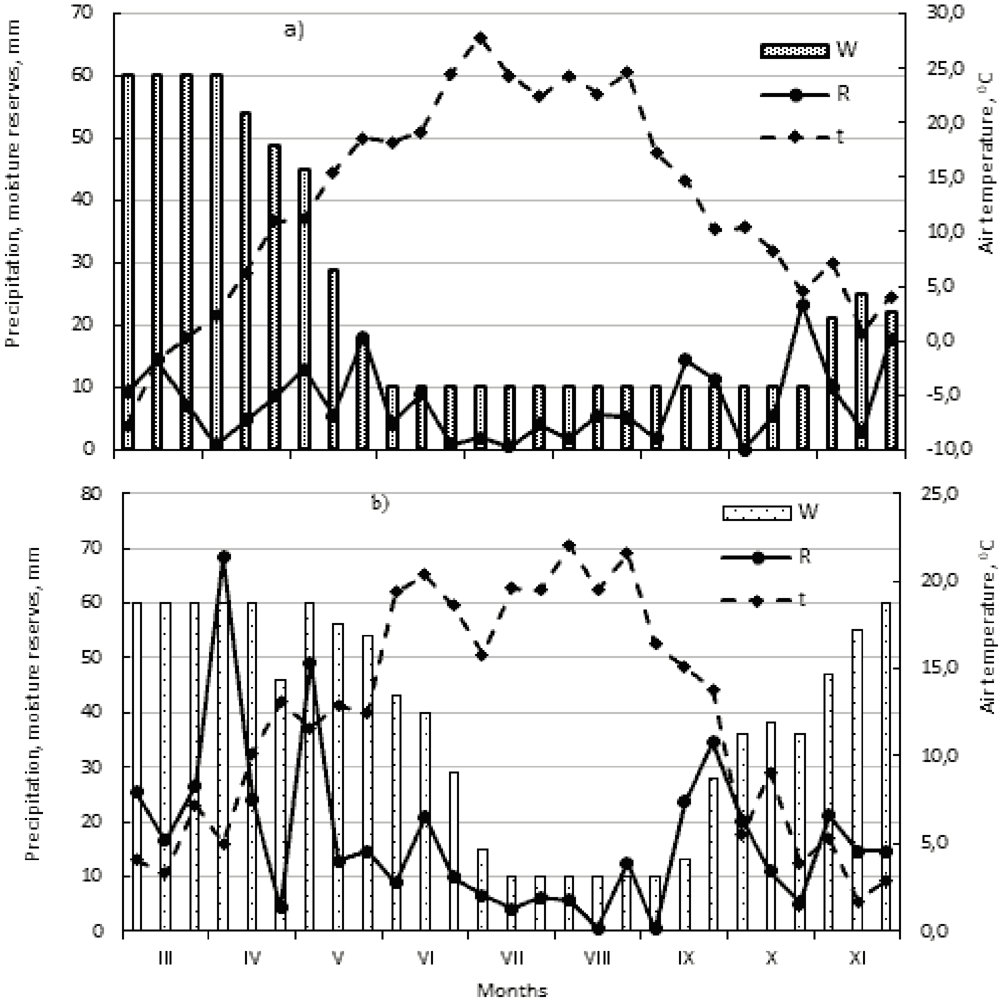

Fig. 1. Dynamics of air temperature (t), amount of precipitation (R), reserves of productive soil moisture (W) in the 0–20 cm layer in 'dry' (*a*) and 'wet' (*b*) years according to the RCP 4.5 climate change scenario

Emission of N_2O. In the period from the second ten days of March to the first ten days of April, the total flow of N_2O emission due to nitrification and denitrification (Fig. 2c) was 0.03–0.29 g N-N_2O/ha•day. The process of denitrification was observed during these two ten-day periods, when anaerobic conditions developed in the upper layer of the soil, and the emission of N_2O owing to this process was insignificant. A gradual temperature rise from 6.3 °C in the second ten days of April to 19.2 °C in the second ten days of June increased the N_2O emission level from 2.8 to 7.2 g N-N_2O/ha•day. The highest level of N_2O emission was observed at higher temperatures (22.7–27.8 °C) from the third ten days of June to the third ten days of August and amounted to 8.2–11.2 g N-N_2O/ha•day. Subsequently, with a gradual lowering of a temperature, this level decreased.

A 'wet' year. Ammonification. For a 'wet' year, it will be typical to have a rather high temperature regime, compared to a 'dry' year, in the first two spring months and a significant amount of precipitation observed during these months. Air temperature in March ranged from 3.3 to 7.2 °C. Moreover, it should be noted that against the background of a high level of moisture reserves in the soil, when the temperature dropped from 4.1 in the first ten days of March to 3.3 °C in the second ten days, the rate of ammonification (Fig. 3a) decreased from 0.178 to 0.164 mg N-NH_4/kg per day. The temperature rise in the third ten days of March to 7.2 °C increased the level of ammonification by almost 1.5 times. In April, the temperature gradually increased from one to another ten-day period, which led to a higher intensity of the ammonification process (from 0.194 to 0.316 mg N-NH_4/kg per day). In May, the temperature was slightly lower compared to the ‘dry’ year, but the high level of soil moisture (54–60 mm in the arable soil layer) created favourable conditions for ammonification, and it remained at the level of 0.361–0.394 mg N-NH_4/kg per day. A relatively significant temperature rise in the first and second ten-day periods of June with still fairly good moistening increased the intensity of the ammonification process to 0.547–0.562 mg N-NH_4/kg per day.

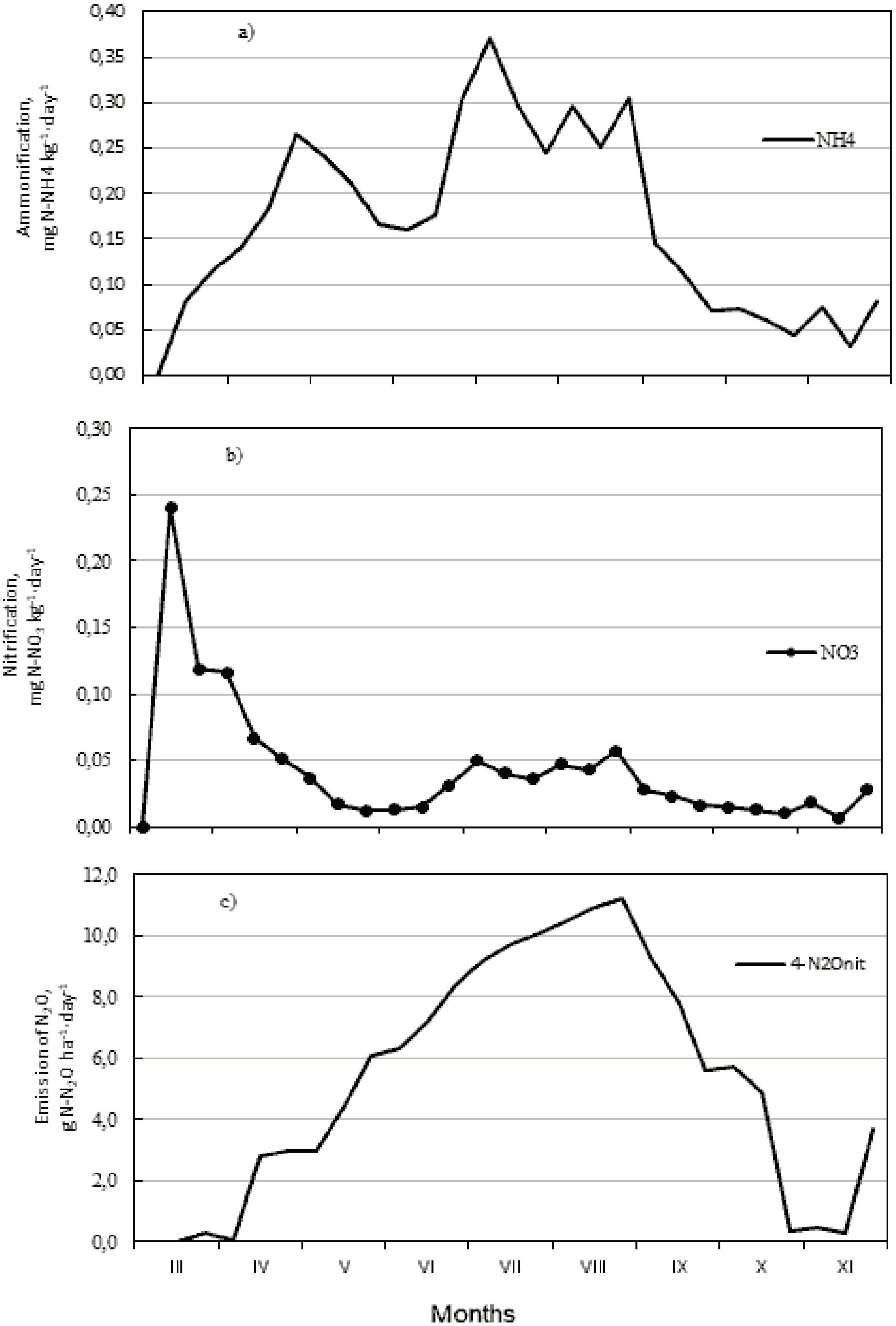

Fig. 2. Dynamics of nitrogen transformation processes in soil: ammonification (*a*), nitrification (*b*) and N_2O emission (*c*) due to nitrification from agroecosystem soils in a ‘dry’ year according to the RCP 4.5 climate change scenario

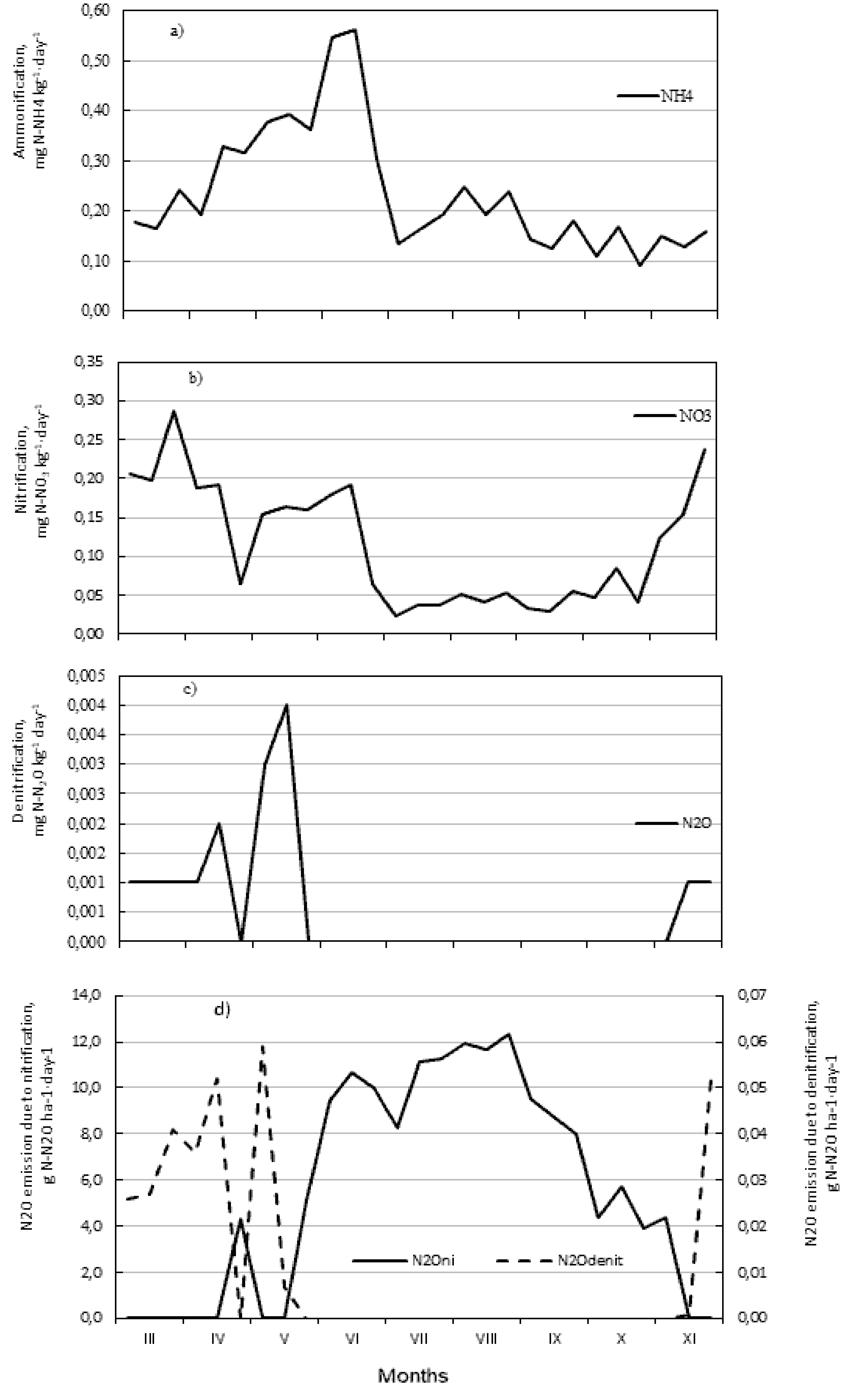

Fig. 3. Dynamics of nitrogen transformation processes in the soil: ammonification (*a*), nitrification (*b*), denitrification (*c*) and N_2O emission due to nitrification – and due to denitrification (*d*) from the agroecosystem soils in a ‘wet year’ according to the climate change scenario RCP 4.5

A lowering of soil moisture in the third ten days of June led to a decrease in the intensity of the process to 0.303 mg N-NH_4/kg per day. In contrast to the 'dry' year, in the 'wet' year the temperature in July was low. It ranged 15.8–19.6 °C, which is significantly lower compared to the temperature level in the 'dry' year (22.4–27.8 °C). This reduced the level of ammonification to 0.134–0.194 mg N-NH_4/kg per day, while under the same moisture conditions in the 'dry' year, a higher temperature level determined a higher intensity of ammonification (0.244–0.372 mg N-NH_4/kg per day). Some increase in temperature in August heightened the level of ammonification accordingly. With the beginning of autumn, against the background of insufficient moistening, a gradual decline in temperature called forth a decrease in the rate of ammonification. Only from the third ten days of September, when moisture supplies in the soil began to replenish, was there some acceleration of ammonification.

Nitrification. As noted earlier, from the first ten days of March to the third ten days of May, a high level of soil moisture was observed (54–60 mm of productive moisture in the arable layer), which contributed to a high level (Fig. 3b) of the nitrification process (0.131–0.286 mg N-NO_3/kg per day). The exception was the last ten days of April, when there was little precipitation (4.3 mm per ten days), which reduced the amount of moisture supplies and led to a decrease in the intensity of the process (up to 0.066 mg N-NO_3/kg per day). With moisture reserves of 40–43 mm in the arable layer of the soil (the first-second ten days of June), a sufficiently high level of nitrification was still maintained.

Later on, a low level of soil moisture until the third decade of October determined a low level of nitrification accordingly (0.033–0.084 mg N-NO_3/kg per day). In November, soil moisture increased (47–60 mm in the arable layer), which provided for a rise of the level of nitrification to 0.124–0.238 mg N-NO_3/kg per day.

Denitrification and N_2O emission. A high level of moisture reserves in the arable layer in the first ten days of March and the second ten days of May created anaerobic conditions in the upper soil layer, which, against a background of the temperature rise, resulted in occurrence of the denitrification process (Fig. 3c), with its intensity ranging from 0.001 to 0.004 mg N-N_2O/kg•day. The emission of N_2O due to the denitrification process (Fig. 3d) ranged 0.7–5.2 g N-N_2O/ha•day. At the same time, the emission of N_2O due to nitrification (Fig. 3d) occurred at almost the same level (0.4–5.1 g N-N_2O/ha•day), which significantly increased only during the third ten days of April, when the level of soil moisture decreased (up to 46 mm in the arable layer).

From the third ten days of May onwards, when moisture reserves in the arable layer decreased (on average, they made up 26 mm for the period), the total flow of N_2O emissions was formed due to the nitrification process. It was comparatively quite high and amounted to 8.2–12.3 g N-N_2O/ha•day in the period from June to August.

The gradual lowering of temperature in the autumn period led to a decrease in the flow of N_2O emissions, and at the end of November it amounted to 3.7–4.0 g N-N_2O/ha•day. An increase in soil moisture in the second and third ten days of November (up to 55–60 mm in the arable layer) created anaerobic conditions, which called forth N_2O emissions owing to denitrification (0.1–5.2 g N-N_2O/ha•day).

Discussion

In laboratory conditions and field experiments, the dependence of the transformation of nitrogen compounds in the soil (ammonification, nitrification, and immobilization) on soil temperature and moisture has been established (Zhou & Ouyang, 2001; Zaman & Chang, 2004; Xu et al., 2014).

Thus, one of the early papers (Myers, 1975) found out that during the research on clay loam in the temperature range from 20–60 °C, the optimal temperature for ammonification was approximately 50 °C. The optimum for nitrification was close to 35 °C, showing a sharp peak at this temperature. On sandy soils (Fu-Sheng et al., 2005), the rate of ammonification decreased with lowering soil moisture. Studies on chestnut and chernozem soil samples investigating the influence of soil moisture on ammonification and nitrification in the soils of two northern plains (Reichman et al., 1966) showed that ammonification and nitrification of soil nitrogen were almost directly proportional to the water content in the soil under absorption from 0.2 to 15 bar. The influence of temperature, moisture and their interaction on nitrogen mineralization in hillside red soils in mid-subtropical region of China was studied (Sheng et al., 2009). The results showed that the rate of soil ammonification and total nitrogen mineralization increased with temperature rising from 12 to 36 °C. Moistening significantly affected the rate of soil nitrification.

The effect of temperature (18, 24 and 37 °C) was studied (Thangarajan et al., 2015) for three different Australian soils with diverse pH (4.30, 7.09 and 9.15). The rate of ammonification increased with rising temperature in all soil types. The influence of temperature on the rate of nitrification was observed in the order of 24 > 37 > 18 °C.

Hence, a rise of air temperature and, accordingly, soil temperature leads to an increase in microbial activity and speed of the biogeochemical processes in the soil, such as mineralization, nitrification, and denitrification. The results we obtained in the qualitative assessment of the tendency for a dependence of the processes on the moisture-temperature regime agree quite well with the data given above. The assessment of the response of the intensity of the ammonification and nitrification processes to the temperature factor in our study showed that for the conditions of a 'dry' year at rather low negative temperatures, both ammonification and nitrification stopped, and at low temperatures they were insignificant. A temperature rise against the background of sufficient moistening caused an increase in the intensity of these processes. In the conditions of a 'dry' year, an increase in temperature to the level of 22.4–27.8 °C called forth a sharp increase in the rate of ammonification to the level of 0.244–0.372 mg N-NH_4/kg per day. For the conditions of a 'wet' year with a sufficiently low (compared to a 'dry' year) temperature regime, a relatively significant temperature rise (up to 19.4–20.4 °C) with still good enough moistening increased the intensity of the ammonification process to 0.547–0.562 mg N-NH_4/kg per day. The dependence of intensity of the ammonification and nitrification processes on the moisture reserves in the soil is deduced.

The transformation of nitrogen compounds, caused by the influence of the moisture-temperature regime of the soil, leads to the release of nitrogen from agricultural fields. There is a high variability of N_2O flows in their response to the moisture-temperature regime and land use types (Giraud et al., 2021; Medinets et al., 2021). Thus, during a short-term laboratory study for typical land use conditions in lowland and highland Scotland, N_2O emissions from soil were simulated under climate change conditions (Medinets et al., 2021). All studied sites were significant sources of N_2O (the range: 157–277 μg N-N_2O/m^2•h; in conversion, this equals 37.68–63.48 g N-N_2O/ha per day) having a general tendency to a decrease with altitude and an increase with fertilizer application and atmospheric N inflow.

A paper (Giraud et al., 2021) gives the average rate of N-N_2O emissions in the conditions of natural pastures in Germany between September 2013 and December 2018, which ranged from 8.6 μg N-N_2O/m^2•h to 13.9 μg N-N_2O/m^2•h (in recalculation, from 2.06 to 3.34 g N-N_2O/ha•day) for diverse conditions of moistening.

In the conditions of France (Henault et al., 2005), for the spring and summer months under diverse soil temperature and moisture values at four observation points of various types of agricultural soils (used for growing winter wheat), the data on N_2O emissions ranging from 0.32 to 27.7 g N-N_2O/ha•day are given, and only at the fifth observation point are two cases mentioned when N_2O emissions comprised 62.5–99.0 g N-N_2O/ha•day.

In Spain (Álvaro-Fuentes et al., 2017), observations on N_2O emissions from abandoned agricultural land and the spring barley agroecosystem showed that they ranged from 0.1 to 5.0 g N-N_2O/ha•day.

In our calculations, performed with the use of the RCP4.5 climate scenario, N_2O emissions from the soil of the winter wheat agroecosystem range from 0.03 to 11.2 g N-N_2O/ha per day in a 'dry' year, and 0.7–12.3 g N-N_2O/ha per day – in a 'wet' year. The obtained results are in satisfactory agreement with the data derived for agricultural soils (Henault et al., 2005; Álvaro-Fuentes et al., 2017).

At a time of better moistening, a higher level of N_2O emissions from the soils of agroecosystems is observed.

In fact, there is a fairly general concept in the literature (Wang et al., 2021) regarding the main factors that influence N_2O emissions; however, the factors and significance of their effects on nitrification, denitrification, and the N_2/N_2O ratio vary according to soil type and climate. The influence of environmental factors on N_2O emissions and the proportion of N_2O emissions from nitrified nitrogen also varies according to soil type and climate and is insufficiently studied. The effects of soil pH and its influence on denitrification are other open questions.

Conclusions

Modelling the transformation of nitrogen compounds in the soils of winter wheat agroecosystems made it possible to assess the variation in the intensity of these processes under climate change conditions. The peculiarities of the influence of moisture and temperature conditions in 'dry' and 'wet' years on the processes of ammonification, nitrification, denitrification, and N_2O emissions from chernozem soils according to the RCP4.5 climate change scenario in the conditions of Eastern Ukraine were identified.

The level of ammonification during the growing season for both 'dry' and partially 'wet' years was mainly controlled by temperature. At the beginning of the period, at negative temperatures below –3 °C, ammonification and nitrification almost stopped, and they slightly increased at temperatures above –2 °C. Indices for the intensity of these processes increased with the temperature rise from 0 °C to 10–11 °C. In the conditions of a 'dry' year, a temperature elevation to the level of 22.4–27.8 °C caused a sharp increase in the rate of ammonification to the level of 0.244–0.372 mg $N\text{-}NH_4$/kg per day and determined a high level of the rate of nitrification (0.116–0.240 mg $N\text{-}NO_3$/kg•day). For the conditions of a 'wet' year with a sufficiently low (compared to a 'dry' year) temperature regime, a relatively significant temperature rise (to 19.4–20.4 °C) with still good enough moistening increased the intensity of the ammonification process to 0.547–0.562 mg $N\text{-}NH_4$/kg•day. The dependence of the intensity of the ammonification and nitrification processes on the moisture reserves in the soil is traced. The level of nitrification for a 'wet' year during the growing season, especially in its second half, was determined by the productive moisture supplies in the arable layer of the soil.

A rise in temperature and a high enough level of moistening (productive moisture supplies in the 0–20 cm layer are close to the lowest moisture content) called forth a high level of nitrification rate (0.116–0.240 mg $N\text{-}NO_3$/kg•day). A high level of moisture reserves in the arable layer at the beginning of the growing season in both 'dry' and 'wet' years formed anaerobic conditions in the upper layer of the soil, that, against the background of rising temperatures, determined an occurrence of the denitrification process, with its intensity ranging from 0.001 to 0.004 mg $N\text{-}N_2O$/kg•day. The emission of N_2O due to the denitrification process comprised 0.03–0.29 g $N\text{-}N_2O$/ha•day in the 'dry' year, and 0.7–5.2 g $N\text{-}N_2O$/ha•day in the 'wet' year. The highest level of N_2O emission owing to nitrification was observed during the 'dry' year in the middle of the vegetation period at high temperatures (22.7–27.8 °C) and amounted to 8.2–11.2 g $N\text{-}N_2O$/ha•day. A decrease in soil moisture reserves during the second half of the growing season reduced the level of N_2O emissions. Nitrification was the main process producing N_2O. The emissions of N_2O with moisture supplies greater than 55 mm in the arable layer occurred owing to denitrification. A rise in temperature increases the level of N_2O emissions.

Thus, for the conditions of Eastern Ukraine, according to numerical experiments with a complex model of greenhouse gas emissions from the agroecosystem soil, and the climate scenario RCP4.5 under the future climatic changes: the peculiarities of the influence of temperature and moisture conditions on the intensity of the processes of ammonification, nitrification and denitrification of chernozem soils have been revealed; the quantitative estimates of the potential for N_2O emission from chernozem soils of the winter wheat agroecosystem in the years with diverse conditions of moistening have been obtained; the environmental factors influencing N_2O emissions from chernozem soils in Eastern Ukraine have been identified.

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