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REVIEW PAPER

Impact of agriculture on N_2O emissions: A review*

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Abstract

Increasing concentrations of GHGs (greenhouse gas concentrations) are accelerating climate change, threatening the continued existence of our civilization. Despite relatively lower concentrations than those of other GHGs, N_2O has a warming capacity 265 times greater than CO_2, and its lifetime in the atmosphere is 9 times longer than that of CH_4. Global annual emissions of N_2O increased by 270% between 1980 and the last decade, and emissions from anthropogenic sources amounted to 43%. The share of agricultural activity in total anthropogenic emissions is 53%. The main source of N_2O emissions related to human activities is agriculture, contributing 53% thereof due to the widespread use of N fertilizers in farming. Modern agriculture tends to use fertilizers in excess. It is possible to reduce fertilizer consumption globally by 30% without reducing crop production. The level of available N and C in agricultural soils determines the amount of N_2O emissions. Other soil characteristics: pH, salinity, structure and microbial activity, are also important, in addition to environmental factors, such as precipitation temperature and landform characteristics. Cultivation factors also have a significant impact on the level of N_2O emissions. For example, the use of high-performance and slow-release nitrogen fertilizers can reduce N_2O emissions and increase crop yields. Despite many benefits attributed to crop residues, they too contribute to the increase in emissions. Current knowledge does not allow us to clearly determine how zero and reduced tillage and agroforestry systems affect N_2O emissions compared to conventional tillage.

Keywords: climate change, N_2O emission, agriculture source, reduce emissions

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INTRODUCTION

N_2O (nitrous oxide) is a virtually non-toxic gas that has been used for analgesia and anesthesia for 160 years, especially in dentistry. However, its presence in the air has global adverse effects. N_2O is the third radiative forcing gas after CO_2 and CH_4, and with global warming potential it is a CHG, with 265 times more impact than CO_2, and an atmospheric lifetime of ~116 years, much longer than CH_4 (Myhre et al. 2013). N_2O is also an important factor in stratospheric ozone depletion. Apart from the greenhouse effect, N_2O also has an impact on the decomposition of ozone in the upper atmosphere. These are the reasons for reducing anthropogenic N_2O emissions because we do not have a technology to reduce the concentration of N_2O in the air (Northrup et al. 2021). Estimates of the sixth IPCC report (Canadell et al. 2021) showed that global N_2O concentrations have increased by more than 23% since the pre-industrial era (1750-2020), accelerating especially in the last decade. The growing food production mainly determines the constant increase in the concentration of N_2O in the air. In the US, for example, total N_2O emissions from soil have tripled since 1900, with 74% coming from agricultural soils (Lu et al. 2022).

The development of agricultural and industrial production is constantly accompanied by an increase in the concentration of N_2O in the air. In the period before the industrial revolution, global N_2O emissions remained relatively constant 6.3±1.1 tg N_2O yr^{-1}. Global average annual N_2O emissions from the most important sources are presented in Table 1. During the period 2007–2016, global emissions increased by 270%. Between 2006 and 2016, emissions from anthropogenic sources accounted for 43% of global emissions. Nitrogen addition in agriculture accounted for the largest share of anthropogenic N_2O emissions, reaching about 52%. Since 1980, emissions from this source have increased by 146%. Actual N_2O emissions are likely to be higher than those estimated (Tian et al 2016).

The application of synthetic fertilizers is the main contributor to N_2O global emissions, and it is estimated at 130.1 Mt CO_2e, of which China accounts for 29.3%, India for 18.2%, the US for 11.8% and the EU for 11.5% (FAO 2022). Reducing N fertilization is a prerequisite for keeping the rise in global temp. below 1.5°C compared to pre-industrial levels. N_2O emissions are recognized as an important component of GHGs, but the level of emissions is likely to be much higher than currently estimated (Northrup et al. 2021). For this reason, the reduction of N_2O emissions should be a priority practice also because currently we do not have a technology analogous to active CO_2 removal from the atmosphere (IPCC 2019).

The use of N-fertilizers in accordance with the needs of crop plants does not reduce yields, does not disturb the balance in the environment, and does not accelerate climate change. However, the rapidly growing world population, accompanied by an increasing demand for food, favors the excessive use

Table 1

The global N_2O mean annual emissions from various sources in 1980, 2000 and 2007–2016 (in Tg N yr^{-1}, only the most important sources), IPCC 2019, Tian et al. 2020, modified by authors

Anthropogenic sources		**1980**	**1990**	**2007-2016**
N addition in agriculture	direct soil	1.5	1.7	2.3
	manure on pasture	0.9	1.0	1.2
	subtotal	**2.6**	**3.0**	**3.8**
Other direct sources	fosil fuels and industry	0.9	0.9	1.0
	biomass burning	0.7	0.7	0.6
	subtotal	**1.8**	**1.9**	**1.9**
Indirect from N addition	atmospheric N deposition on land	0.6	0.7	0.8
	inland waters, estuaries, coastal	0.4	0.4	0.5
	subtotal	**1.1**	**1.2**	**1.3**
Perturbed fluxes*	climate effect	0.4	0.5	0.8
	deforestation effect	0.7	0.7	0.8
	subtotal	**0.1**	**0.1**	**0.2**
Anthropogenic total		**5.6**	**6.2**	**7.3**
Natural fluxes				
Natural soils baseline		5.6	5.6	5.6
Ocean baseline		3.6	3.5	3.4
Lightning and atmospheric production		0.4	0.4	0.4
Natural (inland waters, estuaries, coastal)		0.3	0.3	0.3
Natural total		**9.9**	**9.8**	**9.7**
Total anthropogenic and natural		**15.5**	**16.0**	**17.0**

* Perturbed fluxes from climate (CO_2) land cover change

of N-fertilizers with all its negative effects (Basso et al. 2019). Estimates by Cui et al. (2021) showed that the global potential for reducing direct emissions from agricultural soils without compromising crop production is 30%.

THE AIM AND METHODOLOGY

The aim of our work was to evaluate various aspects of agricultural technology related to the emission of N_2O, a gas with a significant impact on climate change. This assessment was carried out on the basis of an analysis of scientific publications in which the problem of the N_2O – climate relationship was the main topic.

Elements of the Snyder's (2019) method of preparing literature reviews in the field of nature were used. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) schemes were also followed to enable selection of publications and proper literature reviews (Liberati et al. 2009, O'Dea et al. 2021). With few exceptions, peer-reviewed publications from Index Factor journals were selected for the review. When screening the literature, the following databases were used: Web of Science, SCOPUS and Google Scholar, testing the keywords: climate change, N_2O emission, agriculture, N fertilizers, soil properties (pH, moisture, texture, landforms, available carbon microbial activity), N forms, cultivation factors, fertilizer application.

The search through the databases led to the identification of several hundred relevant publications, of which 100 were selected for review. Predominantly, the most recent papers were used, but in reference to earlier publications, sometimes already historical ones.

The increase in food production through nitrogen fertilization causes an increase in emissions of N_2O, an important GHG, thereby contributing to climate change, which leads to a decrease in agricultural yields. Reconciling these two contradictory effects is one of the most challenging tasks in the near future.

N_2O AND AGRICULTURE

The need to increase yields stimulates greater consumption of N-fertilizers, regardless of the economic costs and environmental disturbances (Pannell et al. 2017). In most countries around the world, fertilizers are applied uniformly and in excess, without full consideration of climate and soil conditions and crop characteristics. Excessive fertilizer application results in environmental damage and increased costs (Cui et al. 2018).

The reactive loss of nitrogen to the environment is an important and persistent problem in the world, especially in regions with high productivity, which are key contributors to the increase in air pollution N_2O (Basso et al. 2019). The implementation of so-called precision agriculture technology, which relies on the dependence of the amount of applied N fertilizer on the variability of soil properties in the field, weather conditions, and the demand for N fertilizer in specific crops, can reduce the adverse effects of excess N fertilizer (Cassman et al. 2002).

The introduction of excess N in agriculture through fertilizers causes:

(i) groundwater contamination (Baron et al. 2013);

(ii) eutrophication of coastal and surface waters (Zhou et al. 2019);

(iii) increased NH_3 and NO_x emissions (Liu et al. 2013);

(iv) GHG N_2O emissions (Smith 2017);

(v) ozone depletion in the stratosphere (Ravishankara et al. 2009).

N_2O emissions from agricultural land depend on many factors related to soil, farming methods and the weather. The non-growing season contribution to annual emissions was 38% in corn and 43% in soybeans (Baral et al. 2022).

In agricultural crops, the Emission Factor (EF) is often used to assess N_2O emissions (Thompson et al. 2019). EF is determined by comparing soil N_2O emissions to total N input. Major direct and indirect N emissions come from such sources as synthetic and organic fertilizers, manure, N fixation by living organisms and NOx deposition from non-agricultural sectors. Higher EF values indicate higher N_2O emissions compared to N inputs.

The form of fertilizer N has a significant impact on N_2O emissions. The use of ammonium fertilizer and urea results in higher emissions (EF-1.0) than manure. For N from manure, there is a wide range of results in the literature. Air pollution from nitrogen compounds requires a reduction in mineral fertilization of the soil. In China, it is estimated that about 35% of N deposits can be directly used by crops (Yang et al. 2021).

The amount of N_2O emissions from agricultural soils is influenced by many factors related to soil conditions and cultivation technology (Table 2). Of particular importance are the amount of N and its bioavailable forms, as well as the types and doses of N fertilizers used and their application systems.

Table 2

Factors influencing N_2O emission from agricultural soils

Soil properties	Cultivation factors
N and its forms available Available carbon pH and salinity Texture Temperature Microbial activity Landforms	types of fertilizers and application systems tillage system soil additives: crop residues, biochar, composts, etc. agroforestry irrigation systems

SOIL PROPERTIES

N and its forms available

Significant amounts of N_2O and increasing SOC enlarge N_2O emissions, thus offsetting the mitigation benefits of increased SOC storage. C and N circulation in the soil are closely related to each other, and a change in one will affect the other (Guenet et al. 2021). Increasing the concentration of N compounds, temperature, oxygen availability and hydration raise nitrification and N_2O emissions (Farquharson 2016).

N transformations in agricultural ecosystems are (Robertson and Vitousek 2009):

(i) transformation of insoluble organic compounds into soluble and available ones by mineralization;

(ii) transformation of N from reduced and not very active compounds to oxidized and active ones in the process of nitrification;

(iii) absorption via plants;

(iv) microbial immobilization, which keeps otherwise mobile N from being lost from the environment.

Microbial transformations of nitrification and denitrification are the main but not the only causes of N_2O emissions from agricultural areas (Butterbach-Bahl et al. 2013). Basso and Antle (2020) estimated that the application of N fertilizers based on spatial variability across subfields and the biological requirements of individual crops can reduce N application by 36% with 23% emission reductions (578 kg CO_2e ha^{-1}).

Available carbon and microbial activity

The net uptake of CO_2 from the atmosphere in the agricultural sector is a cheap and effective method for attaining climate change mitigation and other beneficial issues related to agricultural production (Hepburn et al. 2019). Agricultural crops contribute to a significant increase in the concentration of N_2O in the air and increasing SOCs can affect N_2O emissions, possibly causing increases in many cases, thus offsetting the benefits of increased SOC storage associated with climate change (Guenet et al. 2021). Soil N_2O emissions from rice crops depend on soil organic C content and at 28 mg kg^{-1} and 300 mg kg^{-1} these emissions were 35% and 50% of total N emissions, respectively (Chen et al. 2018).

Water-soluble C in SOC fractions promote the increase in the activity of microorganisms, which enhances the ability to nitrification and denitrification (Butterbach-Bahl et al. 2013). Natural microbiological processes have an extremely significant impact on anthropogenic N2O emissions. Soil C increases microbiological activity. Microbial transformations: nitrification, i.e. the conversion of NH_4^+ to NO_3^-, and denitrification, i.e. the conversion of NO_3^- to N_2, in both of which N_2O is a by-product (Mehnaz et al. 2018).

In summary, Guenet et al. (2021), who evaluated extensively meta-analyses and their own research, asserted that the role of SOC sequestration as an important factor in mitigating climate change was overstated due to the underestimation of the role of N_2O emissions. No-tillage can reduce N_2O emissions. According to Henault et al. (2019), organic C content does not necessarily reduce N_2O emissions.

Soil moisture

N_2O emission, especially after applying N-fertilizer, increases significantly with increasing soil moisture. Bateman and Bags (2005) reported that when the water-filled-pore space (WFPS) is > 60%, soil water reduces the amount of available O_2 in the soil, resulting in the formation of anaerobic conditions conducive to N_2O emissions, and with WFPS values over 70%, all N_2O emitted came from denitrification, while at 35-60% WFPS, emission from nitrification dominated.

EFs for N_2O should be assessed separately in dry and wet climates. The IPCC has defined an EF value of 0.6% organic N and 1.6% for inorganic N for a humid climate. These values for a dry climate are set at 0.5% N for organic and inorganic forms (Wang et al. 2021).

pH

Soil pH is recognized as a major factor influencing N_2O emissions from agricultural soils and explaining regional disparities in N_2O emissions. The activity of microorganisms and their population is affected by the pH of the soil, which determines the emission of N_2O (Stehfest, Bouwman 2006). A decrease in soil pH is accompanied by a significant increase in EF N_2O, causing acidic soils to emit more N_2O than alkaline soils. In agricultural soils at pH 6.76, the EF value is 1.0% (Hénault et al. 2019). Decreasing the soil pH by one unit results in an increase in N_2O emissions of 21-119% depending on the original soil pH (4.5-8.5). In the range of 4.5-8.5, lowering the soil pH by 1 results in an increase in emissions by 21-119% (Wang et al. 2018).

Henault et al. (2019) calculated that in France, for example, soil liming has the potential to reduce total N_2O emissions by 15.7%. Żurovec et al. (2021) obtained an even greater effect of liming on N_2O emissions from grass yields. They showed a negative linear relationship between pH and N_2O emissions with emission reductions of up to 39% compared to unlimed fields.

Texture

Soil texture significantly affects N_2O emissions by influencing nitrogen availability, organic carbon and microbial populations. For example, fine-grained soils with increased anaerobic conditions emit more N_2O compared to sandy soils (Gaillard et al. 2016). Soil texture, depending on the amount and size of pores, can indirectly influence N_2O emissions by affecting soil O_2, i.e. by regulating soil moisture and aeration (Chen et al. 2013).

Sandy soils with fewer capillary pores emit less N_2O than finer textured soils. By retaining more water, they help maintain anaerobic conditions affecting the processes of N transformation that favor N_2O emissions. In fine-textured soils, anaerobic conditions are more resistant and can persist for longer periods (Wang et al. 2021). Cui's et al. (2023) research showed that the effect of temperature on N_2O emissions decreased as the soil texture increased.

Landforms

N_2O emissions from agricultural soils are influenced by the topography of the land, which determines biochemical, pedological and hydrological processes. Flat areas emit much less N_2O than those with varied relief and higher humidity (Ashiq et al. 2021a,b). Depressions produce higher emissions than mountain slopes and ridges due to higher soil moisture. At the same time, lower air pressure at higher elevations favors N_2O emissions due to lower back pressure on the soil (Butterbach-Bahl et al. 2013).

CULTIVATION FACTORS

Types of fertilizers and application systems

The methods used in field cultivation by changing the soil environment have a decisive impact on N_2O emissions.

Fertilizers and manure used in farming are the main sources of N_2O emissions from agricultural soils. The effect of fertilization on N_2O emissions is related to the type of fertilizer, its dose and timing of application (Zimermann et al. 2018). Appropriate N fertilization, i.e. the right type of fertilizer, its dose, time and method of application, etc., makes it possible to significantly reduce N_2O emissions without reducing yields (Hassan et al. 2022). The application of N fertilizers based on the spatial variability of a subfield and the biological requirements of individual crops can reduce N application doses by 36% leading to a 23% reduction in emissions (578 kg CO_2e ha^{-1}) – Northrup et al. (2021). Shcherbak et al. (2014) showed that N_2O emissions increase exponentially with N input higher than needed by plants. Urea contains the most N among solid nitrogen fertilizers, and accounts for 60% of the world's N fertilizer use. A reduction in total global N_2O emissions needs effective management of urea (Zhang et al. 2023).

Of particular importance are the amount of N and its bioavailable forms, as well as the types and amounts of N fertilizers used and their application systems. Table 3 shows N_2O emissions from soils fertilized with various fer-

Table 3

N_2O-N emissions from soils fertilized with various fertilizers (Stehfest, Bouwman 2006, Snyder et al. 2009, modified by authors)

Fertilizer source	Mediana (kg ha^{-1})	Range (% of applied N)
Calcium nitrate, potassium nitrate, sodium nitrate	1.56	0.05-11
Ammonium nitrate	1.12	0-30.4
Anhydrous ammonia	1.04	0.05-19.6
Urea	0.96	0.01-46.4
Ammonium carbonate, chloride, or sulfate	0.82	0.01-36
Urea ammonium nitrate	0.78	0.03-16
Ammonium phosphates	0.26	0.06-7
Organic	1.15	0.03-56

tilizers. A very large range of emissions for a specific fertilizer shows that, other than the type of fertilizer, the conditions in which it is applied, namely temperature and humidity of the soil, its properties, pH, etc., have a very significant impact (Dueri et al. 2023, Li et al. 2023). Air pollution from nitrogen compounds requires a reduction in mineral fertilization of the soil. In China, it is estimated that about 35% of N deposits can be directly used by crops (Yang et al. 2021).

The type of fertilizer used has a significant impact on N_2O emissions. According to Carbonell-Bojollo et al. (2022), ammonium nitrate causes the highest emission of all fertilizers. Ammonium fertilizers are slower to increase N_2O emissions than nitrogen fertilizers because the latter immediately start denitrification processes, while ammonia sources must first undergo nitrification. There are different opinions in the literature comparing the impact of using mineral and organic fertilizers on N_2O emissions. Research by Liu et al. (2023) showed that organic fertilizers, compared to chemical fertilizers, emit less NH_3 but significantly more N_2O throughout the growing season. However, for example according to Young, the use of ammonium fertilizer and urea results in higher N_2O emissions than that of manure.

Rahman and Forrestal (2021) studied the effects of different fertilizers on N_2O emissions. They estimated that on grasslands of the temperate zone, the annual N_2O emission was 0.29 kg ha^{-1} for the control area, 1.07 kg ha^{-1} for fertilization with ammonium fertilizer and 2.54 kg ha^{-1} for synthetic nitrate fertilizer. There were no differences in yield and N uptake between fertilizers, ammonium fertilizer resulted in the same yield and N uptake as N fertilizer with much lower N_2O emission.

A study by Friedl et al. (2018) showed that N_2O emissions, after N fertilizer application, increase significantly with increasing soil moisture. When the water-filled pore space is > 60%, water displaces the amount of available O_2 in the soil pores, leading to anaerobic soil moisture conditions that stimulate N_2O synthesis by facultative anaerobic bacteria. However, the latest research by Button et al. (2023) indicated that in some cases, as with the intensity of aerobic denitrification, wet soils may emit less N_2O than dry soils.

State-of-the-art digital agriculture and agronomic modeling methods enable accurate prediction of plant N requirements. Predicting plant response to N by determining soil conditions, weather, terrain, and crop demand based on a geospatial monitoring system enables precise fertilizer application. Basso and Antle (2020) estimate that application of N fertilizers based on subfield spatial variability and bio-demand can reduce N application by 36% while maintaining the spatial variability of the terrain and different needs of plants, which reduces N_2O emissions by 23% (578 kg CO_2eq ha^{-1}) – Northrup et al. (2021).

Enhanced performance nitrogen fertilizers, slow-release fertilizers, nitrification inhibitors can reduce N_2O emissions and increase yields (Hargreaves et al. 2021, Lyu et al. 2021). The specific form of the chemical fertilizer affects the level of N_2O emissions. Application of $CaSO_4 \cdot$ 4 urea cocrystal compared to pure urea can increase yields and reduce N_2O emissions (Bista et al. 2023). Research by Wang et al. (2023) suggests that the use of struvite (magnesium ammonium phosphate – $MgNH_4PO_4 \cdot 6H_2O$) as a nitrogen fertilizer can reduce N_2O emissions compared to commercial urea and complex NPK fertilizers by 40.8-58.1%. However, these are preliminary results that need to be confirmed under different conditions.

SOIL ADDITIVES

Crop residues

Plant residues increase soil carbon stocks and soil fertility, reduce the risk of erosion contributing to increased yields, and therefore contribute to climate change mitigation. However, an additional effect of their use is increased N_2O emissions. N_2O emissions associated with the decomposition of crop residues can offset the positive impact that crop residue recycling has on maintaining or increasing soil C stocks (Lashermes et al. 2022).

Methods to mitigate the impact of crop residues on N_2O emissions typically result in negative side effects: reduced yields and soil C stocks, NO_{3-} leaching and/or NH_{3-} lotilization. Strategies to reduce N_2O crop residue emissions without serious adverse side effects include the use of agents that slow down the nitrification process, N-blocking materials, where the C:N ratio is high, such as compost or miscellaneous waste (Abalos et al. 2022). Hergoualc'h et al. (2019) determined N_2O emission factors from added N in crop residues as 0.005 -0.006- kg N_2O-N kg^{-1} N depending on the type of climate. The use of organic additives with synthetic fertilizers increases EF (Charles et al. 2017).

Biochar

Biochar has a high C content and a high C/N ratio. It can be used as a soil additive, protecting it against degradation, and increasing carbon sequestration (Ribas et al. 2019). Feng and Zhu (2017) showed that an increase in the addition of biochar to corn crops resulted in a decrease in N_2O emissions. The addition of 0.5%, 1% and 2% biochar resulted in the emission of 120.9 g N ha^{-1}, 61.7 g N ha^{-1} and 47.6 g N ha^{-1}, respectively.

The mechanism by which biochar reduces N_2O emissions remains unclear. Liao et al (2021) believe that the larger specific surface area of biochar may increase the activity of nitrous oxide (N_2O) reducing microorganisms, thereby reducing N_2O emissions. Similar to biochar, the addition of organic materials like compost, animal waste and oil cake to aged soil reduces N_2O emissions (Yangjin et al. 2021).

TILLAGE SYSTEM

Tillage practices directly affect yield and N_2O emissions by altering soil properties. Tillage causes an increase in aeration and breaking up of soil aggregates, resulting in an increase in CO_2 emissions. This process is accompanied by the release of organic C, which is conducive to the growth of the activity of microorganisms (Hassan et al. 2022). N_2O emissions in zero tillage and reduced tillage depend on many factors. With the current state of knowledge, it is practically impossible to determine unambiguously the impact of various cultivation methods on N_2O emissions (Feng et al. 2018).

NT (no-till) has no clear effect on N_2O emissions compared to CT (conventional tillage), emissions may be higher, lower or on the same level (CT) (Guenet et al. 2021). For example, a meta-analysis by Mei et al. (2018), based on 212 observations from 40 publications, showed that in general NT increased soil N_2O emissions by 17.8% compared to CT. Similar results were obtained by Garland et al. (2011) in viticulture. NT practices increase the WFPS compared to CT cultivation, which is recognized as a cause of increased N_2O emissions (Stres et al. 2008). On the other hand, studies by Elder and Lal (2008) showed that no tillage significantly reduces N_2O emissions compared to CT. Tellez-Rio et al. (2015) showed that NT reduced N_2O fluxes compared to CT, but only in the spring period, whereas in the remaining months there was no effect of the type of cultivation on emissions. Feng et al. (2018), based on a global meta-analysis, assessed the impact of five factors: cropping system, crop residue management, split application of nitrogen fertilizers, irrigation, and cultivation duration, on the comparison of conventional technology with NT. Studies have shown that the use of NT technology, despite the increase in N_2O emissions, reduced the warming factor by 6.6%.

Meurer et al. (2018) argues that despite uncertainty about the impact of no tillage technology on N_2O emissions, NT practices significantly offset negative N_2O emissions through C sequestration and CH_4 emission reduction. In fields where cultivation has ceased the N_2O emission significantly decreased, probably due to changes in the basic processes of nitrification, denitrification, leading to reduced N_2O synthesis (El-Hawwary et al. 2022).

AGROFORESTRY

Meta-analyses unequivocally show that, despite the variation in systems, conversion of arable land in CA to ASF systems significantly increases SOC stocks (Feliciano et al. 2018). For differences in N_2O emissions between CA and ASF systems, such uniqueness is not present. Syntheses of agroforestry N_2O emissions compared to neighboring CA showed only small differences in favor of ASF in net emissions or no clear direction of change (Kim et al. 2016).

A study by Shao et al. (2023) on different sites and with different plants showed that annual N_2O emissions from monocultures were 110-162% higher than from agroforestry systems. In agroforestry systems, rows of trees competed with microorganisms for N, resulting in a reduction in N_2O emissions produced by microorganisms. The deep rooting of trees in ASF allows N uptake, which reduces its availability for nitrification and denitrification processes, thereby reducing indirect N_2O emissions (Cardinael et al. 2015). In ASF systems, rows of trees are not fertilized, which limits the area of fertilized agricultural crops, and in consequence there is a reduction in N_2O emissions. However, this decrease may be apparent because it is accompanied by a decrease in the area of fertilized crops (Guenet et al. 2021).

IRRIGATION SYSTEMS

By regulating many biological processes, water in the soil can promote N_2O emissions, but also has a mitigating effect on this emission (Carbonell-Bojollo et al. 2022). Soil irrigation leading to higher moisture that increases WSPS creates anaerobic conditions that promote N_2O formation (Bateman, Bags 2005).

The use of low-volume irrigation, such as through the use of drip and subsurface irrigation, can reduce emissions by up to 33% (Scheer et al. 2008). Irrigation methods have a significant impact on the EF value. And so, in the Mediterranean areas of EF: for rain fed crops it was 0.27%, irrigation crops 0.63%, drip irrigation systems 0.51% (Cayuela et al. 2017). A study by Yangjin et al. (2021) showed that drip irrigation compared to flood irrigation reduced N_2O emissions by 8-21% with a non-significant effect on crop yields.

Use of several technologies simultaneously proves effective in reducing N_2O emissions from crops. Applying a combination of different cultivation practices: reducing the addition of N fertilizers and using their more efficient forms, drip irrigation, the addition of biochar and other organic materials, etc., reduced N_2O emissions by 25% (Yangjin et al. 2021). Carbonell-Bojollo et al. (2022) showed that in maize cultivation in the Mediterranean region the use of no-tillage, fertilizers with nitrification inhibitor and the use of 75% irrigation dose significantly reduced N_2O emissions.

CONCLUSION

N_2O emissions are an important anthropogenic factor causing climate change. Despite relatively low concentrations in the air, the global warming potential is 265 times higher than CO_2 and the atmospheric lifetime of ~116 years is 9 times longer than CH_4. Agricultural activity is the main source of N_2O emissions, the largest of which is the application of N fertilizers in crop production. The relationship between agriculture, especially N_2O, and climate is affected by many factors that are often difficult to define and quantify. The problem is extremely complicated because N-fertilization is a basic factor increasing yields, and on the other hand it determines the level of N_2O emissions (Figure 1). New cultivation technologies designed to mitigate

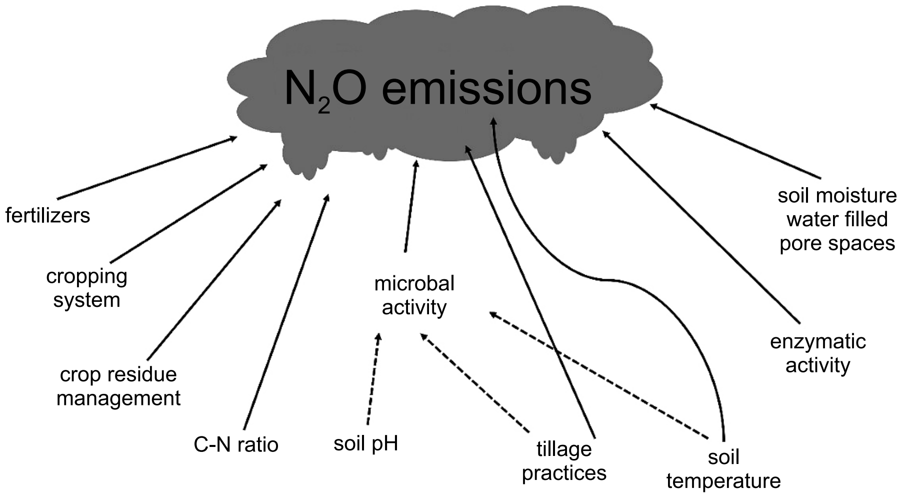

Fig. 1. Factors responsible for N_2O emissions from agricultural soils

climate change by increasing C sequestration mostly contribute to increase N_2O emissions from the soil and contribute to reduced yields. It is therefore necessary to reconcile these contradictory effects by maintaining food production at an appropriate level and mitigating climate change, an important element of which is the reduction of N_2O emissions. However, an accurate assessment of the relationship between emissions and yield levels is currently impossible due to the complexity of the problem and the lag in basic research on the subject. Continued human population growth and famine in many regions are driving an increase in agricultural production, which is conducive to climate change. Therefore, it is necessary to implement new technologies that minimize greenhouse gas emissions without reducing yields.

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