

Digital Technologies for Reducing the Carbon Footprint in the Interests of Sustainable Ecological and Economic Development of Agriculture

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Abstract: - In the context of increasing ecological challenges and the necessity for more sustainable development models, global agriculture faces an important mission to provide food to people. The paper is devoted to the analysis of the main digital technologies and their potential in reducing the carbon footprint and ensuring sustainable ecological and economic development of agriculture. An analysis of the current global and Russian greenhouse gas emissions and their innovative solutions in agriculture and nature management was carried out. A review of the up-to-date technologies used in greenhouses and in the farming sector was presented, namely smart greenhouses and smart farming and their components such as the Internet of Things (IoT), Artificial Intelligence (AI), and big data. The innovative production system in agriculture is aimed at changing methods and approaches of monitoring, forecasting and decision-making. The described production system in agriculture optimizes agricultural production, increases its efficiency and the usage of resources (water, energy, fertilizers) and thus reduces greenhouse gas emissions in the agri-food chain.

Key-Words: - agriculture, digital technologies, carbon footprint, greenhouse gases, climate change, global warming, data analytics, smart farms, sustainability of agricultural production.

Received: February 22, 2026. Revised: April 25, 2026. Accepted: August 16, 2026. Published: October 2, 2026.

1 Introduction

The concept of sustainable rural development in Russia is reflected in the Strategy for Socio-Economic Development of the Russian Federation until 2030. The Strategy involves a balanced development of the country as a whole. At the same time, a number of specific goals are to be reached by the agrarian sector: increasing the production volumes, improving the level of agricultural production, ensuring the employment and income of the rural population, as well as effective use of land resources. Thus, sustainable rural development is impossible without environmental sustainability, which implies preserving and restoring natural ecosystems, minimizing human impact on nature, and preventing overuse of resources for their intergenerational use.

The environmental sustainability of Russian agriculture is aimed at rational use and protection of natural resources and ecosystems. This includes optimal use of bio-fertilizers and of agrochemicals, a variety of measures to prevent soil erosion as well as to counteract land degradation, a careful approach to the use of genetically modified organisms, a production and consumption culture

of safe, healthy and environmentally-friendly foodstuffs and a healthy lifestyle. Education in these issues is also seen as important, [1].

In the context of sustainable ecological and economic development, reducing the carbon footprint in the agricultural sector is becoming an increasingly urgent task. This problem affects not only the ecological balance, but also the profitability of the agricultural sector. Therefore, solving this problem becomes crucial for the implementation of international efforts aimed at mitigating the effects of climate change.

2 The Problem of Greenhouse Gas Emissions in Agriculture

Agriculture is the world's primary source of food production. This vital sector of human activity plays a very significant role in global food security. Agricultural activity, however, generates a considerable quantity of greenhouse gas emissions by humans. These include the production of carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) emissions emanating from a number of

agricultural aspects. These include the emissions that are generated from activities associated with soil use, from the digestive processes of livestock, and from the manure of these animals. Other aspects that contribute to the emissions of greenhouse gases by man include the production of rice and the use of commercial fertilizers [2]. Particularly, agricultural activities contribute to around one third of greenhouse gas emissions [3]. With the ongoing expansion of the global population and corresponding surge in food requirements, agricultural activities are poised to generate escalating levels of greenhouse gases. These trends are particularly evident in developing countries, where there has been an expansion of cultivated land and rapid growth in livestock farming.

Combating climate change and reducing greenhouse gases (GHG) through sustainable agricultural development is a challenge of dimensions. The classical approach to tackle climate change in agriculture by far-reaching changes of land use, large-scale afforestation and input reduction on the farm in the conventional way is very effective, but needs a lot of financial, organizational and time resources before yielding measurable outcomes [4].

Digital technologies open up new opportunities for more efficient management of agricultural processes and minimizing the carbon footprint.

3 Results of the Analysis of Digital Technologies for Reducing the Carbon Footprint

According to data from the World Meteorological Organization (WMO), national statistical offices, and relevant United Nations agencies, the observed increase in global atmospheric concentrations of nitrous oxide (N_2O) is almost entirely attributable to human activities. The primary driver of this trend is the intensive application of synthetic nitrogen fertilizers in agricultural systems. Since the mid-20th century, emissions from the agricultural sector have exhibited a consistent and accelerating upward trajectory. While fossil fuel combustion and industrial processes also contribute to total N_2O emissions, their growth rates over recent decades have been comparatively moderate, underscoring agriculture's dominant role in the emission dynamics [5].

The total amount of Greenhouse gases emitted by human activities worldwide has increased by 1.9% to 53.0 GtCO₂e in 2023 compared to the

previous year. As usual, most of the emissions are produced by only a few countries. In this update, we include the emissions for China, the United States, India, the 27 EU member states, Russia, and Brazil. These 8 countries are responsible for 62.7% of the total amount of Greenhouse gases emitted by human activities worldwide. In contrast, the 100 countries with the lowest Greenhouse gas emissions produce less than 3% of total emissions and are therefore of little relevance for mitigating climate change. As a result, the developed countries and the newly industrializing countries have to bear the main burden of efforts to tackle climate change.

Energy accounts for almost three quarters of global emissions, followed by agriculture [6].

With the development of agriculture and the growth of production, the carbon footprint of the industry has a stable upward trend. Pollution by agriculture in order to reach its objectives the last 35 years increased the amount of greenhouse gases by 18.3% within the last 33 years and keeps on increasing by an average of 0.54% per year. The amount of emitted greenhouse gases in 1990 was 4.98 Gt CO₂ eq and increased to 5.89 Gt CO₂ eq in 2022 (Figure 1, Appendix). So, the environmental impacts of agriculture are also increasing while the world is struggling with climate change.

It is important to note that the reduction of greenhouse gases in the world per capita over more than 30 years by 22.3% is the result of consistent measures to improve the environmental efficiency of production and the introduction of sustainable farming methods.

In Russian agriculture, emissions from cultivated soils of nitrogen oxide (N_2O) (more than 50% in CO₂ equivalent) are responsible for most of the emissions. Nitrous oxide (N_2O) possesses a high global warming potential (GWP), estimated at approximately 300 times that of carbon dioxide (CO₂) over a 100-year time horizon. This means that even relatively small emissions of N_2O contribute disproportionately to radiative forcing and long-term climate change, making it a critical target for mitigation efforts despite its lower atmospheric concentration (Figure 2, Appendix).

The second source of emissions is the internal fermentation of farm animals, responsible for the formation of a greenhouse gas with high global warming potential - methane (CH₄). This gas is able to retain almost 80 times more heat than carbon dioxide. The share in the formation of the carbon footprint is 33.8%.

The analysis of the dynamic series (Table 1, Appendix) showed that the volume of greenhouse gas emissions in Russia from almost all sources of their formation in the period from 2005 to 2021 is growing, with the exception of internal fermentation of farm animals (decreased by 8.5%). In general, sources of greenhouse gas emissions contributed to an increase in the level of emissions from agriculture as a whole by 13.6% or by 14.53 million tons of CO₂ equivalent. The most intensive areas of agriculture turned out to be rice farming and soil cultivation. Rice farming is also one of the main sources of methane due to bacteria that actively spread in a culture-friendly environment.

The effective mitigation of greenhouse gases in agriculture requires an analysis of the currently available low-carbon technologies. Seven strategies for the reduction of greenhouse gas emissions in agriculture have been developed by the United Nations Environment Program (UNEP). This article will outline two of these strategies for the effective mitigation of greenhouse gases in agriculture.

Arable land management: Improved agricultural practices on arable lands that reduce greenhouse gas emissions from soils and increase carbon stocks in croplands, including optimized nutrient management, conservation agriculture, crop residue management, efficient use of water for irrigation, improved rice cultivation practices, and integration of agroforestry systems into agricultural production systems.

Livestock management: Improved nutrition of animals by means of specific additives in their feed such as nitrates, fats or even methane inhibitors like 3-nitrooxypropanol, health of animals and breeding. In the long term, changes in the housing of animals and their manure management systems are necessary in order to reduce methane emissions from enteric fermentation as well as from manure decomposition. Such measures can lead to sustainable production systems.

3. Management of organic fertilizers/solid biological waste (improved storage and treatment, anaerobic decomposition of agricultural waste – anaerobic digestion);

4. Bioenergy (energy crops, solid, liquid, biogas, waste);

5. Pasture management/pasture improvement;

6. Management of organic soils and restoration of degraded lands [7].

Russia is also actively implementing digital production technologies and techniques to reduce the carbon footprint of agriculture. For example,

the Strategy of the Ministry of Economic Development of the Russian Federation on Carbon Regulation to achieve carbon neutrality in agriculture defines precision farming and biofuel production as the main measures by 2060 [8].

The primary focus of agricultural digitization lies in implementing precision farming techniques. These methods stem from the scientific understanding that individual fields exhibit varying characteristics across different sections. Advanced tools like Global Positioning Systems (GPS, GLONASS, Galileo), specialized sensors, aerial photography, satellite imagery, and Geographic Information System (GIS)-based software play pivotal roles in identifying and quantifying these variations [9]. The integration of GPS technology in agricultural machinery enables centimeter-level positioning accuracy, significantly reducing track overlap during field operations such as seeding, fertilizing, and spraying. This precision directly translates into lower fuel consumption, thereby decreasing carbon dioxide (CO₂) emissions from agricultural machinery.

Enable decisions for crop management based on data from in-field sensors for soil moisture, temperature, nutrients, etc. in the field. This allows for site-specific application of fertilizers and plant protection products. This can help to avoid overuse of agrochemicals and prevent losses of nitrogen to the atmosphere as well as to reduce emissions of nitrous oxide (N₂O) and of methane (CH₄) from degraded soils.

For many farming systems, there is empirical evidence that full implementation of precision agriculture could save up to 20% of the fertilizers that are normally used, 15% of the N₂O emissions, and up to 10% of the costs for the use of fertilizers. It has to be noted that the percentage of possible savings can vary greatly depending on the type of crops and the related agricultural systems. Furthermore, the possible savings can also vary depending on the local climate, soils, as well as the level of technology used on the single farm.

In addition to optimal application of fertilizers and plant protection agents, by fully automating the irrigation of crops, precision irrigation systems can also achieve an effective use of water, in terms of the amount of water required and the energy used for the pumping and distribution of irrigation water. The required data for the optimal time and exact place of irrigation are provided by soil moisture sensors as well as by weather forecasts. Learning algorithms are used to predict the required water for the crop. Thus, also the indirect greenhouse gas

emissions (CO_2) are decreased, which are caused by the electricity or fuels used for irrigation. These emissions are part of the overall carbon footprint of agricultural production and are thus decreased by precision irrigation [10].

Soil water management using automated irrigation systems can also enhance soil health. Soil with the right amount of moisture at the right time supports a very active and healthy soil microbiome. The soil microbiome is crucial for the carbon and nitrogen cycling functions, i.e., for the decomposition of organic matter, for the release of nutrients from the soil, and for the storage of carbon in the soil. Preventing waterlogged soils and drought-stressed soils is very important since these conditions promote denitrification processes that release large amounts of greenhouse gases such as nitrous oxide (N_2O) with a global warming potential of approximately 300 times that of carbon dioxide (CO_2). A system that prevents these emissions and promotes long-term soil fertility is very valuable.

The production of livestock leads to the release of a number of different Greenhouse gases. Methane (CH_4) is a major gas produced by livestock through enteric fermentation. In addition to this, manure from livestock as well as soils grazed by livestock can produce Nitrous oxide (N_2O). Together, the emissions from agriculture (including all types of livestock production) contribute to the sector's total share of greenhouse gas emissions. This total is 14.5% of total global anthropogenic GHG emissions and is greater than emissions from the energy and industry sectors.

There are many ways to implement sustainable production methods in combination with the latest technologies in order to reduce greenhouse gas emissions. The use of digesters for the treatment of animal manure as well as of crop residues and other organic waste in order to produce energy in the form of biogas (mainly composed of methane and CO_2) is increasingly being put into practice. The energy thus produced can be used for heating, for the generation of electricity, or it can be upgraded in order to be injected into the gas grid under the commercial name of biomethane. The treatment of the waste in digesters also has a very positive effect on the environment, in that the volume of waste to be treated in an untreated state is greatly reduced, thus avoiding the emission of greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O) to the atmosphere. The remaining digestate is a very valuable fertilizer, which is stable, organic and of a circular nature. When burning biofuels, the amount of carbon dioxide is reduced by 65%, which

reduces the industry's contribution to climate change. An additional environmental advantage of liquid biofuels, such as bioethanol and biodiesel, lies in their significantly lower content of contaminants like chlorine and sulfur compared to conventional fossil fuels. The reduced concentration of these elements translates into lower atmospheric emissions of harmful by-products—such as hydrogen chloride and sulfur dioxide—during combustion. This contributes not only to improved air quality but also to decreased acidification of soils and water bodies, making biofuels a cleaner alternative in both transportation and agricultural machinery applications.

Another promising innovation, particularly in the realm of crop production, is the development and deployment of smart greenhouses. These high-efficiency systems leverage digital technologies to precisely regulate internal conditions—such as temperature, humidity, CO_2 concentration, and artificial lighting—based on real-time crop needs, thereby minimizing energy waste. Integrated with renewable energy sources, such as photovoltaic panels or small-scale wind turbines, smart greenhouses can drastically reduce reliance on fossil-fuel-based electricity and heating. Furthermore, automated nutrient delivery, closed-loop irrigation, and targeted pest control reduce the need for synthetic fertilizers and pesticides, lowering emissions of nitrous oxide and other pollutants.

While the transition to smart greenhouse systems demands substantial initial investment in infrastructure, control systems, and staff training, the long-term benefits are compelling. These include enhanced resource efficiency, year-round production, higher crop yields, and a significantly reduced carbon footprint. As a result, such systems are increasingly being adopted across countries aiming to reconcile food security with climate goals, particularly in regions with challenging climatic conditions or limited arable land.

Smart farms around the world use the latest technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), drones, and Multi-Sensor Networks in their management and monitoring in order to increase their productivity and sustainability. In order to achieve these objectives, smart farms aim to use only the required inputs for the crops and to avoid any waste of the inputs that are used in the farms. Thus, they are trying to reduce the carbon footprint of agriculture by ensuring that the amount of farm inputs required is used in precise amounts in order to achieve the required farm production, while at the same time

they are trying to reduce the waste of farm inputs. Additionally, by using smart farms, it is also possible to reduce fuel consumption and prevent the overapplication of nitrogen, which can cause indirect reduction of emissions from non-optimal use of resources.

Agricultural informatics is a science which deals with the collection, processing and analysis of information of agricultural character to support decisions of a strategic or operational nature. It is essential for sustainable agricultural models and for Smart Farming. In agricultural informatics, farmers and companies in agriculture are supported in a proactive manner by providing them with current information on the state of their crops, the quality of their soils, the weather, and pests. In this way, farmers are able to manage their farms in an effective and sustainable manner.

The core function of agricultural informatics is to support farm management by precisely delivering the required inputs to the crops in the field. Advanced systems for monitoring fields include satellite imagery as well as images in multispectral bands collected by drones flying in the air as well as on the ground by various types of sensors. This type of monitoring makes it possible to precisely identify parts of the field that require water, additional nitrogen, as well as control of pests. In this way, the approach maximizes agricultural production while preventing excessive nitrogen from running off into the waterways and producing N_2O emissions. It also helps prevent excess use of water for irrigating crops and thus reduces energy consumption for pumping water, which in turn leads to the generation of CO_2 emissions. In summary, agricultural informatics increases agricultural productivity and makes farms more resilient while enabling climate-smart agriculture.

Data analytics plays a crucial role in interpreting the huge amounts of information coming from various sensors and monitoring systems and is the basis for predicting crop yields and animal productivity, and tracking soil conditions.

Automated intelligent control systems based on big data and artificial intelligence help to make informed decisions in real time. They can predict weather conditions, plan sowing operations and optimize the operation of agricultural machinery, which can form the basis for developing a strategy to reduce the negative impact on the environment and achieve carbon neutrality.

Agricultural robotics and automation can increase agricultural productivity and make agriculture more sustainable. Precision agricultural

production, timely harvesting of produce, conservation of natural resources and reduction of human labor in agriculture are major goals of agricultural automation. It also saves resources and reduces greenhouse gas emissions through optimized routes for traveling in the field, minimum use of fuels, and less soil disturbance during farm operations by minimizing the number of field operations with farm equipment.

Automation of agricultural production also enables the sustainable use of natural resources, such as water and fertilizers. To give an example, automated irrigation systems in agriculture make full use of soil and weather sensors in order to collect the required data for decisions on irrigation on an ongoing basis. In this way, irrigation water is applied in a precise manner on a spatial and temporal basis. This results in irrigated agriculture being able to save up to 40% of water resources without affecting production levels from the respective crops.

So far, autonomous sprinkling systems with fungicides have been successfully used in specialized crop production (like fruit and berry bushes). The high-resolution computer vision system is able to detect the earliest signs of plant diseases; then the fungicide is sprayed directly on the affected parts of the plants, thus the required amounts of fungicides are dramatically reduced in comparison with traditional methods. Autonomous operation of sprinkling systems is done by onboard solar panels as well as by solar panels installed on the farmer's house; thus, emissions of CO_2 during operation of sprinkling systems are almost completely eliminated.

However, during their application, robotic systems can bring significant benefits to farms and fields, reducing the agricultural environmental impact. To assess the environmental effects of agricultural production systems that incorporate automated technologies, it is possible to use life-cycle assessment (LCA). In terms of the agricultural machinery impact on the environment, the share of negative factors caused by this element could be decreased by the positive factors such as the creation of new jobs and an increase in agricultural production. At the same time, in the framework of the LCA, it is necessary to take into account not only the operational phase of the agricultural robotic systems but also other stages of their life cycles. A number of negative factors are determined by the consumption of specific amounts of energy at the different stages of the life cycles of the materials and the manufacturing processes. In this case, it is necessary to take into account the use

of certain types of raw materials, including the rare earth elements that are not environmentally friendly. From the climate change factor viewpoint, the total emissions of greenhouse gases to the atmosphere, within the framework of the life-cycle assessment, can be equal to or even greater than the emissions that are reduced as a result of the robotic automation of agricultural production. The degree to which greenhouse gas emissions can be decreased by means of robotic agriculture, as well as the net positive effect of such agriculture on the climate,

Reducing greenhouse gas emissions also includes the processes related to the supply of agricultural produce to the market. Such an approach is aimed at minimizing the costs and impacts of transportation as well as at increasing the transparency of agricultural production and sales. Currently, there are quite a few electronic platforms in Russia that are used to promote local producers and to sell and buy products on local markets. Such platforms support the development of the local markets and help to reduce the distance necessary for transportation of the goods to be sold on the market, which in turn leads to a decrease in the emissions that are produced during transportation of the goods over long distances.

At the moment, the Russian Ministry of Economic Development is working to decrease agriculture's carbon footprint and to develop the Strategy of the Ministry of Economic Development of the Russian Federation on Carbon Regulation to achieve carbon neutrality in agriculture by 2060. The strategy includes a number of measures aimed at decreasing the impact of agriculture on climate and ecology, including the implementation of precision agriculture and biofuel production.

The current priorities of Russia in respect of research in precision agriculture are as follows. First, the organization and management of the production of crops using production technologies and their technical support, and, second, energy-efficient crop production on the basis of the principles of biologization and of environmental safety. Work in these two areas is to be directed towards the implementation of the Strategy of the Ministry of Economic Development of the Russian Federation on Carbon Regulation to achieve carbon neutrality in agriculture by 2060.

The second strategic goal focuses on environmental production and resource efficiency to ensure high and sustainable levels of production of agricultural goods and food products of required quality. New production systems for different crops that are environmentally friendly are to be

implemented in order to ensure the most efficient use of all natural resources (of natural origin as well as synthetic).

The strategy for improving the sustainability of agricultural production also involves measures aimed at improving the seed production and distribution systems, and at developing new crop varieties and their hybrids, suitable for local conditions and possessing a number of positive characteristics, including high and sustainable production levels and improved nutritional content. The development of new crop varieties is currently carried out with the aim of breeding varieties that are able to withstand a range of both abiotic and biotic stresses, and which meet a number of specific criteria with respect to a range of key factors including biosafety, the level of residues and economic viability. These new varieties are intended for use in a range of different crops that are better suited to local conditions, and that can be grown using low levels of external input in order to produce sustainable yields. Importantly, they will also help to develop climate-resilient agricultural production systems.

Lastly, there's emphasis on designing novel agronomic protocols for applying pesticides and bioproducts within regionally tailored pest control schemes, adhering strictly to principles of financial viability, ecological conservation, and biosafety.

The Russian agro-industrial sector possesses considerable potential for decreasing greenhouse gas emissions by 2050; reductions could reach up to 40%. This achievement would bolster the international competitiveness of Russian produce, says Vladimir Lukin, head of the validation and verification body of Capt Verification LLC. It is important to take into account that the specifics of the agro-industrial complex lie in the fact that technologies that are aimed at increasing productivity are at the same time technologies that lead to a reduction in the carbon footprint of manufactured products.

To assess the impact of digitalization, which is accumulated by the time factor (X), on greenhouse gas emissions from agriculture, we compare the dynamics of the carbon footprint for 1999-2024 and the growth rate of agricultural production (Figure 3, Appendix).

From 1999 to 2006, there was a marked decline in greenhouse gas emissions associated with the 1998 financial crisis, a sharp decline in agricultural production, a significant decrease in arable land, stagnation in the livestock sector, and a general deterioration in infrastructure. In this regard, energy and transport activity decreased, and the use

of mineral fertilizers and machinery decreased, which ultimately led to a rapid reduction in GHG emissions. To make the forecast, this period was not taken into account due to a change in trend and the resulting extreme in the time series.

After a partial recovery in production caused by active government support and the implementation of national projects aimed at agricultural development, the environmental situation deteriorated again, and by 2008 we see an increase in emissions on the chart.

The next historical period was the financial crisis in 2008, which affected investment activity and financing of the agro-industrial complex, causing a decrease in emissions to the level of 2005. However, the crisis was followed by a new wave of recovery in the agricultural sector: political sanctions and the need for import substitution contributed to an increase in domestic production.

After 2015, there has been a steady increase in emissions due to the intensive development of agriculture, an increase in the production of cereals, oilseeds, meat and dairy products, an increase in livestock numbers, and, as a result, increased logistics activity. According to Rosstat, Russia's industrial output has more than doubled over the past 25 years.

Agriculture emissions in the period 1999 – 2024 are projected to decrease in growth terms by 2.7% in comparison to an increase in agricultural production of 100% over the same period. In other words, there is a considerable decrease in emission intensity or greenhouse gas emissions per unit of agricultural production.

This decoupling testifies to greater resource efficiency in agriculture and the large-scale use of digital and low-carbon technologies (so-called Precision Agriculture, automated irrigation systems, more efficient use of fertilizers and pesticides, etc.). This makes possible an increase in agricultural production and at the same time a decreasing environmental impact.

While absolute emissions of greenhouse gases increase, their rate of increase has fallen behind the rate of increase of agricultural production. This is the only sector of the economy where production is increasing while emissions are not. Its growing energy efficiency and its higher and better environmental performance are thus a very welcome development which is clearly linked to new technologies.

One of the limiting factors may be the introduction of digital solutions into production, as the level of digitalization in Russia is growing every year, the number and level of implementation

of advanced technologies is increasing, as is the volume of investments and the level of costs for the digitalization of economic sectors. The use of digital technology solutions allows for more economical and environmentally friendly use of resources.

The constructed linear trend tells us about a direct positive relationship between the volume of GHG emissions and time. The quality of the model is assessed by the coefficient of determination, which indicates that 77.7% of the variation in the effective feature is caused by the relationship with time. The forecast shows that with a confidence level of 95%, the volume of emissions in the Russian agricultural sector will increase by 0.01 tons of CO₂ equivalent per capita by 2030.

Currently, the positive impact of digitalization on agricultural production far outweighs its effects on greenhouse gas emissions. A vast array of new solutions for agriculture have recently appeared. By means of GPS-guided machines and sensors of the Internet of Things (IoT), as well as systems for processing and analysis of big data, agricultural production can be significantly increased and made more efficient. Yet the enormous potential for the reduction of greenhouse gas emissions, which these solutions have, is not yet being fully utilized. It is not being used because these solutions are being introduced one after another in isolation from each other.

Addressing the challenge of agricultural development in terms of productivity and reduction of the sector's carbon footprint requires a shift from separate solutions to the creation of integrated Sustainable Development Ecosystems (SD Ecosystems). In order to increase agricultural productivity while reducing its negative impact on the environment, digital solutions are to be used in conjunction with low-carbon technologies: renewable energy, precision farming (with precise application of nutrients), biogas recycling and climate-resilient (climate-smart) agriculture. AI can be used for irrigation of crops, while solar power is used for powering pumps. Soils are monitored in real time and automatically and optimally supplied with organic fertilizers of organic origin.

In summary, integration of the digital agriculture ecosystem with the sustainable development ecosystem in agriculture will create additional synergies allowing for sustainable increase in agricultural production and, at the same time, making it environmentally friendly. In the long run, this will enable Russian agriculture to remain competitive while at the same time implementing national climate goals and meeting

requirements of international sustainability standards.

4 Conclusion

Greenhouse gas emissions from agriculture, within the context of sustainable agricultural development and the environmental stress and climate change now faced by the world, is becoming a very serious problem that requires a solution as soon as possible. In terms of absolute quantity of emissions, the share of agriculture in total GHG emissions is significant, and here it is expressed by the quantity of so-called direct emissions of agriculture into the atmosphere in the form of methane (CH₄), nitrous oxide (N₂O) and carbon dioxide (CO₂). In its turn, the latter gas is also emitted by agriculture in the form of so-called indirect emissions, i.e. as a result of consumption of different inputs by agriculture. Emissions of CH₄ and N₂O from agriculture are mainly linked with livestock production (enteric fermentation by animals and manure storage and application). Carbon dioxide is emitted by agriculture mainly as a result of soil tillage that accelerates the process of decomposition of organic matter with the consequent loss of carbon by plants.

There are now many low-carbon technologies that have recently entered agricultural production. These increase farm income while reducing the production of greenhouse gases. New agricultural production is based on digital technologies. The key technology here is precision agriculture that uses GPS, sensors, and monitoring systems of the Internet of Things (IoT), drones, and large databases of big data. The main advantage of such production is a reduction in losses resulting from an overuse of agrochemicals. This also leads to a reduction in consumption of fuel and water for irrigation that in turn results in a fall in production costs and in reduced emissions of greenhouse gases that are measured on a per-unit basis.

As part of the global transition to more sustainable agriculture, low-carbon technologies are now being introduced into Russian agriculture. Many farms have started to implement innovations, and have seen a number of positive changes as a result.

Using low-carbon technologies in agriculture, Russian farmers can become more efficient in their use of natural resources, such as energy, water, and chemicals. By optimizing agricultural production, they will be able to increase their output and boost the quality of their products, thus increasing their income.

By implementing sustainable agricultural production methods, the farmer can now successfully access local niche markets as well as international markets. The latter are currently actively purchasing agricultural products of low carbonization and with confirmed eco-friendliness, with mandatory environmental certificates.

Practices of climate-smart agriculture are aimed at increasing climate change resilience in agricultural producers, i.e., to increase their ability to withstand abiotic and biotic stresses. There are examples of such practices, like conservation tillage, cover crops, and integrated nutrient management, which can reduce negative impacts of stresses on agricultural production, and at the same time improve production results under stress.

Transitioning to a development model that increases agricultural productivity and sustainability at the same time can fundamentally change farming practices. The integration of low-emission agricultural practices and digital technologies will enable Russian agriculture to shift to a competitive, technologically advanced and environmentally sustainable development model, capable of meeting the challenges of future climate change and market conditions.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process The authors wrote, reviewed and edited the content as needed and they have not utilised artificial intelligence (AI) tools. The authors take full responsibility for the content of the publication.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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APPENDIX

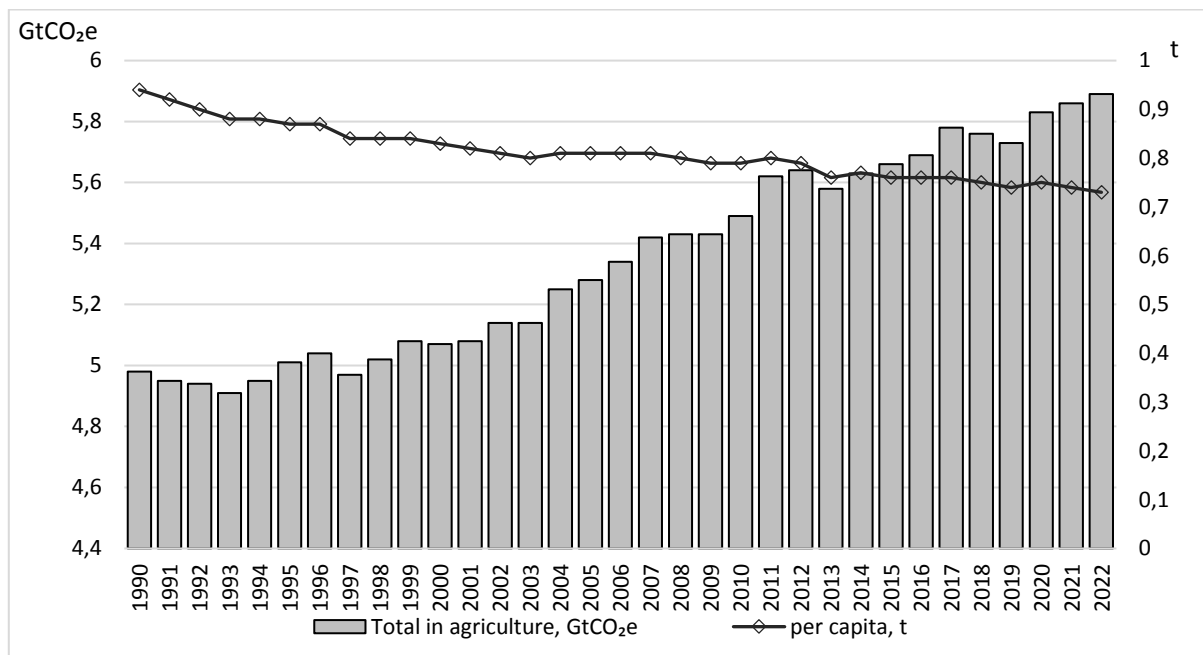


Fig. 1: Dynamics of global greenhouse gas emissions in 1990-2022

Source: built by the authors according to Climate Watch data

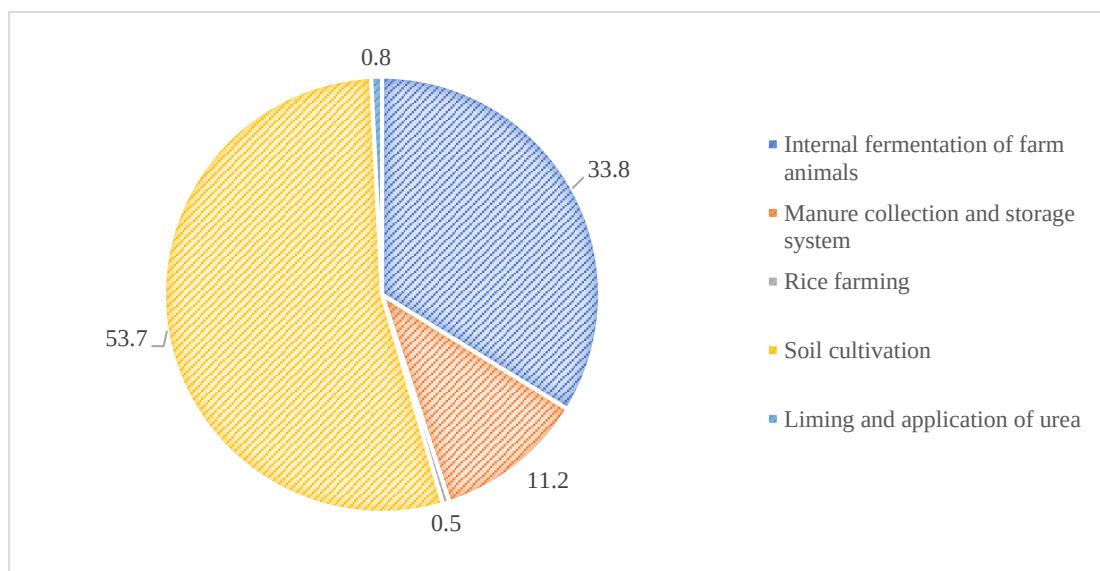


Fig. 2: The structure of greenhouse gas emissions in agriculture in Russia in 2021

Source: built by the authors according to Rosstat data

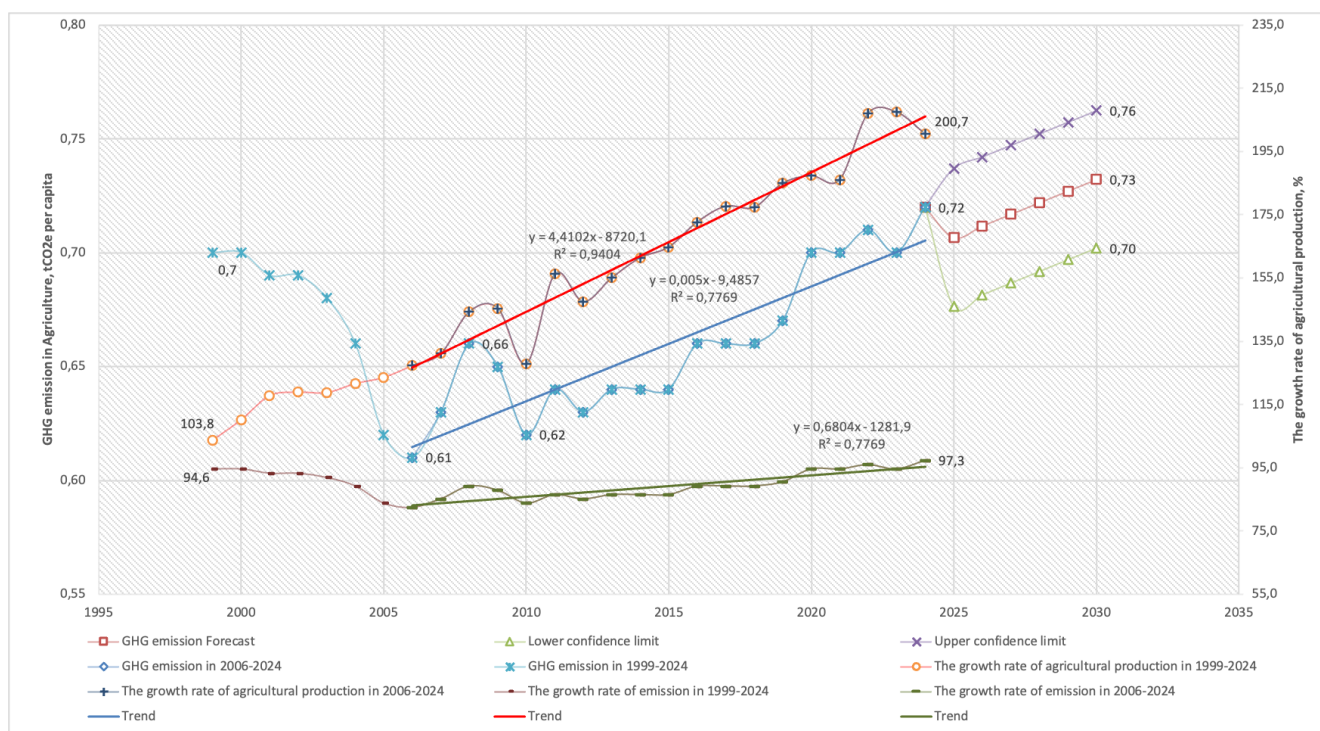


Fig. 3: The impact of digitalization on greenhouse gas emissions from agriculture in Russia from 1999 to 2024
Source: compiled by the authors based on Climate Watch data

Table 1. Analysis of the dynamics of changes in greenhouse gas emissions by sources of its formation in agriculture in Russia for 2005-2021

Sources of greenhouse gases	Absolute increase, million tons of CO ₂ -eq.	Growth rate, %
Internal fermentation of farm animals	-3.80	-8.5
Manure collection and storage systems	2.66	24.4
Rice farming	0.15	35.8
Soil cultivation	15.37	30.9
Liming and application of urea	0.15	18.7
Total for agriculture	14.53	13.6

Source: built by the authors according to Rosstat data