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Environmental tradeoffs of agricultural growth in Russian regions and possible sustainable pathways for 2030

Anton S. Strokov*, Vladimir Y. Potashnikov

Russian Presidential Academy of National Economy and Public Administration, Moscow, Russia

Abstract

The paper analyses the current ecological consequences of agricultural growth in Russia's main regions (*oblast* level) during 2011–2019. Our main hypothesis was that local environmental risks, like waste concentration, would be closely related to global climate risks such as greenhouse gas (GHG) emissions from the production of crops, meat, milk, eggs, and from land use change (LUC) activities leading to a larger carbon footprint. We first analyze official data for agricultural waste and find that 30% of it is concentrated in just two regions (Belgorod and Kursk), while they produce only 10% of agricultural value of Russia. Next, we find that manure nutrients have a high concentration in regions where the livestock production is not balanced with appropriate nutrient use on croplands (Dagestan, Astrakhan, Leningrad, and Pskov regions) which might lead to the pollution of soils and local waters. Next, we test the GLOBIOM partial equilibrium model to evaluate proper agricultural protein production quantities in Russian regions and respective GHG emissions from crop, livestock and land use change activities. We find that 21% of the GHG emission in 2019 came from the conversion of former abandoned agricultural land into cropland (starting from 2011). While some regions such as Krasnodar, Rostov, and Stavropol increase productivity with low carbon footprint, others, like Amur and Bryansk, increase production by cropland expansion without respective productivity growth which leads to higher carbon footprint. Our results for livestock operations show that the main hypothesis did not hold up because regions which increase meat production, like Belgorod, Kursk, Pskov, and Leningrad, have a lower carbon footprint due to the production of pork meat and poultry which have lower GHG emissions due to specific digestion. On the other hand, these regions experience a higher environmental footprint due to the large concentration of waste which could be harmful for local ecosystems. Finally, we use the model to project possible future development up to 2030. Our results show the possible growth of crop and livestock products in most of the regions driven by external demand for food. The extensive scenario shows additional GHG emissions from cropland expansion, while the intensive scenario reveals a larger growth rate accompanied by productivity growth and lower carbon footprint, which is essential in harmonizing the current agricultural and climate policy of Russia.

* Corresponding author, E-mail address: strokov-as@ranepa.ru

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JEL classification: Q15, Q24, Q58.

1. Introduction

Agricultural development is not only a source of food production helping to increase rural welfare and improve food nutrition indicators of all people on our planet, but also is a threat to the environment due to the conversion of natural landscapes for cropland, the pollution of soil and water by chemicals and concentration of waste and manure from large livestock operations. Previous research revealed the global problems arising from agricultural pressure on the environment through decreasing water quality and exacerbating soil fertility losses (Obersteiner et al., 2016; Steffen et al., 2015), threatening biodiversity (Newbold et al., 2016) and increasing emissions of greenhouse gases which contribute to global warming (Tubiello et al., 2015). Nevertheless, humanity still needs food for sustenance, and thus is keen on developing environmentally sustainable agricultural practices (Foley et al., 2011).

The externalities concept of economic theory helps to investigate the environmental pollution problem by putting restrictions on industry expansion in order to increase social welfare by the cost of private welfare (Pigou, 1920). In agriculture, this could be supported by additional taxes for environmentally harmful practices (Stavins, 1999). On the other hand, the theoretical and empirical research of inverse U-shaped environmental Kuznets curve (EKC) tried to find certain economic thresholds which could serve as a turning point for decreasing pollution from industries (Grossman and Krueger, 1990). In the agricultural sector there is evidence of such a curve in the decreasing rates of deforestation in developing countries (Cropper and Griffiths, 1994), or in cases of appropriate application of nitrogen nutrients in order to keep the ecological balance between productivity growth and fertilizer overuse, currently with evidence only for developed countries (Zhang et al., 2015). Some solve this problem by improving policy restriction measures and setting environmental limits for certain doses of inputs, like 170 kg of nitrogen per hectare of cropland in Europe (Van Grinsven et al., 2016). Others suggest investigating the final pollution indicators, like greenhouse gas (GHG) emissions, and observing limits or turning points which might serve as a future threshold for environmentally friendly practices (Kulyk and Augustowski, 2020). In this case the "greening" policy could be very expensive, leading to environmental improvement but also diverse productivity effects for some sectors of agriculture (Smith et al., 2008).

Some economic features of the recent development of Russian agriculture have been revealed, focusing on regional aspects using the total factor productivity approach (Rada et al., 2019). Another paper shows almost 50% crop yield gap from a lack of inputs use (Schierhorn et al., 2014). On the environmental side, only GHG emissions at the country level have been revealed (Schierhorn et al., 2019), with possible implications for low carbon agricultural practices (Romanovskaya et al., 2019). Another research found that cropland expansion could cause severe ecological tradeoffs, including carbon loss from the cultivated soil and biodiversity threats, and Russian regions were divided into several categories reflecting the extent of these types of threats (Meyfroidt et al., 2016). The difference of our approach is in evaluating local and global risks where local risks are manifested by the formation of waste and nitrogen, and global risks consist of evaluating more types of GHG from different agricultural activities in order to properly evaluate the carbon footprint of produced crops, meat and milk.

In order to properly evaluate environmental tradeoffs we suggest analyzing a combination of methods and indicators to reveal different sides of ecological risks, such as the risks to local territories, and to global climate. Local risks could be measured with variables of waste and nitrogen from manure concentration. Global risks are evaluated as GHG emissions in metric tons of CO_2 equivalent ($MTCO_2e$) and respective carbon footprints of main produced crop and livestock products. Our principal hypothesis was that the main Russian agricultural regions should have experienced growth of environmental footprint, like the quantity of waste per value of produced agricultural products, and high nitrogen concentration per hectare of cultivated area; at the same time, these regions should have shown higher carbon footprints per crop and livestock production quantities. In the next sections we will show all three types of environmental tradeoffs for selected agricultural regions of Russia, while the maps with inclusion of all agricultural regions will be located in the Supplementary material 1.

Our paper contributes to regional aspects of Russian agricultural development by measuring the environmental footprint of agricultural production using the data on three ecological indicators: quantity of waste, manures nitrogen concentration and GHG emissions. Thus, the paper is divided into 8 sections, where the first is Introduction, followed by Material and methods part. In Section 3, we analyze the recently published official data on agricultural waste and compare it with our estimates of manure nitrogen concentration in order to understand which regions of Russia can produce a lot of agricultural products with reduced environmental footprint. In Section 4, we investigate the GHG emission problem using a GLOBIOM partial equilibrium (PE) model for proper evaluation of regional distribution of agricultural products and respective carbon footprint from crop and livestock production. Section 5 shows GLOBIOM projections regarding the possible future production rates in agricultural regions of Russia, and describes two possible scenarios which are distinguished by cropland expansion and cropland intensification values. Section 6 reveals main policy measures that could be essential for some regions of Russia to switch from high to low carbon footprint practices. And in Section 7 we end up with a discussion on the accuracy of our results. The conclusion part sums up our main results.

2. Materials and methods

The lack of official data on environmental tradeoffs in Russian regions requires us to use various methods and data. First, we analyze the official data on agricultural production and different ecological indicators in Russian regions—particularly the amount of agricultural waste and concentration of nitrogen from manure. For this we use data from Russian Federal State Statistics Service (Rosstat) on cattle numbers, agricultural production and the value of agricultural products, data from Russian Federal Service for Supervision of Natural Resources

(Rosprirodnadzor) on the amount of waste from agricultural operations,[1] and Russian National Greenhouse Gas Inventories database (Institute of Global Climate and Ecology[2] in Moscow, Russia) for indicators of nitrogen excretion from manure of different types of cattle.[3]

Next, we apply GLOBIOM partial equilibrium (PE) model (Havlik et al., 2013; Havlik et al., 2014). The model is used to estimate future projections on agricultural development of all countries in the world. On the economic side, the model is based on neo-classical assumption of profit maximization of producers, and the welfare increase of consumers, who wish to improve their food security. It uses a previous approach of estimating linear functions with endogenous prices, with the possibility to apply certain technological and political constraints (McCarl and Spreen, 1980). It is a spatially explicit model which can evaluate agricultural and forestry production patterns at the country level or regional level, and also estimate the possible land use change. GLOBIOM served as one of the instruments for European Union strategies and IPCC analysis for evaluating tradeoffs between agricultural development and environmental damage, particularly with estimating GHG flows from different agricultural operations, including conversion of natural landscapes to cropland (Valin et al., 2013; Van Meijl et al., 2018).

The recent development of the model has been on the country specific level, like France (Mosnier et al., 2019), or Russia (Deppermann et al., 2018). We contribute to the research and calibration of the GLOBIOM model for Russia, editing it with spatially explicit data at a regional level (*oblast* level) for crop and livestock production, and harvest area for main crops (wheat, barley, corn, rice, potato, sunflower, soy, rape — 65% of current cropland area in Russia). There are several reasons why we only managed to model such a small share. The GLOBIOM model does not contain variables for annual and permanent grasses which currently cover almost 20% share of Russian cropland. The livestock in the model takes all the necessary grass from pastures. The model also lacks variables for sugar beet, oats, buckwheat, vegetables and melons and some other oil crops. The model does account for sorghum, millet and beans but we could not model these crops due to their small share of cropland — the model in its current form just doesn't find a precise solution for their cultivated areas.

GLOBIOM covers 11 important crops which are grown in most Russian regions — potato, beans, wheat, rice, corn, sorghum, millet, barley, soy, sunflower and rape. On the livestock side it covers beef, pork, sheep and poultry meat production, as well as the production of cow milk and eggs. In this paper we will use protein coefficients (Fuglie, 2015) to convert all primary product quantity into protein equivalent: wheat — 0.142, rice — 0.076, barley — 0.119, corn — 0.096, millet — 0.116, sorghum — 0.111, pulses — 0.226, potato — 0.022, oilseed (soy, sunflower and rapeseed) — 0.392; and for livestock products — meat (beef, pork, poultry, and sheep) — 0.514, cow milk — 0.033, egg — 0.514. These coefficients will help us to properly estimate the carbon footprint of crop and livestock production.

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1 Unfortunately, the data was deleted from the website when we checked its access on October 7th of 2021. We can provide this data — in the original way how it was downloaded — upon request. Now the data is included in the Supplementary materials as a table and maps.

2 http://www.igce.ru/ (in Russian)

3 https://unfccc.int/documents/273489

GLOBIOM covers major GHG emissions from Agriculture, Forestry and Other Land Use (AFOLU) based on IPCC accounting guidelines (IPCC, 2006) including N_2O from the application of synthetic fertilizer and manure to soils, N_2O from manure dropped on pastures, CH_4 from rice cultivation, N_2O and CH_4 from manure management, and CH_4 from enteric fermentation, and CO_2 emissions/removals from land use change processes which include above- and belowground biomass changes from converting natural vegetation (forests, shrublands and grassland) to cropland. CO_2 emissions/removals from afforestation, deforestation, wood production in managed forests are estimated by geographically explicit (0.5×0.5 degree) model G4M that is connected with GLOBIOM (Havlik et al., 2018). All results of the model with GHG are automatically converted to CO_2e. The emission intensities for crop and livestock production were taken from recent updates in the FAO database (FAO, 2019): for cereals—0.13, beef—13.21, sheep meat—27.37, pig meat—1.20, poultry meat—0.26, eggs—1, milk—0.67 (all in MTCO_2e per metric ton of product). In this paper we do not distinguish "emission intensities" from "carbon footprint." Both names are used in the paper to reveal the indicator which is a ratio of GHG emissions to production quantity in a form of MTCO_2e per ton of protein produced. The full table, along with emission intensities per primary product and per protein equivalent of respective product, are provided in Appendix A Table A1. See the full table with regional data in Supplementary material 2.

For proper evaluation of the carbon footprint particularly for crop production we accounted not only N_2O emissions from fertilizers, but also for emissions from land conversion because some regions expanded their cropland areas through ploughing former abandoned cropland. In previous research it was found that almost a third of Russian GHG emissions in agriculture come from land use change (Strokov et al., 2020). Russian National GHG Inventories indicate that for the first time the emissions from land use change (LUC) occurred in 2011. This happened because of conversion of former abandoned land to cropland, and this process continued until 2017, when cropland expansion stopped, according to Rosstat. The main difference between methodology of Russian National GHG Inventories and GLOBIOM is different rates of emissions per hectare— 30 MTCO_2 against 10 MTCO_2 per hectare respectively (Strokov et al., 2020), due to different accounting for upper ground carbon biomass, dead matter and soil carbon quantities. In the present paper, we used the regional data from recent Inventories on the regional rates of soil carbon sequestration on abandoned cropland (IGCE, 2021, vol. 2, p. 80). We converted these carbon values into CO_2 equivalent as a possible 20 year average of land conversion from pastures to cropland according to the methods suggested in Inventories (IGCE, 2021, vol. 1, p. 289).

The GLOBIOM model comprises large sources of data. Originally, the agricultural production data was taken from country level data of FAO of 1999–2001. Thus, it was necessary to update the data to reproduce proper levels of current crop yields and livestock production patterns (particularly for meat, milk, and eggs) in Russian regions. We also focus on accurate estimates of crop areas and respective crop expansion patterns in those regions where land use change actually took place during our focus period of 2011–2019. The peculiar feature of the model is that regional data is distributed through land unique identifier (LUID) boxes which do not match the actual borders of the administrative units in Russia. To set the LUID compliance of Russia, we calculated how many percent of the LUID is located in each of the regions. Since some regions have an area much smaller than the LUID area, small regions closely located to each other have been merged into one (like Lipetsk with Tula, or aggregated North Caucasus Republics). Initially, each region was assigned one LUID, starting with the largest share of LUIDs in the region. Then the shadow price was estimated by fixing harvest area, appropriate demand and trade volumes. After that the constraints for harvest area were relaxed, and costs were assigned to calculate for new shadow prices. Finally, we rerun the model for 2011 and 2019, with constraining upper harvest level for 2019 in order to bring the model values of crop protein and livestock protein maximally close to official data.

And, finally, we use GLOBIOM to model possible future scenarios of Russian agricultural development measuring carbon footprint consequences of 2 main scenarios: extensive growth with cropland expansion, and intensive scenario with only crop productivity increase and constant land use.

3. Analyzing official data — production value, waste, and manure residues

Russian agriculture experienced spectacular growth during the last 20 years (2000–2019) increasing both crop and meat production by improving productivity levels supported by investments in contemporary means of production (Rada et al., 2019). Some of the environmental tradeoffs of this period have been analyzed only at the country level (Strokov et al., 2020; Schierhorn et al., 2019). Thus, we start our analysis with regional distribution of agricultural production (in monetary value), formed waste, and respective waste-value ratio (Table 1).

The top-15 regions of Russian agricultural production produce almost a half of all agricultural value in agricultural organizations of Russia — 1,797 billion rubles against 3,322 billion rubles. The share of these 15 regions in produced agricultural waste is a bit higher — 60% of all Russian agricultural waste. We calculate the waste-value ratio to analyze the production units and regions which generate the highest and the lowest estimate of waste. Results show that in the top-15 regions with high value the variety of waste-value differs a lot — from 2–5 kg per thousand rubles in Rostov and Stavropol regions respectively, then 12–14 kg per thousand rubles for Krasnodar and Voronezh regions (close to average total Russian value), and 32–40 for Kursk and Belgorod regions. We also show some other regions of Russia with relatively low production values but with very high waste-value footprints like 21–29 kg per thousand rubles in Buryatia and Amur region, and 57–59 for Tomsk and Pskov regions.

To check the accuracy of waste data we analyzed the concentration of agricultural animals. For this we estimated the possible amounts of nitrogen from animals' manure using respective livestock number data from Rosstat and nitrogen excretion ratio (kg N) from Russian National GHG Inventories with the following coefficients: 90.1 for cows, 26.6 for other cattle, 11.2 for sheep, 20.3 for swine, and 0.8 for all poultry herd. In Table 2 we show the amount of possible nitrogen formation and the nitrogen-manure ratio, because it is supposed to be applied to the soil as a necessary nutrient.

Nitrogen concentration is a dangerous polluter which can bring harm to the soils and local waters, and thus, to man's health. As we mentioned earlier, the European

Table 1
Value of agricultural production and the amount of produced waste in agricultural organizations of Russia in selected regions in 2019.

No.	Region	Value of agricultural production (billion rubles)	Waste formed in agriculture (MMT)	Waste per value ratio (kg per thousand rubles)
1	Krasnodar region	258	3.0	12
2	Belgorod region	231	9.2	40
3	Voronezh region	141	2.0	14
4	Stavropol region	134	0.6	5
5	Rostov region	129	0.3	2
6	Kursk region	128	4.1	32
7	Tatarstan	125	0.3	2
8	Lipezk region	105	2.9	28
9	Tambov region	99	2.1	21
10	Altai region	82	0.3	4
11	Moscow region	80	0.5	6
12	Chelyabinsk region	74	0.3	3
13	Penza region	72	0.3	5
14	Leningrad region	72	1.0	13
15	Bryansk region	68	0.3	5
	Top-15 total	1,797	27.1	13
	Russia total	3,322	44.9	11
	Other regions with high waste-value ratio			
32	Pskov region	36	2.1	59
49	Tomsk region	20	1.1	57
44	Amur region	23	0.3	29
33	Kaluga region	35	0.9	25
64	Buryatia	5	0.1	21

Note: MMT—million metric tons. The numbers in the first column indicate the order of agricultural value rating, from the highest value of agricultural production to the lowest. In Supplementary material 1 the full picture with terrestrial distribution on the Russia's map with values of agricultural value, waste formation and waste-value ratio is given in Figs. S1–S3 respectively. In Supplementary material 2, the full database for all Russian regions is presented.
Source: Authors' calculations based on Rosstat and Rosprirodnadzor data.

Union sets a certain threshold for maximum nitrogen application at 170 kg N/ha (Van Grinsven et al., 2016). Our results show that most of the Russian regions with a large livestock number and possible large amounts of nitrogen coming from manure have a relatively low nitrogen-cropland ratio. This means that, if full nitrogen levels were to be used, this would only benefit the soils and local crop yields, while some regions show excessive amounts of nitrogen concentration, which could mean that they do not fully use their manure, or it could be left on pastures (like in Dagestan, or Astrakhan region, where the cropland area is too small because of surface and climate conditions). Or this nitrogen surplus could be traded to other regions like in Leningrad region, or applied for high yield technical or vegetable crops which usually require higher rates of nitrogen than grain crops.

If we compare the first 15 regions in nitrogen-from-manure formation with previous waste data we see that some regions take high ranks like Belgorod, Krasnodar, Voronezh, and Stavropol, and also Tatarstan—all of which have a relatively low nitrogen ratio of 19–26 kg N/ha (except for Belgorod region—102 kg N/ha), and relatively low waste-value ratio of 2–12 (except for Belgorod

Table 2
Manure nitrogen and nitrogen-cropland ratio in selected Russian regions in 2019.

Region	Nitrogen from livestock manure (thousand metric tons)	Cropland total (million ha)	Possible nitrogen concentration (kg N/ha)
Belgorod region	145	1.4	102
Dagestan	109	0.4	311
Tatarstan	76	2.9	26
Bashkortostan	75	2.9	26
Voronezh region	65	2.6	25
Rostov region	65	4.7	14
Krasnodar region	63	3.7	17
Stavropol region	61	3.2	19
Kursk region	59	1.6	36
Kalmykia region	56	0.3	177
Altai region	56	5.1	11
Chelyabinsk region	53	1.9	27
Orenburg region	44	4.3	10
Bryansk region	42	0.9	47
Novosibirsk region	42	2.2	19
Volgograd region	41	3.1	13
Tambov region	40	1.8	23
Saratov region	40	4.1	10
Leningrad region	36	0.2	152
Omsk region	35	2.9	12
Astrakhan region	35	0.1	421

Note: In the Supplementary material 1, the maps of Russia with values for nitrogen formation from manure and nitrogen concentration per hectare of cropland are given in Figs. S4 and S5 respectively.
Source: Authors' calculations based on Rosstat and Russian National GHG Inventories coefficients.

region — 40) kg per thousand rubles of produced agricultural products. Most of these regions specialize in diverse agricultural production, meaning that they have a dual specialization like crop and livestock production, with proper technological and policy measures for nutrient applications.

Next, we analyze the crop and livestock production pattern in Russian regions with the GLOBIOM model, which helps us to estimate respective GHG emissions. And we will compare what regions will show the lowest and highest carbon footprint.

4. Results of GLOBIOM model: GHG emissions from agricultural operations and regional carbon footprint

Russian National GHG Inventories (IGCE, 2021) currently show the full amount of GHG emissions at the country level coming from growing crops, methane from rice cultivation, methane and nitrogen from livestock operations and manure handling and carbon dioxide emissions from annual cropland ploughing and, intermittently, land use change operations (like cultivating abandoned land). The GLOBIOM model covers most of these emission sources except for yearly cropland ploughing. Nevertheless, since most of the emissions could be estimated, we think it could be a good instrument for evaluating the carbon footprint of crop and livestock production. But first, we have to understand the accuracy of the model on the production side. In the tables below (Tables 3 and 4) we give a more detailed picture of the main agricultural regions

Table 3
Accuracy of models crop production and cropland acreage estimates for selected Russian regions and selected crops in 2019.

Region	Crop protein production		Cropland acreage	
	Thousand metric tons	Deviation from Rosstat data (%)	Million hectares	Deviation from Rosstat data (%)
Krasnodar region and Adygeya aggregated	2,626	105	3.3	98
Rostov region	2,068	88	4.1	94
Stavropol region	1,921	143	2.8	97
Voronezh region	1,182	93	1.9	90
Belgorod region	1,153	131	1.2	104
Saratov region	1,117	92	2.8	79
Volgograd region	1,032	95	2.5	90
Lipetsk and Tula regions aggregated	939	83	1.8	96
Orenburg region	881	113	3.1	93
Altai region	779	88	3.3	95
Tatarstan	771	120	1.6	101
Tambov region	758	84	1.3	82
Kursk region	736	68	1.2	87
Samara region	634	90	1.3	76
Bashkortostan	540	104	1.4	83
Amur region	537	134	1.1	100

Note: In the "deviation" column, 100% means model estimates correspond to Rosstat data; when deviation number is higher (lower) than 100% — model estimates are higher (lower) than official numbers. The selected crops are wheat, rice, barley, corn, millet, sorghum, pulses, soy, rape, sunflower and potato. Crop protein production variable with estimates for all Russian regions is given as a map in Supplementary material 1 Fig. S6.
Source: Rosstat and authors' calculations using GLOBIOM.

Table 4
Accuracy of model livestock protein production in selected Russian regions in 2019.

Region	Livestock protein production (thousand metric tons)	Deviation from Rosstat data (%)
Belgorod region	451	64
Kursk region	248	114
Chelyabinsk region	245	128
Rostov region	223	234
Voronezh region	212	111
Stavropol region	196	95
Leningrad region	179	129
Krasnodar region and Adygeya aggregated	172	78
Moscow region	168	136
Bashkortostan	147	111
Tambov region	142	69
Lipetsk and Tula regions aggregated	141	67
Mordovia and Ulyanovsk region aggregated	136	95
Sverdlovsk region	126	125
Tatarstan	126	71
North Caucasus Republics aggregated	101	128
Penza region	101	68
Krasnoyarsk region	100	153

Note: Livestock production includes protein from 4 types of meat produced in Russia (beef, sheep, pork and poultry — all in slaughtered weight), cow milk and eggs in ton equivalent. "North Caucasus Republics" include Chechnya, Ingushetia, Kabardino-Balkaria, Karachaevo-Cherkessia, North Ossetia–Alania. The livestock protein distribution in Russian regions in the form of a map is given in Supplementary material 1 Fig. S7.
Source: Rosstat and authors' calculations using GLOBIOM.

of Russia with model estimates and deviation from official Rosstat production values of 2019, when it was the highest crop production year and highest share of cropland expansion in recent historical period.

Table 3 shows that crop acreage mostly demonstrates a 2–10% deviation from official numbers. But the accuracy of crop production varies across regions. Most South and Black Sea regions (Krasnodar, Voronezh, Saratov, and Volgograd) fall within a 10% deviation. But for regions with high crop protein production quantities the model does not always find a precise solution (Stavropol region — 143%, Kursk region — 68% deviation from Rosstat data). The mistakes come from the model's attempt to try to solve the equilibrium for all regions of the world, struggling to find a precise solution for relatively small areas and districts.

Table 4 shows the accuracy of models' estimates for livestock production. Some regions (Kursk, Voronezh and Stavropol) show high accuracy, while others demonstrate substantial errors and deviation from Rosstat data (Belgorod region — 64%, Rostov region — 238%).

The deviation variable is very important for proper interpretation of model results, especially for correct estimation of GHG emissions and respective carbon footprint. Next, we will show the GHG estimates only for regions with high accuracy of model production results — within the 10% deviation from Rosstat data.

In this new version of GLOBIOM we used regionally specific data on cropland change in 2019 relative to 2011 area. We provide two types of estimates of carbon footprint — without LUC emissions (column 4 of Table 5), and with LUC emissions (column 5 of Table 5).

The results in Table 5 (column 1) show top Russian regions with cropland expansion in 2011–2019 with high cropland growth of more than 100 thousand hectares during this period. In the next column we see crop GHG emissions which occurred despite cropland growth, mostly because of increased fertilizer application, and they are relatively low, due to the Russian specific of low fertilizer application. In column 3 we reveal large land use change emissions from cropland expansions which are a lot higher than ordinary emissions from crop growing. As we can see in column 4, if Russian agriculture would have been only based on intensification with current yields, the carbon footprint per unit of crop protein would be relatively low — 0.7 $MTCO_2e$ per metric ton of protein average.

When we analyze the carbon footprint including land use change (column 5) we see that the emissions are a lot larger — for instance Amur region emits 7 $MTCO_2e$ per metric ton of protein, although it grows mostly soybeans with very low carbon footprint 0.1 $MTCO_2$ per metric ton of protein (without cropland expansion). Large emissions from land use change are also found in Bryansk — 9.2 $MTCO_2$ per metric ton of protein where cropland expansion occurred for feeding the increased cattle herd in recent years. Some high yield southern regions have relatively low carbon footprint with LUC: 0.8–1.2 $MTCO_2$ per metric ton of protein in Saratov, Krasnodar, Stavropol, Rostov regions. Some Volga and Ural regions have higher rates — like 4 $MTCO_2$ per metric ton of protein for Mordovia (aggregated with Ulyanovsk regions).

The GLOBIOM model includes methane emissions from enteric fermentation of agricultural animals and methane and nitrogen emissions from manure management. All of this is converted to CO_2e.

Table 5
Cropland expansion, greenhouse gas emissions from crop production and respective crop carbon footprint for selected Russian regions with large cropland expansion in 2019.

Region	Cropland expansion, 2019 to 2011 (million hectares)	Crop GHG emissions (MMTCO_2e)	LUC emissions from conversion of natural landscapes to cropland (MMTCO_2e)	Carbon footprint of crop production (MTCO_2e per metric ton of protein)	Carbon footprint of crop production (with LUC emissions) (MTCO_2e per metric ton of protein)
	1	2	3	4	5
Rostov region	0.449	1.5	1.0	0.7	1.2
Stavropol region	0.402	1.3	0.3	0.7	0.8
Amur region	0.349	0.1	3.7	0.1	7.0
Krasnodar region and Adygeya aggregated	0.347	2.7	0.5	1.0	1.2
Saratov region	0.304	0.7	0.3	0.6	0.9
Lipetsk and Tula regions aggregated	0.298	0.6	2.1	0.6	2.8
Belgorod region	0.254	0.5	1.7	0.4	1.9
Volgograd region	0.218	0.7	0.5	0.6	1.1
Bryansk region	0.175	0.2	2.0	0.7	9.2
Kursk region	0.172	0.5	1.0	0.7	2.0
Voronezh region	0.167	0.8	1.1	0.7	1.6
Samara region	0.139	0.4	0.9	0.6	2.1
North Caucasus Republics aggregated	0.121	0.3	0.2	0.9	1.5
Mordovia and Ulyanovsk region aggregated	0.110	0.3	1.7	0.7	4.0
Orel region	0.102	0.3	0.6	0.6	1.9
Selected regions total	3.605	10.7	17.5	0.7	1.8
Other regions	0.664	5.8	3.6	0.7	1.1
Russia total	4.269	16.5	21.1	0.7	1.6

Note: MMT — million metric tons. LUC — land use change. Cropland expansion map is given in Supplementary material 1 Fig. S8. Emissions from land use change are given in the form of a map in Supplementary material 1 Fig. S9. Crop carbon footprint (including LUC) is presented as a map in Supplementary material 1 Fig. S10.
Source: Authors' calculations using GLOBIOM.

Table 6 shows that GHG emissions from livestock are very important to analyze due to their high share in overall GHG emissions from agricultural activities. The average for Russia is 61% of GHG emissions coming from livestock operations. In some regions livestock accounts for more than 80% of emissions, such as in Bashkortostan, Tver and Kaluga, Leningrad, Tatarstan and Belgorod. Other regions, on the other hand, which specialize more in crop production, have a low share of livestock emissions in GHG emission formation — 34–39% for Kursk, Mordovia and Ulyanovsk (aggregated), Orel, and Voronezh regions. Unfortunately, for some large meat and milk producing regions (Belgorod, Leningrad or Tatarstan), the model does not find an accurate solution, which is due to a linear architecture of the model when it cannot always predict a "booming" type of production growth as it occurred in Belgorod region in recent years.

The livestock operation results in making the products that are vital for health; these include meat, milk and eggs — all of which are rich in protein

Table 6
Greenhouse gas emissions from livestock production and respective livestock carbon footprint in 2019.

Region	Livestock GHG emission ($MMTCO_2e$)	Share of livestock emissions in regions agricultural emissions (%)	Carbon footprint of livestock protein production ($MTCO_2e$ per metric ton of livestock protein)
Bashkortostan	2.6	84	10.7
Zabaykalye	1.6	98	39.4
Stavropol region	1.4	46	5.4
Voronezh region	1.2	39	4.6
Mordovia and Ulyanovsk region aggregated	1.1	35	4.7
Kursk region	0.9	39	3.4
Udmurtia	0.9	94	7.4
Gorno-Altai region	0.8	100	55.0
Nizhegorod region	0.7	73	5.4
Kirov region	0.6	92	10.2
Astrakhan region	0.6	98	16.9
Orel region	0.4	34	5.3
Tver region	0.4	98	4.6
Kaluga region	0.3	93	4.2
Khanty-Mansi Autonomous Area — Yugra	0.0	100	5.0
Selected regions	13.5	61	7.1
Russia total	59.6	61	7.6
Other regions	46.1	61	7.7

Note: MMT — million metric tons. The production side includes protein from meat (beef, sheep, pork and poultry in slaughtered weight), cow milk and eggs. The full distribution of Russian regions for livestock carbon footprint is given in Supplementary material 1 Fig. S11.
Source: Authors' calculations using GLOBIOM.

content. The environmental cost of this production is, on average, higher than the carbon footprint of crops — 7.6 $MTCO_2e$ per metric ton of livestock protein against 1.6 $MTCO_2e$ per metric ton of crop protein (including LUC emissions). Table 6 reveals that regions with high poultry and pig production have relatively low livestock emission levels 3–5 $MTCO_2$ per metric ton of protein (like Kursk, Stavropol, Tver, Kaluga regions), that is due to lower emission rates from enteric fermentation (even absence of enteric fermentation particularly for poultry) and manure management (compared with cattle). By contrast, regions with large cattle numbers and respective beef and milk production have a higher footprint of protein — 10 for Bashkortostan and Kirov region, 16.9 for Astrkhan region, 39.4 for Zabaykalye, or even 55 $MTCO_2e$ per ton for Republic of Altai (Gorno-Altai) region.

5. Projections for 2030

The Russian government recently published three important public policy documents which are directly associated with Russian agricultural growth for 2030: "The strategy of rural development," "The strategy of improving agricultural and fisher industries," and "The state program of land improvement and melioration." All these programs are designed to solve the different production and social problems of Russian territories. Although these programs do not contain much information on concrete production or productivity indicators they do propose that Russia wishes to increase its exports of agricultural and food products through both intensification and productivity growth, and possible land expansion, in order to convert previously abandoned agricultural land back to cropland type. Thus we suggest to model two types of scenarios — an extensive one with continuous cropland growth up to 2030, and an intensive one with stable cropland and only productivity growth.

The model shows (Table 7) that in the extensive scenario it is possible to expand cropland by 5 million hectares by 2030 which will lead to 19.4 million metric tons (MMT) of additional GHG emissions. In the intensive scenario the cropland does not increase, only the yields, and thus the GHG emissions on the LUC side results in a minus sign (–3.2 $MMTCO_2$), which indicates carbon sequestration due to land abandonment. Thus crop emission intensity (carbon footprint) is projected to be almost 2 times lower in the intensive scenario — 0.6 compared with extensive scenario 1.4 and current levels 1.6 (all in $MTCO_2e$ per metric ton of crop protein).

Table 7 shows us the possible pathways of Russian agricultural development of the production side and respective GHG emissions consequences. The crop production growth varies from 125% to 154% in the extensive and intensive scenario respectively, which occurs due to exports development, and the large demand for Russian grain and oilseeds on the markets of Asia and Africa. Livestock

Table 7
Main features and results of extensive and intensive scenarios for aggregate Russian regions.

Variables	2019 model	2030 extensive scenario	2030 intensive scenario	Growth rate 2030ex/ 2019 (%)	Growth rate 2030int/ 2019 (%)
Crop protein production (MMT)	23.744	29.779	36.593	125	154
Livestock protein production (MMT)	7.854	8.250	7.771	105	99
Harvest area for selected crops (million ha)	51.3	56.3	50.6	110	99
Crop protein yield (metric tons/ha)	0.5	0.5	0.7	114	156
Crop GHG emissions ($MMTCO_2e$)	16.5	20.9	25.4	127	154
LUC GHG emissions from cropland expansion ($MMTCO_2e$)	21.1	19.4	-3.2	92	-15
Livestock emissions ($MMTCO_2e$)	59.6	61.0	59.4	102	100
Crop emission intensity (including LUC) ($MTCO_2e$ per ton of protein)	1.6	1.4	0.6	86	38
Livestock emission intensity ($MTCO_2e$ per ton of protein)	7.6	7.4	7.6	98	101

Note: MMT — million metric tons.
Source: Authors' calculations using GLOBIOM.

production appears to have a moderate growth in the extensive scenario — 110%, and a decrease in the intensive scenario — 99%.

In the Supplementary material 1 we show the results of the models 2030 estimate with Russian regions maps of possible regional distribution of crop production (Fig. S12), livestock protein production growth (Fig. S13), cropland growth (Fig. S14), GHG emissions from cropland expansion (Fig. S15), crop emissions-protein ratio (including LUC emissions) in the extensive scenario (Fig. S16) and intensive scenario (Fig. S17) and livestock emissions-protein ration in the extensive scenario (Fig. S18) and intensive scenario (Fig. S19).

The results indicate that in the extensive scenario the highest possible carbon footprint (including LUC) for crop production could be 5.6 $MTCO_2$ per metric ton of protein in Astrakhan region, then followed by Tatarstan (4.4 $MTCO_2$ per metric ton) and Novosibirsk region (4 $MTCO_2$ per metric ton). Cultivating the abandoned soils of these regions has wider environmental repercussions because of the larger carbon sequestration. Ploughing these types of lands in these regions will lead to higher GHG emissions than in other regions of Russia. Most other Russian regions which continue to expand cropland are projected to have a footprint from 1 to 2 $MTCO_2$ per metric ton of protein.

In the intensive scenario Tatarstan and Novosibirsk region show a lot lower carbon footprint of 0.3 and 0.7 $MTCO_2$ per metric ton of protein due to improving yields on constant cropland. Astrakhan region still has a higher footprint due to the possible growth of rice production which, in general, has higher emission intensities than other crops. The model also shows that some regions might experience cropland abandonment and thus contribute to carbon sequestration which will lead to negative emission intensity when calculating carbon footprint with LUC emissions: Amur, Belgorod, and Bryansk regions — from –0.2 to –1.6 $MTCO_2$ per metric ton of protein respectively. But in general, most of the regions in Russia are projected to have a (relatively) similar emission intensity in crop production from 0.7 up to 1.0 $MTCO_2$ per metric ton of protein meaning that yield increase is likely not to lead to high GHG emissions, as it is in extensive scenario with cropland expansion.

6. Policy recommendations

In order to continue agricultural development with low environmental footprint Russia should focus on several strategic steps.

1. Improvement of statistical data. Current Russian agricultural statistics are focused more on the production side. There is a plenty of spatially explicit information on crop and livestock production, and some of the inputs they use, but there is a lack of official data on soil erosion, manure concentration and manure loss, nutrient residues in the soil, pesticide application and residues, and GHG emissions from agricultural operations. All of which are important to show environmental footprints. Without official data collection we can only use sophisticated models which sometimes have a high degree of uncertainty. This is not likely to suffice in the future when sustainable pathways need a dependable scientific background.

2. Due to the lack of regional data we used a partial equilibrium model to estimate proper production concentration in Russian regions and respective GHG

emissions from main crop, land expansion and livestock activities. Our results have shown that land use change (conversion of abandoned land to cropland) leads to large bursts of emissions, and to an insufficient increase in the carbon footprint, especially for crop protein production. We suggest that Russia should look towards strategies involving reduced expansion, especially in Far Eastern regions (Amur region, Jewish Autonomous Oblast, Primoriye)—they are likely to switch to a higher intensification policy. This could be achieved by stimulation and subsidizing additional technological input use instead of cropland expansion. That will help to render the carbon footprint with a minus sign and support carbon sequestration on cropland.

3. The pathways for additional intensification should be balanced with proper laws for controlling nutrient and pesticide application and possible residues in the soil and rural water bodies. Thus, it is likely to set normative thresholds for inputs use in Russian regions. Examples of this can be seen in the USA.[4]

4. The livestock concentration in most Russian regions poses relatively low environmental threats due to large territories (even if only cropland is accounted for nitrogen manure concentration). Nevertheless, we found several territories with very high waste and manure concentration (Leningrad, Pskov, Tomsk, Dagestan and Astrakhan) which need an additional interdisciplinary approach to investigate the possible repercussions for the health of local inhabitants. Thus, all regions could be given some freedom to improve their own laws on livestock concentration and appropriate documentation collection and publishing of open access data on nitrogen and residues concentration in local municipalities in order to prevent the possible environmental threat from agricultural activities. Additional policy and scientific efforts should be directed at manure management and possible transportation of stacked manure in order to move the necessary manure nutrients to municipalities or regions which have a lack of nutrients for crop growing.

7. Discussion

In the last 10 years Russia experienced agricultural growth accompanied by regional concentration of crop and livestock production. In this paper we tried to analyze the ecological footprints of such concentration using different types of data and indicators of local and global risks. Local risks were represented by variables of waste concentration and nitrogen concentration taken from official publications of Rosprirodnadzor, Rosstat and National GHG Inventories. Global risks were evaluated through estimating GHG emissions from crop and livestock production using GLOBIOM partial equilibrium model, which in its GHG module is based on IPCC recommendations of evaluating N_2O, CH_4 and CO_2 gases from main agricultural operations, including land conversion in the land use change sector (in our case we analyzed only conversion of abandoned land to cropland).

[4] For example, in Iowa the farmer is allowed to use only a certain amount of nitrogen to reach particular productivity (yield) threshold. If he exceeds this limit of nitrogen he gets a penalty (a fee). See Iowa Administrative Code by Environmental Protection Commission (Ch. 65, p. 203) for nitrogen application limits in growing crops: https://www.legis.iowa.gov/docs/iac/chapter/11-23-2016.567.65.pdf

Our main contribution to improving GLOBIOM was in calibrating the model with official Rosstat data of crops and livestock production from Russian regions in 2011 and 2019, particularly for crop, eggs, meat and milk production indicators and cropland area values. The results showed that the GLOBIOM model has lower estimates from Russian National GHG Inventories data due to the lack of data for some types of crops and soils. Russian official data show emissions from agricultural activities to be approximately 113 $MMTCO_2e$ in 2019, while GLOBIOM models for Russia show only 76.1 $MMTCO_2e$. This is because official inventories include data on GHG emissions from organogenic agricultural lands, which cover almost half of the crop emissions in inventories. On the land use change (LUC) side agricultural lands are responsible for 83 $MMTCO_2e$ emissions in inventories, and only 21 MMT in GLOBIOM. The latter is due to different estimates of soil and biomass carbon, which need to be corrected separately due to the lack of research in this area.

Here we applied emission intensities (or carbon footprint) from the new version of FAO database (FAO, 2019) which is measured through an emission-production indicator ($MTCO_2e$ per metric ton of product). To summarize the results achieved with GLOBIOM we can say that in most cases for regions with large agricultural production the model generates relatively low carbon footprint of produced protein. This is particularly true for crop production in the South and Black Sea regions of Russia. But for those regions which convert a lot of abandoned land into cropland the carbon footprint is a lot higher — like Amur and Bryansk regions (Amur produces a lot of soy for exports, while Bryansk specializes in cattle ranching, which requires a lot of feedstuff). On the livestock side, the footprint varies by livestock specialization — regions where animals do not have enteric fermentation have a lower carbon footprint (poultry production), whereas cattle which have enteric fermentation have a higher carbon footprint.

When we compare our results with official numbers on the waste concentration in agriculture we see that most regions with high waste-agricultural value ratio specialize in pork production — Pskov and Tomsk regions, and in some way Belgorod, Kursk, and Lipetzk regions (see Table 1). We also check this with data on possible manure nitrogen concentration which show some other regions with high environmental pressure due to small croplands but large volumes of manure coming from poultry production (Leningrad region) or sheep ranching (Dagestan, Kalmykia) — all of which have their own peculiar ways of local development and manure handling (probably through pasture use or using manure for vegetable and potato crops).

Thus, it is important to indicate that it is hard to find a good aggregate of the environmental footprint, but rather we show different aspects of environmental pollution using different variables and by comparing data from different sources.

8. Conclusion

This research shows the concentration of agricultural production in Russian regions and its repercussions in the form of several environmental tradeoffs like waste from production, nitrogen concentration from manure and GHG emissions from all agricultural activities, including land use change.

Our main hypothesis was that local environmental risks, like waste concentration, would be closely related to global climate risks such as GHG emissions from production of crops, meat, milk, eggs, and from LUC activities, leading to a larger carbon footprint.

The paper shows that all these indicators highlight different aspects of agricultural development, revealing production specific threats. The extent of waste, for example, is mostly a good indicator to show the consequences of large swine farms (Belgorod, Kursk, Pskov, and Tomsk regions). The nitrogen manure concentration could be relevant for some regions with large poultry farms (Belgorod and Leningrad regions), and for some regions with large cattle or sheep herd (Kalmyk, Dagestan, and Astrakhan regions) but with less cultivated cropland.

Our main findings show that regions with high agricultural production can experience low carbon footprints (GHG emissions divided by the amount of crop or livestock products). Thus, the main hypothesis was rejected. At the same time these regions can show higher than average environmental footprints through waste and manure nitrogen concentration. Regions with high pork and poultry production like Belgorod, Pskov, and Leningrad regions, are characterized by high waste footprint but low carbon footprint due to lower GHG emissions from pork and poultry. On the other hand, regions like Tatarstan and Krasnodar regions may have higher carbon footprints due to larger cattle herd producing more emissions due to enteric fermentation, but they have lower waste footprints due to more diversified production.

The GHG emission side of the problem shows not only the high carbon footprint of meat and milk production, but reveal opportunities for more intensive crop growing. Currently, many Russian regions continue to expand more cropland and invest less in yield growing which results in high GHG emissions from land use change and large environmental tradeoffs when expanding cropland to fragile territories. When planning future agricultural development, Russian policy makers should collect more diverse regional data on economic-environmental tradeoffs in order to balance private welfare with the social welfare of rural people and future generations.

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References

Cropper, M., & Griffiths, C. (1994). The interaction of population growth and environmental quality. *American Economic Review, 84*(2), 250–254.

Deppermann, A., Balkovic, J., Bundle, S.-C., Di Fulvio, F., Havlik, P., Leclere, D., Lesiv, M., Prishchepov, A., & Schepaschenko, D. (2018). Increasing crop production in Russia and Ukraine — regional and global impacts from intensification and recultivation. *Environmental Research Letters, 13*(2), 1–13. https://doi.org/10.1088/1748-9326/aaa4a4

FAO (2019). *FAOSTAT. Emissions intensities* [Web dataset]. http://www.fao.org/faostat/en/#data/EI

Foley, J. A., Ramankutty, N., Brauman, K. et al. (2011). Solutions for a cultivated planet. *Nature, 478*, 337–342. https://doi.org/10.1038/nature10452

Fuglie, K. (2015). Accounting for growth in global agriculture. *Bio-based and Applied Economics 4*(3), 201–234. https://doi.org/10.13128/BAE-17151

Grossman, G., & Krueger, A. (1991). Environmental impacts of a North American Free Trade Agreement. *NBER Working Paper*, No. 3914. https://doi.org/10.3386/w3914

Havlik, P., Valin, H., Mosnier, A., Obersteiner, M., Baker, J., Herrero, M., Rufino, M., & Schmid, E. (2013). Crop productivity and the global livestock sector: Implications for land use change and greenhouse gas emissions. *American Journal of Agricultural Economics, 95*(2), 442–448. https://doi.org/10.1093/ajae/aas085

Havlik, P., Valin, H., Herrero, M., Obersteiner, M., Schmid, E., Rufino, M. C., Mosnier, A., Thornton, P. K., Bottcher, H., Conant, R. T., Frank, S., Fritz, S., Fuss, S., Kraxner, F., & Notenbaert, A. (2014). Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences, 111*(10), 3709–3714. https://doi.org/10.1073/pnas.1308044111

Havlik, P., Valin, H., Mosnier, A., Frank, S., Lauri, P., Leclere, D., Palazzo, A., Batka, M., Boere, S., Brouwer, A., Deppermann, A., Ermolieva, T., Forsell, N., di Fulvio, F., & Obersteiner, M. (2018). GLOBIOM documentation. Laxenburg: International Institute for Applied Systems Analysis (IIASA). https://iiasa.github.io/GLOBIOM/GLOBIOM_Documentation_20180604.pdf

IGCE (2021). *The National report of the Russian Federation on the inventory of the anthropogenic emissions and sinks of greenhouse gases not controlled by the Montreal Protocol for the years 1990–2010*. Moscow: Institute of Global Climate and Ecology of Roshydromet and RAS (in Russian).

IPCC (2006). *Guidelines for national greenhouse gas inventories. Volume 4: Agriculture, forestry and other land use*. Geneva: Intergovernmental Panel on Climate Change. https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html

Kulyk, P., & Augustowski, L. (2020). Conditions of the occurrence of the environmental Kuznets curve in agricultural production of Central and Eastern European countries. *Energies, 13*(20), 5478. https://doi.org/10.3390/en13205478

McCarl, B., & Spreen, T. (1980). Price endogenous mathematical programming as a tool for sector analysis. *American Journal of Agricultural Economics, 62*(1), 87–102. https://doi.org/10.2307/1239475

Meyfroidt, P., Schierhorn, F., Prishchepov, A., Müller, D., & Kuemmerle, T. (2016). Drivers, constraints and trade-offs associated with recultivating abandoned cropland in Russia, Ukraine and Kazakhstan. *Global Environmental Change, 37*, 1–15. https://doi.org/10.1016/J.GLOENVCHA.2016.01.003

Mosnier, C., Britz, W., Julliere ,T., De Cara, S., Jayet, P.-A., Havlik, P., Frank, S., & Mosnier, A. (2019). Greenhouse gas abatement strategies and costs in French dairy production. *Journal of Cleaner Production, 236*, 117589. https://doi.org/10.1016/j.jclepro.2019.07.064

Newbold, T., Hudson, L. N., Arnell, A. P., Contu, S., De Palma, A., Ferrier, S., Hill, S. L., Hoskins, A. J., Lysenko, I., Phillips, H. R., Burton, V. J., Chng, C. W., Emerson, S., Gao, D., Pask-Hale, G., Hutton, J., Jung, M., Sanchez-Ortiz, K., Simmons, B. I., Whitmee, S., Zhang, H., Scharlemann, J. P. W., & Purvis, A. (2016). Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. *Science, 353*(6296), 288–291. https://doi.org/10.1126/science.aaf2201

Obersteiner, M., Walsh, B., Frank, S., Havlik, P., Cantele, M., Liu, J., Palazzo, A., Herrero, M., Lu, Y., Mosnier, A., Valin, H., Riahi, K., Kraxner, F., Fritz, S., & van Vuuren, D. (2016). Assessing the land resource-food price nexus of the sustainable development goals. *Science Advances, 2*(9), 45–50. https://doi.org/10.1126/sciadv.1501499

Pigou, A. C. (1920). *The economics of welfare.* London: Macmillan.

Rada, N., Liefert, W. & Liefert, O. (2019). Evaluating agricultural productivity and policy in Russia. *Journal of Agricultural Economics, 71*(1), 96–117. https://doi.org/10.1111/1477-9552.12338

Romanovskaya, A. A., Korotkov, V. N., Polumieva, P. D., Trunov, A. A., Vertyankina, V. Y., & Karaban, R. T. (2019). Greenhouse gas fluxes and mitigation potential for managed lands in the Russian Federation. *Mitigation Adaptation Strategies of Global Change, 25*, 661–687. https://doi.org/10.1007/s11027-019-09885-2

Schierhorn, F., Faramarzi, M., Prishchepov, A., Koch, F., & Müller, D. (2014). Quantifying yield gaps in wheat production in Russia. *Environmental Research Letters, 9*(8), 084017. https://doi.org/10.1088/1748-9326/9/8/084017

Schierhorn, F., Kastner, T., Kuemmerle, T., Meyfroidt, P., Kurganova, I., Prishchepov, A., Erb, K.-H., Houghton, R., & Müller, D. (2019). Large greenhouse gas savings due to changes in the post-soviet food systems. *Environmental Research Letters, 14*(6), 065009. https://doi.org/10.1088/1748-9326/ab1cf1

Smith, P., Martino, D., Cai, Z., Gwary, D, Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, B., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., & Smith, J. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society, 363*, 789-813. https://doi.org/10.1098/rstb.2007.2184

Stavins, R. N. (1999). The costs of carbon sequestration: A revealed-preference approach. *American Economic Review, 89*(4), 994–1009. https://doi.org/10.1257/aer.89.4.994

Steffen, W., Richardson, K., Rockström, J., Cornell S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., Vries W. de, Wit, C. A. de, Folke C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science, 347*(6223), 1259855. https://doi.org/10.1126/science.1259855

Strokov, A. S., Deppermann, A., Potashnikov, V. Y., Romanovskaya, A. A., & Havlik, P. (2020). Problems of agricultural policy adaptation within sustainable development goals. *Ekonomicheskaya Politika, 15*(6), 140–165 (in Russian). https://doi.org/10.18288/1994-5124-2020-6-140-165

Tubiello, F. N., Salvatore, M., Ferrara, A. F., House, J., Federici, S., Rossi, S., Biancalani, R., Condor Golec, R. D., Jacobs, H., Flammini, A., Prosperi, P., Cardenas-Galindo, P., Schmidhuber, J., Sanz Sanchez, M. J., Srivastava, N., & Smith, P. (2015). The contribution of agriculture, forestry and other land use activities to global warming, 1990–2012. *Global Change Biology, 21*(7), 2655–2660. https://doi.org/10.1111/gcb.12865

Valin, H., Havlik, P., Mosnier, A., Herrero, M., Schmid, E., & Obersteiner, M. (2013). Agricultural productivity and greenhouse gas emissions: Trade-offs or synergies between mitigation and food security? *Environmental Research Letters, 8*(3), 035019. https://doi.org/10.1088/1748-9326/8/3/035019

Van Grinsven, H. J. M., Tiktak, A., & Rougoor, C. W. (2016). Evaluation of the Dutch implementation of the nitrates directive, the water framework directive and the national emission ceilings directive. *NJAS: Wageningen Journal of Life Sciences, 78*(1), 69–84. https://doi.org/10.1016/j.njas.2016.03.010

Van Meijl, H., Havlik, P., Lotze-Campen, H., Stehfest, E., Witzke, P., Pérez Domínguez, I., Bodirsky, B. L., van Dijk, M., Doelman, J., Fellmann, T., Humpenöder, F., Koopman, J. F. L., Müller, C., Popp, A., Tabeau, A., Valin, H., & van Zeist, W.-J. (2018). Comparing impacts of climate change and mitigation on global agriculture by 2050. *Environmental Research Letters, 13*(6), 064021. https://doi.org/10.1088/1748-9326/aabdc4

Zhang, Y., Davidson, E., Mauzerall, D., Searchinger, T., Dumas, P., & Shen, Y. (2015). Managing nitrogen for sustainable development. *Nature, 528*, 51–59. https://doi.org/10.1038/nature15743

Appendix A

Table A1

Agricultural production, protein production, GHG emission estimates and emission intensities values for 2019.

Name	Product	2019 production primary equivalent (million metric tons)	Crude protein conversion coefficient	Protein production equivalent (million metric tons of protein	GHG emissions in 2019 (million metric tons of CO_2e)	Emission intensity for primary production (metric ton of CO_2e/ metric ton of product)	Emission intensity (carbon footprint) for protein equivalent production (metric ton of CO_2e/ metric ton of protein)
PTRH	Eggs	2.864	0.514	1.472	2.86	1.00	1.9
PTRB	Poultry meat	4.897	0.514	2.517	1.26	0.26	0.5
SGTO	Sheep meat	0.239	0.514	0.123	6.54	27.39	53.3
PIGS	Pork	3.459	0.514	1.778	4.17	1.21	2.3
BOVO	Cow milk	32.982	0.033	1.088	22.22	0.67	20.4
BOVD	Beef	1.703	0.514	0.876	17.92	13.21	25.7
BOVF	Other cattle				4.59		
Cereals	Wheat	74.606	0.142	10.594	7.83	0.10	0.7
Cereals	Corn	14.152	0.096	1.359	1.49	0.11	1.1
Cereals	Barley	20.632	0.119	2.455	1.81	0.09	0.7
Cereals	Rice (including N_2O and CH_4)	1.006	0.076	0.076	0.99	0.98	12.9
Other	Potato	20.177	0.022	0.444	0.51	0.03	1.1
Oilcrops	Sunflower	16.068	0.392	6.299	3.43	0.21	0.5
Oilcrops	Soy	4.339	0.392	1.701	0.05	0.01	0.03
Oilcrops	Rape	2.082	0.392	0.816	0.39	0.19	0.5

Note: Emission intensities for beef include emissions from beef cattle and other cattle. Emissions from crops include only nitrogen emissions of N_2O converted into CO_2 equivalent (CO_2e). The exception is rice, where we have emissions from N_2O and CH_4, both converted into CO2e.

Sources: GHG emission intensities for beef, poultry, pork, eggs, milk and wheat taken from FAO (2019), for other crops calculated by the authors using GLOBIOM. Crude protein conversion coefficients taken from Fuglie (2015).

Supplementary material 1

Maps of main environmental indicators of Russian regional agricultural development

Authors: Anton Strokov, Vladimir Potashnikov

Data type: Image

Explanation note: Maps of the Russian regions where the featured environmental indicators are revealed in the historical and projection period.

Link: https://doi.org/10.32609/j.ruje.8.78331.suppl1

Supplementary material 2

The dataset on agricultural waste, nitrogen concentration, and GHG emissions in Russian regions

Authors: Anton Strokov, Vladimir Potashnikov

Data type: Table

Explanation note: The dataset on main variables of agricultural waste, nitrogen concentration, and GHG emissions (including GHG emission intensities) in Russian regions used for creating maps in Supplementary material 1.

Link: https://doi.org/10.32609/j.ruje.8.78331.suppl2