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Article

Developing a Spatial Emission Inventory of Agricultural Machinery in Croatia by Using Large-Scale Survey Data

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Abstract: Agricultural machinery has an essential impact on climate change. However, its emission data are often missing, which makes it harder to develop policies which could lower its emissions. An emission inventory should first be developed to understand the impact of agricultural machinery on climate change. This article presents a spatial variation of emissions from agricultural machinery in Croatia. Data on agricultural machinery for 2016 was collected via a large-scale survey with 8895 respondents and included machinery type, location data, and fuel consumption by fuel type. Data processing was conducted to optimize the survey results, and the emissions were calculated using the "EEA/EMEP Emission Inventory Guidebook" Tier 1 method. The research shows that two-axle tractors with engine power 61–100 kW had the most significant energy consumption and were responsible for most of the emissions. The highest total emissions were in counties in the Slavonia region, while counties in the Dalmatia region had the highest emissions per hectare of arable land. Results obtained this way enable policies to be developed that will target specific spatial areas and machinery types. Furthermore, this approach could allow precise spatial and temporal emission tracking. A designated institution which could conduct annual surveys and update the agricultural machinery emission data would ensure emission data continuity.

Keywords: climate change; agricultural machinery; emission inventory; non-road emissions; NRMM

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Citation: Lončarević, Š.; Ilinčić, P.; Lulić, Z.; Kozarac, D. Developing a Spatial Emission Inventory of Agricultural Machinery in Croatia by Using Large-Scale Survey Data. *Agriculture* **2022**, *12*, 1962. https://doi.org/10.3390/agriculture12111962

Academic Editors: Riccardo Testa, Giuseppina Migliore, Giorgio Schifani and József Tóth

Received: 31 October 2022
Accepted: 18 November 2022
Published: 20 November 2022

1. Introduction

All vehicles that use fossil fuels have some emissions. These emissions are divided into greenhouse gas emissions, which trap additional heat into the Earth's atmosphere [1], and air pollutant emissions, i.e., substances which can lead to adverse health effects, primarily affecting respiratory and cardiovascular systems [2,3]. Emission levels are continuously rising globally [4], and lowering emissions presents one of the most prominent global goals. On a worldwide level, the Paris Agreement indicated a global intention of keeping the increase in global average temperature to well below 2 °C, which means lowering greenhouse gas emissions by at least 40% by 2030 compared with 1990 [5]. This has also been reaffirmed by the Glasgow Climate Pact [6]. The European Union (EU), via the European Commission, further increased its ambition to lower overall carbon dioxide (CO_2) emissions by 2030, setting a goal of 55% CO_2 emission reduction compared with 1990 [7].

Developing an emission inventory is the first step in determining a course of action to reduce emissions. Listing emissions by source and quantity for each tracked pollutant enables defining the primary emissions sources. Since the development of an emission inventory is a long-term process which requires a continuous collection of data via various sources, it represents one of the most reliable tools in developing technologies. An emission inventory also polices for emission reduction [8,9], especially on the local level [10]. Furthermore, it shows the effectiveness of policies already in place [11].

In some areas of the emission inventories, there is a significant lack of data, such as non-road mobile machinery (NRMM). The lack of data in this area (NRMM) is mainly because NRMM has been seen as a much smaller pollutant than road vehicles. Emission limits for NRMM are generally much more liberal than emission limits for road vehicles worldwide, including the EU [12,13]. Consequently, there is less research concerning NRMM and little data collection from government bodies. The first step in collecting data about NRMM would be for the government to designate an institution for data collection [14]. This would enable long-term data collection on a national scale, enabling the use of new information in line with new technologies to achieve the previously mentioned targets. Once collected, the NRMM emission data could be presented in a visually engaging way. Such is the case in the United Kingdom, where the NRMM emission inventory, for example, has provided spatial data on primary pollutants [11]. A similar case is present in the USA, where the Environmental Protection Agency (EPA)-developed NRMM emission inventory for 2017 offers data disaggregated by federal states [15].

As a subgroup of NRMM, agricultural machinery is an important area of NRMM research. As with the other NRMM, there is a lack of data necessary to develop national emission inventories for researching fuels, operating modes of the machinery, and making connections to other socioeconomic areas, etc. [16]. An emission inventory would greatly help to formulate long-term policies for emission reduction from agricultural machines and significantly affect their future total emissions [17,18]. In China, in the Beijing region, emissions of carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_X), particulate matter (PM), and the total emissions from agricultural machinery decreased by 63.11%, 62.93%, 72.07%, 74.67%, and 68.66%, respectively, from 2006 to 2016, due to regulations which promoted emission-reduction technologies. In the Yangtze River Delta region, overall air quality was poorer during the heavy agricultural work season [19], with similar results on a national level [20]. However, adding emission-reduction technologies to the agricultural machinery puts a considerable financial strain on machinery owners [21], and is not as efficient as procuring new machinery [22].

Apart from a lack of general machinery data, developing an agricultural machinery emission inventory is also tricky because of a lack of research on agricultural machinery emissions during fieldwork, which is mainly due to many different types of machinery and field conditions. Gathering activity data from real-world operating conditions, such as engine load profiles, idling times, differences between other machinery operators, etc., helps determine the actual emissions of agricultural machinery instead of using models based on laboratory research. Without this data, the results of emission inventories can have high degrees of uncertainty [23]. Based on engine load factors throughout a typical working day, measurement results can have variability as high as a factor of 20 [24]. Emissions also vary among different land types where machinery is used. For example, machinery working in vineyards can emit up to 80% more emissions compared with arable land for the same land area [25]. However, gathering detailed on-site data on a large scale represents a significant financial strain and is time-consuming.

The EMEP/EEA Air Pollutant Emission Inventory Guidebook includes three methods of determining agricultural machinery emissions, depending on available data [26]. The Tier 1 method uses only primary NRMM data, i.e., fuel consumption and emission factors. Tier 2 is a method that requires more data as it also uses data on fuel consumption based on equipment type and technology level. The most precise method is the Tier 3 method which is used when there are no available data for fuel consumption but other data are available, e.g., annual hours of use, engine size, and machinery age. However, since the available data on agricultural machinery is substantially limited, most countries have no emission inventories for agricultural machinery at the national level. Existing emission inventories are made mainly by collecting information about vehicle sales or extrapolating data from machinery imports. In Switzerland, data on total fuel sales for agriculture is only available up to 2004 [27]. NRMM emissions in Germany are reported by the Federal German Environment Agency using vehicle stock data. However, activity data are taken from various resale platforms, and further investments towards real-world measurements are needed [22]. A similar system of data collecting is in place in Denmark, where the Association of Danish Agricultural Machinery Dealers provides annual sales data, but there is no available activity data [28]. The Netherlands also has only vehicle sales data but no activity data [29]. Sweden uses the Tier 3 method described in the EMEP/EEA Air Pollutant Emission Inventory Guidebook, which uses activity data and machinery age [26] for its national emission inventories [30]. Regarding Croatia, there are currently no official data on agricultural machinery emissions. Additionally, there are no data on which to base initial assessments since there is no continuous data collection regarding the machinery numbers or types of activity, making it very difficult to develop an emission inventory.

More reliable data can be collected by conducting a large-scale survey. By collecting the data via a questionnaire, accurate data can be collected about fuel consumption, several different types of machinery, land types, etc., and it provides more accurate data about real-world fuel consumption [20,31]. However, conducting a large-scale survey is logistically and financially consuming, thus requiring logistical and financial support, in most cases, from governmental bodies [32]. Such large-scale surveys are conducted in the Netherlands [33] and Sweden [34], where several governmental bodies participate in national surveys on energy statistics. The Finnish model offers publicly available data on NRMM emissions divided into subcategories by emission source, fuel type, end-use of NRMM and year, even providing future estimations up to the year 2040 [35].

As previously mentioned, most countries do not have an agricultural machinery emission inventory, or if they do, it is developed based on vehicle stock data or vehicle sales without using actual data from the agricultural entities. This paper aims to develop a spatial agricultural machinery emission inventory using large-survey data. An emission inventory for agricultural machinery can be developed without conducting a census or gathering detailed on-site activity data. Such an emission inventory, with emission data by machinery category and county, offers a baseline for developing policies for specific areas or machinery types. Furthermore, this paper represents the first emission inventory for agricultural machinery in Croatia, with results disaggregated spatially, by counties, and by machinery type. The survey includes several thousand respondents. Agricultural machinery emissions are compared with energy consumption and emissions from road vehicles. Additionally, spatially disaggregated emissions are compared with the respective total distribution of agricultural land.

2. Materials and Methods

2.1. Data Collection and Classification of Agricultural Machinery

As mentioned in the introduction, no official data on agricultural machinery emissions in Croatia is currently available. In order to establish a baseline for future research and emission scenario development, data on as much agricultural machinery as possible must be collected. Since a large-scale survey is both financially demanding and time-consuming, data were collected in collaboration with the Croatian Bureau of Statistics (CBS) as a part of a large project concerning energy consumption in the agricultural sector in Croatia. Although only limited types of data could be collected (e.g., machinery age and hours of operation), this survey project provided the infrastructure necessary to collect data on a maximum number of machines.

An invitation to fill out the survey via a web application or a field survey was sent to every agricultural entity to collect the maximum amount of data possible. The CBS provided administrative data on all agricultural businesses, and data were collected from December 2017 to April 2018. The respondents were asked to fill in data on machinery type, the number of machines for each class, fuel type (diesel or gasoline), fuel consumption for each piece of machinery in litres, land type, agricultural land area in hectares, and business type. Data on the business type was used during data processing and classification. The participants were divided into three business type groups: family farms, eco-producers, and enterprises. A total of 8895 respondents participated in the survey, and their spatial distribution is shown in Figure 1. Most respondents were located in Osječko-baranjska and Vukovarsko-srijemska counties, with 1421 and 1070 respondents, respectively. These results are expected since this part of Croatia is traditionally oriented towards agricultural activity and features most of the total agricultural entities. Krapinsko-zagorska county had the smallest number of respondents, with 125 respondents.

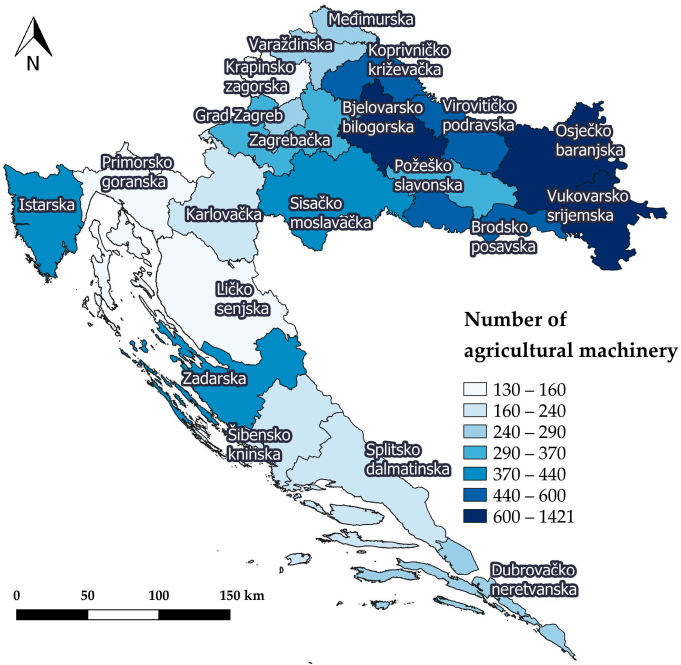


Figure 1. Spatial distribution of the number of respondents in the survey.

Classification of agricultural machinery for the survey was done based on a previous CBS survey on agricultural machinery numbers from 2003, in which the most often used agricultural machinery was included. The same categorisation of eight equipment categories was included in the survey (Table 1). Since agricultural tractors are the most used agricultural machinery, they were divided into single-axle tractors and two-axle tractors. Two-axle tractors were further divided into several categories based on engine power.

Table 1. Categories of equipment included in the survey.

Category	Equipment
1	Single-axle tractors
2	Two-axle tractors
2.1	up to 40 kW
2.2	from 41 to 60 kW
2.3	from 61 to 100 kW
2.4	more than 100 kW
3	Combine harvesters
4	Machinery for potatoes and sugar beet
5	Machinery for fodder plants
6	Other harvesting machinery
7	Balers
8	Other

2.2. Data Processing and Classification

Because the CBS had data on the location of all survey respondents, each survey respondent was assigned a unique identification number. This enabled merging survey results with the existing CBS data, which helped to determine the areas of highest agricultural machinery emissions, i.e., sites of their highest atmospheric impact. The CBS provided a database to select the municipality and county for each respondent. Furthermore, it provided the information necessary for showing the results on a national level, which was done using weight factors, calculated on an individual participant level, considering location, business type and agricultural land area. Weighing factors were added on a municipality level based on the calculations according to the formula:

$$WF_{i,j,k} = (A_{i,k}/A_{j,k}), \quad (1)$$

where $WF_{i,j,k}$ is the weighing factor; $A_{i,k}$ is the total agricultural land area on a county level; $A_{j,k}$ is the total agricultural land area on a municipality level; i is the county number (i = 1, . . . , 21); j is the municipality number (j = 1, . . . , 560), and k is the business type (k = 1, . . . , 3).

Data were also refined by conducting plausibility control of the answers. After calculating average fuel consumption for a particular machinery class, outliers and illogical inputs were removed (e.g., inputs of the wrong fuel type or a wrong order of magnitude). This was done by comparing individual fuel consumption per hectare of arable land with the county average and conducting a manual plausibility control for every record of consumption, an order of magnitude, or more different from the average. The top and bottom 5% of average fuel consumption were also controlled. Another plausibility control introduced in the survey was a question requiring data on total fuel bills for 2016. In Croatia, legal agricultural and marine entities can use blue diesel fuel. Blue diesel has the same properties as regular diesel fuel but is approximately 40% cheaper. The legal entities must keep all the bills and use blue diesel only for business. Comparing blue diesel bills and blue diesel fuel consumption enabled additional plausibility control for this fuel.

2.3. Calculating Agricultural Machinery Emissions

Total emissions from agricultural machinery were calculated for carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbon (HC), nitrogen oxide (NO_X) and particulate matter (PM) emissions using the method listed in the 2019 EEA/EMEP Emission Inventory Guidebook. The Tier 1 method was used, since the only data concerning emissions that were collected were data on machinery numbers, engine power class for two-axle tractors, and fuel consumption [26]:

$$E_{i,j,m,n} = \Sigma(FC_{i,m,n} \times EF_{i,j}), \quad (2)$$

where $E_{i,j,m,n}$ is the emission of the pollutant for each fuel type from a machinery category in a county; $FC_{i.m.n}$ is the fuel consumption for each fuel from a machinery category in a county; $EF_{i,j}$ is the emission factor for a specific pollutant for each fuel type; i is the fuel type (i = 1, 2); j is the pollutant type (j = 1, . . . , 5); m is the machinery category (m = 1, . . . , 8), and n is the county (n = 1, . . . , 21). Emission factors were obtained from the EEA/EMEP Emission Inventory Guidebook and are shown in Table 2 [26].

Table 2. Emission factors of gasoline and diesel fuel for agricultural machinery.

Pollutant	Emission Factor (kg/ton of Fuel)	
	Diesel	**Gasoline** [1]
Carbon dioxide (CO_2)	3160	3197
Carbon monoxide (CO)	11.149	770.368
Methane (CH_4) [2]	0.087	0.665
Non-methane volatile organic compounds (NMVOC) [2]	3.542	18.893
Nitrogen oxides (NO_X)	34.457	7.717
Particulate matter 10 (PM_{10}) [3]	1.913	0.157
Particulate matter 2.5 ($PM_{2.5}$) [3]	1.913	0.157

[1] Values for four-stroke gasoline engines are used; [2] CH_4 and NMVOC emissions are summed and presented as CH emissions in the results; and [3] PM_{10} and $PM_{2.5}$ emissions are summed and presented as PM emissions in the results.

Spatial visualization of emissions was done for 21 counties in Croatia, which enables the identification of areas of more considerable atmospheric impact of agricultural machinery. An additional spatial visualization was made by comparing these emissions with each county's total agricultural land area. Furthermore, data on agricultural machinery emissions were compared with emissions from road vehicles to better show the impact of agricultural machinery relative to their energy consumption on a national level.

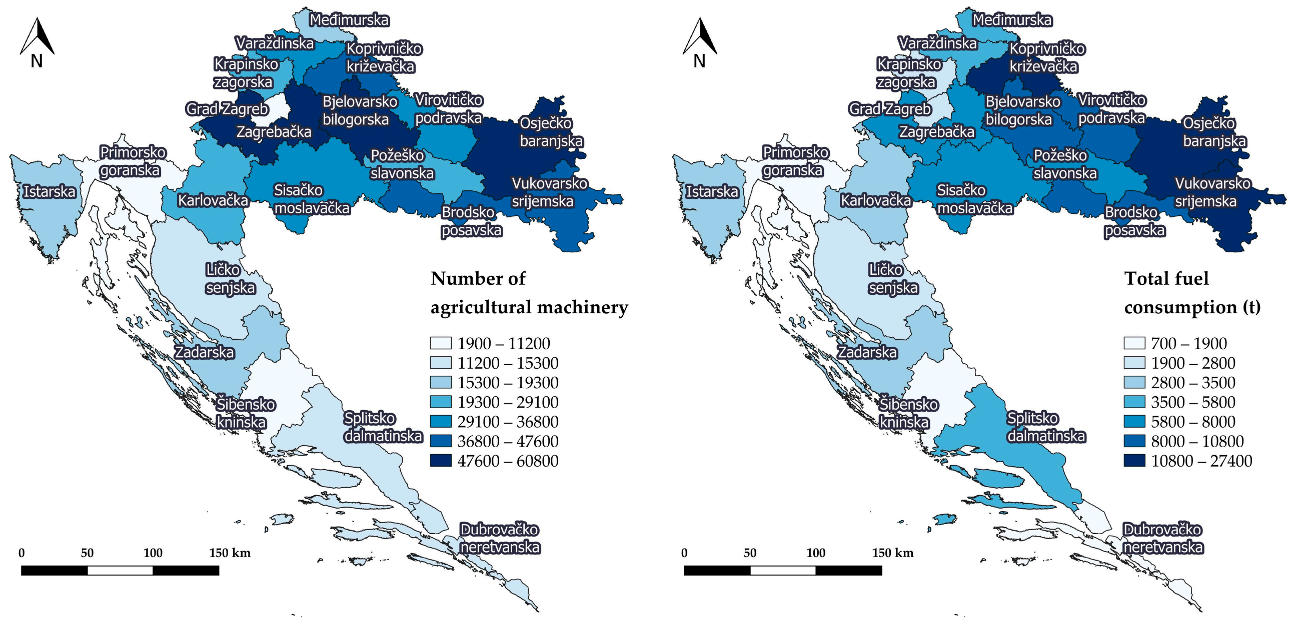
3. Results and Discussion

3.1. Number of Agricultural Machines and Fuel Consumption

The number of agricultural machines and diesel and gasoline fuel consumption per county are shown in Table 3. Osječko-baranjska county had the most significant number of machines, with 60,758 machines. Zagrebačka county observed a similar number of machines with 57,358 machines but significantly lower fuel consumption of 7189 tons, compared with 27,417 tons of fuel in Osječko-baranjska county. This indicates that most of the agricultural machines in Zagrebačka county have lower fuel consumption per machine compared with Osječko-baranjska county, which may be due to fewer hours worked per machine in Zagrebačka county. This difference is also spatially shown in Figure 2a,b, which indicate the number of machines and the total fuel consumption per county, respectively.

Table 3. The number of agricultural machines and diesel and gasoline fuel consumption per county.

County	Number of Machines	Fuel Consumption (tons of Fuel)	
		Diesel	Gasoline
Bjelovarsko-bilogorska	54,646	10,682	12
Brodsko-posavska	38,508	9404	11
Dubrovačko-neretvanska	11,287	1544	100
Grad Zagreb	10,877	2303	21
Istarska	17,868	3361	7
Karlovačka	20,318	2938	77
Koprivničko-križevačka	43,861	11,142	11
Krapinsko-zagorska	25,985	2354	32
Ličko-senjska	13,099	1944	2
Međimurska	16,095	3554	5
Osječko-baranjska	60,758	27,401	16
Požeško-slavonska	23,685	6279	12
Primorsko-goranska	1938	711	12
Sisačko-moslavačka	33,718	7410	13
Splitsko-dalmatinska	13,295	5374	59
Šibensko-kninska	6441	1468	18
Varaždinska	36,104	3891	16
Virovitičko-podravska	33,310	10,614	9
Vukovarsko-srijemska	46,479	17,628	3
Zadarska	17,587	3216	19
Zagrebačka	57,358	7186	3
Total	583,216	140,404	458



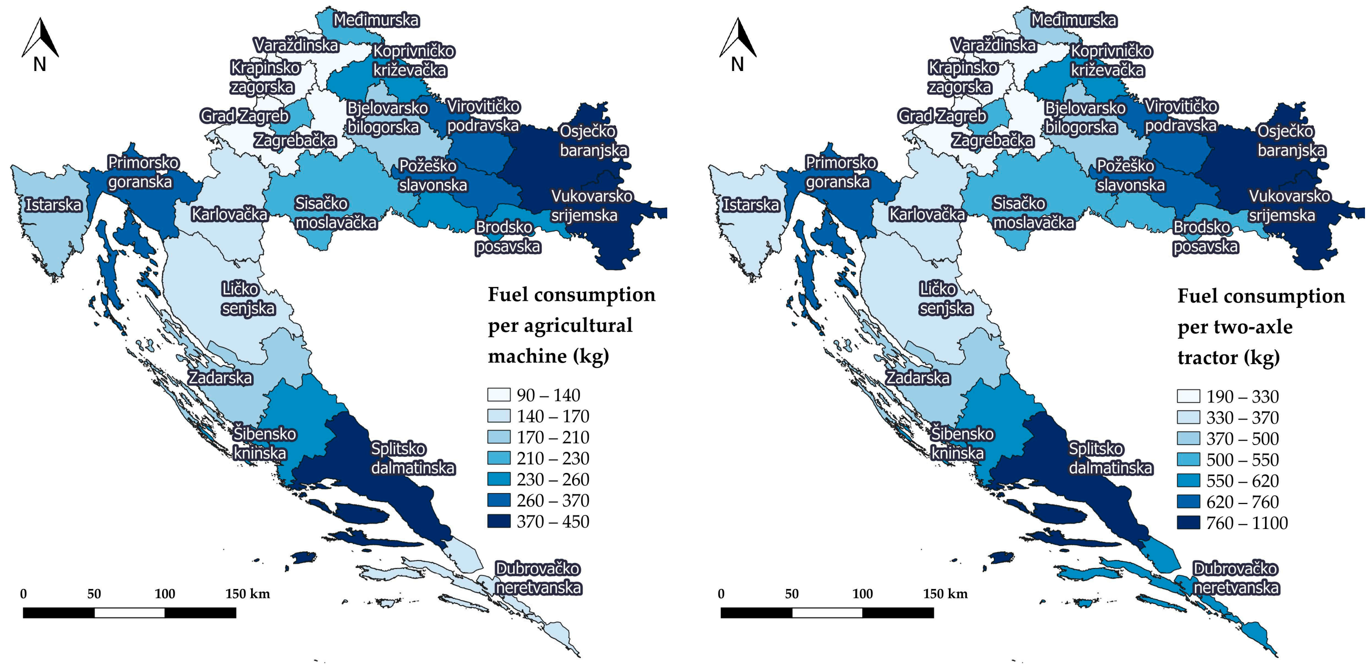
(**a**) (**b**)

Figure 2. Spatial distribution of the number of agricultural machines (**a**) and total fuel consumption (**b**).

The results were also calculated based on the machinery category. Table 4 shows the number of agricultural machines and diesel and gasoline fuel consumption for all machinery categories. Diesel is almost exclusively used, with 140,404 tons of fuel out of the total 140,462 tons used by agricultural machinery, or 99.95%. The other harvesting machinery category has the highest number of machines, with 258,745. The second largest machinery group by machinery number is two-axle tractors, with 111,113 tractors, and is also the largest group for fuel consumption, with 78% of total fuel consumed. Fuel consumption per agricultural machine is shown in Figure 3a. Osječko-baranjska county had the most significant fuel consumption per agricultural machine, with 451 kg of fuel per machine, followed by Splitsko-dalmatinska županija with 409 kg. Krapinsko-zagorska county had the lowest fuel consumption of 92 kg per machine, which could be due to larger machinery with more downward engine displacement or power. Since two-axle tractors have the most significant fuel consumption, their fuel consumption per county and per tractor is shown in Figure 3b. Splitsko-dalmatinska and Osječko-baranjska counties have the most considerable consumption, with 1100 and 948 kg of fuel per two-axle tractor, respectively.

Table 4. Number of agricultural machines and diesel and gasoline fuel consumption for all machinery categories.

Class	Equipment	Number of Machines	Fuel Consumption (tons of Fuel)	
			Diesel	Gasoline
1	Single-axle tractors	56,039	17,057	171
2	Two-axle tractors	111,113	112,051	2.1
2.1	up to 40 kW	57,184	25,405	1.4
2.2	from 41 to 60 kW	31,579	26,250	/
2.3	from 61 to 100 kW	16,598	33,043	/
2.4	more than 100 kW	5752	27,354	/
3	Combine harvesters	8604	9730	/
4	Machinery for potatoes and sugar beet	654	248	/
5	Machinery for fodder plants	5203	16	0.1
6	Other harvesting machinery	258,745	1035	221
7	Balers	51,515	154	0.4
8	Other	73,232	112	61
	TOTAL	565,105	140,404	458



(**a**) (**b**)

Figure 3. Spatial distribution of the fuel consumption per agricultural machine (**a**) and fuel consumption per two-axle tractor (**b**) in tons of fuel.

3.2. Emissions from Agricultural Machinery

After determining fuel consumption, CO_2, CO, HC, NO_X, and PM emissions were calculated using Equation (2). The results are shown by county and by machinery category. For machinery categories, as with fuel consumption, emissions are disaggregated for two-axle tractors. The Tier 1 method of the EMEP/EEA Air Pollutant Emission Inventory Guidebook differentiates emission factors by machinery category for different fuel types; the other emission factors are used for gasoline and diesel fuel. The emissions were calculated individually and then aggregated by machinery categories. For example, CO_2 emissions for single-axle tractors were calculated individually and then aggregated for all diesel and gasoline single-axle tractors. Table 5 shows emissions for all the equipment categories in tons. For CO_2, emissions are presented in kilotons. Two-axle tractors had the most significant proportion of emissions in all of the calculated emission types. The most important proportion of emissions of two-axle tractors was for CO_2 and NO_X emissions, with a proportion of 80%, followed by a proportion of 79% for PM emissions. As with the fuel consumption, two-axle tractors with engine power from 61 to 100 kW had the most significant emissions in all the calculated emission types. Machinery for fodder plants had the lowest emissions, with a 0.01% proportion of emissions for all emission types.

Table 5. Emissions for all the equipment categories in tons.

Class	Equipment	Emissions (tons, Kilotons for CO_2)				
		CO_2	CO	HC	NO_X	PM
1	Single-axle tractors	54.4	302	103.8	588.2	66.5
2	Two-axle tractors	354.1	1286.4	407.2	3861	428.7
2.1	up to 40 kW	80.3	292.2	92.5	875.4	97.2
2.2	from 41 to 60 kW	82.9	301.1	95.3	904.5	100.4
2.3	from 61 to 100 kW	104.4	379	119.9	1138.6	126.4
2.4	more than 100 kW	86.4	313.7	99.3	942.5	104.7

Table 5. *Cont.*

Class	Equipment	Emissions (tons, Kilotons for CO_2)				
		CO_2	CO	HC	NO_X	PM
3	Combine harvesters	30.7	111.6	35.3	335.3	37.2
4	Machinery for potatoes and sugar beet	0.8	2.8	0.9	8.6	1
5	Machinery for fodder plants	0.1	0.3	0.1	0.6	0.1
6	Other harvesting machinery	4	149.3	57.9	36.3	5.6
7	Balers	0.5	2	0.7	5.3	0.6
8	Other	0.6	39.4	15.4	4	0.9
	TOTAL	445.1	1893.5	621	4839.2	540.6

Emissions for all machinery categories by emission type are shown in Figure 4. When combined, single-axle and two-axle tractors are responsible for most emissions for all emission types. Their proportion is the highest for NO_X emissions, 92%, and the lowest for HC emissions, with a proportion of 82%.

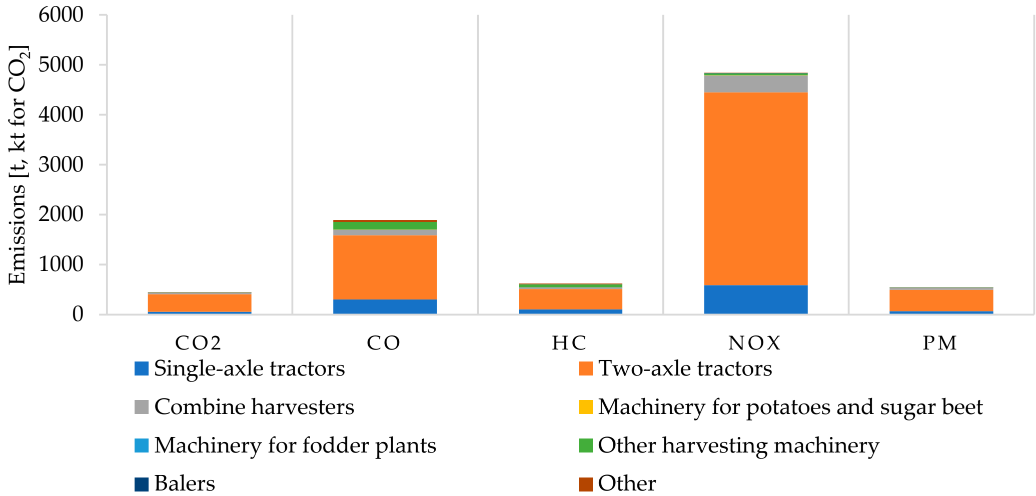
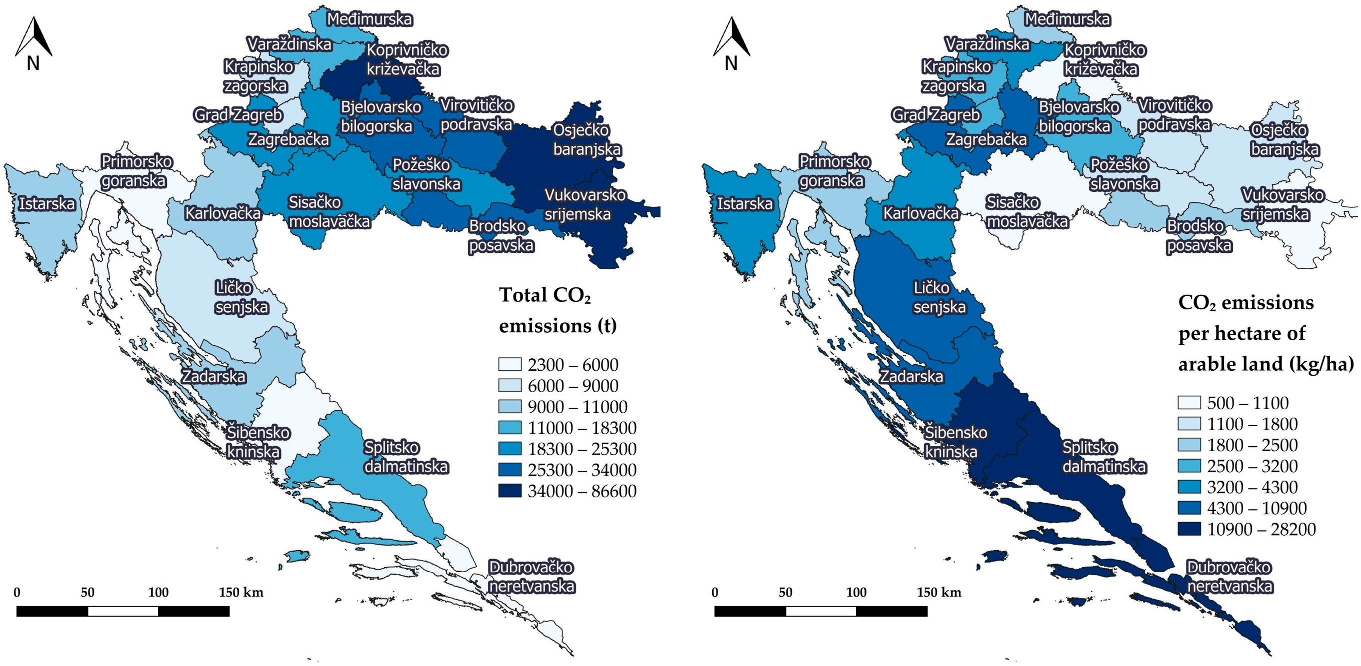


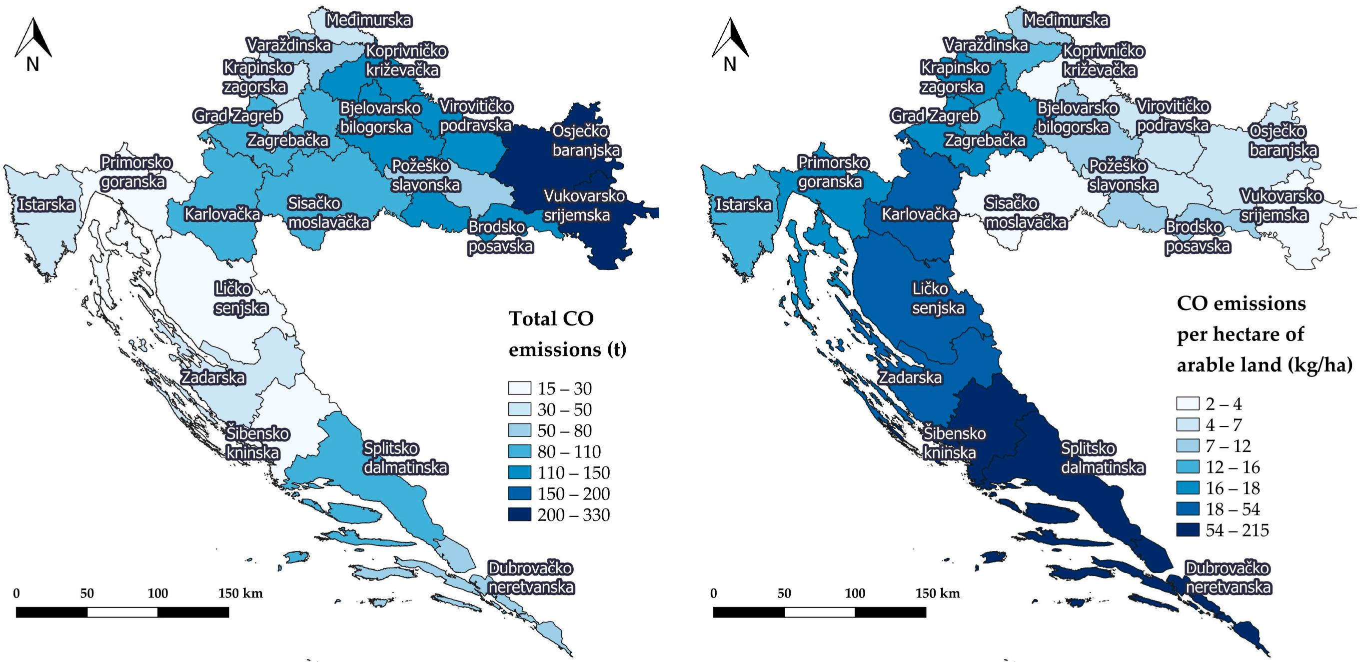
Figure 4. Emissions for all machinery categories by emission type.

Figures 5–9 show a spatial distribution of total emissions and emissions by a hectare of arable land for all emission types by a county. The numbers used to prepare those figures are given in Appendix A in Tables A1 and A2. Figure 5a,b show the spatial distribution of total CO_2 emissions and the spatial distribution per hectare of arable land for CO_2, respectively. Osječko-baranjska county had the most significant of total CO_2 emissions, with 86.6 kt. When considering CO_2 emission per hectare of arable land, Osječko-baranjska county only had 1.1 t/ha of emissions. For comparison, Splitsko-dalmatinska county had the most significant emissions per hectare of arable land at 28.2 t/ha, followed by Dubrovačko-neretvanska county with emissions of 14 t/ha. Koprivničko-križevačka county had the lowest emissions of 0.5 t/ha. The spatial distribution of total CO emissions and the spatial distribution per hectare of arable land for CO are shown in Figure 6a,b, respectively. Osječko-baranjska county had the most significant total of CO emissions, with 324 t. Dubrovačko-neretvanska county had the most significant CO emissions per hectare of arable land, with 215 kg/ha.



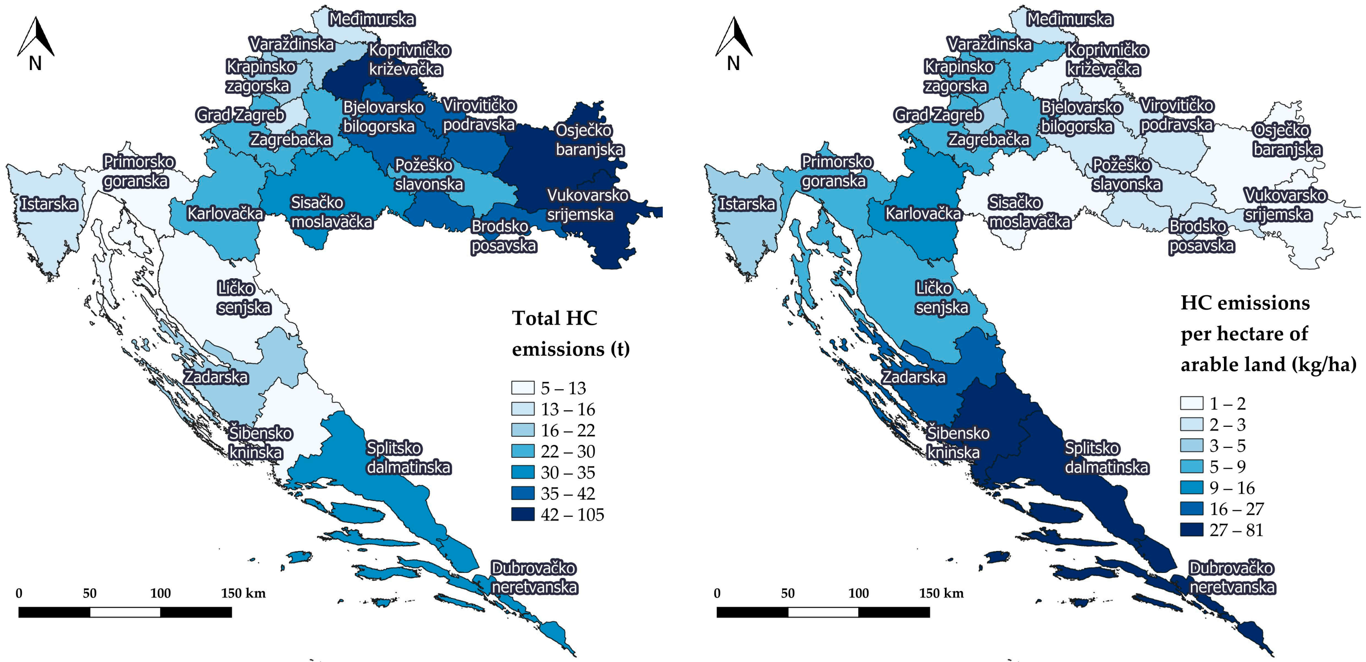
(**a**) (**b**)

Figure 5. Spatial distribution of total carbon dioxide (CO_2) emissions (**a**) and spatial distribution of CO_2 emissions per hectare of arable land (**b**).



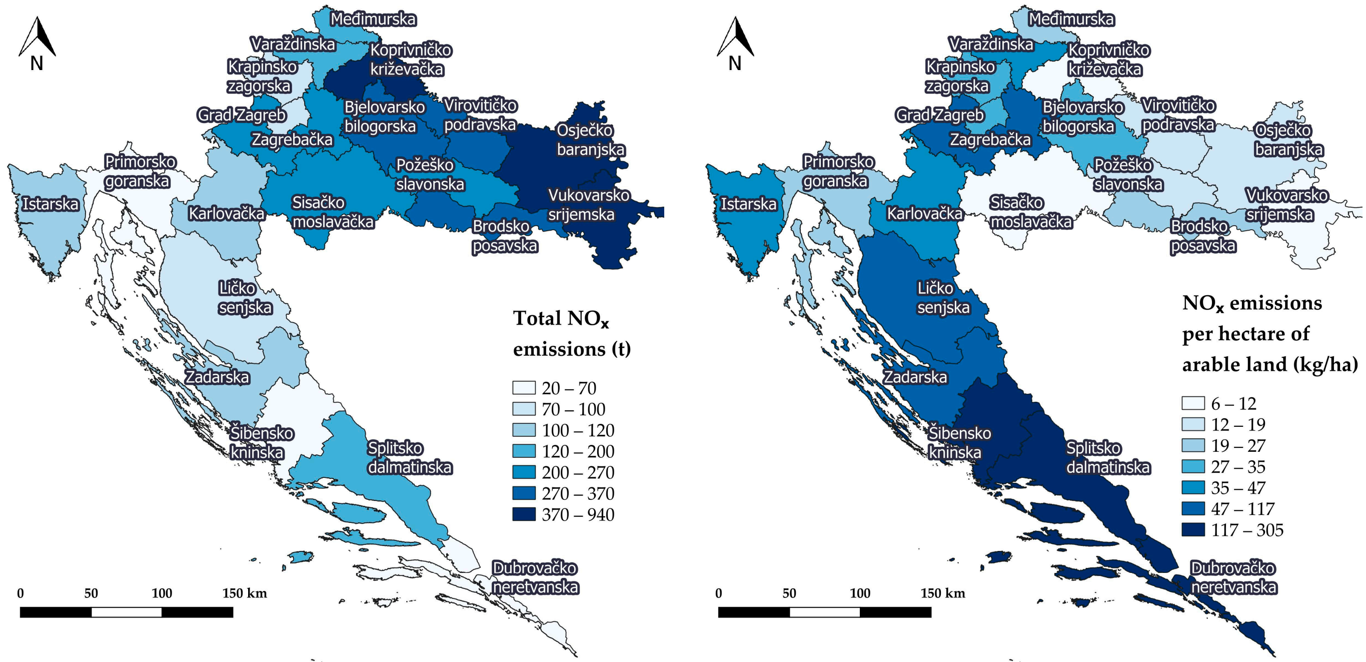
(**a**) (**b**)

Figure 6. Spatial distribution of total carbon monoxide (CO) emissions (**a**) and spatial distribution of CO emissions per hectare of arable land (**b**).



(**a**) (**b**)

Figure 7. Spatial distribution of total hydrocarbon (HC) emissions (**a**) and spatial distribution of HC emissions per hectare of arable land (**b**).



(**a**) (**b**)

Figure 8. Spatial distribution of total nitrogen oxide (NO_X) emissions (**a**) and spatial distribution of NO_X emissions per hectare of arable land (**b**).

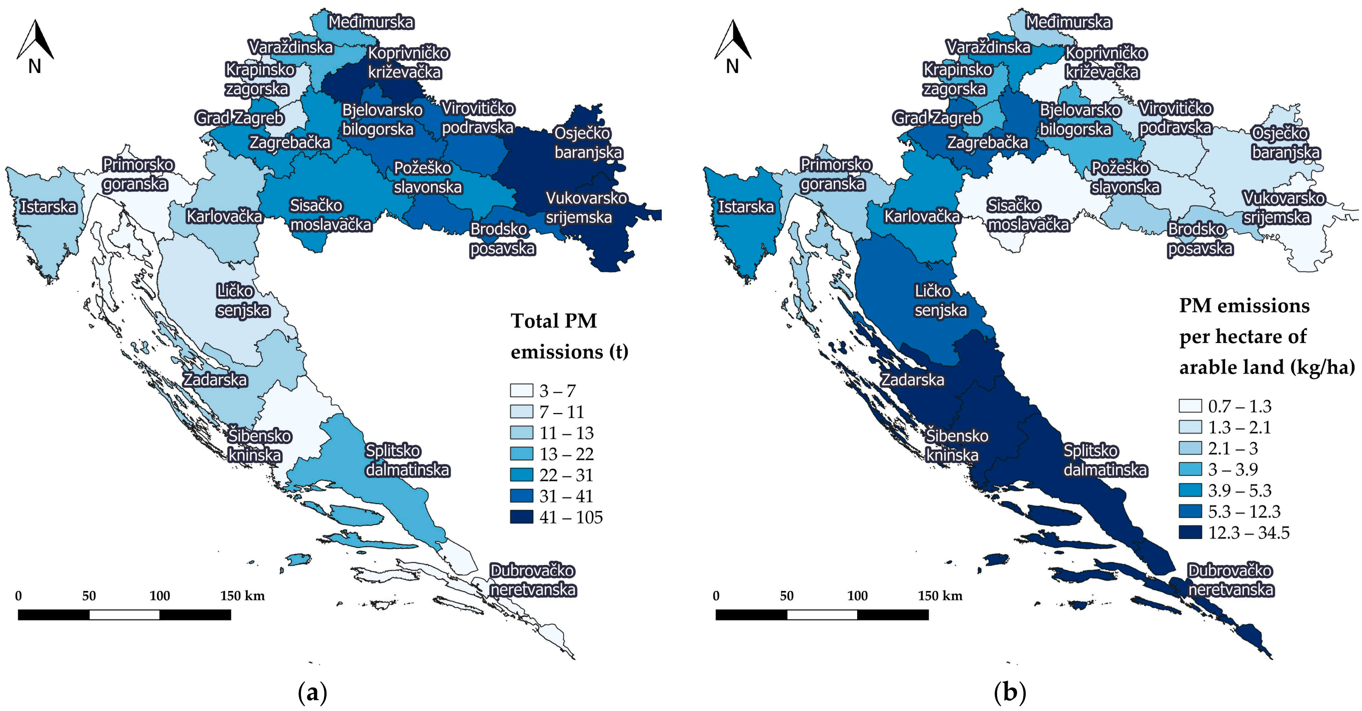


Figure 9. Spatial distribution of total particulate matter (PM) emissions (**a**) and spatial distribution of PM emissions per hectare of arable land (**b**).

Figure 7a,b show the spatial distribution of total HC emissions and the spatial distribution per hectare of arable land for HC, respectively. Osječko-baranjska county had the most significant total of HC emissions, with 103.4 t. When considering HC emissions per hectare of arable land, Dubrovačko-neretvanska county had the most critical emissions per hectare of arable land at 81 kg/ha.

The spatial distribution of total NO_X emissions and the spatial distribution per hectare of arable land for NO_X is shown in Figure 8a,b, respectively. Osječko-baranjska county had the most significant total of NO_X emissions, with 944 t. Contrary to CO_2, CO, and HC emissions, where Dubrovačko-neretvanska county had the most critical emissions per hectare of arable land, Splitsko-dalmatinska county had the most significant NO_X emissions per hectare of arable land, with 305 kg/ha. This is due to Splitsko-dalmatinska county having a more substantial proportion of diesel consumption in total agricultural machinery fuel consumption than Dubrovačko-neretvanska county. While Dubrovačko-neretvanska county had 94% of diesel fuel consumption in total fuel consumption, Splitsko-dalmatinska county had a share of 99%. Since NO_X emissions per ton of fuel are significantly larger for diesel fuel than for gasoline fuel, Splitsko-dalmatinska county had more significant NO_X emissions per ton of arable land.

Figure 9a,b show the spatial distribution of total PM emissions and the spatial distribution per hectare of arable land for PM, respectively. Osječko-baranjska county had the most significant total of PM emissions, with 105 t. When considering PM emissions per hectare of arable land, Splitsko-dalmatinska county had the most critical emissions per hectare of arable land at 34.5 kg/ha. As with the NO_X emissions, Splitsko-dalmatinska county had the most significant emissions per hectare of arable land due to having a more substantial proportion of diesel fuel in total fuel consumption compared with Dubrovačko-neretvanska county.

The spatial distribution of emissions indicates that continental counties in the eastern continental part of Croatia have the highest emissions for all emission types. This is expected since that part of Croatia is the central region of agricultural production due to its topography. Osječko-baranjska, Vukovarsko-srijemska, Koprivničko-križevačka, Bjelovarsko-bilogorska, Virovitičko-podravačka and Brodsko-posavska counties are the six counties with the highest emissions for all emission types, as is shown in Figures 5–9. When considering emissions per hectare of arable land, counties in the southern part of Croatia have the highest emissions for all emission types. Figures 5–9 show that Dubrovačko-neretvanska, Splitsko-dalmatinska, Šibensko-kninska and Zadarska counties have the highest emissions for all emission types, despite having lower total emissions compared with the six counties mentioned above, which is due to the influence of mountainous terrain.

Since there are no official data on agricultural machinery emissions in Croatia, there is no way to validate the results from the survey with the existing data. Thus, a comparison of the results of the emissions from agricultural machinery with emissions from road vehicles was made for Croatia and six other countries. The purpose of this comparison is to show that agricultural machinery has much higher emissions than road vehicles when looking at its respective share in energy consumption. Furthermore, the purpose is to show that the data broadly differ among countries. A comparison was made for energy consumption and CO_2, CO, HC, NO_X, and PM emissions. Table 6 presents a comparison of energy consumption and emissions of agricultural machinery with road vehicles for the year 2016 for Croatia and six other European countries with official data on agricultural machinery emissions: The Netherlands, Sweden, Finland, Denmark, Germany, and Switzerland. Emissions for Switzerland are shown for 2015 since only data for that year are available. It can be seen that agricultural machinery emits much more emissions for some emission types compared with their respective proportion of energy consumption. In Croatia, for example, agricultural machinery consumed 6.8% of energy compared with road vehicles, but they emitted 58.6% of HC, 36.7% of PM and 19.8% of NO_X emissions. The results for all emissions vary by country. For example, in Finland, HC emissions from agricultural machinery are 40.2% compared with road vehicles, whereas in the Netherlands, they are only 1.3%. This may be due to the poor quality of data for agricultural machinery. The Netherlands, Denmark, Germany and Switzerland estimate their agricultural machinery emissions using only vehicle stock or vehicle sales data. No further data are collected, and no surveys are made to collect, e.g., activity data. However, Finland and Sweden conduct annual data gathering on a very limited basis [36]. Further research is necessary for an in-depth explanation of this data discrepancy.

Table 6. Comparison of emissions for Croatia [37,38] and six other European countries which have official data on agricultural machinery emissions: The Netherlands [33], Sweden [34], Finland [35], Denmark [28], Germany [39], and Switzerland [27].

Country	Energy Consumption	Emissions in Comparison with Road Vehicles				
		CO_2	CO	HC	NO_X	PM
Croatia	6.8%	7.3%	6.4%	58.6%	19.8%	36.7%
Netherlands	No data [1]	4.4%	0.8%	1.3%	10.5%	7.3%
Sweden	No data [1]	6.7%	21.5%	15%	7.0%	40.8%
Finland	7.5%	8.6%	25.1%	40.2%	13.3%	34.6%
Denmark	8.1%	8.6%	20.4%	20%	15.6%	59.3%
Germany	4.2%	3.5%	4%	6.7%	8.1%	59%
Switzerland	3%	2.9%	16.7%	9.5%	8.2%	31.8%

[1] There are no official data for road vehicles and agricultural machinery energy consumption.

Since this research presents the first emission inventory of agricultural machinery in Croatia, further research is needed for data to be comparable and verified. As seen from the data in Table 6, HC and PM emissions from agricultural machinery are much higher for a unit of consumed energy than road vehicles, indicating that further research on agricultural machinery emission-reduction technology in Croatia is needed. Adding emission-reduction technologies, such as oxidation catalysts, selective catalytic reduction, NO_X adsorbers, diesel particle filters, and gasoline particle filters, can considerably lower overall emissions [40]. The light scattering device offers cost-friendly solutions for lowering fugitive dust emissions [41]. Researching new propulsion types using hybrid technologies and electricity are necessary for achieving climate neutrality in agriculture [42,43]. Research on on-site infrastructures, such as solar panels for charging machinery, can be used to develop models for sustainable farming [44]. However, the electrification of agricultural machinery is still in the early stages [45].

Additional surveys could gather other data to use more detailed emission methods and compare them with the results of this paper. Additionally, more detailed data on emission-reduction technologies could show how emission-reduction technology and machinery electrification can spatially reduce overall emissions in Croatia and other areas for different machinery categories. However, the first step would be to increase the existing emission inventory accuracy by surveying with additional data gathering. Information on machinery age and work hours would enable more detailed Tier 2 or Tier 3 methods from the EMEP/EEA Air Pollutant Emission Inventory Guidebook [46]. The comparison between multiple models of determining an agricultural emission inventory would result in cost-optimal emission research.

4. Conclusions

Emissions from agricultural machinery impact the climate, produced food, and the health of the agricultural workers. The first step in emission control is data analysis, where an emission inventory plays the most critical role. In this paper, a spatial emission inventory was developed via data gathered from a large-scale survey with 8895 respondents in Croatia. After determining the fuel consumption, agricultural machinery emissions were calculated using the EEA Tier 1 method. Two-axle tractors had the most significant fuel consumption and emitted the most emissions for all emission types. A spatial presentation of emissions showed that Osječko-baranjska county had the most emissions, with 86,637 t of CO_2, 324 t of CO, 103 t of HC, 944 t of $NO_{X,}$ and 105 t of PM. However, the most arable land emissions per hectare were present in Dubrovačko-neretvanska and Splitsko-dalmatinska counties. Dubrovačko-neretvanska had the most CO and HC emissions, with 215 kg CO/ha and 81 kg HC/ha, whereas Splitsko-dalmatinska county had the most CO_2, $NO_{X,}$ and PM emissions, with 28,218 kg CO_2/ha, 305 kg NO_X/ha, and 35 kg PM/ha.

Without an official figure to compare the results, data verification was done by relating the results with the emissions from road vehicles and comparing those relations with other relative values in some other countries. When comparing fuel consumption and emissions of agricultural machinery with those of road vehicles, it is evident that agricultural machinery in Croatia in 2016 had a more significant proportion of emissions than their respective share in fuel consumption, except for CO emissions, and with no data for road vehicles for PM emissions. A comparison with other countries indicated similar proportions, i.e., a higher proportion of emissions compared with energy consumption in the Netherlands, Sweden, Finland, Denmark, Germany, and Switzerland, except for CO_2 emissions in Finland and CO emissions in Germany. Unfortunately, there is no official data for agricultural machinery energy consumption in the Netherlands and Sweden. Future studies could focus on determining additional information, such as vehicle age or work hours, or information on emission-reduction technologies, in order to determine the effects on overall emissions.

Lack of data presents a significant problem in developing an emission inventory for agricultural machinery. Conducting an extensive survey can ensure that quality data can be collected, enabling policies to target specific areas and machinery categories. This task could be done annually by an institution with enough resources to collect and process the data. Government funding for such an institution would benefit its stability and capacity to develop annual emission inventories. It is essential to determine which data can be accurately collected from the agricultural entities to avoid collecting unreliable data and to ensure that the agricultural entities can fill the survey with accurate and up-to-date data. Collaborating between government, academic, and professional institutions with agricultural entities can help optimize data selection and collection. The critical point, however, is to ensure the continuity of surveying.

Author Contributions: Conceptualization, D.K. and Z.L.; methodology, Š.L. and P.I.; investigation, Š.L.; resources, Š.L.; software, Š.L.; writing—original draft preparation, Š.L.; writing—review and editing, D.K.; supervision, D.K. and Z.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Commission, European Structural and Investments Funds 2014–2020, grant number KK.01.1.107.0038, by the research project of the Energy Institute Hrvoje Požar, "Development of an integrated solution for strategic long-term climate and energy policy planning and development of joint climate and energy plans".

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Restrictions apply to the availability of these data. Data were obtained from the Croatian Bureau of Statistics and are available at https://dzs.gov.hr/ (accessed on 10 October 2022) with the permission of the Croatian Bureau of Statistics.

Acknowledgments: In this section, you can acknowledge any support given which is not covered by the author contribution or funding sections. It may include administrative and technical support or donations in kind (e.g., materials used for experiments).

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A

Table A1. Emissions of agricultural machinery by county.

County	Emissions (t, kt for CO_2)				
	CO_2	CO	HC	NO_X	PM
Bjelovarsko-bilogorska	10,694	33,795	42	130	368
Brodsko-posavska	9415	29,752	37	115	324
Dubrovačko-neretvanska	1644	5198	30	80	53
Grad Zagreb	2324	7344	13	39	79
Istarska	3368	10,643	14	43	116
Karlovačka	3015	9531	30	82	101
Koprivničko-križevačka	11,153	35,244	43	135	384
Krapinsko-zagorska	2386	7542	16	47	81
Ličko-senjska	1946	6151	8	24	67
Međimurska	3558	11,244	14	44	122
Osječko-baranjska	27,417	86,637	103	324	944
Požeško-slavonska	6291	19,879	26	79	216
Primorsko-goranska	722	2283	5	15	25
Sisačko-moslavačka	7423	23,456	30	93	255
Splitsko-dalmatinska	5433	17,170	34	98	185
Šibensko-kninska	1487	4699	10	28	51
Varaždinska	3907	12,348	18	55	134
Virovitičko-podravska	10,623	33,568	41	127	366
Vukovarsko-srijemska	17,631	55,714	65	204	607
Zadarska	3235	10,223	16	48	111
Zagrebačka	7189	22,717	27	84	248
Total	445,138	621	1894	4839	541

Table A2. Emissions of agricultural machinery per hectare of arable land by county.

County	Emissions per Hectare of Arable Land (kg)				
	CO_2	CO	HC	NO_X	PM
Bjelovarsko-bilogorska	13,316	2538	3	10	28
Brodsko-posavska	15,661	1900	2	7	21
Dubrovačko-neretvanska	370	14,045	81	215	145
Grad Zagreb	2780	2642	5	14	29
Istarska	2788	3818	5	15	42
Karlovačka	2266	4205	13	36	45
Koprivničko-križevačka	64,968	542	1	2	6
Krapinsko-zagorska	2591	2911	6	18	31
Ličko-senjska	1229	5004	6	19	54
Međimurska	6079	1850	2	7	20
Osječko-baranjska	79,593	1089	1	4	12
Požeško-slavonska	12,782	1555	2	6	17
Primorsko-goranska	958	2382	6	16	26
Sisačko-moslavačka	39,156	599	1	2	7
Splitsko-dalmatinska	608	28,218	56	161	305
Šibensko-kninska	336	14,005	29	84	151
Varaždinska	3419	3612	5	16	39
Virovitičko-podravska	21,599	1554	2	6	17
Vukovarsko-srijemska	54,693	1019	1	4	11
Zadarska	982	10,407	16	49	113
Zagrebačka	4852	4682	6	17	51
Average	13,316	2538	3	10	28

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