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Article

Analysis of Air Pollutant Emissions for Mechanized Rice Cultivation in Korea

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Abstract: In Korea, rice is a major staple grain and is mainly cultivated using various agricultural machinery. Air pollutants emitted from agricultural machinery have their origins mainly from the exhaustion of internal combustion engines. In this study, emission characteristics of five main air pollutants by European Environment Agency's Tier 1 method for rice cultivation was analyzed. Diesel is a main fuel for agricultural machinery and gasoline is generally used only for rice transplanters as a fuel in Korea. Tractors consume 46% of total fuel consumption and 56% of diesel fuel consumption. Gasoline used for rice transplanters accounts for 17% of total fuel consumption each year. Tractors and rice transplanters are emitting 82% of all total pollutants. From 2011 to 2019, the total amount of air pollutant emissions was decrease by 15%. That accounted for the reduction of rice cultivation fields in those periods. Rice transplanting operation was in charge of 42% of total emissions. Then, harrowing, harvesting, tilling, leveling, and pest control operations generated 10%, 10%, 8%, 8% and 7% of total emissions, respectively. The contribution of each air pollutant held 54% of CO, 39% of NOx, 5% of NMVOC, and 2% of TSP from the total emission inventory. The three major regions emitting air pollutants from mechanized agricultural practices were Jeollanam-do, Chungcheongnam-do, and Jeollabuk-do, which consume 55% of total fuel usage in rice farming. The total amount of air pollutant emissions from rice cultivation practices in 2019 was calculated as 8,448 Mg in Korea.

Keywords: Air Pollutant Emissions; Rice Cultivation; Agricultural Machinery; Tier 1 Methodology; Geographic Information System

1. Introduction

Rice (Oryza sativa L.) is a globally cultivated species and is the most cultivated crop in many Asian countries [1]. Rice (Oryza sativa L.) is the staple food for four billion people. The top three main rice producers in Asia are China, India, and Indonesia, while Korea is at position 15th in Asia [2, 3]. Korea is the one of the largest crop producing countries with $1{,}643\times10^3$ ha total arable area for crops and produces a total grain production of $4{,}375\times10^3$ tons in 2015 [4, 5]. Rice is a staple crop and is cultivated in 730×10^3 ha in 2019 in Korea [4].

Traditionally agriculture produces and consumes energy in one form or another; fossil fuel energy, electric energy, animal power and human power [6]. The amount of energy used in agricultural production has increased intensively because the traditional, low energy input farming is being replaced by modern high energy systems to produce more products efficiently [7]. Agricultural practices including tillage, planting, fertilizer spreading, harvesting etc. were done mostly by various machinery and have been recognized as a significant source of atmospheric particulate matter (PM) and gaseous pollutants which adversely affect human health and regional environment [8, 9, 10]. Agriculture is an industry that is directly or indirectly affected by climate change while emitting air pollutants through the use of various agricultural machinery in producing agricultural products [11].

Along with the mechanization of agricultural farming in Korea, more animal and human powers that used to be the main agricultural power sources in the past were substituted by agricultural machinery in the recent decades. Most of agricultural practices necessary to cultivate rice have been mechanized; the degree of mechanization is reported to be 98.6% [12]. Air pollutants emitted from agricultural machinery have their origins mainly from the exhaustion of internal combustion engines. Fossil fuels used in internal combustion engines include diesel, gasoline, kerosene, heavy oil, etc. Among them, agricultural machinery uses mainly diesel and gasoline as their fuels in Korea. Given the growing importance of agricultural machinery, researchers started to estimate the emissions at the city, regional or country level [13, 14]. The agricultural machinery emissions of NOx, PM_{10}, VOCs and CO were estimated at 16,209, 1,348, 1,933 and 7,097 Mg, respectively, in 2015, and 16,249, 1,330, 1,902 and 7,038 Mg, respectively, in 2018 in Korea [15]. The emissions of agricultural machinery were not negligible even they were not evenly distributed in a whole year. They could be extremely large on preparing fields for seeding or planting and harvesting seasons. When agricultural machines are intensively used, their emissions could be comparable with on-road vehicles and play an important role on air quality [16].

The current agricultural machinery emission inventories were developed based on the machinery activity data (mileage, work output or fuel usage) and corresponding air pollutant emission factors [17, 18, 19]. The National Institute of Environmental Research (NIER) in Korea published a recommendation to estimate the amount of air pollutants from the use of various agricultural machinery [20]. Many data should be provided to calculate the yearly amount of eight air pollutants from agricultural machinery use. The emission factor, rated power, and load factor data are provided by the NIER handbook. But other data including the number and working hours of each machinery type also are required for calculation process. The European Environment Agency (EEA), on the other hand, adopts a somewhat different approach to calculate the amount of air pollutants from agricultural machinery [21]. Even with different methods developed, there is still a huge gap between current data and the real-world in-use activity. Firstly, the number of agricultural machines owned in a certain area cannot indicate the actual amount of machinery used. During the busy farming season, a large amount of agricultural machinery is rented and used, and some unused agricultural machinery may be included. Secondly, the working environment and utilization rate differ depending on the crop cultivation environment.

The objectives of the study are to analyze emission characteristics of five main air pollutants by EEA Tier 1 method for rice cultivation in Korea from 2011 to 2019 every two year. In addition, the spatial distribution of the amount of five pollutants was visualized by geographic information system (GIS) on country scale.

2. Materials and Methods

There are several important factors in the calculation of emission inventory.

2.1. Calculation of Air Pollutant Emissions

Tier 1 method developed by the EEA was used to calculate air pollutants in the study. As shown in Eq. (1), the calculation of emissions requires fuel consumption used for rice producing and emission factors for each air pollutant emitted from agricultural engines.

$$E_{i,j,k} = \sum\{FC_{i,k} \times EF_j\} \quad (1)$$

where, $E_{i,j,k}$ is amount of emission of pollutant from agricultural machinery of region; $FC_{i,k}$ is amount of fuel consumption by agricultural machinery of region; EF_j is emission

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factor of pollutant (kg/ton fuel); i is agricultural machinery type (i=1, ⋯, 4); j is type of air pollutant (j=1, ⋯, 5); k is region (k=1, ⋯, 10).

2.2. Factors Related to Calculating Amount of Fuel Consumption

About four types of agricultural machines including tractors, power tillers, rice transplanters, and combines, are frequently used for rice cultivation in Korea. The power tiller is a two-wheel tractor, sometimes called a walking tractor, and performed various agricultural operations. The power tiller was an important role in the mechanization of Korean agriculture. The tractors are equipped with various implements such as plow, rotavator, and harrow, etc. and are used for tilling, harrowing, leveling, transportation, etc., and power tillers are currently equipped with small gasoline engines and are mainly used for using in pesticide spreading operation in the study. Rice transplanters and combines are currently equipped with diesel engines. Data on the amount of fuel consumed per rice acreage could be obtained from the relevant literature [22]. Rice cultivation fuel consumption is classified according to the type of machinery and equipment used, and is listed as shown in Table 1.

Table 1. Fuel consumption data for machinery and implements used in rice cultivation [22].

Machinery	Implement	Fuel	OE [1] (h/ha)	FC [2]	
				Liter/h(B)	Liter/ha(A×B)
Tractor	Plow	Diesel	2.9	7.8	20.6
	Rotavator	Diesel	3.7	7.5	26.0
	Soil preparation equip.	Diesel	2.9	7.8	20.6
	Others	Diesel	-	-	40.2
Power Tiller	Power sprayer	Diesel	9.9	2.0	19.8
Transplanter		Gasoline	3.5	3.3	8.4
Combine		Diesel	2.6	10.7	27.8

[1] OE: Operation efficiency, [2] FC: Fuel consumption

Table 2. Rice cultivation area of each region in Korea [4].

Region	Rice Cultivation Area (ha)				
	2011	2013	2015	2017	2019
CHB [1]	44,504	42,893	39,786	33,069	33,247
CHN [2]	152,947	151,814	146,319	134,035	132,174
GAW [3]	35,955	33,968	32,300	29,710	28,640
GYB [4]	110,550	108,501	104,712	99,551	97,465
GYG [5]	91,727	88,949	82,071	78,484	76,642
GYN [6]	79,563	77,732	73,934	67,895	65,979
JEB [7]	130,696	126,799	121,765	118,340	112,146
JEJ [8]	430	302	128	113	45
JEN [9]	174,930	170,690	170,185	161,442	154,091
TMC [10]	32,521	30,977	28,144	30,072	29,384
Total	853,823	832,625	799,366	754,713	729,814

[1] CHB: Chungcheongbuk-do, [2] CHN: Chungcheongnam-do, [3] GAW: Gangwon-do, [4] GYB: Gyeongsangbuk-do, [5] GYG: Gyeonggi-do, [6] GYN: Gyeongsangnam-do, [7] JEB: Jeollabuk-do, [8] JEJ: Jeju-do, [9] JEN: Jeollanam-do, [10] TMC: Total of 8 metropolitan city

The cultivated area of rice by year was searched by the Statistics Korea. It is the rice cultivated area from 2011 to 2019 every two year. As shown in Table 2, rice cultivation areas of studied regions were prepared from 9 provinces and 1 total metropolitan city (TMC) including 8 metropolitan cities in Korea.

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2.3. Emissions Factors

The emission factors of five air pollutants used in the study are listed in Table 3. They are obtained from the Air Pollutant Emission Inventory Guidebook from EMEP/EEA [21].

Table 3. Emission factors of diesel and gasoline fuel [21].

Pollutant	Emission Factor (unit: kg/ton fuel)	
	Diesel	Gasoline
CO	11.469	770.368
NOx	34,457	7.117
TSP [1]	1.913	0.157
NMVOC [2]	3.542	18.893
NH_3	0.008	0.004

[1] TSP: Total suspended particles, [2] NMVOC: Non-Methane Volatile Organic Compounds

2.5. Spatial Allocation of Emission

Total amount of emissions calculated in the study was allocated visually to understand the emission characteristics of each region. Emissions of five air pollutants have been assigned to each region and used the QGIS software version (3.10.11). Emissions for agricultural machinery and agricultural work used for rice cultivation are allocated to the vector layer according to the electronic geographic information.

3. Results and Discussion

3.1 Amount of Fuel Consumption

3.1.1. Amount of Fuel Consumption by Region

Table 4 shows diesel (D) and gasoline (G) fuel consumption of target regions. Gasoline is used only in rice transplanters, and diesel is used for the tractors, power tillers, and combines. Fuel consumption is in the order of Jeollanam-do, Gyeongsangnam-do, and Jeollabuk-do, accounting for 55% of the total fuel consumption for mechanized farming in Korean agriculture.

Table 4. Calculated amounts of diesel, gasoline usage.

Region	Fuel usage (kl)									
	2011		2013		2015		2017		2019	
	D [11]	G [12]	D [11]	G [12]	D [11]	G [12]	D [11]	G [12]	D [11]	G [12]
CHB [1]	6,898	374	6,648	360	6,167	334	5,436	295	5,153	279
CHN [2]	23,707	1,285	23,531	1,275	22,679	1,229	20,775	1,126	20,487	1,110
GAW [3]	5,573	302	5,265	285	5,007	271	4,605	250	4,439	241
GYB [4]	17,135	929	16,818	911	16,230	880	15,430	836	15,107	819
GYG [5]	14,218	771	13,787	747	12,721	689	12,165	659	11,880	644
GYN [6]	12,332	668	12,042	653	11,460	621	10,524	570	10,227	554
JEB [7]	20,258	1,098	19,654	1,065	18,874	1,023	18,343	994	17,383	942
JEJ [8]	67	4	47	3	20	1	18	1	7	0
JEN [9]	27,114	1,469	26,457	1,434	26,379	1,430	25,024	1,356	23,884	1,294
TMC [10]	5,041	273	4,801	260	4,362	236	4,661	253	4,554	247
Total	132,343	7,172	129,057	6,994	123,898	6,714	116,980	6,340	113,121	6,130

[1] CHB: Chungcheongbuk-do, [2] CHN: Chungcheongnam-do, [3] GAW: Gangwon-do, [4] GYB: Gyeongsangbuk-do, [5] GYG: Gyeonggi-do, [6] GYN: Gyeongsangnam-do, [7] JEB: Jeollabuk-do, [8] JEJ: Jeju-do, [9] JEN: Jeollanam-do, [10] TMC: Total of 8 metropolitan city, [11] D: Diesel, [12] G: Gasoline

3.1.2. Amount of Fuel Consumption by Agricultural Machinery

Table 5 shows the fuel consumption by agricultural machinery from 2011 to 2019 every two year. Tractor, power tiller, rice transplanter and combine fuel consumption in

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2011 were 64,549 kl, 16,906 kl, 23,736 kl and 34,324 kl, respectively. Tractor, power tiller, rice transplanter and combine fuel consumption in 2019 decreased by 15% from 2011 to 55,173 kl, 14,450 kl, 20,289 kl and 29,339 kl. Tractors account for 46% of total fuel consumption and 56% in the diesel fuel consumption. It can be seen that tractors are used more often than other agricultural machines. Gasoline used in rice transplanters accounts for 17% of total fuel consumption each year.

Table 5. Calculated amounts of fuel usage by agricultural machinery.

Machinery	Implement	Fuel	Fuel usage(kl)				
			2011	**2013**	**2015**	**2017**	**2019**
Tractor	Plow	D [1]	17,589	17,152	16,466	15,547	15,034
	Rotavator	D [1]	22,199	21,648	20,783	19,623	18,975
	Soil preparation equip.	D [1]	17,589	17,152	16,466	15,547	15,034
	Others	D [1]	7,172	6,994	6,714	6,340	6,130
Power Tiller	Power sprayer	D [1]	16,906	16,486	15,827	14,943	14,450
Transplanter		G [2]	23,736	23,147	22,222	20,981	20,289
Combine		D [1]	34,324	33,472	32,134	30,339	29,339
	Total		139,515	136,051	130,613	123,320	119,252

[1] D: Diesel, [2] G: Gasoline

3.2 Emissions of Air Pollutants by Agricultural Machinery

Figure 2 shows biennial air pollutant emissions from 2011 to 2019 by each agricultural machinery. The total emissions from agricultural machinery is gradually decreasing. From 2011 to 2019, the total air pollutant emissions are decrease by 15%. Tractors and rice transplanters are two main sources of air pollutant emissions. They are emitting 82% of all total pollutants.

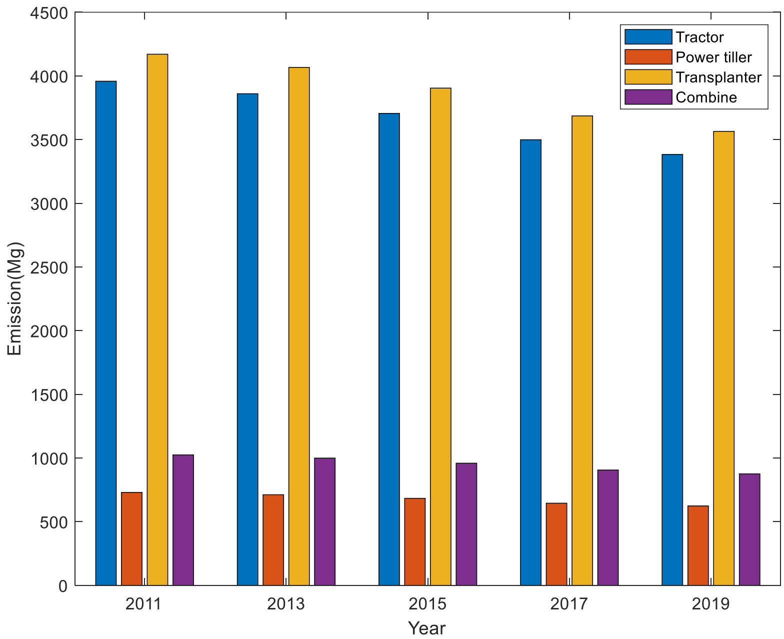
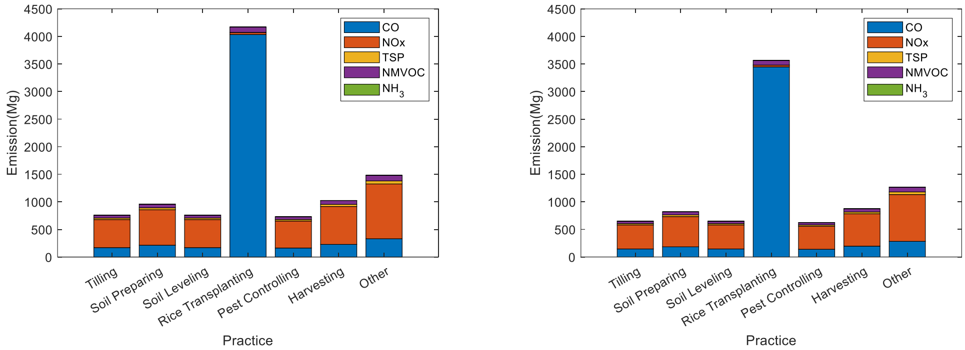


Figure 2. Annual change in rice cultivation air pollutant emissions by agricultural operation.

Figure 3 shows the contribution rate of each agricultural operations to the total emissions of rice cultivation over the past 9 years. Rice transplanting operation was the highest at 42%, harrowing and harvesting operation was 10% each, tilling and leveling operation was 8%, and pest control operation was 7%, followed by that. Analyzing the contribution rate for each air pollutant was CO 54%, NOx 39%, NMVOC 5%, and TSP 2% in that order.



(a) (b)

Figure 3. Calculated air pollutant emissions due to rice cultivation by various agricultural practices: (a) 2011; (b) 2019.

3.3 Spatial and Temporal Distribution of Air Pollutant Emissions

Figure 4 shows biennial air pollutant emissions from 2011 to 2019. Annual emissions of air pollutants from rice cultivation by agricultural machinery are gradually decreasing. The total amount of air pollutants of CO, NOx, TSP, NMVOC and NH_3 in 2019 are 4,537 Mg, 3,306 Mg, 182 Mg, 421 Mg and 0.78 Mg, respectively. The spatial distribution of air pollutants is shown in Figure 5, respectively. In general, the areas where rice cultivation emits air pollutants are concentrated in areas with large cultivated filed. Relatively low emissions are generally distributed in areas with low population densities and low rice production. In addition, economically developed large cities emit less air pollutants due to less agricultural activity.

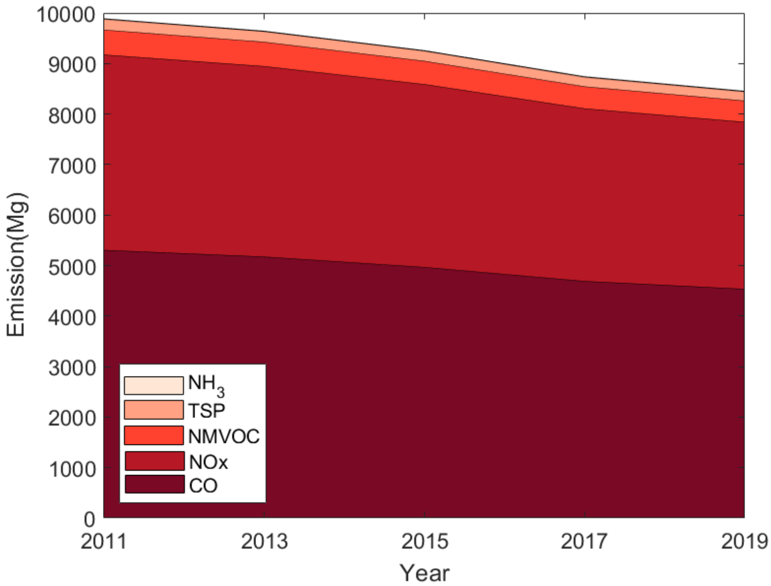


Figure 4. Annual changes in rice cultivation air pollutant emissions.

Table 6 and 7 show the amount of each air pollutant emitted by each region of 2011 and 2019. Based on the calculated data in 2019, the total emission of rice cultivated air pollutants in Korea is 8,448 Mg. The main emission area of air pollutants is the western part of the Korea, which has huge plain for rice cultivation. Jeollanam-do, Chungcheongnam-do, and Jeollabuk-do account for 21%, 18%, and 15% of total air pollutants. Gangwon-do and Chungcheongbuk-do, which have many mountains and mountain range, have low emissions due to the influence of topography.

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Table 6. Calculated air pollutant emissions due to rice cultivation by region in Korea (2011).

Region	Emission (Mg/yr)					
	CO	NOx	TSP	NMVOC	NH_3 (×10^2)	Total
CHB [1]	277	202	11	25	5	515
CHN [2]	951	693	38	88	16	1,770
GAW [3]	224	163	9	21	4	416
GYB [4]	687	501	28	64	12	1,280
GYG [5]	570	416	23	53	10	1,062
GYN [6]	495	360	20	46	8	921
JEB [7]	813	592	33	75	14	1,513
JEJ [8]	2.673	1.948	0.108	0.248	0.046	4.977
JEN [9]	1,088	792	44	101	19	2,025
TMC [10]	202	147	8	19	3	376
Total	5,308	3,868	213	493	91	9,883

[1] CHB: Chungcheongbuk-do, [2] CHN: Chungcheongnam-do, [3] GAW: Gangwon-do, [4] GYB: Gyeongsangbuk-do, [5] GYG: Gyeonggi-do, [6] GYN: Gyeongsangnam-do, [7] JEB: Jeollabuk-do, [8] JEJ: Jeju-do, [9] JEN: Jeollanam-do, [10] TMC: Total of 8 metropolitan city

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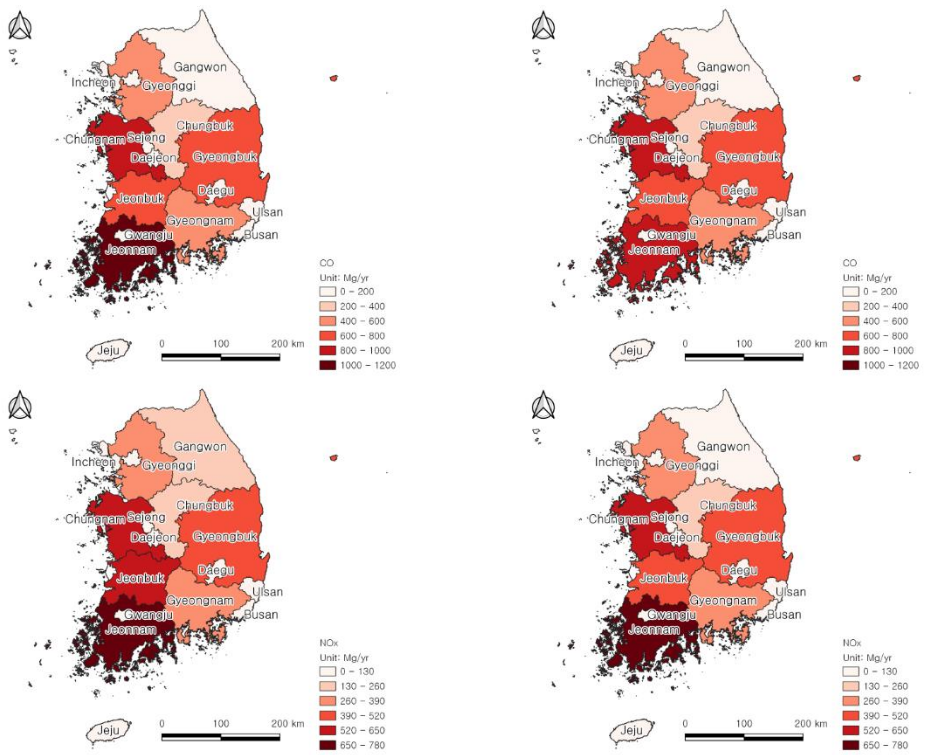
Table 7. Calculated air pollutant emissions due to rice cultivation by region in Korea (2019).

Region	Emission (Mg/yr)					
	CO	NOx	TSP	NMVOC	NH_3(×10^2)	Total
CHB [1]	207	151	8	19	4	385
CHN [2]	822	599	33	76	14	1,530
GAW [3]	178	130	7	17	3	332
GYB [4]	606	442	24	56	10	1,128
GYG [5]	476	347	19	44	8	887
GYN [6]	410	299	16	38	7	764
JEB [7]	697	508	28	65	12	1,298
JEJ [8]	0.280	0.204	0.011	0.026	0.005	0.521
JEN [9]	958	698	39	89	16	1,784
TMC [10]	183	133	7	17	3	340
Total	4,537	3,306	182	421	78	8,448

[1] CHB: Chungcheongbuk-do, [2] CHN: Chungcheongnam-do, [3] GAW: Gangwon-do, [4] GYB: Gyeongsangbuk-do, [5] GYG: Gyeonggi-do, [6] GYN: Gyeongsangnam-do, [7] JEB: Jeollabuk-do, [8] JEJ: Jeju-do, [9] JEN: Jeollanam-do, [10] TMC: Total of 8 metropolitan city

The spatial distributions of major three air pollutants, CO, NOx, and TSP, of 2011 and 2019 are shown in Figure 5. Major changes of the amount of CO and TSP are observed in Jeollanam-do region. It indicates huge reduction of rice transplanter in that region. NOx is decreased and observed visually in Jeollabuk-do and Gangwon-do from 2011 to 2019. In general, main rice producing regions are located in western parts, which emitting large portion of air pollutants, of Korea. Relatively low emissions are generally distributed in north eastern parts with mountainous terrains. In addition, economically developed large cities emit less air pollutants due to the lack of agricultural fields in Korea.



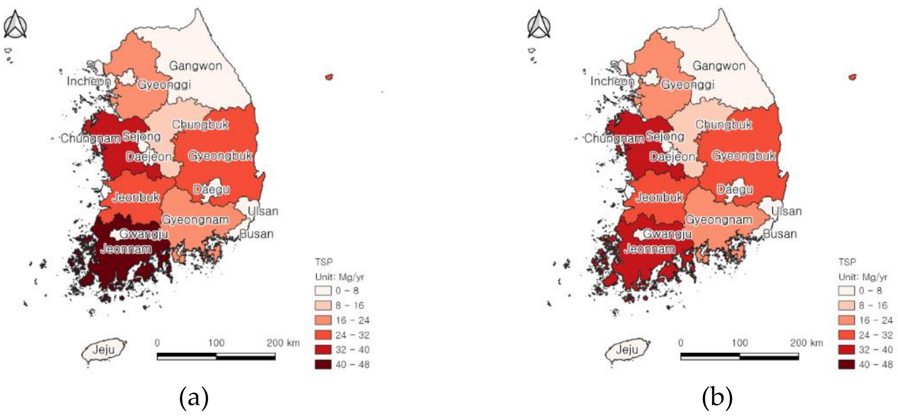


Figure 5. Spatial distribution of emissions of CO (top row), NOx (middle row), and TSP (bottom row) from Korean rice cultivation; (a) 2011: (b) 2019.

4. Conclusions

In this study, we calculated and analyzed five air pollutants emitted from four agricultural machinery from 2011 to 2019 in Korea. The total amounts of fuel consumed annually of tractors, power tillers, rice transplanters, and combines were calculated to estimate air pollutant emissions. Also, the amount of fuel consumed by 9 regions were analyzed. Total yearly fuel consumption from 2011 to 2019 was calculated as 139.5 Ml, 136,1 Ml, 130.6 Ml, 123.3 Ml, 119.3 Ml, respectively. Tractors consumed 46% of the total fuel used for rice production. Rice transplanting operation generated the highest air pollutant emissions among various agricultural operations. Also, it was found rice transplanters were the main source of CO emission. As a result of analyzing air pollutants emitted by region, Jeollanam-do, Chungcheongnam-do, and Jeollabuk-do were main regions. From 2011 to 2019, air pollution emissions emitting from rice cultivation was decreased by 15%. It is presumed that the rice cultivation areas decreased, so did air pollutant emissions.

The results of analysis of air pollutants emissions in this study can improve the air quality management of local areas. It can contribute to establish effective policies to manage energy consumptions and to protect the health of farmers.

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