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Greenhouse gas emissions from tractor-based rice paddy preparation in Thailand

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ABSTRACT
Greenhouse gas (GHG) emissions from agricultural machinery are critical to advise sustainable rice cultivation. According to the Intergovernmental Panel on Climate Change (IPCC) guidelines, GHG emissions were calculated based on observed fuel consumption rates. We used a 36-horsepower diesel tractor during soil preparation in paddy field sizes (0.04, 0.08, 0.16, 0.24, 0.32, and 0.48 hectares). The three evaluated implements were as follows: a vertical disc plough, a rotary tiller, and a harrow. The results show that the relationship between the field capacity of tractors and plot size was significantly positive. Meanwhile, technical time loss from implement lifting tended to decrease in large plots due to tractors' improved maneuverability, compared to smaller plots. The highest emission profile was the first tillage stage, followed by the second tillage stage and the harrowing stage, respectively. CO_2 amounts released from the first tillage stage, the second tillage stage, and the harrowing were 40.82, 35.80, and 17.67 CO_2e kilogram/hectare, respectively. Total GHG emissions from three tillage stages decreased with increasing plot size; the largest plot had the lowest GHG emissions (79.64 CO_2e kilogram/hectare). Larger paddy fields required lower fuel consumption rates, reduced GHG emissions, and minimized technical time losses. Land consolidation and precision leveling could substantially cut emissions from Thai rice farming.

Contribution/Originality: This was one of the first studies in Thailand to examine the associations among paddy fields, tractor capacity, and GHG emissions. Small paddy fields increased GHG emissions due to inefficient navigation. Therefore, the results of this study show that a minimum paddy area of 0.24 hectares for a 36-horsepower tractor not only increased efficiency but also reduced environmental impact.

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1. INTRODUCTION

In the world, rice is the third most widely cultivated grain, and nearly one-fifth of the total calories consumed are derived from it. Its roles include contributions to the economy, food security, and serving as an important food source in many countries, especially in Asia. However, traditional rice production practices cause several negative environmental impacts. For example, approximately 1.5% and 48% of total global greenhouse gas (GHG) emissions originate from rice cultivation and agricultural croplands, respectively (Food Forward NDCs, 2024). Thailand is not only a major global rice producer and exporter but also has over 10 million hectares of rice-growing areas. Methane (CH_4) and nitrous oxide (N_2O) released from rice cultivation into the atmosphere cause climate change (Chung, Lee, Kim, Kang, & Kim, 2022). In addition to rice cultivation, agricultural machinery in the production process is another GHG source. Although agricultural technology has significantly increased the yield and efficiency of rice farming in Thailand, it is also a significant source of GHG emissions, particularly from the fuel used to power machinery (Pathak, Agarwal, Jain, & Rai, 2022). Land preparation, the first and most crucial step in rice cultivation, requires various agricultural machinery such as ploughs, tillers, and harrows. These tools require fuel to operate, resulting in fuel combustion and the release of carbon dioxide (CO_2), the primary greenhouse gas from such combustion (Ren, Liu, & Yang, 2023). Also, diesel used in tractors generates CO_2 as the main greenhouse gas (GHG) source. The highest diesel consumption and CO_2 emissions are associated with soil ploughing using traction, followed by harrowing/tilling and land preparation stages, including land levelling (Department of Alternative Energy Development and Efficiency, 2017). Specifically, diesel requirements for these stages are approximately 6.25–12.5, 3.13–6.25, and 1.88–3.13 liters per hectare, respectively. Correspondingly, CO_2 emissions for soil ploughing, harrowing/tilling, and land levelling are estimated at 16.75–33.50, 8.38–16.75, and 5.00–8.38 kg CO_2e/hectare, respectively. In addition to CO_2 emissions, soil disturbance caused by ploughing can lead to the production of other greenhouse gases such as N_2O and CH_4, contributing further to environmental impacts (Intergovernmental Panel on Climate Change, 2014).

Nowadays, mechanization is most commonly used in every agricultural stage, including tillage, irrigation, and harvesting, except sowing and transplanting rice seedlings. CO_2 gas is released directly from fuel combustion and indirectly from machinery production. For instance, indirect CO_2 gas emitted from machinery usage in cultivation in Vietnam's Mekong Delta was 0.02 tons per hectare (Nguyen & Nguyen, 2023). In general, the size of the paddy fields is the main factor affecting fuel consumption, but land preparation equipment for rice production can contribute to the quantity of GHG emissions. Also, wheel slips in tractors signify excessively worn tires, which can lead to wasted rotations and increased fuel consumption (Department of Primary Industries, 2021).

Uncorrelated machinery size to the farms' scales and characteristics results in two unfavorable economic repercussions (Edwards, 2020). Large machinery is an over-investment and requires a higher cost (Edwards, 2020). Similarly, large tractors are inefficient for small or non-rectangular-shaped farms since large amounts of fuel are wasted during headland turns (Cropilots, 2025). The heavy weight of machinery generates more soil compaction; the soil's properties, like this, are not good for long-term productivity (Solex Corporation, 2024). On the other hand, small machinery can result in yield or quality losses due to the inability to complete cultivation and harvesting within a limited time frame. The delays caused by using smaller machines and the reduction in labor costs may exceed the economic losses (Cropilots, 2025). One crucial factor often overlooked is time cost. If machinery is too small relative to the cultivated area, upgrading to a slightly larger machine can significantly reduce labor costs and minimize lost time.

Fuel costs are the main variable cost of tractor operation. Although larger tractors consume more fuel per hour, they work faster and are suitable for larger fields. On the other hand, smaller tractors use less fuel and are more efficient for smaller plots (Cropilots, 2025). According to the sensitivity analysis of the fuel consumption model, tractor size is the most significant factor. For example, improper tractor size increases fuel consumption by 10 to 41% (Van Linden, Vangeyte, & De Baerdemaeker, 2015). Fuel efficiency in agriculture depends not only on machinery but also on operating techniques such as using high gears and reducing engine speed (RPM) during tillage to save fuel. In some circumstances, large machinery is not the best choice since it consumes more fuel, increases production costs, and results in higher greenhouse gas emissions.

In Thailand, land ownership is a major obstacle to modernizing agriculture since most farmers have small-scale paddy fields with scattered land. Due to the small size and non-rectangular shape of rice fields, the use of heavy agricultural machinery is not cost-effective. Also, scattered land ownership limits effective resource management, particularly water resources (Lertphum, 2017).

In Thailand, farmers grow rice using the alternating wet and dry (AWD) irrigation system to minimize greenhouse gas emissions, particularly methane (CH_4). The traditional method involves storing water in paddy fields throughout the cropping season, whereas the AWD system alternates between flooding and drying the soil surface. During the drying phase, oxygen penetrates the soil, inhibiting anaerobic microorganisms, known as methanogens, from growing and producing methane (Sriphirom & Rossopa, 2023). However, the AWD irrigation system has limitations. Firstly, it is only effective in irrigated areas and cannot be applied to all soil types, especially saline and sandy soils, due to their low water-holding capacity. Secondly, proper ground leveling in paddy fields is essential for effective water management, as uneven ground can result in some areas being flooded while others are dry.

Previous studies indicate that electric tractors are a sustainable option for reducing GHG emissions. Nevertheless, the practical implementation of electric tractors is currently hindered by very high investment costs and a lack of supporting infrastructure, such as charging stations. Unlike diesel tractors, which are more durable and faster, electric tractors are currently less cost-effective (Karki, Shrestha, Sharma, Tuladhar, & Basnet, 2024).

Although Thailand is the world's leading rice producer, we still lack data for improving agricultural sustainability. The objective of this study was to investigate the proper tractors for rice paddy production since the suitable tractor size can improve operational efficiency, reduce energy consumption, and decrease GHG emissions from agriculture. Additionally, we explored GHG emissions from tractors during soil preparation across a range of rice fields to address this fundamental gap.

2. METHODOLOGY

The study was conducted during the wet-season rice cultivation period, and the data were collected once during the cropping season in Sakon Nakhon Province, Northeast Thailand (Figure 1). The experimental fields were mostly clay, with water depths ranging from 5 to 20 cm, and a hardpan at an average depth of 23 cm. For soil preparation, a small tractor with a 36-horsepower diesel engine and 1,230 kilograms in weight was used, as shown in Figure 2 (Udomkitmongkol, 2011). For the first plowing, the six-disc vertical plow with a 0.61-meter disc, 38-degree working disc angle, and 1.25-meter width was used in the 400-drive section. A rotary tiller with a working width of 1.65 m, a mass of 350 kg, and an operating rotational speed of 540 rpm was employed for the second tillage. Finally, a harrow with a 2-meter width and 95-kilogram weight was employed to level the soil surface effectively before the rice-planting phase.

The experimental paddy planting plot sizes were as follows: 0.04, 0.08, 0.16, 0.24, 0.32, and 0.48 hectares. Each experimental plot was investigated in triplicate. Each plot was rectangular in shape, with a length approximately 1.2 times the width. Data were collected at initial tillage, subsequent tillage, and the final harrowing stages. The data on variable factors such as tractor-wheel slip, the effective field capacity of the tractor, its fuel consumption rate, and the duration of implement lifting during headland turns were recorded (Regional Network for Agricultural Machinery, 1995). For GHG emissions from diesel engines, the determination was based on observed fuel consumption rates, adhering to the Intergovernmental Panel on Climate Change (IPCC) guidelines, specifically adapted for the Thai environmental context (Intergovernmental Panel on Climate Change, 2006). The formulas were employed for GHG emission calculations.

$GHG_{total} = (\text{Fuel consumption}_{diesel} \times EF_{CO2}) + (\text{Fuel consumption}_{diesel} \times EF_{CH4} \times GWP_{CH4}) + (\text{Fuel consumption}_{diesel} \times EF_{N2O} \times GWP_{N2O})$.

Where: GHG_{total} is the total GHG emissions in kilograms of carbon dioxide equivalent (kgCO2e).

$\text{Fuel consumption}_{diesel}$ is the amount of diesel fuel consumed (litres).

EF_{CO2} is the CO_2 emission factor for diesel fuel, equal to 2.698722 kgCO_2/litre.

EF_{CH4} is the CH_4 emission factor for diesel fuel, equal to 0.000142038 kgCH_4/litre.

EF_{N2O} is the N_2O emission factor for diesel fuel, equal to 0.000142038 kgN_2O/litre.

GWP_{CH4} is the Global Warming Potential of CH_4, equal to 28.

GWP_{N2O} is the Global Warming Potential of N_2O, equal to 265.

Statistical analysis: Pearson's correlation coefficient was applied to examine the relationship between the size of the paddy field and tractor performance during land preparation. The analysis focused on the relationships between field size and average wheel-slip rate, movement speed, field capacity, implement lifting time, and fuel consumption. To reflect real operating conditions, the correlations between various land preparation stages and tractor performance were calculated separately. The strength and direction of the correlations were interpreted according to Cohen, Cohen, West, and Aiken's (2003) guidelines, where r values range from −1 to +1. A p-value below 0.05 is considered statistically significant. This approach can address changing plot sizes associated with improvements in working efficiency, reductions in technical time loss, or decreases in fuel consumption, as these factors are directly related to greenhouse gas emissions during tractor-powered soil preparation.

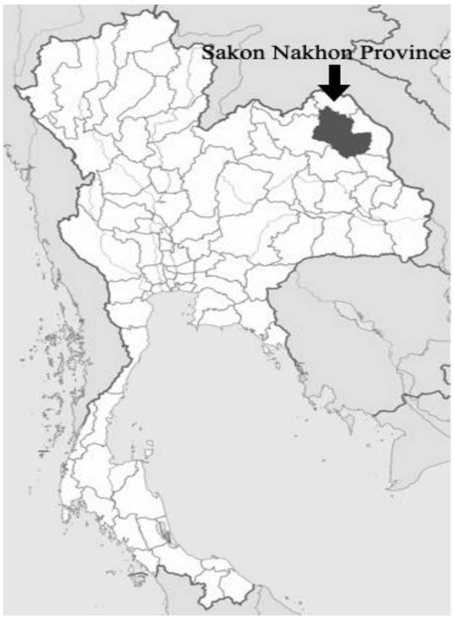

Figure 1. Sakon Nakhon Province, Northeast Thailand.
Source: Wikimedia Commons (2025).

Figure 2. A 36-horsepower diesel wheeled tractor.

3. RESULTS AND DISCUSSION

Vertical disc plow usage during the first tillage stage shows that soil conditions resulted in relatively high wheel slip rates. As a result, percentages of the wheel slip rates of the right driving wheel and the left driving wheel were 29.82-43.96 and 28.85-42.12%, respectively. The tractor speed during the plowing stage, the tractor's field capacity, fuel consumption rate, and implement lifting time during turning at the head of the plot were 4.34-4.73 kilometers per hour, 0.21-0.53 hectares per hour, 11.19–21.31 liters per hectare, and 0.25–1.94 hours per hectare, respectively (Table 1). Pearson's correlation analysis of tractor performance variables during the primary tillage stage shows that field area size had a significant positive relationship with field capacity ($r = 0.96$, $p < 0.01$). Namely, as the field area increases, the work rate, the amount of area plowed per unit of time, also increases. Conversely, the field area had a significant negative relationship with fuel consumption and implement lifting time ($r = -0.92$ and $r = -0.90$, respectively; $p < 0.01$). (Table 2).

Table 1. The values of wheel-slip rates, movement speed, field capacity, implement lifting time, and fuel consumption for the primary tillage.

Area size (ha)	Wheel slip rate		Movement speed (km/hr)	Field capacity (ha/hr)	Implement lifting time (hr/ha)	Fuel consumption (liter/ha)
	Right drive (%)	Left drive (%)				
0.04	38.25	35.67	4.67	0.21	1.94	21.31
0.08	43.00	42.12	4.57	0.27	1.44	18.63
0.16	29.82	28.85	4.51	0.40	0.63	13.94
0.24	43.96	39.59	4.34	0.43	0.44	13.06
0.32	35.92	36.95	4.68	0.51	0.38	11.25
0.48	31.64	31.25	4.73	0.53	0.25	11.19
Avg.	37.10	35.74	4.58	0.39	0.84	14.90

Table 2. Pearson correlations (r) between variables: area size, average values of wheel-slip rate, movement speed, field capacity, implement lifting time, and fuel consumption for primary tillage.

Variable	1	2	3	4	5	6
1. Area Size (ha)	1					
2. Avg. Wheel-Slip Rate (%)	-0.25	1				
3. Movement Speed (km/hr)	0.19	-0.66	1			
4. Field Capacity (ha/hr)	0.96**	-0.24	0.26	1		
5. Implement Lifting Time (hr/ha)	-0.90**	0.09	-0.09	-0.95**	1	
6. Fuel Consumption (liter/ha)	-0.92**	0.20	-0.20	-0.99**	0.98**	1

Note: ** Statistically significant at the 0.01 level (p-value < 0.01).

For the secondary tillage using a rotary tiller, the percentages of the right and the left wheel slip rates for the tractor's driving wheels were 15.96-29.99% and 15.38-29.67%, respectively. The tractor speed during the tilling stage across different plot sizes ranged from 4.05 to 4.90 kilometers per hour, the field capacity was between 0.36 and 0.58 hectares per hour, and fuel consumption varied from 12.25 to 14.19 liters per hectare. No implement lifting time was recorded during the second tillage stage since operators did not lift the rotary tillers from the ground (Table 3). However, the rotary tillers were employed continuously to work across the fields, eliminating headland turns during this stage. Based on Pearson's correlation analysis, there was a significantly positive relationship between field area size and field capacity ($r = 0.93$, $p < 0.01$). Similar to the first tillage stage, as the field areas increased, work rates and the area plowed per unit of time also increased. Conversely, there was a significantly negative relationship between field areas and fuel consumption ($r = -0.98$, $p < 0.01$) (Table 4).

Table 3. Average values of wheel-slip rate, movement speed, field capacity, implement lifting time, and fuel consumption for secondary tillage.

Area size (ha)	Wheel-slip rate		Movement speed (km/hr)	Field capacity (ha/hr)	Implement lifting time (hr/ha)	Fuel consumption (liter/ha)
	Right drive (%)	Left drive (%)				
0.04	15.96	16.39	4.89	0.36	0.00	14.19
0.08	19.41	18.23	4.79	0.40	0.00	13.56
0.16	17.76	15.38	4.90	0.51	0.00	13.00
0.24	29.99	29.67	4.31	0.52	0.00	12.88
0.32	17.81	16.01	4.83	0.54	0.00	12.50
0.48	20.20	19.57	4.05	0.58	0.00	12.25
Avg.	20.19	19.21	4.63	0.49	0.00	13.06

Table 4. Pearson correlations (r) between variables: area size, average values of wheel-slip rate, movement speed, field capacity, implement lifting time, and fuel consumption for secondary tillage.

Variable	1	2	3	4	5	6
1. Area size (ha)	1					
2. Avg. wheel-slip rate (%)	0.16	1				
3. Movement speed (km/hr)	-0.23	-0.49	1			
4. Field capacity (ha/hr)	0.93**	-0.08	0.17	1		
5. Implement lifting time (hr/ha)	-	-	-	-	1	-
6. Fuel consumption (liter/ha)	-0.98**	-0.24	0.33	-0.95**	-	1

Note: ** Statistically significant at the 0.01 level (p-value < 0.01).

Compared to primary tillage, the second tillage stage requires less digging force and operates at shallower soil layers. As a result, engine power requirements for the second tillage stage are lower than those of the first tillage stage. Due to fewer headland turns, fuel consumption is reduced during the second tillage stage. Therefore, these conditions lead to noticeably lower fuel consumption per hectare during this second stage. A certain level of wheel slip and energy loss still occurs in the second tillage stage, and the overall fuel efficiency in this stage is higher compared to primary tillage.

For land leveling using a harrow, the percentages of the right and left wheel slip rates due to soil conditions ranged from 18.38% to 31.66% and 18.43% to 30.45%, respectively. The tractor's speed during tilling across different plot sizes was between 5.71 and 6.34 kilometers per hour. The field capacity of the tractor varied from 0.68 to 0.96 hectares per hour, and fuel consumption ranged from 4.63 to 8.38 liters per hectare. Similar to the first tillage stage, no implement lifting time was recorded during harrowing. Pearson's correlation analysis of tractor performance variables during harrowing indicates a significant positive relationship between field area size and field capacity ($r = 0.83$, $p < 0.05$) (Table 5). Other variables, such as wheel slip rate, movement speed, and fuel consumption, did not show significant relationships with other variables. Since harrowing requires less force than plowing, there were slight interrelationships between the factors. Due to the small sample size, statistical analysis of the results was limited (Table 6).

Table 5. Average values of wheel-slip rate, movement speed, field capacity, implement lifting time, and fuel consumption for harrowing.

Area size (ha)	Wheel-slip rate		Movement speed (km/hr)	Field capacity (ha/hr)	Implement lifting time (hr/ha)	Fuel consumption (liter/ha)
	Right drive (%)	Left drive (%)				
0.04	18.38	18.43	5.71	0.80	0.00	4.63
0.08	26.02	24.13	5.83	0.71	0.00	8.38
0.16	25.96	25.27	6.34	0.94	0.00	6.25
0.24	31.66	30.45	4.85	0.68	0.00	8.31
0.32	30.35	29.01	5.52	0.96	0.00	5.50
0.48	25.96	25.23	5.64	0.95	0.00	5.63
Avg.	26.39	25.42	5.65	0.84	0.00	6.45

Table 6. Pearson correlations (r) between variables: area size, average values of wheel-slip rate, movement speed, field capacity, implement lifting time, and fuel consumption for harrowing.

Variable	1	2	3	4	5	6
1. Area size (ha)	1					
2. Avg. wheel-slip rate (%)	0.54	1				
3. Movement Speed (km/hr)	0.13	0.15	1			
4. Field capacity (ha/hr)	0.83*	0.40	0.40	1		
5. Implement lifting time (hr/ha)	-	-	-	-	1	-
6. Fuel consumption (liter/ha)	0.11	0.70	-0.41	0.01	-	1

Note: * Statistically significant at the 0.05 level (p-value < 0.05).

Analysis of the relationship between plot size and tractor field capacity during both the first and second tillage stages reveals that when the plot size increased from 0.04 to 0.24 hectares, the tractor's field capacity increased rapidly. However, when the plot size increased from 0.04 to 0.48 hectares, the tractor's field capacity increased as a curvilinear line (Figure 3). When the plot size exceeded 0.24 hectares, field capacity gains occurred at a slower rate. Compared to the first and second tillage stages, harrowing significantly affected field capacity at all plot sizes and increased rapidly, especially at smaller plot sizes.

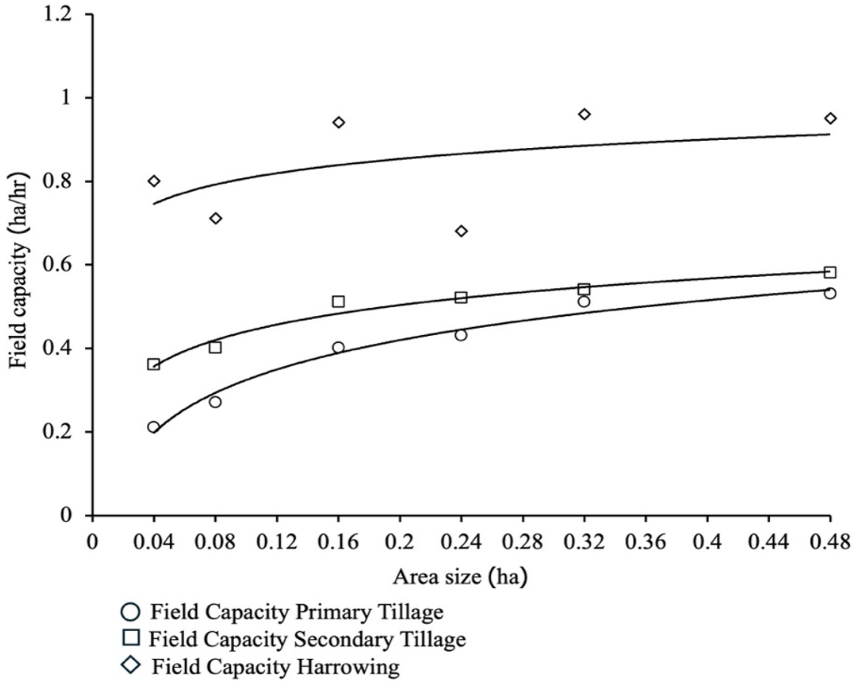

Figure 3. Field capacity of tractors in land preparation.

The relationship between the implement lifting time per hectare and plot size was clearly inverse. When the implement lifting time per hectare decreased significantly, the plot size increased. The highest implement lifting time per hectare was observed in 0.04- to 0.08-hectare plots, since tractors must frequently turn at the headlands and raise the plows. The implement lifting time per hectare was below 0.5 hours per hectare when the plot size was approximately 0.16–0.24 hectares. When the plot size exceeded 0.24 hectares, the implement lifting time was approximately zero. This result indicates that time loss due to lifting the implement becomes almost negligible in larger fields (Figure 4).

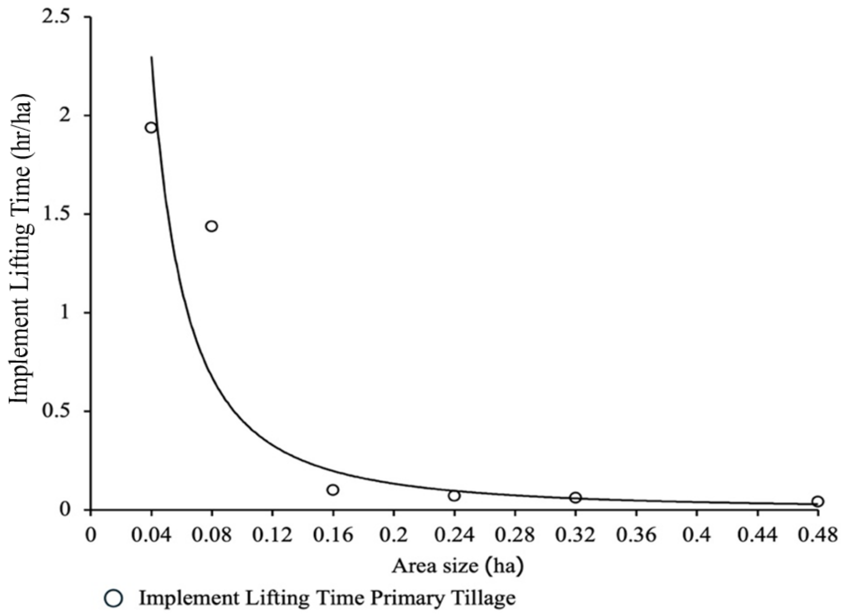

Figure 4. Implement lifting time during soil preparation.

Soil preparation using tractors is a significant source of GHG emissions, especially during the first tillage stage. The emitted CO_2 ranged from 30.66 to 58.40 kilograms per hectare. Compared to the first tillage stage, the second tillage stage generates less and more consistent CO_2 emissions, with values from 33.57 to 38.88 kilograms per hectare. Land levelling using harrows produces between 12.67 and 22.95 kilograms per hectare. The total GHG emissions from all preparation steps were summed for each plot size, with total emissions ranging from 79.64 to 111.16 kilograms per hectare (Table 7). The relationship between plot size and GHG emissions indicates that the first tillage stage produced the highest CO_2, followed by the second tillage stage, and then harrowing, respectively (Figure 5). As plot size increased, emissions from the first tillage stage decreased in a curvilinear manner. Across all plot sizes in this study, harrowing was the activity that produced the lowest CO_2 emissions. GHG emissions from agricultural tillage in Europe depended on soil-preparation methods. The GHG emission figures from this study were consistent with those from a previous survey by Sokal and Kachel (2025). For example, no-till and conventional tillage methods emit 89.36 and 180.76 CO_2 kilograms per hectare, respectively.

Table 7. Greenhouse gas emissions from tractors during rice field preparation (CO_2e kilogram/hectare).

Area size (ha)	GHG primary Tillage	GHG secondary Tillage	GHG Harrowing	Total GHG for rice field preparation
0.04	58.40	38.88	12.67	109.96
0.08	51.04	37.17	22.95	111.16
0.16	38.19	35.62	17.13	90.95
0.24	35.80	35.28	22.78	93.86
0.32	30.83	34.25	15.07	80.15
0.48	30.66	33.57	15.41	79.64
Avg.	40.82	35.80	17.67	94.28

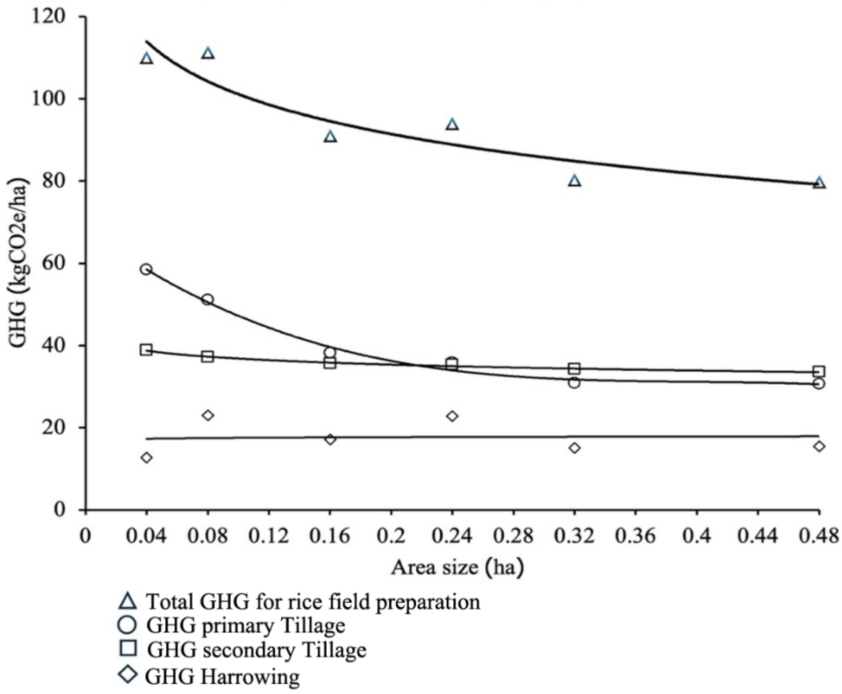

Figure 5. Effect of area size (hectare) on greenhouse gas (GHG) emissions (CO_2e kilogram/Hectare) from the primary tillage, secondary tillage, harrowing, and total rice field preparation.

Additionally, the relationship between paddy field size and GHG emissions during rice field preparation was clearly negative. The Pearson correlation coefficient (r) was greater than 0.80, indicating a very strong correlation and a significant relationship (p-value < 0.05). Nevertheless, GHG emissions from harrowing show no significant correlation with paddy field size (Table 8). Harrowing during soil preparation is more fuel-efficient than tillage stages since it only disturbs the topsoil, requires less traction power, and reduces both operational time and fuel consumption. On the other hand, tillage practices disturb the soil structure and enhance CO_2 emissions by increasing soil aeration and disrupting soil aggregates. Therefore, organic carbon is released and stimulates microbial activity responsible for greenhouse gas (GHG) emissions (Hassan et al., 2022). In addition to organic carbon released, tillage requires more fuel than harrowing due to higher soil resistance and fuel demand. The results are in agreement with a previous study that the percentages of machinery and fuel contributors to total GHG emissions were 11% and 89%, respectively (Elsoragaby et al., 2024).

On the other hand, agricultural machinery managers play a crucial role in determining and adjusting tillage parameters such as tractor power, soil texture, plowing depth and speed, initial soil moisture, bulk density, and plowing equipment. These properly configured factors can reduce fuel consumption (Al-Sager, Almady, Marey, Al-Hamed, & Aboukarima, 2024).

Table 8. The correlation between paddy fields and greenhouse Gas (GHG) emissions from soil preparation.

Correlation	r	*p*-value	Strength	Direction
Total GHG	-0.90	0.013*	Very strong correlation	Negative
GHG primary tillage	-0.88	0.021*	Very strong correlation	Negative
GHG secondary tillage	-0.93	0.008*	Very strong correlation	Negative
GHG harrowing	-0.16	0.76	Very weak correlation	Negative

Note: * Statistically significant at the 0.05 level (p-value < 0.05).

4. CONCLUSION AND RECOMMENDATIONS

Paddy field size significantly influenced tractor field capacity, fuel consumption rate, and technical time loss in soil preparation for rice cultivation. Unlike smaller fields, larger fields had higher field capacity. On the other hand, large paddy field size significantly reduced fuel consumption and technical time losses, especially during the first and second tillage stages. Tractor-powered soil preparation led to greater GHG emissions from fuel consumption in smaller plots, compared to larger plots.

According to the analysis of correlations among six paddy field sizes, the size of paddy fields greater than 0.24 hectares tends to emit lower GHG emissions and achieve higher tractor operating time efficiency. Therefore, a paddy field size of approximately 0.24 ha or more is considered appropriate and provides the highest efficiency in the operation of agricultural machinery.

One limitation of this study was the particular location. The experimental rice field was in Sakon Nakhon Province, Northeastern Thailand, since the results in this study may be impractical for other geographic areas. Furthermore, the study was limited to one tractor type and six small-scale plot combinations. As a result, this research methodology has to be reproduced in other parts of Thailand and expanded to encompass a wider variety of tractors and implement sizes. Further research on tillage equipment design needs to reduce operational times, improve soil preparation efficiency, and decrease fuel consumption, as all of these factors contribute to greenhouse gas emissions reduction.

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Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: Both authors contributed equally to the conception and design of the study. Both authors have read and agreed to the published version of the manuscript.
Disclosure of AI Use: The author(s) used OpenAI's QuillBot and Grammarly to edit and refine the wording of the Introduction. All outputs were reviewed and verified by the authors.

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