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Calculating Fuel Efficiency for Head-Feeding Combine Harvesters

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Abstract

We investigated the impact of crop and soil conditions at the time of harvesting on the fuel efficiency of head-feeding combine harvesters and developed a correction method for quantitatively calculating fuel efficiency under comparable conditions. The fuel consumption during travel and driving increased with the softness of the soil, showing a strong correlation with the index of hardness indicated by the Yamanaka model soil penetrometer. We also confirmed that the fuel consumption during travel and driving increased with the mass of rough rice in the grain tank. As a result of a multiple regression analysis using a stepwise regression for hourly fuel consumption under various conditions, the fuel consumption during reaping, conveying, threshing, sorting, and cutting can be calculated from the flow rate of dried crop (kg s^{-1}), number of unhusked rice grains per gram (g^{-1}), and moisture content of unhusked rice (%). We used the multiple regression equation developed in this study to propose a method for extending it to other combines. Furthermore, to easily calculate the fuel efficiency of head-feeding combine harvesters in a 3,000 m^2 area, we developed an algorithm that accounts for each fuel consumption component in determining fuel efficiency, considering the mechanical elements of head-feeding combine harvesters and crop conditions, and confirmed its validity.

Discipline: Agricultural Engineering
Additional key words: flow rate of dried crops, grain number per gram, moisture content of unhusked rice, rate of work, soil surface hardness

Introduction

In Japan, automobile assemblers are required to achieve a higher level of performance than the standard fuel efficiency established by the 1979 Act on the Rational Use of Energy. Consequently, significant technical advancements have been made to enhance the fuel efficiency of automobiles. The recent reduction in greenhouse gas emissions following the Kyoto Protocol of 2005 has helped curb global warming. The implementation of standards and regulations for automobiles is not limited to Japan; these regulations have also been enacted in the US, the EU, and other Asian countries. Unlike automobiles, agricultural machines are not covered by these laws. However, as most agricultural machines have internal combustion engines or drying burners, improved fuel efficiency will play a crucial role in reducing greenhouse gas emissions.

Regulations on fuel efficiency and gas emissions for automobiles are developed by measuring both metrics based on the actual driving velocity pattern designated in the respective countries. Regulations on fuel efficiency do not exist for agricultural machinery in Japan. However, regulations on gas emissions for agricultural machinery have been enforced. Unlike automobiles, these regulations are enforced for emissions from engines mounted on machinery, rather than for emissions from the entire vehicle. To measure gas emissions, a fixed load pattern is given to the engine while controlling the engine revolution during the measurement process. Simultaneously measuring fuel efficiency and gas emissions for agricultural machinery could be advantageous in terms of repeatability of the test, as well as in terms of time and labor. The load patterns in the 8 Mode Method (Testing

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Cycle C1) and the NRTC Method (JIS B 8008-4 2009, JIS B 8008-11 2008) are currently used to measure gas emissions from agricultural machinery equipped with diesel engines. However, these patterns are designed with a holistic view of diesel-powered special motor vehicles, including construction machinery. Consequently, the operating environment for this design differs from that of agricultural machinery, and these patterns are dissimilar to those found in in-field work. A difference has been reported between the actual operational status of tractors and the 8 Mode Method (Seki et al. 2006), indicating that current testing methods for gas emissions are not suitable for investigating fuel efficiency.

Tomita et al. (2013) measured the torque in head-feeding combine harvesters and found that such harvesting requires continuous high-load work. Head-feeding combine harvesters are widely used in Japan and are now also used in other Asian countries. Conventionally, the full-tank method, which involves filling the fuel tank before and after harvesting, has been utilized to evaluate the fuel efficiency of head-feeding combine harvesters (Suzuki 1980). This is a fact-based test method because field testing is conducted. However, the repeatability of the obtained data is reduced by the variation in fuel efficiency performance that depends on the crop and field conditions during the test. Head-feeding combine harvesters have their own tank to store unhusked rice. They repeat the processes of "harvesting" and "90° turn." Once the storage tank is full, they transport the unhusked rice to a truck waiting adjacent to the paddy field and discharge it. Each of these processes has varying fuel efficiency characteristics that affect the overall fuel efficiency.

In a previous study on the fuel efficiency of combine harvesters, Spokas & Steponavičius (2009, 2010) conducted experiments on harvesting wheat using conventional combine harvesters at different harvesting velocities. They reported that fuel consumption per unit time increased with increasing flow rate, while both crop harvesting and fuel consumption decreased with increasing reaping height. Baruah & Panesar (2005a, 2005b) reported an energy demand model for each component of conventional combine harvesters. This group also conducted multiple regression analyses based on the results of harvesting tests with paddy rice plants and wheat plants using seven conventional combine harvesters (engine power of 29.0-55.0 kW, wheel drive system) and associated the developed models. Sakai et al. (1988) calculated the fuel consumption per unit area required for paddy rice plant harvesting in four categories: "load by crop feeding," "load by reaping, threshing, and sorting parts," "load by traveling," and "load by engine without working." However, no studies have examined the impact of yield per unit time and crop conditions on fuel efficiency for head-feeding combine harvesters.

This study was based on the work structure of head-feeding combine harvesters and considered that the fuel efficiency of these harvesters is affected by: fuel consumption during travel and driving (FC_{TD} (L h^{-1})); fuel consumption during reaping, conveying, threshing, sorting, and cutting (FC_{RCTSC} (L h^{-1})); fuel consumption during a 90° turn ($FC_{90°}$ (L/a turn)); fuel consumption during transport (FC_T (L h^{-1})); and fuel consumption during unhusked rice discharge (FC_D (L kg^{-1})) (Fig. 1). FC_{TD} is defined as the amount of fuel required to travel without harvesting crops on the driving harvesting parts, and FC_{RCTSC} is obtained by subtracting FC_{TD} from the fuel consumption required for harvesting paddy rice plants (fuel consumption during harvesting, FC_H (L h^{-1})). $FC_{90°}$ and FC_D are measured to obtain the fuel consumption required for making a 90° turn and paddy rice discharge, respectively. FC_T is the fuel required to transport to the truck waiting adjacent to the field.

We previously clarified the impact of soil surface hardness and its increase with the mass of rough rice in the grain tank on fuel consumption (Yamasaki 2020). We also clarified the relationship between crop conditions at the time of harvesting and the fuel consumption (Yamasaki 2021). Based on these results, we have developed a method for calculating the efficiency of head-feeding combine harvesters required for harvesting a specific area.

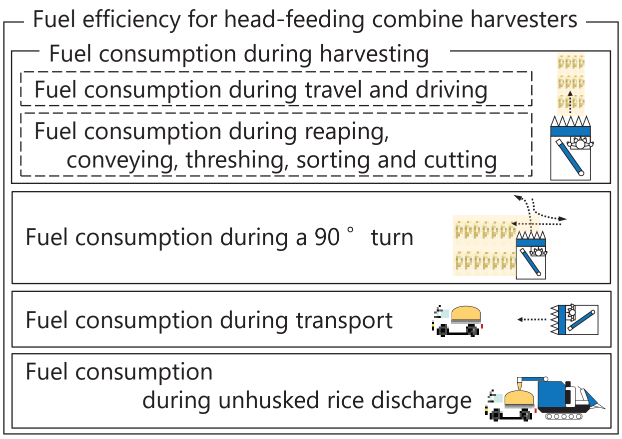


Fig. 1. Fuel efficiency components of head-feeding combine harvesters

Testing method

1. Method of evaluating fuel consumption during travel and driving (Yamasaki 2020)

(1) Impact of soil surface hardness on fuel consumption during travel and driving, FC_{TD}

We used four models of four-row head-feeding combine harvesters, made by Japanese manufacturers, for testing. The engine speed was set to the rated revolution output, with the travel velocity for three testing sections set at 70%, 80%, and 90% of the maximum velocity at harvesting. The test was conducted with an empty grain tank. To obtain testing results under different field conditions, locations in various post-harvest paddy rice fields were selected to ensure they were not rutted. The soil surface hardness was measured on flat ground without crawler tracks, which should also be at the center of both inter-row space and inter-hill space. A Yamanaka model soil penetrometer (DAIKI RIKA KOGYO, Push-Cone DIK-5553) was used, following the Standard Methods for Soil Analysis and Measurement (Commission for Standard Methods for Soil Analysis and Measurement 2003).

(2) Impact of increased machinery body mass by the harvested crop relative to fuel efficiency during travel and driving, FC_{TD}

A four-row head-feeding combine harvester was provided. To conduct the test, the engine revolution was set to the rated revolution output, with three testing sections set at 70%, 80%, and 90% of the maximum velocity at harvest for the travel velocity. We conducted unloaded travel on a concrete surface while activating the reaping, threshing, and sorting parts of the machinery, with the grain tank fully loaded (631 kg) with unhusked rice. We then varied the mass of unhusked rice (“grain mass”) in the grain tank to 529, 332, 233, and 0 kg, to continue the measurement in a similar manner.

2. Method of evaluating fuel consumption during reaping, conveying, threshing, sorting, and cutting (Yamasaki 2021)

(1) Measurement of fuel consumption during harvesting, FC_H

The test equipment was a four-row head-feeding combine harvester. We performed 18 tests by harvesting paddy rice plants (*Oryza sativa* L. cultivars: Koshihikari, Sainokagayaki, Sainominori, and Asanohikari) under different conditions. Three reaping levels were selected by setting the number of rows between 3 and 5, and the harvesting velocity was set to four ratios (i.e., 60%, 70%, 80%, and 90%) of the maximum velocity at harvest. Test A consisted of 12 experimental plots with a combination of three reaping levels and four harvesting velocities, which were performed 14 times. Test B consisted of seven experimental plots: 3 rows, 60%; 3 rows, 70%; 3 rows, 80%; 4 rows, 70%; 4 rows, 80%; 5 rows, 70%; and 4 rows, 90%. Test B was performed four times.

(2) Measurement of fuel consumption during travel and driving, FC_{TD}

Following the harvesting examination, we continued to use the same head-feeding combine harvester and set the travel velocity to 60%, 70%, 80%, and 90% of the maximum velocity at harvest. We allowed the head-feeding combine harvester to travel without harvesting by operating in harvesting mode, and permitted the reaping, conveying, threshing, sorting, and cutting unit to operate during unloaded travel. During the examination, we selected areas in the field that were not dilapidated, using an empty grain tank.

(3) Analytical methods

We classified the samples so that the sample for the multiple regression model (training set) and the sample for model verification (Test Set) had a ratio of 2:1; the mean and variance of FC_{RCTSC} were equivalent in both sets. A multiple regression analysis was used to determine the effect of crop conditions on fuel consumption, using the SAS Add-In 7.1 for Microsoft Office (SAS Inc.) statistical analysis software on the following objective and explanatory variables with a stepwise regression based on inputs with a significance probability (*P*-value) of $P \leqq 0.050$ and removals with $P \geqq 0.100$.

We calculated FC_{RCTSC} as an objective variable as the difference between the measured FC_H and FC_{TD}. The hourly fuel consumption (converted to 15°C) in the measurement section was calculated by recording the fuel flow rate and fuel temperature.

$$FC_{RCTSC} = FC_H - FC_{TD} \tag{1}$$

Possible explanatory variables were flow rate of wet straw F_{WS} (kg s^{-1}), flow rate of dried straw F_{DS} (kg s^{-1}), flow rate of wet unhusked rice F_{WR} (kg s^{-1}), flow rate of dried unhusked rice F_{DR} (kg s^{-1}), flow rate of wet crop F_{WC} (kg s^{-1}), flow rate of dried crop F_{DC} (kg s^{-1}), moisture content of unhusked rice MC_R (N g^{-1}), straw unhusked rice ratio R_{SR} (-), moisture content of straw MC_S (%), wet straw yield Y_{WS} (kg/m^2), 1,000 grains weight $W_{1,000grains}$ (g), number of unhusked rice grains per gram $N_{R\text{-}1g}$ (g^{-1}), required force for detaching unhusked rice RF_{DR} (N), and cumulative force of detaching unhusked rice per gram $CF_{DR\text{-}1g}$ (N g^{-1}). We selected explanatory variables for which hourly fuel consumption was considered to increase with higher values.

3. Calculation algorithm of fuel efficiency in a 3,000 m^2 area for head-feeding combine

(1) Prerequisites for algorithm creation

In creating the algorithm, we performed calculations under conditions as close as possible to the actual harvest. However, our primary purpose is to fairly compare fuel efficiency among different models. When the working components of head-feeding combine harvesters in the algorithm are too close to the actual harvest in detail, the operator may be unable to maintain the data reproducibility between tests. For example, although the fuel consumption for oblique cutting in the four corners of a paddy field is different from that during normal harvesting, even if the fuel consumption during normal harvesting is approximated, there is no significant problem in comparing the fuel consumption among different models. Therefore, we determined the prerequisites shown in Table 1 so that the fuel efficiency in a 3,000 m^2 area (L/3,000 m^2) could be calculated by simply adding each fuel consumption component shown in Figure 1.

We used the Microsoft Excel spreadsheet (Microsoft Corporation) and its Visual Basic for Applications macro function to create software ("fuel efficiency calculation software") to calculate fuel efficiency based on the new algorithm.

(2) Software operation check and evaluation

Tomita et al. (2006) developed a simulator for the rate of work and confirmed that it has no practical problems compared to actual harvesting. The simulator for the rate of work consists of five corners: reaping, roundabout reaping, dividing reaping, return reaping, and discharge. It is assumed that the truck for transporting unhusked rice waits at the position of the short-side center on the approach path side. This simulation method for the rate of work was adopted as an alternative to the rate of work measured in paddy fields in the National Test used by the Ministry of Agriculture, Forestry and Fisheries of Japan until 2018 (MAFF, 2004). The simulator for the rate of work and the fuel efficiency calculation software were compared to verify whether the combination of each component is appropriate. We measured each parameter for a four-row head-feeding combine harvester as an evaluation object and calculated the rate of work in a 3,000 m^2 area using each software approach. Table 2 lists the input parameters for each software for the rate of work. The FC_D was defined as the fuel consumption required to discharge 1 kg of unhusked rice. The moisture content of unhusked rice was 22.1 ± 0.05% when FC_D was measured. The yield of unhusked rice (L-23% w.b./m^2) was calculated from the yield and bulk density of unhusked rice, and the time required for 5 m after starting was calculated from the value of harvesting velocity without considering acceleration and deceleration. The crop and soil conditions in Table 1, as well as the fuel efficiency calculation software, are considered general conditions for harvesting paddy rice plants, based on consultations with Japanese manufacturers of head-feeding combine harvesters, researchers, and farmers.

The validity of fuel efficiency is usually verified by comparing it with the measured fuel efficiency in paddy rice plant fields. However, because measured fuel efficiency is greatly affected by crop conditions at the time of harvesting, it is difficult to obtain comparable fuel efficiency in actual fields unless the crop and soil conditions in 3,000 m^2 paddy fields are uniform. Moreover, because fuel efficiency is calculated by

Table 1. Prerequisites to calculate fuel efficiency

No.	Prerequisites
1	The paddy field has a rectangular shape 30 m × 100 m. This is because this field shape has long been adopted as a standard shape in field improvement projects by MAFF since 1963.
2	With reference to the standard, operation, and explanation of the land improvement project plan and design "Plan: Footing area maintenance (paddy field)" (The Japanese Society of Irrigation, Drainage and Rural Engineering 2013), there shall be a space where trucks for transporting unhusked rice can wait and an approach path to the paddy field on the short side of the paddy field.
3	The truck for transporting unhusked rice waits at a position on the short side of the paddy field, which is the shortest distance from the head-feeding combine harvesters heading for discharging.
4	The four corners of the paddy field are provided with a space capable of smoothly turning, and oblique cutting and hand reaping are not required when harvesting the outermost periphery.
5	In the entire process, harvesting is carried out by counterclockwise roundabout reaping, and all turns measure 90°.
6	The fuel consumption required for harvesting should be the same if the area to be harvested is the same regardless of the direction and location of harvesting.
7	Crop and soil conditions shall be the same throughout the test field.

Table 2. Overview of the input parameters for each software

	Simulator for the rate of work		Fuel efficiency calculation software	
	Parameter	Input value	Parameter	Input value
Crop conditions	Unhusked rice yield (kg-15% w.b./m^2)	0.67	Unhusked rice yield (kg-15% w.b./m^2)	0.67
	Moisture content of unhusked rice (%)	23	Unhusked rice yield (L-23% w.b./m^2)	1.32
	Bulk density (kg L^{-1})	0.56	Bulk density (kg L^{-1})	0.56
Paddy field conditions	Paddy field area (m^2)	3,000	Paddy field area (m^2)	3,000
	Length (m)	100	Length (m)	100
	Width (m)	30	Width (m)	30
	Hand reaping area (m^2)	0		
Machine conditions	Range of harvest (m)	1.20	Range of harvest (m)	1.20
	Range of reaping blade (mm)	1,440	Capacity of grain tank (L)	1,000
	Overall length (mm)	4,245	Maximum velocity (m s^{-1})	1.44
	Capacity of grain tank (L)	1,000	Harvesting velocity (m s^{-1})	1.20
	Maximum velocity (m s^{-1})	1.44	Discharge speed (kg s^{-1})	5.00
	Harvesting velocity (m s^{-1})	1.20	Time required for a turn (s)	10.2
	Time required 5 m after departure (s)	4.35		
	Discharge speed (kg s^{-1})	5.00		
	Distance from dividing straw rod to tip of reaping blade (mm)	765		
	Distance from reaping blade to crawler's contact surface (mm)	845		
	Ground contact length of crawler (mm)	1,425		
	Minimum turning radius of machine (m)	2.50		
	Minimum turning radius of crawler (m)	1.70		

combining the same components as the rate of work, we considered that the usefulness could be confirmed by comparing the rate of work and verifying its validity.

Results and discussions

1. Method of evaluating fuel consumption during travel and driving (Yamasaki 2020)

(1) Relation between index of hardness and fuel consumption during travel and driving

Hourly fuel consumption was confirmed to increase in response to an increase in the travel velocity. Thus, we obtained a regression equation relating travel velocity to hourly fuel consumption for each test section using the least squares method to calculate the hourly fuel consumption at 80% of the maximum velocity at harvest. We noted a strong correlation between the index of hardness X (mm) and fuel efficiency ratio FE_R (the hourly fuel consumption in each field divided by the one on the road). From the regression equation obtained via the least squares method, we calculated an index of hardness of approximately 23 mm, corresponding to hourly fuel consumption equivalent to road travel.

Figure 2 shows the proposed correction model of FC_{TD} per the soil conditions, based on our results. We connected the plot (23, 1) at which the fuel efficiency ratio is equivalent to traveling on the road and the plot (a, b) at which hourly fuel consumption was measured, to obtain an equation to explain the relation between index of hardness X (mm) using the provided machinery and fuel efficiency ratio, FE_R.

$$FE_R = \left\{\frac{(\mathrm{b}-1)X}{\mathrm{a}-23}\right\} + \left(\frac{\mathrm{a}-23\mathrm{b}}{\mathrm{a}-23}\right) \tag{2}$$

To correct the impact of soil surface hardness, we calculate the fuel efficiency ratio under standard conditions by substituting X = 15 in Equation (2), assuming that the index of hardness for surface soil hardness under standard conditions is 15 mm.

(2) Impact of an increase in the machinery body mass due to the harvested crops on fuel efficiency during travel and driving

Regarding an increase in grain mass, we confirmed an increase in the hourly fuel consumption, FC_{TD}. Based on the results, we propose the following correction method for fuel efficiency. By applying hourly fuel consumption FC_{TD} in both empty and full grain tank status, along with grain mass M_F (kg) when the grain

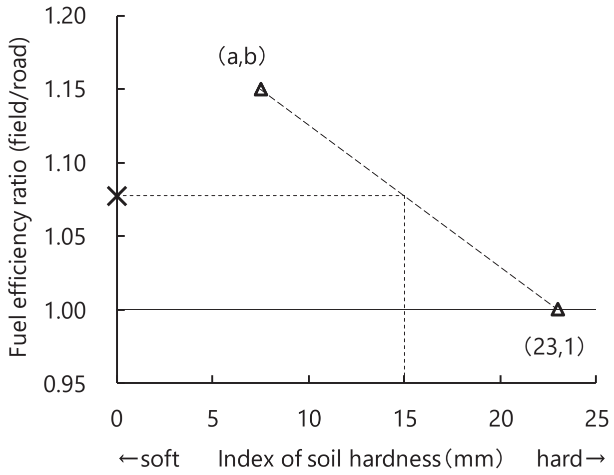


Fig. 2. Correction model of fuel efficiency during travel and driving in accordance with soil conditions

tank is full, we obtain ε (kg^{-1}), a coefficient to correct the impact of the grain mass on hourly fuel consumption FC_{TD}. Using ε, the hourly fuel consumption FC_{TD} when the grain mass is M (kg) can be expressed as $FC_{TD\text{-}M}$ (L h^{-1}) by the equation below.

$$\varepsilon = \frac{FC_{TD-F} - FC_{TD-E}}{FC_{TD-E} \times M_F} \tag{3}$$

$$FC_{TD-M} = (\varepsilon \times M + 1) \times FC_{TD-15} \tag{4}$$

where
$FC_{TD\text{-}F}$: FC_{TD} on a solid road when the grain tank is full (L h^{-1})
$FC_{TD\text{-}E}$: FC_{TD} on a solid road when the grain tank is empty (L h^{-1})
$FC_{TD\text{-}15}$: FC_{TD} corrected when the index of hardness is 15 mm (L h^{-1}).

Due to the change in M over time during harvest testing, $FC_{TD\text{-}M}$ also constantly changes. We would thus obtain an additional amount of fuel consumption caused by an increase in grain mass. Based on these considerations, Figure 3 shows the relation between work time T (h) and an increase in the hourly fuel consumption caused by an increase in grain mass, during harvest work in which grain mass increased from M_B (kg) to M_A (kg). The influence of the unhusked rice weight in each harvesting process IF_{RG} (L) is the integral of fuel flow rate with respect to time (the shaded area of the figure), and therefore can be expressed as:

$$IF_{RG} = (M_B + M_A) \times \varepsilon \times FC_{TD-15} \times T \times \frac{1}{2} \tag{5}$$

As for $FC_{90°}$ and FC_T, which differ from FC_{TD} only in terms of their working velocity, the above correction method can be applied in the same way, considering the impact of surface soil hardness and grain mass on fuel consumption.

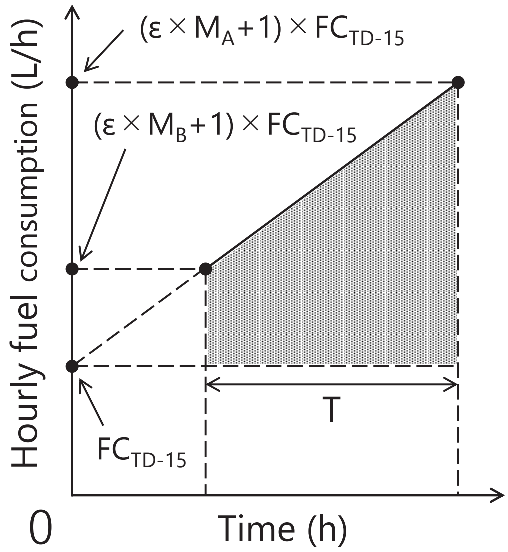


Fig. 3. Relation between working time and increase in hourly fuel consumption caused by an increase in grain mass

2. Method of evaluating fuel consumption during reaping, conveying, threshing, sorting, and cutting (Yamasaki 2021)

(1) Derivation and verification of the equation for calculating hourly fuel consumption

The multiple regression model showing FC_{RCTSC} was as follows:

$$FC_{RCTSC} = (1.52 \times F_{DC}) + (0.0577 \times N_{R-1g}) + (0.0490 \times MC_R) - 3.65 \tag{6}$$

We confirmed the relationship between the FC_{RCTSC} (the measured value) and the calculated values obtained by substituting each numerical value into each explanatory variable of the above equation. In the training set, $R^2_{adj.}$ exhibited a high value of 0.887, and the value of SEC was calculated to be 0.238 L h^{-1}. The prediction accuracy of the developed model was 0.883 for $R^2_{adj.}$ and 0.233 L h^{-1} for SEP. The results were generally similar, and we judged that a good data regression was derived by the value of R^2_{adj}.

(2) Comparison with other head-feeding combine harvesters

Equation (6) is a unique equation for the head-feeding combine harvester used in this study (the standard combine). It cannot be applied to other head-feeding combine harvesters (the target combines) for which hourly fuel consumption evaluation is desired. To compare the standard combine harvester to the target combine harvesters using Equation (6), we propose the following procedure (Fig. 4).

① Harvesting tests are undertaken by changing the number of reaping rows, harvesting velocity, and harvesting time using the target combines. The crop and harvesting velocity of the test is substituted into each variable in the equation to obtain hourly fuel consumption units when harvested with the standard combine.

② A regression equation is created using the least squares method between the calculated hourly fuel consumption values and the measured hourly fuel consumption of the target combines.

③ The regression equation is used to confirm the superiority or inferiority of the fuel consumption to the target combine in the state of the value of the standard combine set by evaluators.

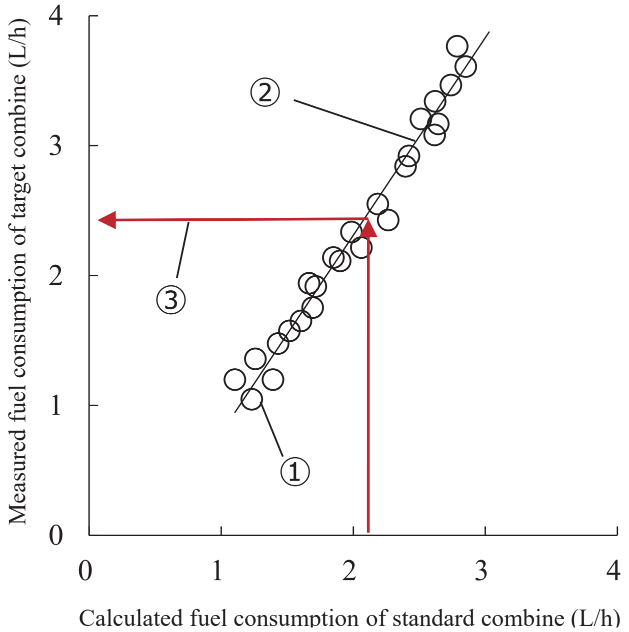


Fig. 4. Application of the method to other combines
The regression line is indicated by a solid line.

As a result of verifying this method using five head-feeding combine harvesters (including those with engine power and number of reaping rows different from the standard combine), we obtained good coefficients of determination. Therefore, it was confirmed that the proposed method could be applied to head-feeding combine harvesters with different engine power and number of reaping rows.

3. Calculation algorithm of fuel efficiency in a 3,000 m² area for head-feeding combine

(1) Consideration of the discharge process

The timing of discharge and the moving distance depend on the numerical values of the grain tank capacity, unhusked rice yield, moisture content of unhusked rice, and bulk density of unhusked rice. To create an algorithm for discharge, we defined the processes involved in discharge, as shown in Table 3, taking into account the prerequisites outlined in Table 1.

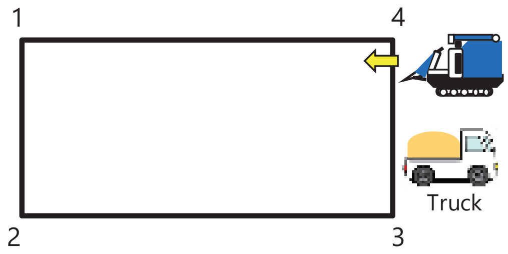
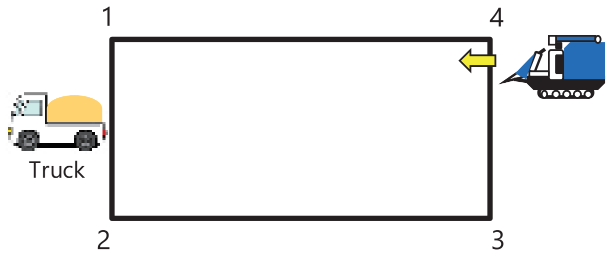
We assumed two patterns: a case in which the truck stands on the approach path side of a combine harvester (Case 1) and a case in which the truck stands on the opposite side (Case 2). 90° turns performed in the four corners of the paddy field are performed by a combination of 45° forward turns and 45° reverse turns. Moreover, all discharge-related turns are performed forward and can be viewed as two 45° forward turns. Therefore, there would be no difference between forward and reverse turns in fuel consumption and the required time for turning; hence, we treated all 90° turns the same. Regarding the discharge timing, fuel efficiency and work rate are improved by discharging before or after harvesting the side where the truck is standing, rather than waiting to discharge until the grain tank is full. Head-feeding combine harvesters equipped with yield sensors have become popular recently, and those that predict when the grain tank is full and encourage discharge at the optimum time are already available on the market. Thus, our assumption is reasonable.

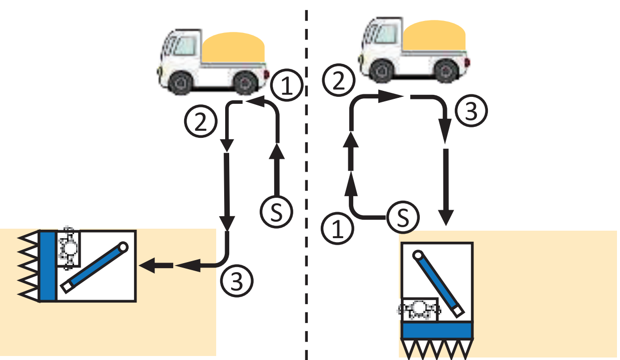
(2) Algorithm for calculating fuel efficiency in a 3,000 m² area

Figure 7 illustrates an algorithm for calculating fuel efficiency in a 3,000 m² area based on the discharge process. First, whether the results of Case 1 or Case 2 shown in Table 3 are to be calculated is selected (Fig. 7 (a)). The harvest of one side and a 90° turn are defined as one process, and the number of work processes N is calculated from the reaping width W_R (m) according to Equation (7) (Fig. 7 (b)).

$$N = \left[\frac{30}{W_R}\right] \times 2 - 1 \tag{7}$$

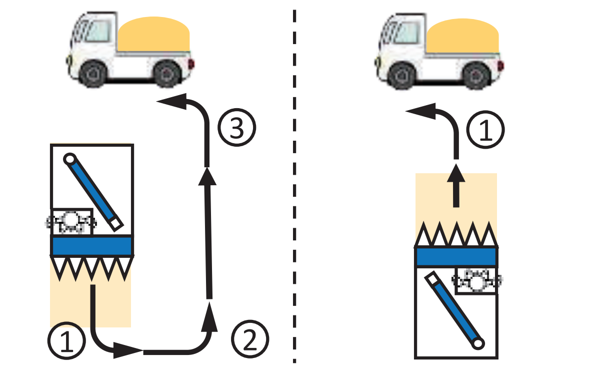
Table 3. Process for discharge

	Case 1	Case 2
		
	Numbers 1- 4 indicate the corners of the unreaped paddy rice plant region.	
Common matters	The fuel consumed in moving for a discharge is reduced by one turn, which would have been required if it had not been directed to the discharge, and is defined as two turns and a round trip to the truck (Fig. 5). When the truck for transporting unhusked rice is located in front of the combine harvester, the fuel consumed in moving for discharging after the harvest is one turn and one way transfer to the truck, and when the truck is in back of the combine harvester, it is three turns and one way transfer to the truck (Fig. 6). The fuel consumed by moving to the truck for discharge and turning is affected by the grain weight of the grain tank as it heads for the discharge.	
Individual matters	If the grain tank is expected to be filled during the reaping of 3-4, the operator shall proceed to discharge from position 3 in advance. When discharging in 3, the weight of unhusked rice in the grain tank affects the fuel consumption required for one turn and the outward trip to the truck. If the grain tank is expected to be filled during the reaping of 4-1, 1-2, and 2-3, then the operator shall proceed to discharge from position 4 in advance. When discharging in 4, the weight of unhusked rice in the grain tank affects the fuel consumption required for two turns and the outward trip to the truck.	If the grain tank is expected to be filled during the reaping of 1-2, the operator shall proceed to discharge from position 1 in advance. When discharging in 1, the weight of unhusked rice in the grain tank affects the fuel consumption required for one turn and the outward trip to the truck. If the grain tank is expected to be filled during the reaping of 2-3, 3-4, and 4-1, then the operator shall proceed to discharge from position 2 in advance. When discharging in 2, the weight of unhusked rice in the grain tank affects the fuel consumption required for two turns and the outward trip to the truck.



(A) After long side harvest (B) After short side harvest

Fig. 5. Movement of the combine harvester
Ⓢ:starting position; Arabian figures: number of turns



(A) Discharge at the front of the combine harvester (B) Discharge at the rear of the combine harvester

Fig. 6. Movement of the combine harvester toward discharge after finishing harvesting
Arabian figures: number of turns

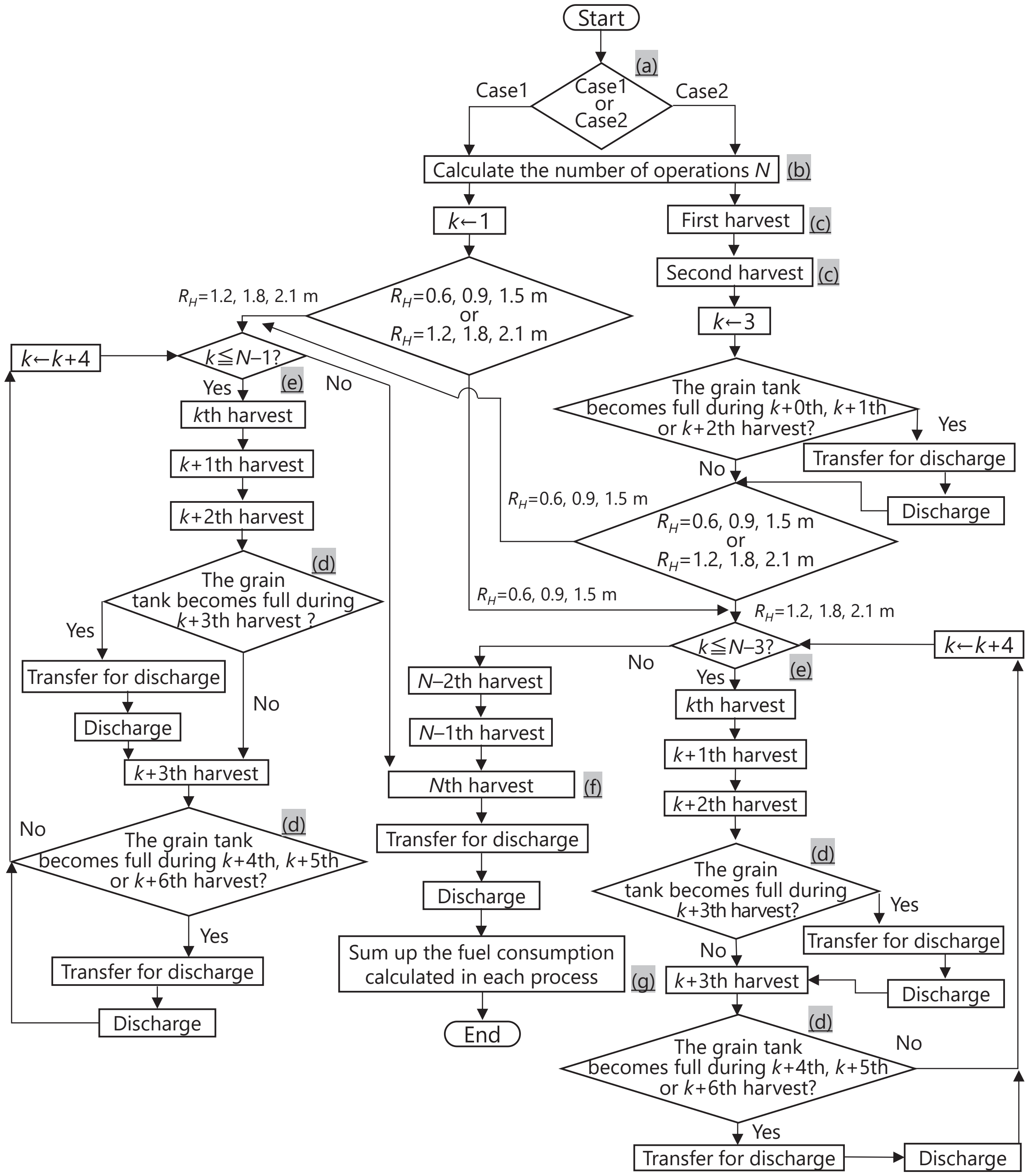


Fig. 7. Algorithm for the fuel efficiency calculation

where

⌈ ⌉: Ceiling for Gauss' symbol.

The fuel consumption increased due to the influence of the unhusked rice weight in each harvesting process. The IF_{RG} (L) is calculated using Equation (8) (Fig. 7(c)). Equation (8) is defined with reference to Equation (5).

$$IF_{RG} = (M_B + M_A) \times \varepsilon \times FC_{TD} \times \frac{D_H}{60^2 V_H} \times \frac{1}{2} + M_A \times \varepsilon \times FC_{90°} \quad (8)$$

where

M_B: Grain mass before harvest work (kg)

M_A: Grain mass after harvest work (kg)

ε: Coefficient to correct the impact of grain mass (kg^{-1})

D_H: Distance during harvesting (m)

V_H: Harvesting velocity ($m\ s^{-1}$).

When the head-feeding combine harvester reaches the side where the truck is standing, it is determined whether the grain tank will be full by the end of harvesting the side or by the next three processes. If the grain tank is expected to be full, the head-feeding combine harvester moves to the truck and discharges the unhusked rice (Fig. 7 (d)). At the time of discharging, Equations (9) and (10) are calculated for the fuel consumption during transport and 90° turns for discharging unhusked rice $AFC_{T\&90^\circ}$ (L) and the time $T_{T\&90^\circ}$ (s).

$$AFC_{T\&90^\circ} = FC_T \times (\varepsilon \times M_A + 2) \times \frac{D_T}{60^2 V_T} + FC_{90^\circ} \times 2 \text{ [Fig. 6(A)]}$$
$$AFC_{T\&90^\circ} = FC_T \times (\varepsilon \times M_A + 2) \times \frac{D_T}{60^2 V_T} + FC_{90^\circ} \times (\varepsilon \times M_A + 2) \text{ [Fig. 6(B)]} \quad (9)$$

$$T_{T\&90^\circ} = \frac{D_T}{V_T} \times 2 + T_{90^\circ} \times 2 \quad (10)$$

where
D_T: Distance during transport (m)
V_T: Transport velocity (m s^{-1})
T_{90°: Time during a 90° turn (s).
Each time harvesting is performed in four processes (one lap), it is determined whether harvesting will be completed during the next lap (Fig. 7(e)). Whether the last lap is composed of one or three processes depends on the harvest range. After harvesting in the *N*th process, the head-feeding combine harvester moves to the truck and discharges the unhusked rice (Fig. 7 (f)). Equations (11), (12), (13), (14), (15), and (16) are used to calculate FC_{RCTSC} in the 3,000 m^2 $FE_{RCTSC\text{-}3000m^2}$ (L/3,000 m^2) and the harvesting time in the 3,000 m^2 $T_{H\text{-}3000m^2}$ (s/3,000 m^2), the turning time in the 3,000 m^2 $T_{90^\circ\text{-}3000m^2}$ (s/3,000 m^2), the fuel consumption excluding the influence of the unhusked rice weight during traveling, driving, and 90° turns in the 3,000 m^2 (not including transport for discharge) $FE_{TD\&90^\circ\text{-}3000m^2}$ (L/3,000 m^2), FC_D in 3,000 m^2 $FE_{D\text{-}3000m^2}$ (L/3,000 m^2), and the time in the 3,000 m^2 $T_{D\text{-}3000m^2}$ (s/3,000 m^2) as

$$FE_{RCTSC-3000m^2} = \frac{FC_{RCTSC}}{60^2 V_H \times W_R} \times 3000 \quad (11)$$

$$T_{H-3000m^2} = \left\{ \frac{3000 - \left(100 - W_R \left\lfloor \frac{N}{2} \right\rfloor\right) \times \left(30 - W_R \left\lfloor \frac{30}{W_R} \right\rfloor\right)}{R_H} + \left(100 - W_R \left\lfloor \frac{N}{2} \right\rfloor\right) \right\} \times \frac{1}{V_H} \quad (12)$$

$$T_{90^\circ-3000m^2} = T_{90^\circ} \times (N-1) \quad (13)$$

$$FE_{TD\&90^\circ-3000m^2} = FC_{TD-15} \times \frac{T_{H-3000m^2}}{60^2} + FC_{90^\circ} \times (N-1) \quad (14)$$

$$FE_{D-3000m^2} = FC_D \times Y_R \times \frac{100-15}{100-23} \times 3000 \quad (15)$$

$$T_{D-3000m^2} = Y_R \times \frac{100-15}{100-23} \times 3000 \times \frac{1}{BD} \times S_D \quad (16)$$

where
Y_R: Unhusked rice yield (moisture content at 15% conversion) (kg m^{-2})
BD: Bulk density (kg L^{-1})
S_D: Discharge speed (L s^{-1})
$\lfloor\ \rfloor$: floor for Gauss' symbol.
In addition, the sum of IF_{RG} in the 3,000 m^2 $IF_{RG\text{-}3000m^2}$ (L/3,000 m^2), $AFC_{T\&90^\circ}$ in the 3,000 m^2 $FE_{T\&90^\circ\text{-}3000m^2}$ (L/3,000 m^2), and the time during transport and 90° turns in the 3,000 m^2 $T_{T\&90^\circ\text{-}3000m^2}$ (s/3,000 m^2) were calculated using Equations (17), (18), and (19).

$$IF_{RG-3000m^2} = \sum_{k=1}^{N} (IF_{RG-k}) \quad (17)$$

$$FE_{T\&90^\circ-3000m^2} = \sum_{k=1}^{N_D-1} (AFC_{T\&90^\circ-k}) + FC_T \times \varepsilon \times M_E \times \frac{D_T}{60^2 V_T} + FC_{90^\circ} \times \varepsilon \times M_E \text{ [Fig. 7(A)]}$$
$$FE_{T\&90^\circ-3000m^2} = \sum_{k=1}^{N_D-1} (AFC_{T\&90^\circ-k}) + FC_T \times \varepsilon \times M_E \times \frac{D_T}{60^2 V_T} + FC_{90^\circ} \times \varepsilon \times M_E \times 3 \text{ [Fig. 7(B)]} \quad (18)$$

$$T_{T\&90^\circ-3000m^2} = \sum_{k=1}^{N_D-1} (T_{T\&90^\circ-k}) + \frac{D_T}{V_T} + T_{90^\circ} \text{ [Fig. 7(A)]}$$
$$T_{T\&90^\circ-3000m^2} = \sum_{k=1}^{N_D-1} (T_{T\&90^\circ-k}) + \frac{D_T}{V_T} + T_{90^\circ} \times 3 \text{ [Fig. 7(B)]} \quad (19)$$

where
$IF_{RG\text{-}k}$: IF_{RG} at the kth process (L)
N_D: Number of discharges
$AFC_{T\ \&90°\text{-}k}$: Fuel consumption during transport and 90° turns at the kth discharge (L)
M_E: Grain mass at the end of the harvest work (kg)
$T_{T\&90°\text{-}k}$: Time during transport and 90° turns at the kth discharge (s).
The fuel consumption and time were totaled, and the fuel efficiency in the 3,000 m² FE_{3000m^2} (L/3,000 m²) and the rate of work in the 3,000 m² T_{3000m^2} (s/3,000 m²) were calculated using Equations (20) and (21) (Fig. 7 (g)).

$$FE_{3000m^2} = FE_{RCTSC-3000m^2} + FE_{TD\&90°-3000m^2} + FE_{D-3000m^2} + IF_{RG-3000m^2} + FE_{T\&90°-3000m^2} \quad (20)$$

$$T_{3000m^2} = T_{RCTSC-3000m^2} + T_{TD\&90°-3000m^2} + T_{D-3000m^2} + T_{T\&90°-3000m^2} \quad (21)$$

(3) Calculation of the fuel efficiency and rate of work in a 3,000 m² area

Table 4 shows the breakdown of the calculation results by the simulator for the rate of work and fuel efficiency calculation software. The time for harvesting was 2,194 s with the simulator for the rate of work and 2,083 s with the fuel efficiency calculation software; it took longer for the simulator, which carried out return reaping. Shito et al. (2010) used a self-propelled harvesting roll baler to harvest 3,000 m² and measured the rate of work both counterclockwise roundabout reaping and return reaping. In this report, like our results, it took longer to carry out return reaping: 357 s with the simulator for the rate of work and 490 s with the fuel efficiency calculation software. The duration of each 90° turn was 7.8 s with the simulator for the rate of work and 10.2 s in the measured value, and the difference between the simulator and the measured value affected it. Regarding the time for transport, the simulator for the rate of work did not consider turning during the transport.

The rate of work by the simulator was 3,129 s/3,000 m². On the other hand, the rate of work in Case 1 was 3,220 s/3,000 m², and that in Case 2 was 3,157 s/3,000 m². The relative error to the simulator for the rate of work was as small as 2.9% and 0.9%. We confirmed the validity of this software in calculating the rate of work. In terms of fuel efficiency, because each component is calculated in the same combination as the rate of work, we considered that the total fuel efficiency in the 3,000 m² area could be estimated using this software.

Because the number of calculations increases as the number of harvesting processes increases, the processing time of this software is affected by the reaping width. Therefore, we used three personal computers: ①Intel Xeon (2.66 GHz) CPU, 24 GB memory, 500 GB HDD; ② Intel Core i3 (3.70 GHz) CPU, 4 GB memory, 500 GB HDD; and ③ Intel Pentium IV (3.06 GHz) CPU, 2 GB memory,: 120 GB SDD with different specifications as samples and measured the time required for calculating by changing the range of harvesting from 0.6 m (two rows) to 2.1 m (seven rows). There was no significant difference in the number of harvesting processes or the specifications of the personal computers, and the calculation time was as short as 0.4 s.

Provisions for the future

This research enables the establishment of standards for fuel efficiency and the publication of fuel efficiency performance in catalogs and websites of head-feeding combine harvesters. This will contribute to the increased use of fuel-efficient head-feeding combine harvesters among farmers. We believe that farmers will be able to choose machines based on their fuel efficiency performance, which will lead to improved overall fuel efficiency, similar to the case of automobiles. It can also be used by manufacturers to appropriately evaluate technology for improving fuel efficiency, thereby promoting technological development. In 2021, the Ministry of Agriculture, Forestry and Fisheries (MAFF) established the “Strategy for Sustainable Food Systems,”

Table 4. Breakdown of the fuel efficiency calculations

	Simulator for the rate of work	Fuel efficiency calculation software	
		Case 1	Case 2
Time for harvesting (s)	2,194	2,083	2,083
Time for turning (s)	357	490	490
Time for transport (s)	134	203	140
Time for discharge (s)	444	444	444
Total (s)	3,129	3,220	3,157

which stated the need for "Zero CO_2 emission from fuel combustion in agriculture, forest, and fisheries." We believe that the need for this research will continue to grow.

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