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Working Load Analysis of a 42 kW Class Agricultural Tractor According to Tillage Type and Gear Selection during Rotary Tillage Operation

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Abstract: The objective of this study was to analyze the effect of tillage type (i.e., primary and secondary tillage) and gear selection (P1L2 to P1L4) on the working load of tractor–implement systems during rotary tillage. Soil properties change with depth, and differences in properties along the depth distribution, such as the location of formation of the hardpan layer, internal friction angle, and moisture content, affect the load of rotary tillage operations. Therefore, the physical properties of soil along the field depth distribution were measured to analyze the effect of tillage type and gear selection on workload in rotary tillage. In addition, a load measurement system equipped with PTO torque meter, axle torque meter, proximity sensor, and RTK-GPS were configured on the 42 kW agricultural tractor. The experimental results show that the combination of tillage type and gear selection has a wide-ranging effect on the tractor's workload and performance when the rotavator operated at the same tilling depth. Overall working load was higher by up to 14% (engine) and 29.1% (PTO shaft) in primary tillage compared to secondary tillage when the gear selection was the same. When the tillage type is the same, it was analyzed that the overall average torque increased by up to 35.9% (engine) and 33.9% (PTO shaft) in P1L4 compared to P1L2 according to gear selection. Based on load analysis results, it was found that the effect of gear selection (Engine: 4–14%, PTO: 12.1–28.6%) on engine and PTO loads was higher than that of tillage type (Engine: 31.6–35.1%, PTO: 31.9–32.8%), and the power requirement tended to decrease in secondary tillage. Therefore, working load should be considered according to the soil environment and tillage type when designing agricultural machinery system.

Keywords: working load; agricultural tractor; rotary tillage; soil property; tillage type

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1. Introduction

In Korea, agricultural tractors have a working area of 18.9 ha per unit and an operation rate of 74.3%. Tractors not only simply pull attached implements, but also deliver the required power to drive attached implements through a power take-off (PTO) shaft [1]. In particular, agricultural power using PTO is mainly used for high-load agricultural work such as powered disc plow, rotary, and baler operation. Because tractors are subjected to large and irregular working load fluctuations depending on the type of agricultural work performed, it is necessary to analyze the largest fluctuation load on the tractor to ensure reliability [2,3].

For the optimal design of agricultural tractors and implements, it is necessary to measure and analyze the load data generated during agricultural work [4]. Basically, various load measurement tests were conducted for plow tillage. The initial working load analysis study was conducted mainly in the soil bin test bed to analyze soil–tool interaction. Raper [5] conducted a study related to the analysis of minimum draft force generation according to subsoiler geometry via a soil bin test. As a result, it was confirmed that the soil disruption was better with less resistance in the bentleg shanks than in the straight shanks. Other studies have conducted various types of soil–tool interaction study related to working conditions and load influence parameters on the basis of field experiments. Naderloo et al. [6] analyzed the tillage depth and travel speed effect on draft force using three types of plow treatment under clay loam soil conditions. Additionally, Moeenifar [7] conducted field experiments to analyze the influence of tillage depth and penetration angle on soil–thin blade interaction. In addition, Aday and Ramadhan [8] conducted draft force and distribution area analysis studies with respect to single-tine and double-tine conditions in the subsoiler. In another study, Kichler et al. [9] conducted field tests to analyze the effect of transmission gear selection on tractor performance and fuel cost as a function of the geometric shape of the subsoiler during deep tillage operations. The field test results showed that the productivity rate increased as the appropriateness of gear selection increased, while the fuel cost decreased. In another study, Kim et al. [10] analyzed the effect of soil water content on the traction performance of agricultural tractors during tillage operation. On the basis of the results of the test, it was concluded that overall tractor traction performance parameters such as axle torque, slip and traction increased proportionally with increasing soil water content. In addition, Kim et al. [11,12] conducted field tests to analyze the field environment (i.e., soil texture and soil properties) and the effect of tillage depth and gear selection on the working load of tractors during tillage operations.

In addition, some studies have conducted field load measurement tests for agricultural operations using PTO power. Lee et al. [13] conducted field tests to measure the PTO working load during rotary tillage and baler operation in Korean upland fields. In another study, Behera et al. [14] analyzed the effects of tillage depth and travel speed on PTO torque, draft force and fuel consumption in rota-cultivators. Additionally, Kim et al. [15,16] conducted a load analysis study on the effect of different gear combinations on the PTO working load during rotary tillage. In another study, Kim et al. [17] conducted field measurement testing of the PTO working load of a multi-purpose cultivator in order to identify the weak part of the PTO gear train.

Rotary tillage is used in both primary and secondary tillage operations. It is also useful for puddling the field before paddy transplantation. However, load analysis studies with respect to the soil working environments and tillage types used in primary and secondary methods have not been performed. Therefore, this study was conducted to evaluate the working load of 42 kW class agricultural tractor with respect to tillage type and gear selection during rotary tillage, which is the most widely used agricultural operation that uses tractor PTO power. The main purposes were to (1) develop a field load measurement system with an experimental design, (2) measure and analyze the working load data during rotary tillage, and (3) perform an analysis of the effect of tillage type and gear selection on tractor working load.

2. Materials and Methods

2.1. Measurement of Field Soil Properties

Basically, all working loads of agricultural machinery originate from the soil environment. Since the rotary work was performed in two fields with different physical properties, soil property measurement tests were performed. Figure 1 shows the soil sampling procedure of the field soil properties. Soil properties were measured using the uniform grid (3 m × 3 m) sampling method in the field [18]. The test field was divided into 10 uniform grid squared, and soil sampling was performed in each grid square to measure the physical

properties of the soil, and in the case of the cone penetration test and vane shear test, which were performed to measure the engineering properties of the soil, 10 tests were performed in each grid, for a total of 100 tests.

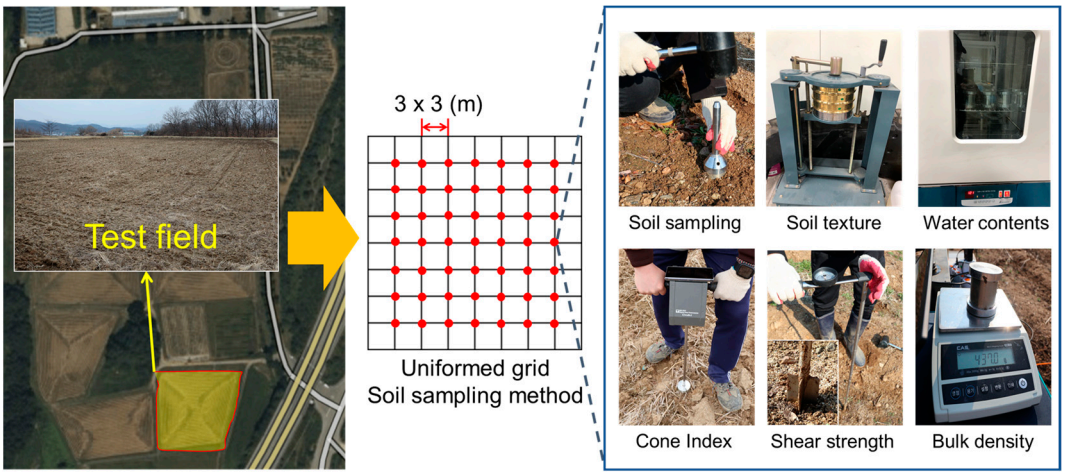


Figure 1. Sampling procedure of field soil property using uniformed grid method.

First, soil sampling was performed in each test field, A and B, using a 100 mL soil sampling tube (DIK-1801, Daiki Rika Kogyo Co., Ltd., Akagidai, Japan) and a soil sampling device (DIK-1815, Daiki Rika Kogyo Co., Ltd., Akagidai, Japan). To measure the soil water content, the soil specimen was dried at a temperature of 110 °C for 24 h [19] using the oven-drying method (SH-DO-100FGB, Samheung Energy, Sejong, Republic of Korea). The soil texture of field site was analyzed using the USDA soil classification method [20] using a sieve shaker (HJ-4560, Heungjin, Gimpo, Republic of Korea) [21].

Additionally, cone index and shear strength, which are the most important parameters among soil mechanical properties, and have the greatest impact on agricultural workload, were measured using a cone penetrometer (DIK-5532, Daiki Rika Kogyo Co., Ltd., Akagidai, Japan) [22,23] and a shear ring-type soil resistance meter (DIK-5503, Daiki Rika Kogyo Co., Ltd., Saitama, Japan), respectively.

In this study, the soil properties measured in this study were obtained using Equations (1)–(3) [24,25]:

$$W = \frac{100W_w}{W_s}, \tag{1}$$

where W is the soil water content (%), W_w is the water weight of the soil specimen, and W_s is the weight of solids in the soil specimen.

$$\gamma = \frac{W}{V}, \tag{2}$$

where γ is the bulk density (g/cm^3), W is the total weight of the soil specimen (kg), V is the total volume of the soil specimen (cm^3).

$$\tau = \frac{3M}{28\pi r^3}, \tag{3}$$

where τ is the shear strength of soil (kPa), M is the soil resistance torque that caused the on-field vane shear test (Nm), and r is the radius of shear box.

2.2. Tractor–Implement System

Figure 2a shows a rotavator (WJ185A, Woongjin Machinery, Gimje, Republic of Korea), often used in studies on soil–machine interactions to analyze working load using PTO power. The rotavator undertakes a high-load operation compared to other agricultural operations,

such as plowing. Therefore, it is suitable for soil–tool interaction studies of agricultural machinery using PTO power. The rotavator has a maximum tillage depth of 200 mm, and the dimensions are 810 mm × 2020 mm × 1130 mm (length × width × height). In addition, it has 7 flanges and 42 tillage blades, with a working width of 1820 mm. The detailed specifications of the attachment implement are shown in Table 1.

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

Figure 2. Tractor–implement system used in this study: (**a**) rotavator (WJ185A, Woongjin, Republic of Korea); (**b**) 42 kW class agricultural tractor (TX58, TYM, Gongju, Republic of Korea).

Table 1. Specifications of the rotavator.

Item	Specification
Company	Woongjin
Model	WJ185A
Required power (kW)	35~45
Length (mm) × width (mm) × height (mm)	810 × 2020 × 1130
Tillage width (mm)	1820
Weight (kg)	405
Max. tillage depth (mm)	200
Number of flanges	7
Number of blades	42

In this study, a 42 kW tractor (TX58, Tong Yang Moolsan, Gongju, Republic of Korea) was used, considering that the specifications of the rotavator indicate that a power source of 35~45 kW is required, as shown in Figure 2b. The overall dimensions of the agricultural tractor body were 3695 mm × 1848 mm × 2560 mm (length × width × height), with a rated power of 35.6 kW and a maximum torque of 211.8 Nm. The test tractor's total weight was 3894 kg, and with the inclusion of the DAQ system (229 kg) and a front loader (450 kg) (HIT400 L, Hanil Industry Co., Ltd., Gyeongsan, Republic of Korea). The agricultural tractor used in the field experiment was equipped with a mechanical transmission power shuttle, and through a combination of 4 main gears and 6 subgears, a total of 48 gears (24 forward gears, 24 reverse gears) could be shifted, depending the tilling work, and the maximum speed was 33.8 km/h. In addition, the PTO power train is a three-stage power train, and has rotational speeds of 540, 750, and 1000 rpm, respectively. The specifications of the agricultural tractor are shown in Table 2.

Table 2. Results of measured soil properties of test field according to soil depth.

Parameters	Soil Depth: 0 to 10 cm	Soil Depth: 10 to 20 cm
Water contents (WC, %)	20.6 ± 1.2	17.7± 1.1
Bulk density (γ, kg/m^3)	1571.7 ± 75.2	1830 ± 30.6
Cone index (CI, kPa)	801.8 ± 277.6	2065.9 ± 643.1
Shear strength (τ, kPa)	25.1 ± 7.2	64.3 ± 14.4

2.3. Working Load Measurement System

Figure 3 shows the overall measurement system of a 42 kW agricultural tractor for measuring working load during the rotary tillage. The DAQ (data acquisition) system was Dewesoft X (Dewesoft 3X, Dewesoft, Trbovlje, Slovenia), and the working load was measured simultaneously during rotary tillage at a sampling rate of 1 kHz. The working load measurement system used to analyze the effect of soil properties on the design load of the tractor–implement system during tillage operations is as follows:

$$V_{th} = \frac{\pi D_{rw} N_{rw} GR 3.6}{60} \tag{4}$$

where V_{th} is the theoretical speed of the tractor in the working direction (km/h), D_{rw} is the diameter of the rear wheel axle (m), N_{rw} is the wheel axle rotational speed as calculated by proximity sensors (rpm), and GR is the gear ratio,

$$S = \left(\frac{V_{th} - V_a}{V_{th}}\right) \times 100 \tag{5}$$

where S is the slip ratio (%) and V_a is the travel speed as the actual working speed of the tractor, as measured by RKT-GPS (km/h).

Figure 3. Configuration of the field load measurement system.

The engine load measuring unit featured a 5 kNm strain gauge torque transducer mounted on the flex plate to measure the engine torque (T_e), which measured the torque data with non-contact sensor telemetry through an amplifier. The engine rotational speed (N_e) was measured by sampling at 100 Hz based on wireless CAN (Controller Area Net-

work) communication and then synchronized with other working load data at 1 kHz using DAQ system. In addition, the engine power requirement can be obtained as follows:

$$P_e = \frac{2\pi T_e N_e}{60,000} \tag{6}$$

where P_e is the power requirement of the engine (kW), T_e is the engine torque (Nm) measured by the flex plate torque transducer, and N_e is the engine rotational speed (rpm) measured by controller area network (CAN) communication.

The torque of the wheel axle and the PTO shaft was measured using a flange-type torque transducer (Sensor telemetrie GmbH PCM16, MANNER, Spaichingen, Germany). The wheel axle torque and PTO torque data from each torque transducer were amplified by internal amplifiers. The torque range of the transducer was 15–30 kNm. In addition, a proximity sensor (CYGTS211B-PO2, Chen Yang Technologies GmbH & Co. KG, Finsing, Germany) was installed on the inner side of each wheel axle in order to measure wheel axle rotational speed. This method of measuring rotational speed has been used in previous studies [26,27]. An antenna integrating a torque transducer, a proximity sensor and an amplifier was installed inside and outside each wheel axle shaft to precisely measure the wheel axle load and the PTO axle load simultaneously. In the case of the proximity sensor, the measuring range was up to 20,000 rpm with a response frequency of 1–20 kHz. In addition, the power requirements of the agricultural tractor were analyzed in order to evaluate the working load of wheel axles and PTO shafts during rotary tillage operations, as follows:

$$P_w = \frac{2\pi T_w N_w}{60,000}, \tag{7}$$

where P_w is the power requirement of the wheel axle (kW), T_w is the wheel axle torque (Nm), as measured by the wheel torque meter, and N_w is the wheel axle rotational speed (rpm), as measured by the proximity sensor.

$$P_{PTO} = \frac{2\pi T_{pto} N_{pto}}{60,000}, \tag{8}$$

where P_{PTO} is the power requirement of the PTO shaft (kW), T_{PTO} is the PTO shaft torque (Nm), as measured by the PTO torque transducer, and N_{PTO} is the rotational speed of the PTO shaft (rpm), as measured by CAN communication.

To measure fuel consumption, an oval gear flowmeter (OG2-SS5-VHQ-B, Titan Enterprises, Sherborne, UK) was installed at the fuel injection inlet and outlet. Specific fuel consumption (SFC), which is often used as a performance indicator for fuel consumption, can be obtained using the following equation. The fuel cost was also calculated using the method described in another study [9].

$$FC = \frac{60(F_{in} - F_{out})}{0.83}, \tag{9}$$

$$SFC = \frac{FC}{P_e}, \tag{10}$$

$$PR = \frac{TS \times WW}{10}, \tag{11}$$

$$\text{Fuelcost} = FC \times \frac{1}{PR} \times FP, \tag{12}$$

where *FC* is the fuel consumption of the engine (kg/h), F_{in} is the flow rate (L/min) measured by the flow meter installed at the fuel inlet of the engine, F_{out} is the flow rate (L/min) measured by the flow meter installed at the fuel outlet of the engine, *SFC* is the specific fuel consumption (g/kWh), *PR* is the productivity rate (ha/h), *TS* is the travel speed measured

by RTK-GPS (km/h), *WW* is the working width (m), fuel cost (USD/ha), and *FP* is the fuel price (1.31 USD/kg).

2.4. Field Experimental Design

In this study, field experiments were conducted to analyze the effect of tillage type and gear selection on the working load of agricultural tractors during rotary tillage. The field test site was located at 37°93′67.2″ N and 127°78′20.6″ E. After carrying out the soil property measurements using the equipment and method described in Section 2.1, rotary tillage was repeatedly performed using a tractor equipped with a field load measurement system.

The test was performed on the basis of the 3 × 2 split-plot design under three different gear selection (combinations of a PTO stage 1 and transmission gear stages L2 to L4 (i.e., P1L2, P1L3, and P1L4)) and two tillage types (primary and secondary tillage), as shown in Figure 4. Under no-load conditions, the first PTO gear stage had a PTO shaft rotational speed of 540 rpm, and the L2, L3, and L4 transmission gear stages had theoretical travel speeds of about 1.57, 2.25, and 3 km/h, respectively, at rated engine rotational speed. However, a load measurement test for rotary tillage was performed under full-throttle conditions in four-wheel-drive mode, taking into consideration the driving propensities of farmers. In addition, the plowing depth was set to about 10–12 cm, and the engine, axle, PTO, travel speed, and slip were measured three times with each test condition as the target measurement parameter.

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

Figure 4. Load measurement test during rotary tillage: (**a**) primary tillage; (**b**) secondary tillage.

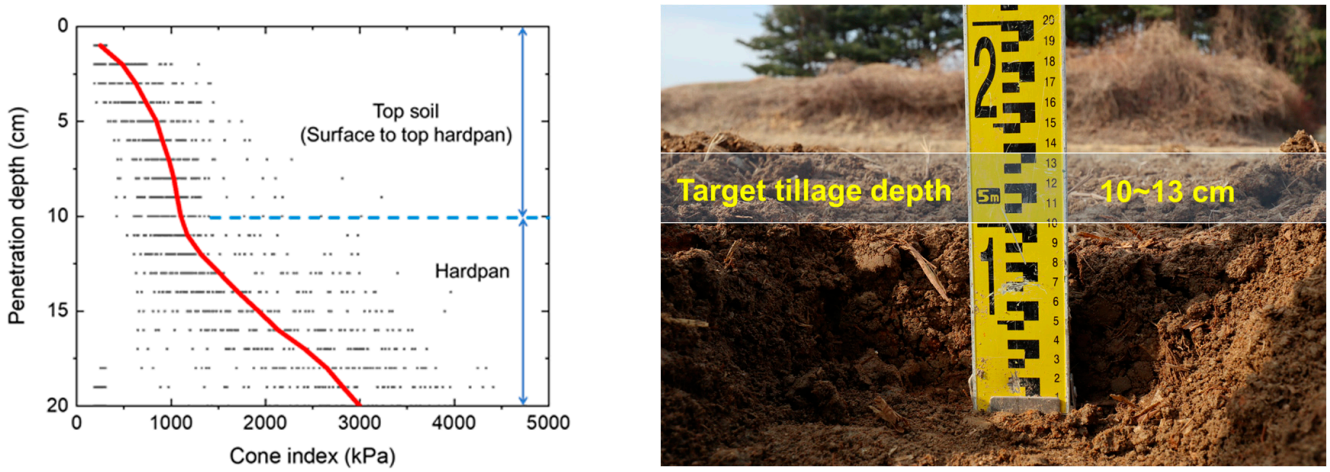
3. Results

3.1. Analysis of Soil Properties

In general, soil compaction in agricultural soils increases with the repeated use of heavy machinery such as tractors. Therefore, the distribution tendency of soil properties varies depending on the soil depth [28]. First, from the results of the cone penetration test analysis performed to see the distribution of mechanical properties of the soil, it was found that the cone index value rapidly increased at around 10 cm, as shown in Figure 5. Specifically, it showed an average value of 801.8 ± 277.6 kPa at a depth of about 0–10 cm and an average value of 2065.9 kPa at a depth of 10–20 cm. The average values at a depth of 10–20 cm were found to be 2.57 times higher than those measured at 0–10 cm.

Based on the results of the cone penetration test, the field soil properties were measured by dividing it into two depths. Table 3 shows the results of field measurement of soil quality divided into two depth sectors according to the soil depth, top soil (0–10 cm) and hardpan (10–20 cm). As a result, of soil analysis, the test field site was analyzed as loam (sand 46%, silt 34%, clay 20%). In general, it is known that the deeper the soil layer, the higher the soil compaction and the lower the porosity, and the lower the water content than the topsoil. This field test site also showed that the topsoil had an overall average soil water content of 20.6 ± 1.2%, which was 10% higher than that of the hardpan depth (17.7 ± 1.1%). As for

the overall average bulk density result, the hardpan was analyzed to have an average of 1830 ± 30.6 kg/m^3, 16.4% higher than the top soil (1571.7 ± 75.2 kg/m^3), which showed similar bulk density results to the range of 1500–2100 kg/m^3 reported in studies using actual field experiments for tillage operations [29,30]. Additionally, as a comparison group, the bulk density of soil failure by each of the primary (rotary tillage) and secondary tillage (rotary tillage after plowing) was measured, and the results showed 1483.2 ± 10.9 kg/m^3 and 1431.2 ± 17.2 kg/m^3, respectively. Finally, in the case of shear strength, the average value of 64.3 ± 14.4 kPa in hardpan was 2.56 times significantly larger than top soil value (25.1 ± 7.2 kPa).



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

Figure 5. (**a**) Analysis of cone penetration test results; and (**b**) target tillage depth.

Table 3. Results of overall average travel speed and slip ratio according to driving conditions.

Driving Conditions	Theoretical Speed (km/h)	Travel Speed (km/h)	Slip Ratio (%)
Primary × P1L2	1.73 ± 0.03	1.7 ± 0.14	1.42 ± 5.31
Primary × P1L3	2.47 ± 0.04	2.44 ± 0.16	1.27 ± 6.21
Primary × P1L4	3.29 ± 0.06	3.26 ± 0.25	0.51 ± 6.54
Secondary × P1L2	1.73 ± 0.02	1.68 ± 0.08	2.43 ± 4.63
Secondary × P1L3	2.47 ± 0.02	2.42 ± 0.12	2.04 ± 4.81
Secondary × P1L4	3.29 ± 0.05	3.24 ± 0.17	1.43 ± 4.99

3.2. Travel Speed with Wheel Slippage

The overall average results of tillage depth and slip ratio are shown in Table 4. Since the travel speed was about 5–6% higher than the travel speed at the rated engine rotation speed in all gear stages, it was confirmed that the engine rpm was slightly higher than the rated speed. This was attributed to the fact that high loads such as plow tillage did not occur to such an extent that the engine load caused the engine rotational speed to drop below the rated engine rotational speed. In addition, the travel speed showed a very low slip ratio of 0.51~2.43%, considering the full-throttle condition of 2300 rpm. It was found that the harder the road surface (primary tillage) and the higher the travel speed (high transmission gear stage), the lower the overall average slip ratio, but the more frequent the negative slip based on larger data oscillation.

Table 4. Results of fuel efficiency by tillage type and gear selection.

Driving Conditions	FC [1] (kg/h)	SFC [2] (g/kWh)	PR [3] (ha/h)	Fuel Cost ($/ha)
Primary × P1L2	7.19	358.07	0.31	30.38
Primary × P1L3	7.56	336.10	0.44	22.51
Primary × P1L4	7.84	326.73	0.59	17.41
Secondary × P1L2	6.87	396.58	0.31	29.03
Secondary × P1L3	7.73	338.62	0.44	23.01
Secondary × P1L4	7.85	329.73	0.59	17.43

[1] FC: fuel consumption; [2] SFC: specific fuel consumption; [3] PR: productivity rate.

3.3. Engine Load

The overall measured results of engine torque are shown in Figure 6. In the case of engine rotation speed, only a difference of less than 1% was observed as a result of whether primary (within 0.83%) or secondary tillage (within 0.65%) conditions were employed under full-throttle (about 2300 rpm). In the case of engine torque, average engine torques of the working sections of 84.06 ± 7.24 Nm (P1L2), 95.67 ± 5.54 Nm (P1L3), and 111.55 ± 9.92 Nm (P1L4) were observed as a function of gear selection in primary tillage, and average engine torques of the working sections of 73.69 ± 6.86 Nm (P1L2), 91.88 ± 6.59 Nm (P1L3), and 100.15 ± 4.06 Nm (P1L4) were observed in secondary tillage. Under the same gear selection condition, the engine torque increased by 4.12% (P1L3) to 14.07% (P1L2) as a function of the tillage type. In addition, it was found that the engine torque increased by up to 32.7% (primary tillage) or 35.9% (secondary tillage) under the same tillage type. Basically, the overall average engine torque showed higher values in primary tillage under the same gear selection conditions, while there was a difference in engine torque of up to 51.37% as a function of the combination of tillage type and gear selection.

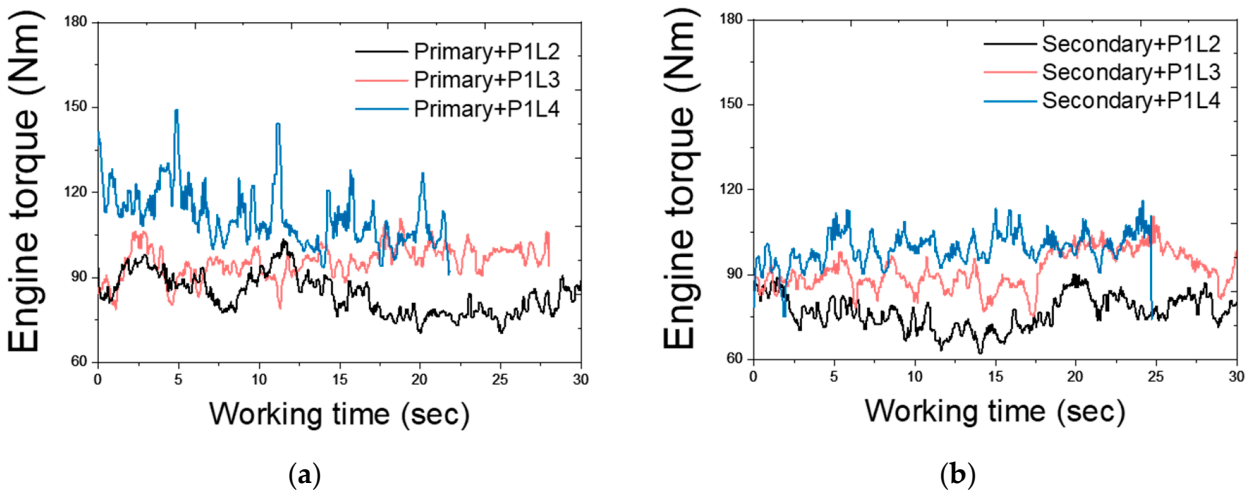


Figure 6. Results of engine torque data according to tillage type and gear selection during rotary tillage: (**a**) primary tillage; (**b**) secondary tillage.

3.4. PTO Shaft Load

The overall measured results of PTO shaft torque are shown in Figure 7. In the case of primary tillage, the overall average PTO shaft torque for the working section with respect to gear selection was 256.1 ± 36.8 Nm (P1L2 at 564.5 rpm), 286.2 ± 32.1 Nm (P1L3 at 563 rpm), and 343.1 ± 42.7 Nm (P1L4 at 559.8 rpm). In the case of secondary tillage, the results of PTO shaft torque were 200 ± 28.3 Nm (P1L2 at 565.4 rpm), 255 ± 29.7 Nm (P1L3 at 563.4 rpm), and 265.7 ± 22.2 Nm (P1L4 at 561.8 rpm). In the field test, the data measured for the secondary tillage method showed an average PTO torque value that was 10.1–22.6% lower than that of the primary tillage method due to the influence of the physical properties of soil, which changed rapidly with primary tillage, despite the rotary operation being

performed at the same travel speed, gear selection, and tillage depth. This phenomenon of increasing PTO shaft torque with increasing forward speed and decreased PTO shaft torque for secondary tillage was also observed in a 2018 study analyzing performance using a combined offset disc harrow [31].

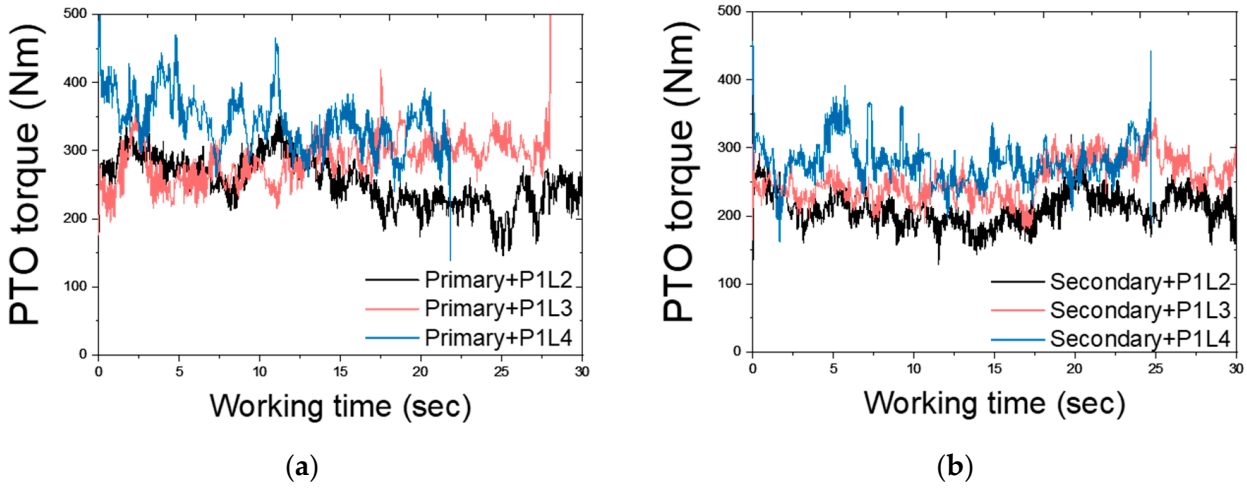


Figure 7. Results of PTO shaft torque as a function of tillage type and gear selection during rotary tillage: (**a**) primary tillage; (**b**) secondary tillage.

3.5. Axle Shaft Load

3.5.1. Front Wheel Axle

The overall measurement results for front wheel torque are shown in Figure 8. In the case of primary tillage, the overall average front axle torques for the working section according to each gear selection were 487.5 ± 124 Nm (P1L2 at 9.57 rpm), 566.6 ± 157 Nm (P1L3 at 13.73 rpm), and 541.2 ± 213.5 Nm (P1L4 at 18.16 rpm), respectively. In the case of secondary tillage, the results of front wheel axle torque were 823.9 ± 134.8 Nm (P1L2 at 9.73 rpm), 869.5 ± 173.1 Nm (P1L3 at 13.7 rpm), and 878.7 ± 108.7 Nm (P1L4 at 18.2 rpm), respectively. Overall, secondary tillage showed average values for each gear selection that were 1.55–1.69 times higher than those for primary tillage, which was attributed to the fact that the power distribution in the engine was affected by the higher PTO load in primary tillage. However, it was confirmed that the pitch angle at the center of gravity of the tractor continuously occurred due to the soil–tool interaction in primary tillage, resulting in unstable load transfer. The standard deviation of the tractor's torque was also higher by 23% at P1L4 than that for secondary tillage.

3.5.2. Rear Wheel Axle

The overall results measured for rear wheel torque are shown in Figure 9. Basically, the rear wheel axle load, like the front wheel axle torque, did not show a linear relationship according to gear selection. However, it was analyzed that the rear axle load under secondary tillage conditions was 21% (P1L2) to 49% (P1L3) higher for all gear selections than under primary tillage conditions. In the case of primary tillage, the overall average rear axle torque for the working section according to each gear selection was 555.9 ± 127 Nm (P1L2 at 6.41 rpm), 622 ± 167.8 Nm (P1L3 at 9.18 rpm), and 549.3 ± 213.1 Nm (P1L4 at 12.18 rpm), respectively. In the case of secondary tillage, the results of rear wheel axle torque were 673.7 ± 136.8 Nm (P1L2 at 6.42 rpm), 930.3 ± 195 Nm (P1L3 at 9.19 rpm), 772.7 ± 278.1 Nm (P1L4 at 12.2 rpm), respectively. Based on these results, it was also concluded that the power requirements distributed to the axles were relatively high, as the power requirements in the engine and PTO shaft were relatively reduced in the rear wheels as well.

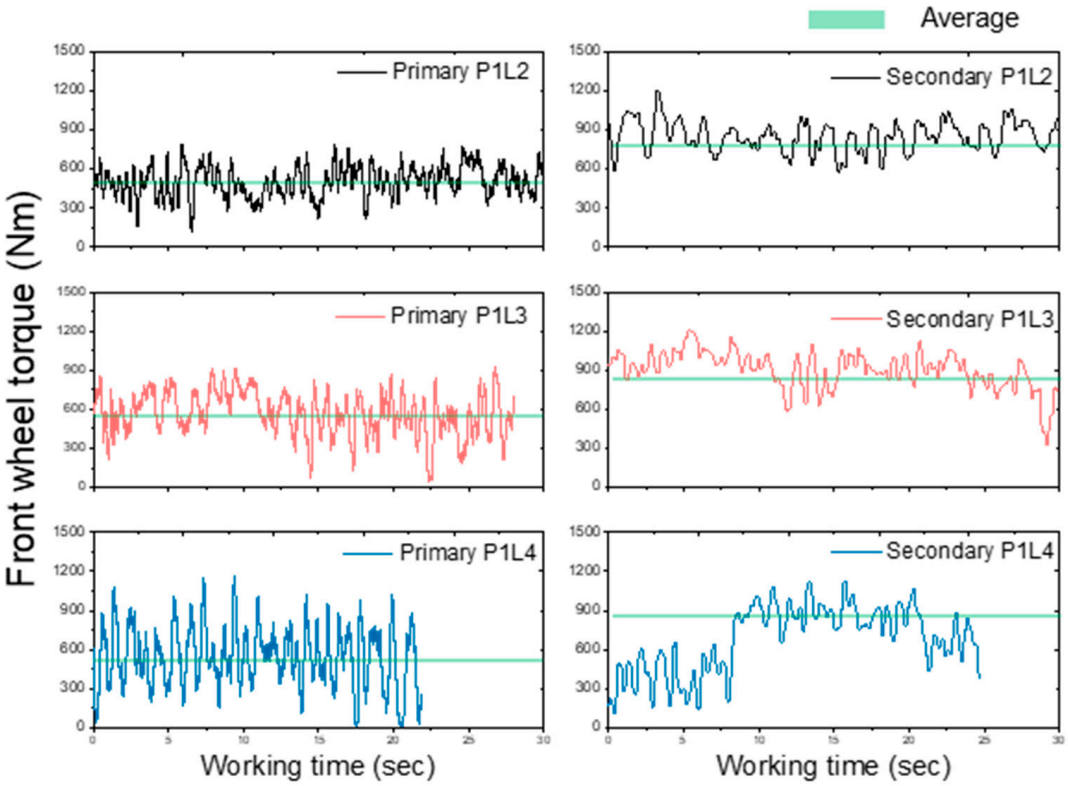


Figure 8. Results of front wheel axle torque data according to tillage type and gear selection during rotary tillage.

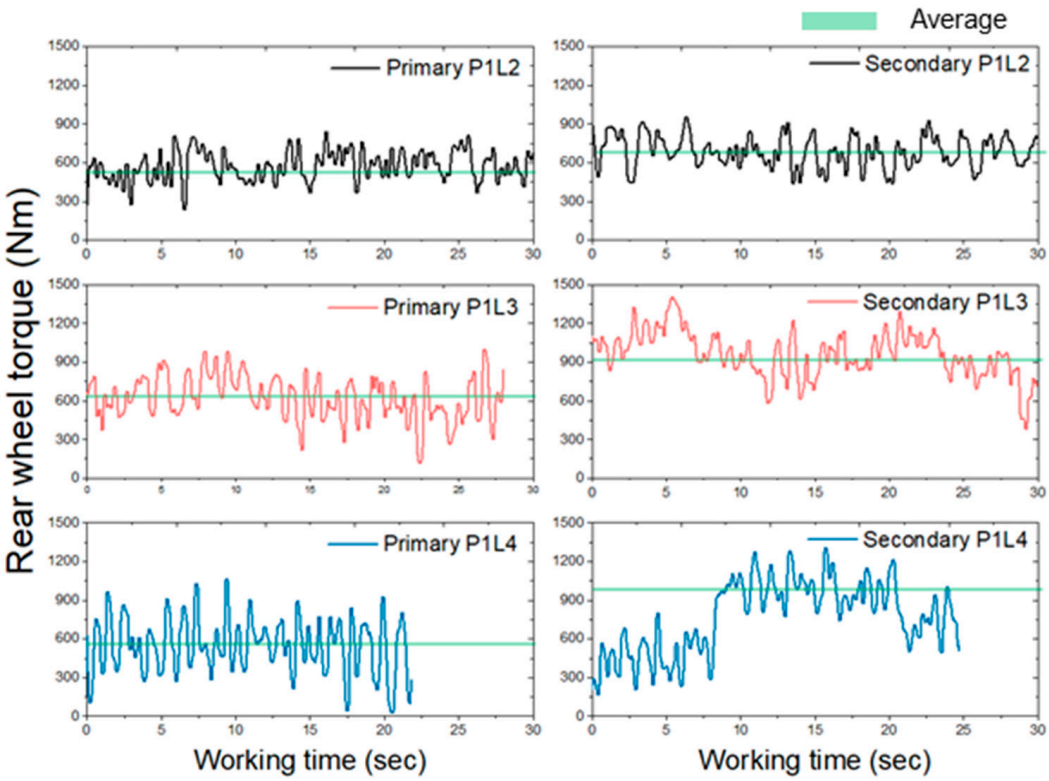


Figure 9. Results of rear wheel axle torque data according to tillage type and gear selection during rotary tillage.

3.6. Fuel Efficiency

The fuel efficiency of a 42 kW agricultural tractor depending on tillage type and gear selection is shown in Table 4. In terms of fuel usage, the FC when working with P1L4 was up to 1.09 times higher than the FC when working with P1L2. In terms of fuel efficiency, the SFC when working with P1L2 was up to 1.2 times higher than the SFC when working with P1L4. From a cost perspective, the fuel cost of working with P1L2 was up to 1.74 times higher than that when working with P1L4. In general, it has been reported that in order to obtain maximum fuel efficiency during tillage operations, it is required that the work be performed under the conditions of using the high torque ranges in the appropriate slip range [32]. Therefore, in the case of this test, where the slip rate did not change significantly when increasing the number of gears, the higher the torque value at a higher gear ratio, the better the fuel efficiency.

4. Discussion

In this study, the influence of soil–tool interaction (i.e., tillage type, gear selection, soil properties) during rotary plowing work was investigated. Based on a report on the effect of soil compaction on crop root growth from the USDA [33,34], test soil form an agricultural field was analyzed before the tillage operation in order to evaluate the degree to which the physical properties of the field affect (over 1630 kg/m^3) or limit crop root growth (over 1800 kg/m^3). The results of the test showed that the bulk density measured from 1571 to 1830 kg/m^3 decreased to a level of 1431 to 1480 kg/m^3. This was judged as indicating that tillage type directly affects the soil–tool interaction.

In general, there are reports suggesting that the rear axle load is 3 to 8 times greater than the front axle load during plowing [11,12]. However, unlike plowing, the load transfer increased toward the front wheel, and the front wheel axle torque showed a similar level to the rear wheel axle torque. In other words, the rotavator increases the soil thrust in the working direction, giving the same effect as pushing the vehicle forward. This was found to be the same as the effect of strengthening the soil–tyre interaction with an auxiliary iron wheel. In addition, for the same reason, it was found that negative slip, which momentarily produces a higher travel speed than the theoretical speed of the vehicle, partly and momentarily occurs in some sections.

Figure 10 shows the relative histogram results of power requirements as a function of tillage type and gear selection. On the basis of the results of power requirement analysis, it can be seen that engine and PTO power have tendencies that are different from the wheel axle power requirements. In the case of wheel axle power under the same gear selection conditions, it was found that the required power in secondary tillage was 21–81% higher than in primary tillage. The reason for this phenomenon is that primary tillage reduces the internal friction of the soil [35]. In another study by Kim et al. [36], it was reported that with increasing value of the slip ratio range, the axle torque also increased. Table 4 shows that the slip ratio increased more during secondary tillage than during primary tillage, overall. Therefore, it seems that the power requirement of the wheel axle increased more during secondary tillage than during primary tillage in this study. In the case of the rotary tillage performed in this study, it was found that the effect of tillage method was greater than the effect of gear selection for the axle load, which is in contrast to the engine and PTO load. Conversely, it was analyzed that the effect of gear selection (Engine power: 4–14%, PTO power: 12.1–28.6%) on engine and PTO loads was greater than that of tillage type (Engine power: 31.6–35.1%, PTO power: 31.9–32.8%), and the load tended to decrease in secondary tillage.

Compared to the test conditions in the specifications of the actual rotavator, considering that only up to 62.1% of the maximum engine capacity (42 kW) was used, it was deemed that this work could be performed in a harder and stickier environment than the loam soil in which this study was conducted. In addition, it was concluded that the work efficiency will increase more when rotary tillage is performed under the conditions of a

tillage depth deeper than 12–13 cm, a wider work width (over 1820 mm), and a work speed faster than 3.24 km/h in the same working environment.

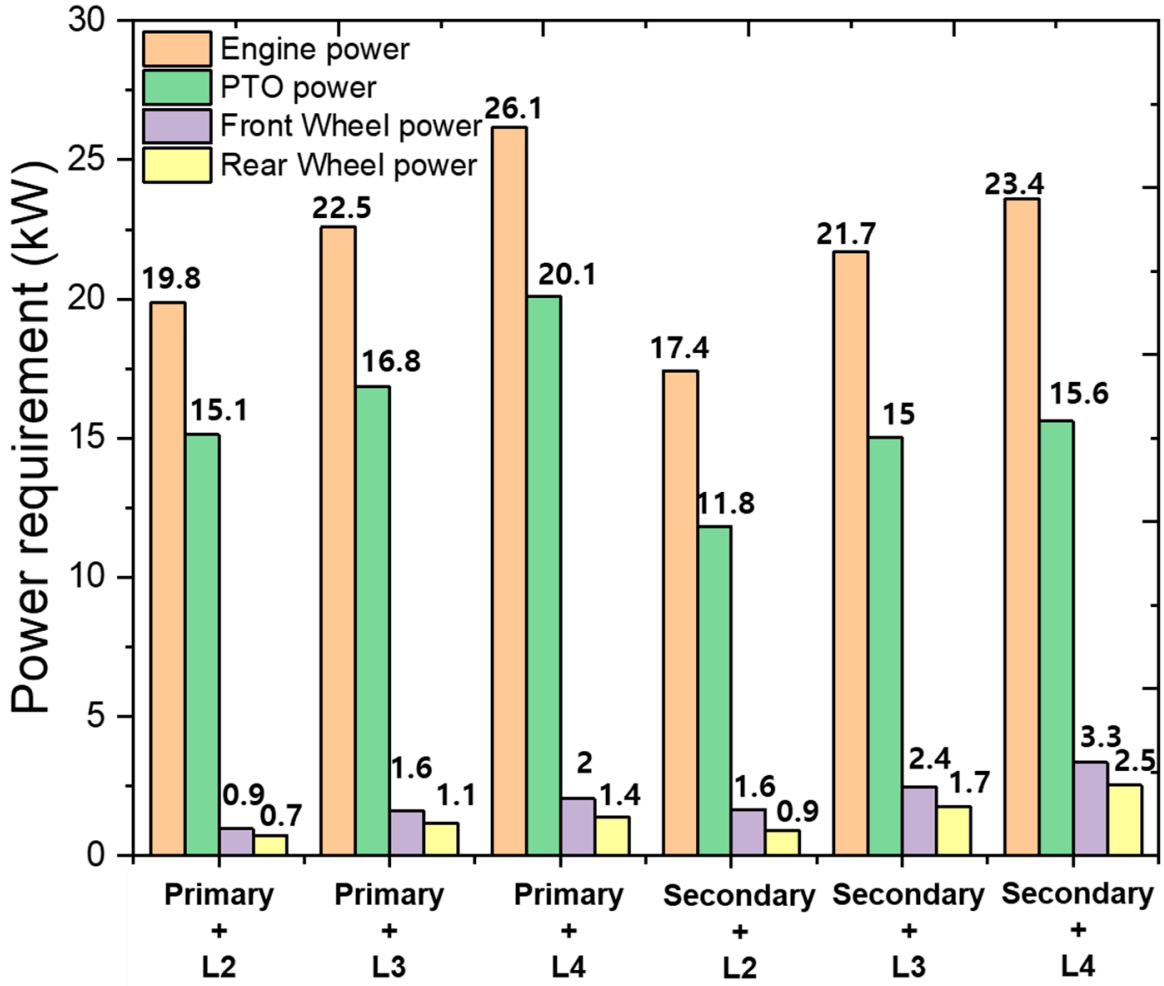


Figure 10. Analysis of power requirement as a function of tillage type and gear selection.

5. Conclusions

In this study, a field load measurement test was conducted to analyze the effect of tillage type (i.e., primary tillage or secondary tillage) and gear selection (i.e., P1L2, P1L3, or P1L4) on the tractor working load (i.e., engine load, wheel axle load, and PTO shaft load, as well as travel speed) during rotary tillage operations. The major conclusions obtained were as follows.

1. By measuring the soil properties according to depth, it was confirmed that the core index, shear strength, and water content, which are the main properties that affect the load of cultivation work, changed in accordance with the change in depth. In particular, soil bulk density was measured to decrease by 9–19% under rotary operation. Therefore, soil properties as a function of tillage type, which is a typical soil–tool interaction process, should be considered first when evaluating the performance of the operation of agricultural machinery or in field tests.
2. Overall average torque was higher by up to 14% (engine) and 29.1% (PTO shaft) in primary tillage than in secondary tillage when the selected gear was the same. When the tillage type was the same, it was found that the overall average torque increased as a result of gear selection by up to 35.9% (engine) and 33.9% (PTO shaft) in P1L4 compared to P1L2.

3. In the case of fuel efficiency, it was revealed that the effect of gear selection was greater than the effect of the tillage type. When working on loam field (soil water content of 17–20%, bulk density of 1571–1830 kg/m^3, and cone index of 801–2065 kPa), the most suitable gear for reducing fuel consumption was found to be P1L4.
4. In addition, based on the power requirement results, from the perspective of the machine, when working on loamy soil with a tillage depth of 10 to 13 cm, 66.7–77% of the power generated by the engine was consumed by the PTO shaft. This shows that the force applied to the implements during rotary operation is greater than the traction load.
5. In the case of the power requirements, the power required on the same tillage type increased with increasing gear ratio. During secondary tillage, the overall power required decreased due to changes in key soil properties such as bulk density, cone index, and vane shear torque. Therefore, it was judged that design modification is necessary in order to have a wide working width, and that in some cases, rotary tillage will be possible at a deeper tillage depth or at a higher travel speed. It is expected that performance evaluation and optimal design of soil operation machinery in various working environments will be possible through similar field verification procedures in future studies.

Recently, various agricultural work environments have been defined, and virtual agricultural performance evaluation or load prediction simulation studies are being conducted through modeling. It is important to secure a database for the definition of agricultural work environments and load analysis. The results of this study are expected to be of use in future studies for designing loads in research on modeling and the verification of agricultural machinery systems such as soil–tool and soil–tyre interaction during agricultural operation.

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