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Research article

Specific energy requirements and soil pulverization of a combined tillage implement

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ABSTRACT

Reducing energy use in soil preparation has become increasingly important since it is a major cost in planting. Experiments were conducted with a combined tillage implement consisting of a subsoiler and a rotary harrow to reduce the cost due to step reduction in soil preparation. Three tillage operations, two forward speeds, and two rotational rotor speeds were determined as input factors in this study. Soil clod size, performance parameters, and the specific energy requirements of a combined tillage implement were investigated. The field experiments were using two different soil conditions. Increasing the rotor speed from 299 to 526 rpm decreased the mean soil clod diameter at a depth of 0–200 mm from 22.98 to 19.83 mm and from 31.77 to 26.57 mm for fields 1 and 2, respectively. The specific energy requirement was affected significantly by rotor speed and tillage operation. The specific energy requirements for the combined tillage implement with an on-frame pivot joint and an on-pivotable-shank joint were less by 10.4 and 21.1% and by 18.4 and 24.7%, for fields 1 and 2, respectively, compared to the total power requirement for the separate use of a subsoiler and a rotary harrow.

1. Introduction

Field preparation is one of the most important and expensive operations in crop production. Soil quality after tillage is mainly influenced by soil condition, soil type, and tillage operation parameters including implements, forward speed, depth, and tools (Bögel et al., 2016). Soil factors like clod size and clod distribution are influenced by tillage operations. Tillage practices should loosen the soil as much as possible so that the planter opens easily (Ghazavi et al., 2010). It is very important to know which parameters can reduce the mean soil clod diameter and trafficking in the field. Energy use in field preparation is of great concern to scientists and farmers. The tillage operation requires the most energy on farms (Al-Suhaibani and Ghaly, 2013). There are between eight and ten tillage operations for conventional land preparation which not only consume a large amount of energy but also adversely affect soil compaction induced by the intensive traffic of machinery (Usaborisut and Niyamapa, 2010). Therefore, using a combined tillage implement and reducing the number of passes is gaining popularity due to its positive effects on time, efficiency, and costs. Tillage tools are often designed to minimize the draft force and power requirements (Bögel et al., 2016). Various combinations of machinery or implements with rotary-powered tillage have been developed and have been found to be more energy efficient than similar single, passive tillage tools when they were tested under actual field conditions (Shinners et al., 1993). A combined tillage tool simultaneously uses two or more types of tillage implement to accomplish primary and secondary tillage in a one-pass operation for seedbed preparation (Prem et al., 2016). The potential benefits of combining a passive implement as a primary implement and an active implement as a secondary tillage implement are:

1. Reduction in the number of tillage operations which can reduce subsoil compaction (Manian et al., 1999), the time of field operation, and fuel and labor costs (Al-Janobi and Al-Suhaibani, 1998; Sahu and Raheman, 2006; Kailappan et al., 2001).
2. Reduction in the draft force due to the soil cutting of the active tool providing some thrust force (Shinners et al., 1990).
3. More effective operational power use due to the direct transmission of power to the tillage elements through a mechanical power train rather than through the soil-tire interface (Anpat and Raheman, 2017; Hendrick, 1980; Shinners et al., 1993).

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4. Fewer larger-sized clods in the soil, which provide medium soil uniformity, good moisture holding capacity, and eventually reduce evapotranspiration (Kailappan et al., 2001; Janeth et al., 2014).

The current study developed and tested a combined tillage implement of a subsoiler and a rotary harrow under actual field conditions to investigate tillage energy utilization and soil clod size. The influence of tillage operation, rotor speed, and forward speed were considered in the study.

2. Material and methods

2.1. Developed combined tillage implement

The developed combined tillage implement consisted of a subsoiler and a rotary harrow which together were able to complete the tasks of subsoiling and harrowing in one pass. The subsoiler had two straight shanks 500 mm apart and was attached by a rotary harrow with two different linkage configurations. The rotary harrow had four rotors with 250 mm spacing between adjacent rotors and a total working width of 1,000 mm and the combined tillage implement and sensor used in field test as shown in Fig. 1 (a), (b), and (c). Each shank of the subsoiler was located centrally between a pair of rotary harrow rotors. Assuming that configuration between two implements may produce different results for the drawbar pull and power requirement of the combined tillage implement, two linkage configurations between the subsoiler and the rotary harrow were provided and were termed as follows: 1) "on-frame pivot joint" whereby the rotary harrow was joined to the frame of the subsoiler allowing the force generated by the rotary harrow to act directly onto the frame of the subsoiler and to push the whole subsoiler including the shanks that were fixed to the frame as shown in Fig. 2 (a); and 2) "on-pivotable shank joint" whereby the rotary harrow was joined to the set of movable parallel mechanism members that hit the pivotable shank of the subsoiler when they moved forward by the force generated by the rotary harrow and allowing the shanks to pivot with a maximum angle limitation of 3° resulting in the longitudinal amplitude at the tip of the shanks being 30 mm as shown in Fig. 2 (b).

2.2. Experimental site

The combined tillage implement was tested in experimental fields with two different soil types (clay and clay loam) in Nakhon Pathom province, Thailand. The consistency limits using simple tests followed the procedures outlined in the USDA standards (USDA-NRCS, 2000). Soil dry bulk densities and moisture contents were obtained from soil samples in two layers (0–200 and 200–400 mm). Cone index values were collected using a hand-operated cone penetrometer with a 30° cone angle and a diameter of 12.83 mm following procedures outlined in the ASAE standards (ASAE S313.3, 2005) at 0–500 mm depth. The tested soil properties are listed in Table 1.

2.3. Instrumentation and experimental design

The combined tillage implement was powered by a Massey Ferguson series 390 4WD 87 hp diesel tractor. The instrumentation system was set to measure the draft force, rotational speed, and PTO torque. The draft forces were measured using two sets of three-pin transducers: one set at the joining points between the tractor and the subsoiler and the other set at the joining points between the subsoiler and the rotary harrow as shown in Fig. 1 (a). The developed pin transducer used the strain gauges connected in a full Wheatstone bridge to measure the draft force. The rotary harrow was powered by the tractor's PTO shaft and the torque was measured using a torque transducer (TP-50KMCB, Kyowa Electronic Instruments Co. Ltd., Tokyo, Japan). The rotational speed of the rotary harrow was measured using an inductive sensor. A universal recorder (EDX-200A, Kyowa Electronic Instruments Co. Ltd., Tokyo, Japan) was used to amplify the signal and record the experimental data from all measuring devices. The sampling rate was 200 Hz. The sensors and the data acquisition system (DAS) are shown diagrammatically in Fig. 3.

The experiments were conducted in two fields under three operating parameters: tillage operation, forward speed, and rotational speed of the rotor. There were three different tillage operations: two one-pass operations by the combined tillage implement with different linkage configurations and one two-pass operation firstly by the subsoiler, followed by the rotary harrow. The levels of these variables are given in Table 2. The operating tillage depths of implements during the experimental field test were set at 400 mm for the subsoiler and 200 mm for the rotary harrow. Each treatment was replicated three times. An experimental plot 30 m long × 1.5 m wide was used for each observation. Each experiment was laid out in a factorial randomized complete block design with three replications. In total, 105 tests were conducted in the two fields, with 60 tests for the combined tillage implement and 45 tests for a sole implement.

The specific energy for a particular machine configuration was calculated using Eq. (1) (Shinners et al., 1990; Hendrick, 1980):

$$SE = \frac{\left[\frac{P_{pto}}{\mu_{pto}} + \frac{P_{dr}}{\mu_{dr}}\right]}{V \ x \ W} x \ \ 10 \tag{1}$$

where:

SE = specific energy, kWh ha^{-1},
P_{pto} = PTO power, kW,
μ_{pto} = PTO power transmission efficiency, assumed to be 0.82,
P_{dr} = drawbar power, kW,
μ_{dr} = drawbar power tractive and transmission efficiency, assumed to be 0.49,
V = actual forward speed, km h^{-1},
W = width tilled, m.

After testing, exactly 6 kg of loosened soil was collected in each treatment plot from the two layers (0–100 and 100–200 mm) to measure the soil clod diameter. Each soil sample was sieved based on gradations in size (>50.0, 38.1, 31.5, 19.0, and <9.5 mm diameter as shown in Table 3), weighed, and then the mean soil clod diameter was calculated using Eq. (2) (RNAM, 1983). The relative distribution of all clod sizes was determined as a percentage of the total soil sieved for each observation.

$$dsc = (5A \times 15B \times 27.5C \times 37.5D \times 45E \times NF)/W \tag{2}$$

where:

dsc = mean soil clod diameter, mm,
N = mean of measured diameters of soil clods retained on the largest aperture sieve, mm,

$$W = A + B + C + D + E + F \ (kg) \tag{3}$$

Data from each experimental field were analyzed separately. Statistical analysis was carried out on the performance parameters, specific energy, and mean soil clod diameter. Duncan's multiple range tests were used to determine significance at a probability of 5%.

3. Results and discussions

The results of the analysis of variance for the mean soil clod diameter at depth 0–200 mm are given in Tables 4 and 5 for fields 1 and 2, respectively. The rotational speed of the rotor had a significant influence on the mean soil clod diameter in both fields. The mean soil clod diameters in different layers were significantly different in both fields. However, the soil clod diameter produced by the combined tillage implement with two linkage configurations and by separately working the subsoiler and rotary harrow were not significantly different in both

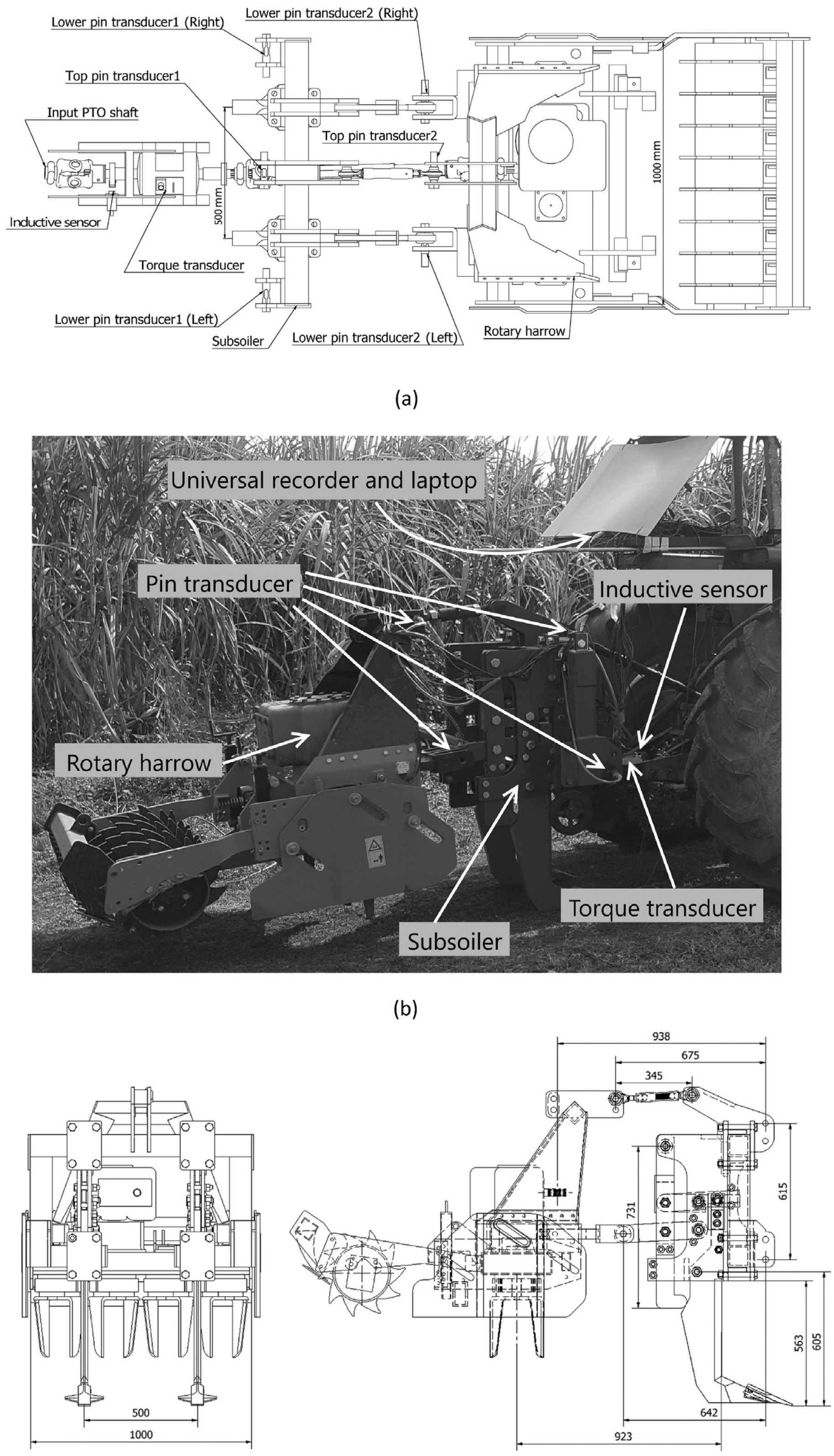


Fig. 1. (a) Power transmission system of combined tillage implement and location of sensors, (b) The combined tillage implement with installed sensors used in field test, and (c) The dimension of combined tillage implement (mm).

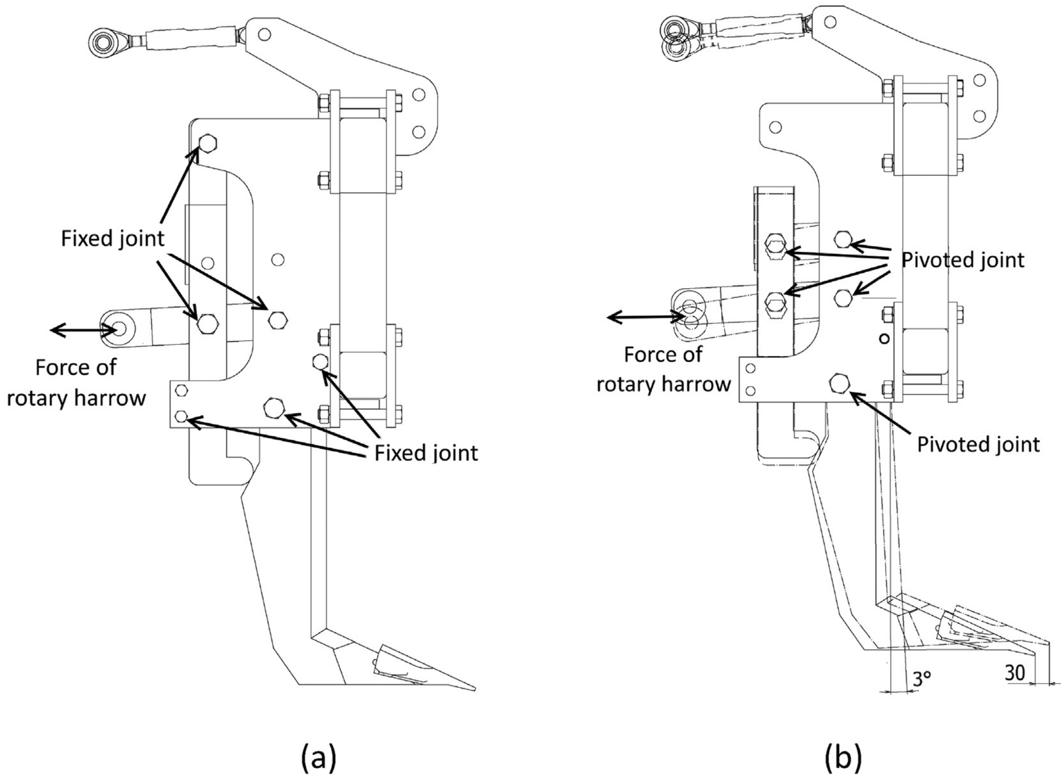


Fig. 2. Linkage configurations: (a) On-frame pivot joint, and (b) On-pivotable shank joint.

fields.

When the rotor speed increased from 299 to 526 rpm, the mean soil clod diameter at 0–200 mm depth decreased from 22.98 to 19.83 mm and from 31.77 to 26.57 mm for fields 1 and 2, respectively. Separate observations on each soil layer as the rotor speed increased indicated that the mean soil clod diameter at 0–100 mm depth decreased from 25.43 to 21.51 mm and from 39.04 to 30.95 mm for fields 1 and 2, respectively, while they were not different at 100–200 mm depth in both fields as shown in Tables 6 and 7. The forward speeds showed little effect on the mean soil clod diameter for field 1 (clay loam soil), in which the mean soil clod diameter an increased a little from 21.01 to 21.80 mm when the forward speed increased from 1.89 to 2.78 km h^{-1}. On the other hand, in field 2 (clay soil), there was a significant increase in the mean soil clod diameter from 25.91 mm to 31.69 mm when the forward speed increased from 1.79 km h^{-1} to 3.33 km h^{-1}. In both fields, the mean soil clod diameter decreased with an increase in the rotor speed of the rotary harrow, which agreed with the results reported by Fang et al. (2016). They conducted rotavator tests under heavy straw conditions at three rotational speeds and found that the rotational speeds had significant effects on the mean clod diameter (37.23, 29.67, and 23.69 mm at rotational speeds of 180, 230, and 280 rpm, respectively) because a higher rotational speed led to a smaller bite length.

In field 1, the forward speed did not affect the soil clod diameter. Since the soil was not hard (cone index was low, only 1.3 MPa), similar soil pulverization was obtained even with a higher forward speed. However, in field 2 with a cone index of 2.9 MPa, the mean soil clod diameter increased with increasing forward speed. This may have been because of the longer bite length. The lower speed ratio between the rotational speed and forward speed might have been the main cause of this phenomenon. In addition, the dynamic action of the soil and tillage

Table 1
Soil properties in tested fields.

		Field 1		Field 2	
Particle size distribution (%)*	Sand (2–0.02 mm)	39.2		21.1	
	Silt (0.02–0.002 mm)	32.6		35.6	
	Clay (<0.002 mm)	28.2		43.2	
	Plastic limit	20.7		21.7	
	Liquid limit	29.8		34.5	
Consistency limits classification		Clay loam**		Clay**	
		Range	Average	Range	Average
Soil cone index (MPa)		1.0–1.6	1.3	1.8–5.0	2.9
Moisture content (% db) at depth of					
0–200 mm		12.2–18.3	16.0	11.0–17.3	14.3
200–400 mm		16.5–19.8	18.6	17.8–21.1	19.0
Dry bulk density (g cm^{-3}) at depth of					
0–200 mm		1.5–1.8	1.6	1.5–1.7	1.6
200–400 mm		1.6–1.8	1.7	1.6–1.7	1.7

* Hydrometer test (Klute, 1886).
** Following the procedures outlined in the USDA standards (USDA-NRCS, 2000).

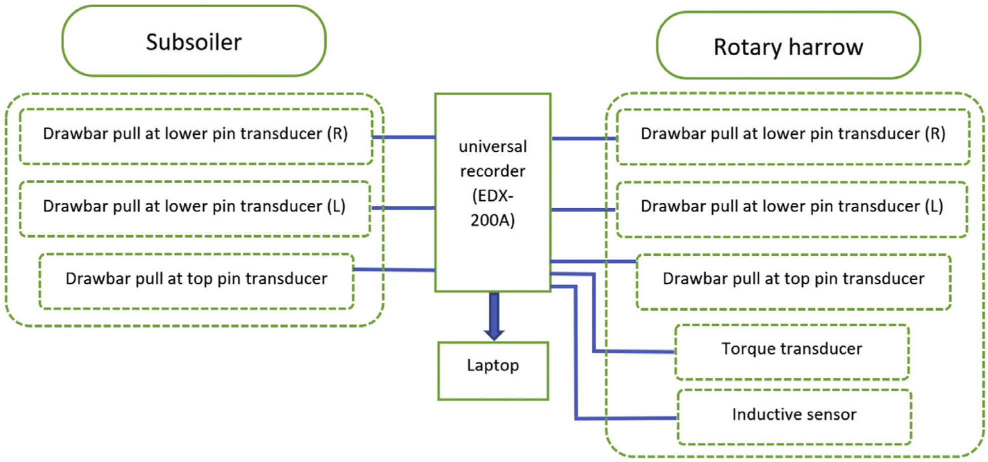


Fig. 3. Block diagram of sensors and data acquisition system.

tool might also have partly helped this phenomenon as Bukhari et al. (1981) also observed in their work. They indicated that the soil crumbling of a tillage combination (moldboard plow + spring-tooth harrow) decreased with an increasing forward speed from 4.06 to 8.63 km h^{-1}.

Tables 6 and 7 show that one pass using the developed combined tillage implement or two passes using the subsoiler, followed by the rotary harrow seemed to obtain similar results since there was no significant difference in the mean soil clod diameter. The results confirmed that using the combined tillage implement could help reduce the steps in the seedbed preparation and should be an effective way of soil preparation due to savings in both time and operational cost.

The mean soil clod diameters in field 1(clay loam soil) compared to field 2 (clay soil) were 21.41 and 29.17 mm, respectively. The soil type and the soil strength may have contributed to the difference in the soil clod diameter in these two fields. Kumar and Manian (1986) found that using a combination tillage tool resulted in greater pulverization in a red soil than a black cotton soil.

Figs. 4 and 5 present the results of the relationship between tillage condition and percentage of soil clod distribution for field 1 (clay loam soil) and field 2 (clay soil), respectively. It was clear in both fields that when operating at the higher rotor speeds, the percentages of soil clod size less than 9.5 mm were higher. In the clay loam soil, the average amount of soil clod size less than 9.5 mm was greater (54.57%) than in the clay soil (36.96%). At rotor speeds of 299 and 526 rpm, the percentage of soil clod size larger than 50 mm was in the range 6.36–13.45% at 0–200 mm depth in the clay soil. At rotor speeds of 299 and 526 rpm in the clay loam soil, the percentage of soil clod size larger than 50 mm was in the range 3.24–6.14% at 0–200 mm depth. In both fields, the percentage of soil clod size less than 9.5 mm at 100–200 mm depth was more than at 0–100 mm depth. The results from these conditions showed that the percentage of soil clod size less than 9.5 mm was higher at 100–200 mm depth than at 0–100 mm depth in both fields. This may have been due to the smaller-sized soil clods dropping into the deeper soil layer through the gaps caused by soil disintegration due to harrowing. The vibration during the operation was possibly another factor for the smaller-sized soil clods moving into the deeper soil layer. Clay soil might have higher strength parameters than clay loam soil since the average amount of soil clod diameter larger than 500 mm in the clay soil field was greater than in the clay loam soil field.

Table 2
Variable levels for tests in two fields.

Experiment 1 Testing of implements for field 1	
1.1 Testing combined tillage implement	
Linkage configuration	(on-frame pivot joint and on-pivotable shank joint)
Theoretical forward speed	(1.89 and 2.78 km h^{-1})
Rotational speed of rotor	(299 and 526 rpm)
1.2 Testing of units working separately	
1.2.1 Subsoiler	
Theoretical forward speed	(1.89 and 2.78 km h^{-1})
1.2.2 Rotary harrow	
Theoretical forward speed	(1.89 and 2.78 km h^{-1})
Rotational speed of rotor	(299 and 526 rpm)
Experiment 2 Testing of implements for field 2	
2.1 Testing combined tillage implement	
Linkage configuration	(on-frame pivot joint and on-pivotable shank joint)
Theoretical forward speed	(1.79, 2.67, and 3.33 km h^{-1})
Rotational speed of rotor	(299 and 526 rpm)
2.2 Testing of units working separately	
2.2.1 Subsoiler	
Theoretical forward speed	(1.79, 2.67, and 3.33 km h^{-1})
2.2.2 Rotary harrow	
Theoretical forward speed	(1.79, 2.67, and 3.33 km h^{-1})
Rotational speed of rotor	(299 and 526 rpm)

Table 3
Weight of soil retained on the sieve.

Size of sieve aperture (mm)	Diameter of soil passing the sieve to the next smallest sieve aperture (mm)	Representative diameter of soil (mm)	Weight of soil (kg)
9.5	<10	5	A
19.0	10–20	15	B
31.5	20–35	27.5	C
38.1	35–40	37.5	D
50	40–50	45	E
	50>	N	F

Table 4
Analysis of variance for mean soil clod diameter at 0–200 mm depth in field 1.

Source	Type III sum of squares	df	Mean square	F value	Sig.
Corrected model	657.203	14	46.943	3.028	0.002
Intercept	32989.969	1	32989.969	2128.051	0.000
Soil layer (S)	306.668	1	306.668	19.782	0.000**
Tillage condition (T)	89.650	2	44.825	2.891	0.064^{ns}
Forward speed (F)	11.174	1	11.174	0.721	0.399^{ns}
Rotational speed of rotor (R)	179.013	1	179.013	11.547	0.001**
F × R	0.647	1	0.647	0.042	0.839^{ns}
S × R	10.680	1	10.680	0.689	0.410^{ns}
T × R	13.714	2	6.857	0.442	0.645^{ns}
S × F	0.097	1	0.097	0.006	0.937^{ns}
T × F	12.069	2	6.035	0.389	0.679^{ns}
S × T	33.492	2	16.746	1.080	0.346^{ns}

* Significant at 5%; ** Significant at 1%; ns, not significant.

Table 5
Analysis of variance for mean soil clod diameter at 0–200 mm depth in field 2.

Source	Type III sum of squares	df	Mean square	F value	Sig.
Corrected model	5615.658	19	295.561	13.654	0.000
Intercept	91893.668	1	91893.668	4245.156	0.000
Soil layer (S)	3664.507	1	3664.507	169.287	0.000**
Tillage condition (T)	59.356	2	29.678	1.371	0.259^{ns}
Forward speed (F)	629.906	2	314.953	14.550	0.000**
Rotational speed of rotor (R)	728.417	1	728.417	33.650	0.000**
F × R	80.957	2	40.479	1.870	0.160^{ns}
S × R	225.738	1	225.738	10.428	0.002**
T × R	72.310	2	36.155	1.670	0.194^{ns}
S × F	65.911	2	32.955	1.522	0.224^{ns}
T × F	45.827	4	11.457	0.529	0.715^{ns}
S × T	42.729	2	21.364	0.987	0.377^{ns}

* Significant at 5%; ** Significant at 1%; ns, not significant.

Table 6
Mean soil clod diameter in layers (0–100 and 100–200 cm) for three tillage operations in field 1.

Variable	Level	Mean soil clod diameter at depth					
		0–100mm		100–200mm		0–200mm	
		mm	SD	mm	SD	mm	SD
Tillage operation	Combined tillage implement with on-frame pivot joint	21.39a**	4.96	19.19a	5.39	20.29a	5.19
	Combined tillage implement with on-pivotable shank joint	25.43a	4.97	20.42a	2.75	22.93a	4.68
	Subsoiler + Rotary harrow	23.59a	3.58	18.40a	1.53	20.99a	3.78
Theoretical forward speed (km h^{-1})*	1.89	23.11a		18.91a		21.01a	
	2.78	23.83a		19.77a		21.80a	
Rotational speed (rpm)	299	25.43b		20.53a		22.98b	
	526	21.51a		18.15a		19.83a	

* Theoretical forward speed is the forward speed of tractor under no-load condition.
** Based on Duncan's new multiple range test, mean values with the same lowercase letter in the same column within the same block are not significantly different at 5% level.

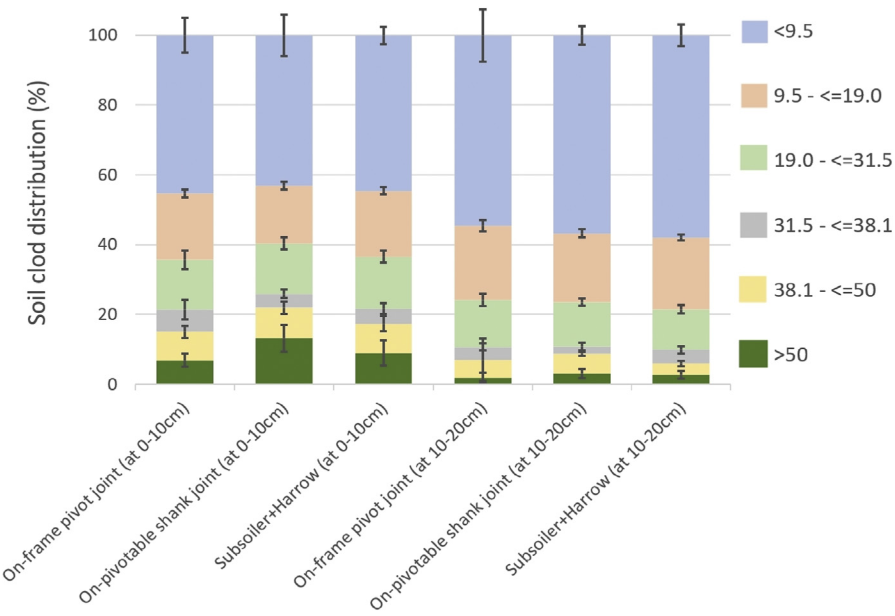
The average values of the performance parameters and specific energy requirements for the three tillage operations at different forward speeds and rotor speeds are given in Tables 8 and 9. For both fields, the type of tillage operation had a significant influence on the specific energy. Based on Eq. (1), the specific energy for a combined tillage implement with the on-frame pivot joint and the on-pivotable shank joint were less by 10.4% and 21.1% and by 18.4% and 24.7%, for fields 1 and 2, respectively, compared to the summation of the units being used separately (pass 1 using a subsoiler and pass 2 using a rotary harrow). The rotational speed of the rotor significantly affected the specific energy in both fields. Operating at rotor speeds from 299 to 526 rpm increased the specific energy from 24.20 to 27.28 kWh ha^{-1} and from 26.57 to 29.52 kWh ha^{-1} in fields 1 and 2, respectively. The combined tillage implement with the two linkage configurations required less drawbar power, PTO power, and specific energy than for separately working the subsoiler and the rotary harrow in both fields. The specific energy requirements for the combined tillage implement with the two linkage configurations were not significantly different. The results from both fields indicated that the combined tillage implement with the two linkage configurations used less specific energy than working the subsoiler and the rotary harrow separately. Similarly, Ahmadi (2017) reported that combining active and passive tillage elements led to the improved overall efficiency of the combined machine. These results agreed with Shinners et al. (1990), who found that the machine configuration with two active and two passive elements significantly affected the specific energy. Since increasing the rotor speed required more power, this resulted in greater specific energy requirements for all tillage conditions in both fields. The previous work conducted by Weise (1993) showed a similar tendency. He observed that the power requirement of the rotor increased significantly with the rotor speed.

Analyses for all tillage operations showed that the forward speed did not significantly affect the specific energy in both fields. Increasing the

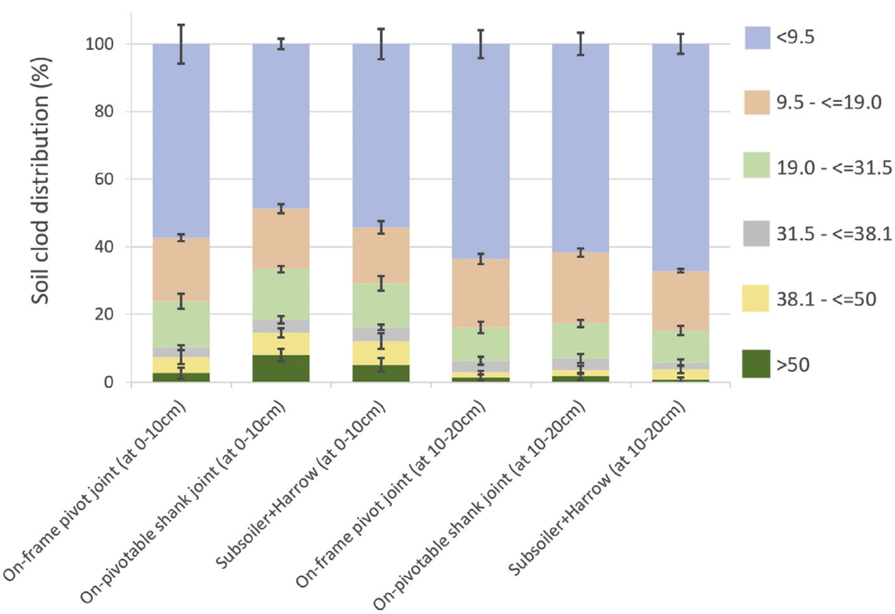
Table 7
Mean soil clod diameter in layers (0–100 and 100–200 cm) for three tillage operations in field 2.

Variable	Level	Mean soil clod diameter at depth					
		0–100mm		100–200mm		0–200mm	
		mm	SD	mm	SD	mm	SD
Tillage operation	Combined tillage implement with on-frame pivot joint	36.08a**	8.70	24.32a	4.89	30.19a	9.16
	Combined tillage implement with on-pivotable shank joint	35.05a	5.42	21.92a	3.75	28.49a	8.09
	Subsoiler + Rotary harrow	33.85a	7.04	23.79a	5.29	28.82a	7.98
Theoretical forward speed (km h^{-1})*	1.79	30.64a		21.19a		25.91a	
	2.67	36.22b		23.58ab		29.90b	
	3.33	38.13b		25.26b		31.69b	
Rotational speed (rpm)	299	39.04b		24.49a		31.77b	
	526	30.95a		22.19a		26.57a	

* Theoretical forward speed is the forward speed of tractor under no-load condition.
** Based on Duncan's new multiple range test, mean values with the same lowercase letter in the same column within the same block are not significantly different at 5% level.



(a) Rotor speed of 299 rpm



(b) Rotor speed of 526 rpm

Fig. 4. Variation in clod size distribution under different tillage conditions in field 1 (clay loam soil). (a) Rotor speed of 299 rpm, (b) Rotor speed of 526 rpm.

forward speed significantly increased the drawbar power and PTO power in both fields. In field 1, the tests conducted at the two different forward speeds (1.89 and 2.78 km h^{-1}) resulted in increases in the drawbar power and PTO power from 15.42 to 24.36 kW and from 12.10 to 14.78 kW, respectively. In field 2, when the forward speed increased from 1.79 to 3.33 km h^{-1}, the drawbar power and PTO power increased from 14.47 to 30.70 kW and from 12.60 to 17.37 kW, respectively. The faster operating forward speed could produce a higher drawbar power and PTO power requirements in both fields. Similarly, Weise (1993) found a linear increase in the PTO power of a combined tillage machine (wing tines and rotor) as a function of the forward speed. Askari et al. (2017) observed that increasing forward speed from 1.8 to 3.5 km h^{-1} resulted in increasing of the draft with three subsoil tillage tines (subsoiler, bentleg and paraplow). Upadhyaya et al. (1984) observed that a ripper combined with a spider required PTO power from 38.8 to 67.0 kW when operating with a forward speed from 3.4 to 7.6 km h^{-1}. Ranjbarian et al. (2015) found that the drawbar power increased as the forward velocity increased. In field 2, the combined tillage implement with the on-frame pivot joint required a higher drawbar power but less PTO power compared to the combined tillage implement with the on-pivotable shank joint, which required a lower drawbar power but a little higher PTO power. It seemed that under the hard soil conditions in field 2, the rotary harrow with the on-pivotable shank joint could generate more thrust force directly to the shanks of the subsoiler and consequently helped to reduce the drawbar power of the subsoiler and the whole set of the combined tillage implement.

The combined tillage implement with two linkage conditions required less drawbar power than separately working the subsoiler and

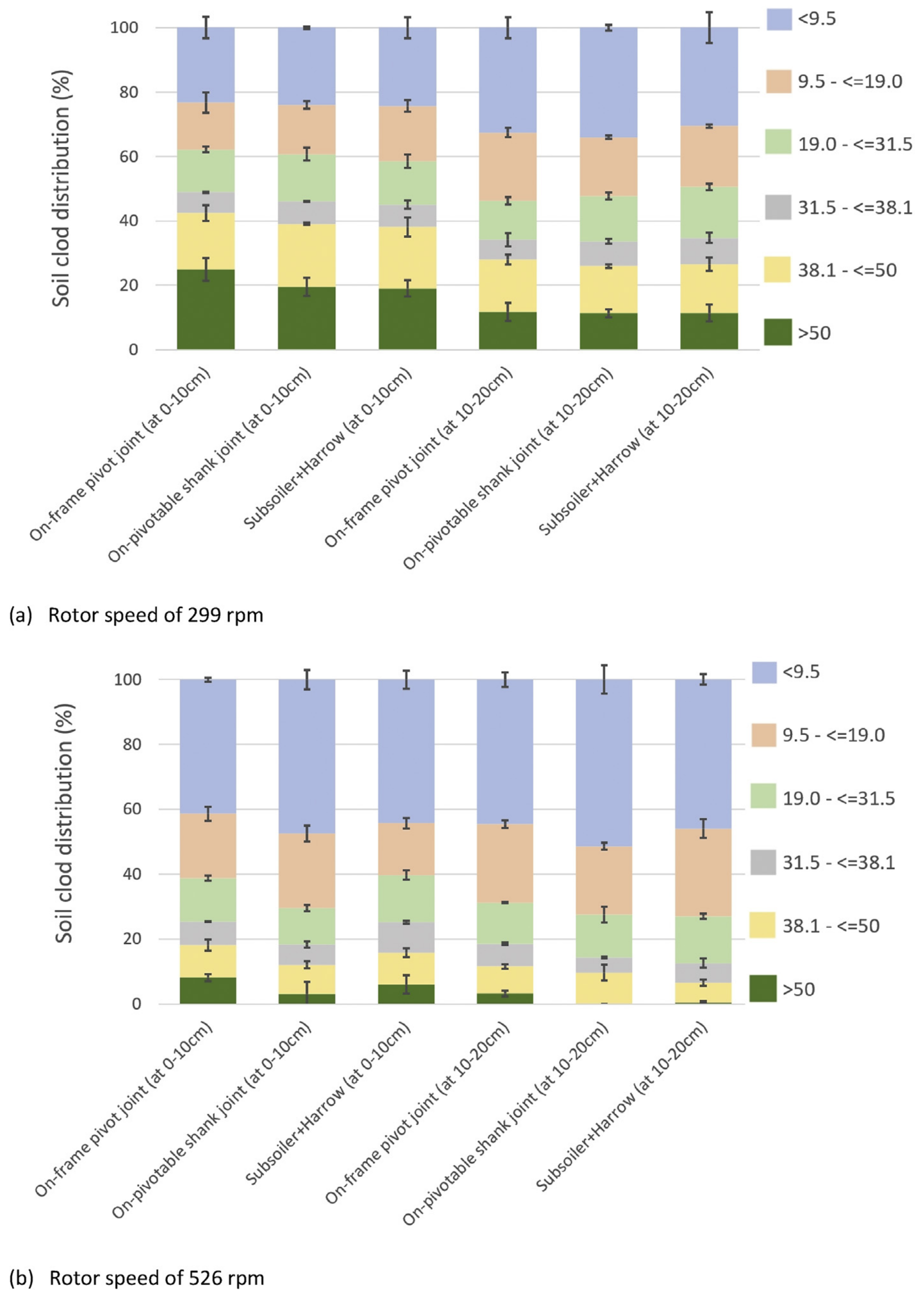


Fig. 5. Variation in clod size distribution under different tillage conditions in field 2 (clay soil). (a) Rotor speed of 299 rpm, (b) Rotor speed of 526 rpm.

Table 8
Performance parameters and specific energy requirements for three tillage operations in field 1.

Variable	Level	Slippage		Drawbar power		PTO power		Specific energy	
		(%)	SD	kW	SD	kW	SD	kWh ha^{-1}	SD
Tillage operation	Combined tillage implement with on-frame pivot joint	5.90b	1.50	19.34b***	5.68	12.83b	2.65	25.79b	2.68
	Combined tillage implement with on-pivotable shank joint	4.66a	1.25	17.15a	4.67	11.59a	3.27	22.67a	3.38
	Subsoiler + Rotary harrow	4.00a**	0.77	23.18c	4.65	15.90c	3.83	28.77c	2.36
Theoretical forward speed (km h^{-1})*	1.89	4.49a		15.42a		12.10a		25.98a	
	2.78	5.21a		24.36b		14.78b		25.51a	
Rotational speed (rpm)	299	5.08a		19.81a		10.78a		24.20a	
	526	4.62a		19.97a		16.09b		27.28b	

* Theoretical forward speed is the forward speed of tractor under no-load condition.
** The summation of subsoiler and rotary slippages.
*** Based on Duncan's new multiple range test, mean values with the same lowercase letter in the same column within the same block are not significantly different at 5% level.

Table 9
Performance parameters and specific energy requirements for three tillage operations in field 2.

Variable	Level	Slippage		Drawbar power		PTO power		Specific energy	
		(%)	SD	kW	SD	kW	SD	kWh ha^{-1}	SD
Tillage operation	Combined tillage implement with on-frame pivot joint	6.94a	1.50	22.77b***	7.24	13.10a	3.24	27.41a	2.63
	Combined tillage implement with on-pivotable shank joint	6.01a	0.83	21.35a	5.71	15.12b	4.25	27.12a	3.51
	Subsoiler + Rotary harrow	9.41b**	2.42	24.00b	8.21	17.56c	5.40	29.61b	2.91
Theoretical forward speed (km h^{-1})*	1.79	6.75a		14.47a		12.60a		27.54a	
	2.67	7.61a		22.94b		15.82b		27.98a	
	3.33	8.00a		30.70c		17.37c		28.61a	
Rotational speed (rpm)	299	7.53a		23.12b		11.99a		26.57a	
	526	7.40a		22.29a		18.54b		29.52b	

* Theoretical forward speed is the forward speed of tractor under no-load condition.
** The summation of subsoiler and rotary slippages.
*** Based on Duncan's new multiple range test, mean values with the same lowercase letter in the same column within the same block are not significantly different at 5% level.

the rotary tiller in both fields; the on-pivotable shank joint seemed to help the combined tillage implement and required less drawbar power than the on-frame pivot joint but the difference was not significant. The direct action of a rotary harrow on the pivotable shank might have transferred the force more effectively to help break the soil than by acting on the frame of the subsoiler. The increase in the drawbar power and PTO power requirements with increasing forward speed might have been because the longer bite size needed more force to cut the soil and the shear strength of the soil increased with the increased speed of the operating tool (Ahaneku and Ogunjirin, 2005).

The effect of forward speed, rotational speed of the rotor, and tillage operation on the slippage is shown in Tables 8 and 9. The combined tillage implement with the on-pivotable shank joint had slippage of 4.66% and 6.01% for field 1 and field 2 respectively, which were less than the slippage of 5.90% and 6.94% generated by the on-frame pivot joint configuration. The forward speed did not significantly affect the slippage. When the forward speed increased, the slippage increased from 4.49% to 5.21% and 6.75%–8.00% for field 1 and field 2, respectively, but this difference was not significant. In addition, the rotational speed of the rotor did not significantly affect the slippage in both fields.

4. Conclusion

Based on the test results that produced no significant difference in the mean soil clod diameter, the combined tillage implement may be an effective way of soil preparation to save time and cost in operations, since it needed only one pass in contrast to the two passes required if the subsoiler and rotary harrow were used separately. The rotational speed of the rotor influenced the soil clod diameter, as the soil clod diameter at 0–200 mm depth decreased from 22.98 to 19.83 mm and from 31.7 to 26.57 mm for fields 1 and 2, respectively, when the rotor speed increased from 299 to 526 rpm. The percentage of soil clod size less than 9.5 mm was higher at 100–200 mm depth than at 0–100 mm depth in both fields. The combined tillage implement produced a significant reduction in the specific energy requirements for seedbed preparation. The specific energy requirements for the combined tillage implement with the on-frame pivot joint and the on-pivotable shank joint were less by 10.4 and 21.1% and by 18.4 and 24.7%, for fields 1 and 2, respectively, than for the energy summation for the units being used separately as a subsoiler and rotary harrow.

Declarations

Author contribution statement

Prathuang Usaborisut: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Kittikhun Prasertkan: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

ASAE Standards, 2005. S313.3: Soil Cone Penetrometer, pp. 866–867.
Ahmadi, I., 2017. A power estimator for an integrated active-passive tillage machine using the laws of classical mechanics. Soil Tillage Res. 171, 1–8.
Ahaneku, I.E., Ogunjirin, O.A., 2005. Effect of tractor of forward speed on sandy loam soil physical conditions during tillage. Niger. J. Technol. 24 (1), 51–57.
Al-Suhaibani, S.A., Ghaly, A.E., 2013. Comparative study of the kinetic parameters of three chisel plows operating at different depths and forward speed in a sandy soil. Int. J. Eng. Sci. 2 (7), 42–59.
Anpat, R.M., Raheman, H., 2017. Investigations on power requirement of active-passive combination tillage implement. Eng. Agric. Environ. Food 10 (1), 4–13.
Al-Janobi, A.A., Al-Suhaibani, S.A., 1998. Draft of primary tillage implements in sandy loam soil. Am. Soc. Agric. Eng. 14 (4), 343–348.
Askari, M., Shahgholi, G., Abbaspour-Gilandeh, Y., 2017. The effect of tine, wing, operating depth and speed on the draft requirement of subsoil tillage tines. Res. Agric. Eng. 63 (4), 160–167.
Bögel, T., Osinenko, P., Herlitzius, Th., 2016. Assessment of soil roughness after tillage using spectral analysis. Soil Tillage Res. 159, 73–82.
Bukhari, B.S., Soos, P., Lehichzky, L., Bherural, T.D., 1981. Performance of tillage implement combination. Agric. Mech. Asia, Afr. Lat. Am. 12 (3), 33–36.
Ghazavi, M.A., Hosseinzadeh, B., Lotfalian, A., 2010. Evaluating physical properties of potato by a combined tillage machine. Nat. Sci. 8 (11), 66–70.
Hendrick, J.G., 1980. A powered rotary chisel. Trans. ASAE (Am. Soc. Agric. Eng.) 23 (6), 1349–1352.
Janeth, C., Richard, O., Karuku, G.N., Kathumo, V.M., 2014. Efficiency of combined tillage practices, cropping systems and organic inputs on soil moisture retention in Yatta Sub-County, Kenya. J. Agric. Environ. Sci. 3 (2), 287–298.
Kailappan, R., Vijayaraghavan, N.C., Swaminathan, K.R., Amuthan, G., 2001. Combination tillage tool - II performance evaluation of the combination tillage tool under field conditions. Agric. Mech. Asia, Afr. Lat. Am. 32 (4), 9–12.
Manian, R., Nagaiyan, V., Kathirvel, K., 1999. Development and evaluation of combination tillage bed furrow-former. Agric. Mech. Asia, Afr. Lat. Am. 30 (4), 22–29.
Prem, M., Swarnkar, R., Kantilal, V.D.K., Jeetsinh, P.S.K., Chitharbhai, K.B., 2016. Combined tillage tools- a review. Curr. Agric. Res. J. 4 (2), 179–185.

RNAM, 1983. RNAM Test Codes & Procedures for Farm Machinery. Regional Network for Agricultural Machinery, Pasay City, the Philippines.
Ranjbarian, S., Askari, M., Jannatkhah, J., 2015. Performance of tractor and tillage implements in clay soil. J. Saudi Soc. Agric. Sci. 16, 154–162.
Sahu, R.K., Raheman, H., 2006. An approach for draft prediction of combination tillage implements in sandy clay loam soil. Soil Tillage Res. 90 (1-2), 145–155.
Shinners, K.J., Alcock, R., Wilkes, J.M., 1990. Combining active and passive tillage elements to reduce draft requirements. Trans. ASAE (Am. Soc. Agric. Eng.) 33 (2), 400–404.
Shinners, K.J., Wilkes, J.M., England, T.D., 1993. Performance characteristics of a tillage machine with active–passive components. J. Agric. Eng. Res. 55 (4), 277–297.
USDA-NRCS (U.S. Department of Agriculture, National Resources and Conservation Service), 2000. Soil Texture Calculator. www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/%20?cid=nrcs142p2_054167.
Upadhyaya, S.K., Williams, T.H., Kemble, L.J., Collins, N.E., 1984. Energy requirements for chiseling in coastal plain soils. Trans. ASAE (Am. Soc. Agric. Eng.) 27 (6), 1643–1649.
Usaborisut, P., Niyamapa, T., 2010. Effects of machine-induced soil compaction on growth and yield of sugarcane. Am. J. Agric. Biol. Sci. 5 (3), 269–273.
Weise, G., 1993. Active and passive elements of a combined tillage machine: interaction, draught requirement and energy consumption. J. Agric. Eng. Res. 56 (4), 287–299.