INTERNATIONAL JOURNAL OF AGRICULTURE & BIOLOGY
1560–8530/2006/08–4–499–503
http://www. fspublishers.org

Energy Requirement of Site-specific and Conventional Tillage as Affected by Tractor Speed and Soil Parameters

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ABSTRACT

Most sandy soils of the Southeastern Coastal Plain of U.S.A. have a compact layer that requires alleviation by costly annual deep tillage operations. Site-specific variable-depth tillage, which modifies soil physical properties to the specific depth of compacted layer has potential to reduce costs, labor, fuel and energy requirements. Although technology for site-specific tillage is available, there is very limited information on the fuel and energy of site-specific tillage in southeastern coastal plain soils. Tests were conducted on three different coastal plain soils to compare energy requirement of site-specific tillage compared to conventional uniform-depth tillage operations. Also, the effects of tractor speed, soil texture, moisture contents, and electrical conductivity on energy requirement and fuel consumption were determined. The energy and fuel saving to 50% and 30%, respectively were achieved by site-specific variable-depth tillage as compared to conventional uniform-depth tillage in a loamy sand soil type. The draft force increased as the travel speed increased in all soil types. However, the tillage depth had the greatest effect on the draft and drawbar power than the tractor speed. The effect of soil moisture content on draft force and fuel consumption was no significant in loamy sand and sandy loam soil types. However, draft force and fuel consumption had a negative correlation with the soil moisture contents. Soil EC was highly correlated to soil texture ($R^2 = 0.916$) and draft force across the field.

Key Words: Precision agriculture; Tillage energy; Conventional tillage; Site-specific tillage; Tractor speed; Soil moisture; electrical conductivity

INTRODUCTION

Most up-land soils of the southeastern Coastal Plain of USA have a compacted zone or hardpan about 15 to 36 cm deep and 5 to 15 cm thick. Farmers in this region rely heavily on the use of annual uniform-depth deep tillage to manage soil compaction, which improves yields (Garner *et al*., 1989; Khalilian *et al*., 2004). However, farmers usually do not know where annual sub-soiling is required in a field, or the required depth of sub-soiling. In addition, there is a great amount of variability in depth and thickness of hardpan layers from intra- and inter-field (Clark, 1999; Raper *et al*., 2000a b; Gorucu *et al*., 2001). There is very little to gain from tilling deeper than the compacted layer and in some cases it may be detrimental to till into the deep clay layer (Garner *et al*., 1989). Applying conventional uniform-depth tillage over the entire field may be either too shallow or too deep and can be costly.

A high-energy input is required to disrupt hardpan layer to promote improved root development and increased drought tolerance. Significant savings in tillage energy could be achieved by site-specific management of soil compaction. Site-specific variable-depth tillage system can be defined as any tillage system, which modifies the physical properties of soil only, where the tillage is needed for crop growth objectives. Raper (1999) estimated that the energy cost of sub-soiling can be decreased by as much as 34% with site-specific tillage as compared to the uniform-depth tillage technique currently employed by farmers. Also Fulton *et al.* (1996) reported a 50% reduction in fuel consumption by site-specific or precision deep tillage.

Tillage implement energy is directly related to working depth, tool geometry, travel speed, width of the implement and soil properties (Gill & Vanden Berg, 1968; Palmer & Kruger, 1982). Soil properties that contribute to tillage energy are moisture content, bulk density, cone index and soil texture (Upadhyaya *et al*., 1984). It has been reported that draft on tillage tools increases significantly with speed and the relationship varies from linear to quadratic. Similarly effect of depth on draft, also varies linearly (Al- Janobi & Al-Suhaibani, 1998).

The technology for site-specific tillage (variable depth tillage) is available (Khalilian *et al.*, 2002) and the concept of site-specific tillage has been reported (Raper, 1999; Gorucu *et al*., 2001). Nonetheless this is an emerging technology and scarce information is available on draft and energy requirements of variable-depth tillage, an important consideration in selecting tillage systems. Furthermore, there is a need to determine the effects of tractor speed and soil parameters such as texture, moisture and electrical conductivity on energy requirements of site-specific and conventional uniform-depth tillage operations in coastal plain soils. The development of this information is the prime concern for an economical management of soil compaction and adoption of this technology by southeastern farmers. The objectives of this study were (a) to compare the energy requirement and fuel consumption between site-specific tillage and conventional uniform-depth tillage on three different coastal plain soils and (b) to determine the effects of tractor speed and soil parameters such as texture, moisture and electrical conductivity on tillage energy requirements and tractor fuel consumption.

MATERIALS AND METHODS

Equipment. A commercially available soil electrical conductivity (EC) meter (Veris Technologies 3100, USA) was used to map the EC of the test field (Lund *et al*., 1999). The system was equipped with six coulter-electrodes. One pair of electrodes supplies current into the soil, while others measure the voltage drop between the coulters. The system can measure the EC in either the top 30 or 90 cm of soil.

A DGPS-based penetrometer system mounted on a John Deere Gator was used to quantify geo-referenced soil resistance to penetration (Khalilian *et al*., 2002). The driver of the Gator could operate the penetrometer (Fig. 1). Soil cone index values were calculated from the measured force required pushing a 130 mm^2 base area, 30-degree cone into the soil (ASAE Standards, 2004).

A front-wheel-assist, 78.3 kW (105 HP) instrumented tractor (John Deere, 4050) was used to collect the energy consumption data during the tillage operations. The instrumentation system consisted of a three-point-hitch dynamometer, a fuel flow meter, engine speed (RPM) sensor, several ground speed sensors (fifth wheel, radar & ultrasonic), differential geographical positioning system (DGPS) unit, a data logger and an optical sensor determining the start and end of each plot (Gorucu *et al*., 2001).

DGPS-based equipment for controlling the tillage depth to match soil physical parameters was used in this experiment (Fig. 2). This equipment can control the tillage depth "on-the go" using either a soil compaction map, inputs from an instrumented shank, or entering the tillage depth data manually in the computer (Khalilian *et al*., 2002). The two out-side shanks of a 4-row sub-soiler were removed for the tillage energy requirement study. This enabled to run the sub-soiler as deep as 46 cm at ground speed of up to 11 km hr^{-1} without overpowering the tractor.

Field test. Field experiments were carried out, on coastal plain soils, during the fall of 2004 at the Edisto Research and Education Center of Clemson University near Blackville, South Carolina (Latitude 33˚ 21″N, Longitude 81˚ 18″W). The 2.5-ha test field had three different soil types: Faceville loamy sand, Fuquay sandy loam and Lakeland sand. Table I shows soil characteristics of the test areas.

Prior to initiation of tests, EC measurements were obtained to determine variations in soil texture and soil physical properties across the field. A geo-referenced EC-map was developed using SSToolbox GIS software. The results showed a great amount of variability in soil EC and the field was found to be an ideal site for variable-depth tillage study. The test field was then divided into 4 x 5 m rectangular plots and soil samples were collected from each plot and analyzed for soil texture. Fig. 3 shows soil electrical conductivity map, soil types and plot arrangements over the entire field.

A complete set of cone penetrometer measurements were obtained with the DGPS-based penetrometer system across the entire field. Nine geo-referenced penetrometer measurements, 1.5 m apart, were taken from each plot. The depth and thickness of the hardpan were determined from the data using the criteria given by Taylor and Gardener (1963). Within each plot, the tillage depth was set to rupture compact layers of the soil with cone index values above 2.07 MPa.

Tillage experiments consisted of twelve treatments arranged in randomized complete blocks with three replications in each soil type. The treatments included two tillage systems (site-specific & uniform-depth), three levels of tractor speed (6, 8 & 9.5 km h^{-1}), and two levels of soil moisture contents (Table I).

RESULTS AND DISCUSSION

The penetrometer data in each location was analyzed using an algorithm written in QBASIC program (Gorucu *et al*., 2001) for determining the tillage depth and for completely removing the hardpan layer. A single depth-value was assigned to each plot by averaging the nine predicted-tillage-depth values within that particular plot. Using these data three tillage zones were identified in each soil type. The optimum tillage depth was the differentiating factor for each management zone. In each zone, two tillage treatments (uniform-depth & site-specific) were replicated thrice. The conventional uniform-depth tillage was performed 46 cm deep to completely disrupt the root impeding layer. The site-specific tillage was applied according to the geo-referenced optimum tillage depth maps generated from soil compaction data.

The predicted tillage depth in Faceville soil type ranged from 20 to 36 cm. In both Fuquay and Lakeland soil types, the tillage depth varied from 28 to 46 cm. The three tillage-depth selected in each soil type for the site-specific tillage were: 20, 30 and 36 cm in Faceville soil type; 28, 40 and 46 cm in Fuquay soil type; and 28, 38 and 46 cm in Lakeland soil type. It is apparent from the results that the

Table I. Soil classification, texture and average moisture content of the test areas

Soil type	Family	Sand (%)	Clay (%)	Moisture (% d.b.), averaged over top 0.46 m of soil profile	
				dry condition	Wet condition
Faceville	Clayey-kaolinitic - thermic, Typic Paleudults	78.3	12.5	9.9	13.5
Fuquay	Loamy-siliceous-thermic, Arenic PlinthicPaleudults	85.5	8.9	6.7	11.6
Lakeland	Siliceous-thermic-coated, Typic Quartzipsamments	89.5	6.3	5.3	7.6

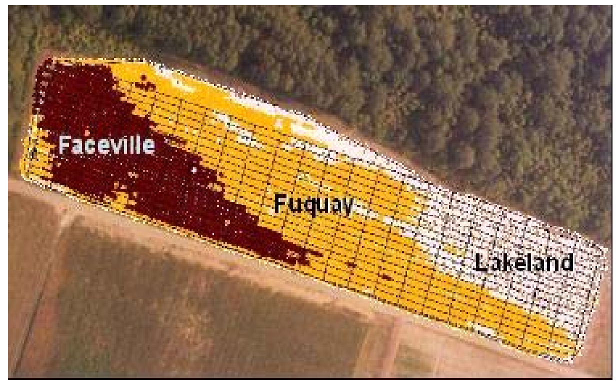
Fig. 1. Hydraulically operated penetrometer system with DGPS unit

Fig. 2. The control system for variable-depth tillage operations

hardpan layer is not uniform and there are some loosened soil layers due to previous tillage operations. The top layer of the soil is not uniform, either and has some compacted regions due to traffic or soil layers from the hardpan layer moved up-ward during tillage operations. In addition, there is a great amount of variability in the depth of the clay layer under the hardpan layer. These are clearly the reasons behind the high number of soil cone index profile conditions. These results are in agreement with the findings of the previous researchers (Clark, 1999; Raper, 1999; Gorucu, 2001). The uniform-depth tillage treatment was kept constant (46 cm deep) in all soil types.

Statistical analysis of energy requirement by using Proc ANOVA in SAS software (SAS Institute, 1999) clearly showed significant difference between tillage treatments in every soil types ($P < 0.01$). Also fuel consumption was significantly different in Faceville ($P < 0.01$) and other two soil types ($P < 0.05$) between site-

Fig. 3. Aerial photograph and soil electrical conductivity map of the experimental field



specific and conventional uniform-depth tillage. The results of the previous researches in the same region (Gorucu, 2001) and other places with different soil types (Fulton, 1996; Raper, 1999) clearly verify these results.

Table II lists tillage energy requirements and fuel consumptions of conventional uniform-depth tillage and site-specific tillage for three coastal plain soil types. Tillage energy and fuel consumption were calculated based on drawbar power and areas of the field. Comparison of tillage energy and fuel consumption for both tillage systems in Faceville soil type showed that energy and fuel saving of 50% and 30%, respectively could be achieved by using site-specific tillage system. Also these savings were 21% and 8% for Fuquay and 26.1% and 8.5% Lakeland soil type, respectively. Raper (1999) reported that energy and fuel savings of 57% and 60%, respectively were achieved by applying the site-specific or variable-depth tillage. Also Gorucu (2001) estimated that energy and fuel savings of 56.3% and 33.8%, respectively could be achieved by adopting the variable-depth tillage over the uniform, constant-depth (conventional) tillage. The differences between results could be because of the variety in soil types. The results showed a significant increase in draft force with an increase in tillage depth in all soil types. Also, the tillage depth significantly affected the fuel consumption (L/ha) in Faceville soil type. There was no difference between fuel consumption in 38 and 46 cm depth in Fuquay soil type and in 38 and 46 cm depth in Lakeland soil type (Table II).

Although not statistically different, the draft force increased with an increase in tractor speed in all soil types. Fig 4 shows the effects of speed on draft force in each soil type. Also the results showed a strong correlation between the tractor speed and fuel consumption (L/ha^{-1}) in each soil types. This is due to increase in draft force and consequently

Table II. Energy and fuel use for site-specific and conventional uniform-depth tillage

Soil Type	Tillage Depth (cm)	Field Size (m^2)	Draft Force (kN)	Drawbar Power (kW)	Fuel Consumption (lha^{-1})	Fuel Use (liter)	Energy (kW-hr)
			SITE-SPECIFIC TILLAGE				
	20	176.5	5.68^d	13.07^d	8.73^d	0.154	0.195
Faceville	30	176.5	12.15^c	27.27^c	10.59^c	0.187	0.417
	36	176.5	14.18^b	32.01^b	11.16^b	0.197	0.487
		Total energy and fuel use for site-specific tillage				***0.538***	***1.099***
			CONVENTIONAL UNIFORM-DEPTH TILLAGE				
	46	529.5	21.55^a	45.75^a	14.42^a	***0.764***	***2.219***
			SITE-SPECIFIC TILLAGE				
	28	176.5	7.15^c	16.41^c	8.61^b	0.152	0.245
Fuquay	40	176.5	12.13^b	27.57^b	10.87^a	0.192	0.416
	46	176.5	13.80^a	31.94^a	11.00^a	0.194	0.524
		Total energy and fuel use for site-specific tillage				***0.538***	***1.185***
			CONVENTIONAL UNIFORM-DEPTH TILLAGE				
	46	529.5	14.10^a	32.23^a	11.03^a	***0.584***	***1.49***
			SITE-SPECIFIC TILLAGE				
	28	176.5	4.43^c	10.04^b	8.38^b	0.148	0.152
Lakeland	38	176.5	7.34^b	16.19^a	9.63^a	0.17	0.254
	46	176.5	9.11^a	19.69^a	10.09^a	0.178	0.306
		Total energy and fuel use for site-specific tillage				***0.496***	***0.712***
			CONVENTIONAL UNIFORM-DEPTH TILLAGE				
	46	529.5	9.50^a	20.88^a	10.23^a	***0.542***	***0.963***

Means followed with same superscript letter within a column for a given soil type are not significantly different at $P < 0.05$ according to LSD test (SAS, 1999).

increase in drawbar power. However, the tillage depth had greater effect on the draft and drawbar power than the tractor speed. Fig. 5 shows the effect of speed on draft force in different depths within each soil type.

The effect of moisture content on draft force and fuel consumption was not evident at loamy sand (Faceville) and sandy loam (Fuquay) soil types. However, an increase in soil moisture content resulted in a decrease in draft forces and fuel consumptions. In sandy soil type (Lakeland), draft forces and fuel consumptions decreased significantly, when soil moisture content increased. This could be due to significant changes in cone index value, since only in this soil type cone index values were significantly affected by soil moisture contents compared to other soil types. These results are in agreements with Raper *et al*. (2004) that reported for Coastal Plain soils. Also findings of many researches show that cone index and bulk density values decrease with an increase in soil moisture content. Therefore, it could be logical if cone index value changes were used due to justification of soil moisture content effects on draft force.

Results showed that use of soil EC to predict soil texture and tillage draft requirement was very successful. There was strong linear correlation between soil EC and both soil texture and tillage draft requirement at a given depth and speed. This indicates that draft requirement strongly vary with soil texture and depends on clay and sand content of soil. Also for practical applications, EC data can be used to predict areas of the field with high or low tillage draft requirements. The Veris system provided reading from 0.1 to 7.0 ms m^{-1}, predicting percentage of clay across the field with a linear correlation coefficient of 0.912 and percentage of sand with a correlation coefficient of 0.916.

Fig. 4. The effect of speed on draft force in each soil type

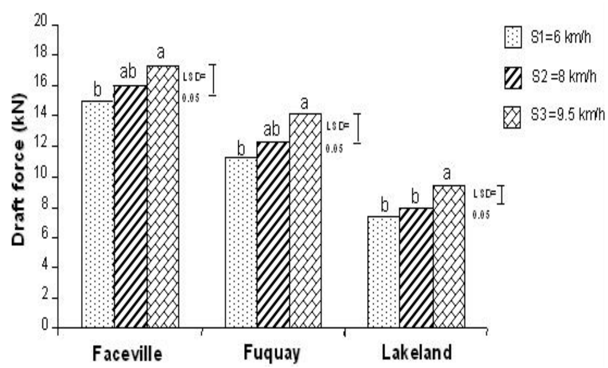


Fig. 5. Draft forces vs. travel speed at different tillage depth within three soil types

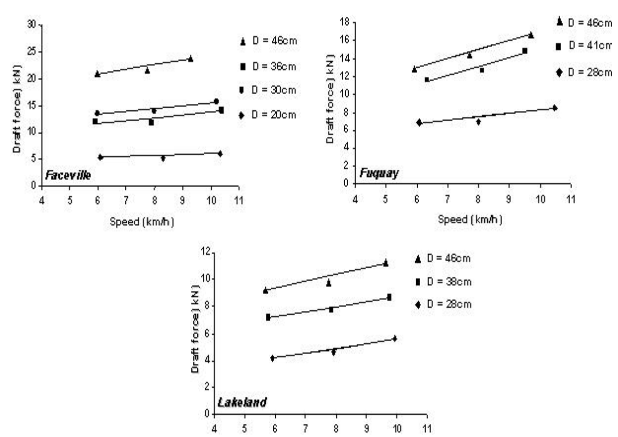


Fig. 6. Effect of soil texture (percentage of clay) on soil electrical conductivity

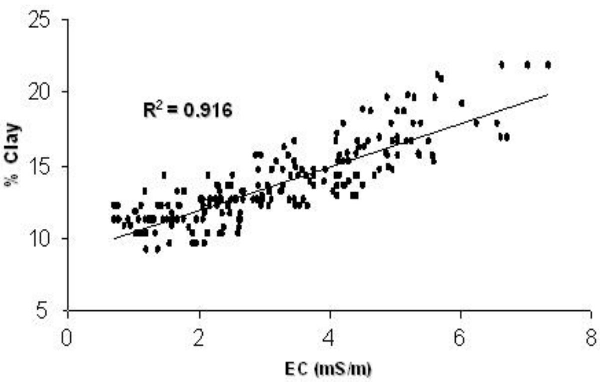


Fig. 7. Effect of soil electrical conductivity on draft force

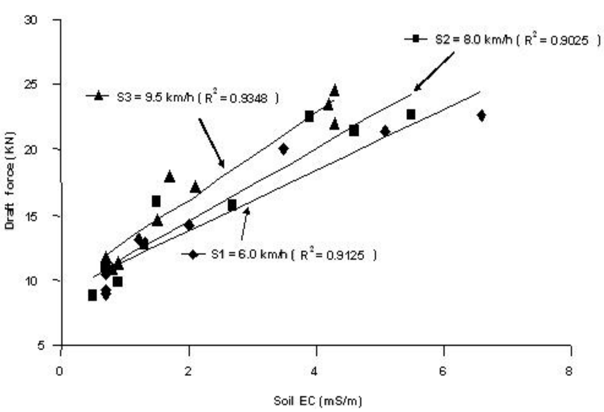


Fig 6 shows the effects of soil texture (% clay) on soil electrical conductivity. A portion of the draft-requirement data with the same tillage depth (46 cm) was selected to investigate the correlation between draft and soil EC. There was a very strong correlation between EC data and tillage draft force at a given speed. Fig 7 shows the effects of EC data on draft force at three different speeds that have been obtained within three different soil types.

CONCLUSIONS

The site-specific tillage resulted in a considerable energy saving of 50% and fuel saving of 30% in loamy sand soil type compared to conventional uniform-depth tillage. The draft force increased as the travel speed increased in all soil types. However, the tillage depth had greater effect on the draft and drawbar power than the tractor speed. The effect of soil moisture content on draft force and fuel consumption was not significant in loamy sand and sandy loam soil types. However, draft force and fuel consumption had a negative correlation with the soil moisture contents. Soil EC data were correlated to soil texture. There was a strong linear correlation between soil electrical conductivity and draft force across the field.

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(Received 19 December 2005; Accepted 01 June 2006)