Effect of tillage implement (spring tine cultivator, disc harrow), soil texture, forward speed, and tillage depth on fuel consumption and tillage quality

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Abstract

Over the years, tillage became less intense due to environmental safety requirements to minimise fuel and labour time. Mainly, this is achieved by reducing the depth of tillage. However, highly cut winter rape stubble is the main challenge for reduced tillage to prepare clear soil, especially as the summer droughts intensify. This study aimed to determine the optimal tillage performances of the spring tine cultivator and compact disc harrow and establish the fuel consumption required to achieve the preferred level of soil structure formation and residue incorporation on loam and clay loam soil after a rape harvest. The fuel consumption depends on the desired level of soil tillage intensity, implement type, tillage depth (5 and 8 cm), and forward speed (1.4, 1.9, 2.5, 3.1, and 3.6 m·s^{-1}). The tractor 'CASE IH 135' was instrumented with a different data acquisition system and was used to perform the indicators of stubble tillage. The research examines the dependence of the tractor-implement regime mode on the soil aggregate ratio, which varied from 0.10 to 0.21, and the residue interblending ratio, which varied from 0.60 to 0.96. The relationship was established by obtaining the tillage quality level and reduced fuel consumption, which varied from 3.4 to 5.9 L·ha^{-1}, depending on soil type. Minimising fuel consumption and sufficient quality of oilseed rape stubble cultivation was achieved by reducing the depth but not the tillage speed.

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Key words: Soil structure; residue incorporation; fuel consumption.

Acknowledgements: this research was supported by the program '*Productivity and sustainability of agricultural and forest soils*' implemented by the Lithuanian Research Centre for Agriculture and Forestry.

Received for publication: 4 February 2022.
Accepted for publication: 22 June 2022.

Journal of Agricultural Engineering 2022; LIII:1371
doi:10.4081/jae.2022.1371

Introduction

Tillage affects soil health, processes of humification and its distribution, and food production safety. Tillage requires most of the energy of crop production activities and affects the environment. Therefore, fuel consumption for tillage increases proportionally with draft force and speed. To reduce tillage costs, it is essential to know the draft requirement for different implements to choose the right implement in each case. Energy is required to prepare the soil at various levels to ensure excellent conditions for crop development. Tilling forms the soil structure, including physical, chemical, and biological parameters, and their relationship, which can influence soil productivity (Dexter, 2004). A good aggregation condition of the soil is described as the aggregate size result of plant growth because it is vital to have a clear seedbed for crop seed germination (Braunack and Dexter, 1989; Bronick and Lal, 2005; Atkinson *et al.,* 2009).

Pagliai *et al.* (1989) stated that soil is considered moderately porous when the total macroporosity is between 10 and 25% of the image analysis. After a high-cut winter oilseed rape harvest, there is a large mass of stubble, plant residues, and roots. Incorporating this high-cut rape stubble into the soil layer is a complex process, especially in clay loam; it increases the draft requirement and fuel consumption. The correct incorporation of straw and plant residues ensures the smooth decomposition process of micro-organics is working well. Studies conducted by Liu *et al*. (2010) indicated that a higher speed of tillage operation could reduce residue cover. The correct tillage for mineralisation of residues, microbial biomass, and extractable organic matter in the soil after oilseed rape straw incorporation in the soil allows the plants to grow to achieve high yields under the appropriate conditions (Jensen *et al.,* 1997; Christian and Miller, 1986). However, soil quality and straw quantity play an important role in ensuring excellent microbe life productivity and nitrogen of microbial-related processes in the soil profile (Ocio *et al.,* 1991). The post-harvest tillage forms the soil structure and surface, which can affect the further soil preparation for sowing. That is why the quality of post-harvest tillage processing must be in line with the high agronomic requirements because the decomposition process of residues is faster when the incorporation quality is better (Pires *et al.,* 2017). Physical soil quality is described by indicators such as bulk density, penetration resistance, infiltration rate, water-holding capacity, electrical conductivity, soil pH, and soil nitrate respiration (Reynolds *et al.,* 2009). The shape and size of soil aggregates as the quality of tillage are quickly detectible by the soil surface at first sight. The soil's physical qualities and crop yields correlate significantly with the visual soil structure (Mueller *et al.,* 2009). Murphy *et al*. (2013) performed visual soil assessment schemes to assess surface structure in a soil monitoring program. The quality of tillage was visually assessed in the research of Voßhenrich *et al*. (2003, 2005), and the incorporation and distribution were evaluated using the 'mesh raster' method and the 'straw index' method. Reduced tillage is a wide-ranging concept; compared to conventional tillage systems, it minimises fuel and labour requirements but must ensure soil productivity for excellent crop conditions. It requires a detailed specification of the actual soil preparation methods and machinery components appropriate for individual situations. Optimising an aggregate regime mode can reduce expenditure, environmental pollution by combustion products, and greenhouse gas emissions (Janulevičius and Damanauskas, 2015). Studies by Serrano *et al*. (2007) and Grisso *et al*. (1996) showed the complicated relationship between draft, speed, and fuel consumption of operation. The draft is a factor that primarily influences fuel consumption during the tillage operation, as described in the ASAE Standard S296.2. That means when reducing the draft, the fuel consumption decreases too. Karparvarfard and Rahmanian-Koushkaki (2015) stated that the fuel consumption results varied based on data from an actual experiment; hence, the equations from ASAE are general and approximate. Studies by McLaughlin and Campbell (2004) showed that a wide range of standard draft force up to±50% can be expected in the same broad textured soil class. The ASAE standard describes tillage draft as a function of machine type, width, depth, and speed:

$$D = F_i \left(A + B \cdot S + C \cdot S^2 \right) W \cdot T \qquad (1)$$

where D is the implement draft force (N); F_i is a dimensionless soil texture adjustment parameter with different values for fine, medium, and coarse-textured soils (1, 0.88, and 0.78); A, B, and C are machine-specific parameters (for offset disc harrow: 364, 18.8, and 0); S is the field velocity ($km \cdot h^{-1}$); W is the width of the implement (m), and T is the tillage depth (cm).

Soil type and conditions are essential factors contributing to variations of implement draft, which is proportional to soil cutting resistance force and depth (Sahu and Raheman, 2006). The depth of tillage is the primary determinant of the power required to pull an implement, with speed often having a significant effect (Naderloo *et al.,* 2009). The linear regression equation obtained by Al-Janobi and Al-Suhaibani (1998) to determine the draft force D (Kgf) involves the working depth d (cm), moisture content R, soil cone index C (MPa), and speed S ($km \cdot h^{-1}$):

$$D = 81.305 \cdot d - 3.799 \cdot S - 113.384 \cdot R - 28.781 \cdot C + 265.272 \qquad (2)$$

The regression equation of Sahu and Raheman (2006) to calculate draft forces is:

$$D = (573 + 208 \cdot S) \cdot d \qquad (3)$$

where S and d represent the forward speed and working depth, respectively.

The regression equation resulting from the study of Kheiralla *et al*. (2004) is:

$$D_h = -1.2723 + 0.1421 \cdot d + 0.9328 \cdot S - 0.0676 \cdot S^2 \qquad (4)$$

where d and S are the implement working depth and speed, respectively, and D_h is the draft force per meter of the machine width.

From the equations above, it is visible that depth and speed are the main components that influence the draft. For fuel savings, the draft should be minimised, for which depth and speed are reduced. Nalavade *et al*. (2010) found for stubble disc harrowing on sandy clay loam at shallow depths (50-100 mm) that draft force increased about 30% when the implement speed increased from 2.2 $km \cdot h^{-1}$ to 4.2 $km \cdot h^{-1}$. Moreover, Ranjbarian *et al*. (2017) found that the draft force of disc ploughing increased about 19% when its forward speed increased from 1.5 $km \cdot h^{-1}$ to 3 $km \cdot h^{-1}$ on clay soil. The draft prediction equation is related to soil conditions, tillage depth, and speed; therefore, the following parameters were examined in this research.

A decrease in tillage depth is needed to effectively use fuel resources in agricultural crop production as one of the constituents of environmental sustainability. There is much research into the biologic and mineral composition of soil and physical properties, but the post-harvest tillage quality level to save fuel is not addressed. The literature also provides the results of numerous computer-based calculation methods for tillage performance during soil ploughing and various tillage in a sustainable way. However, the results are unrelated to agronomical practices, including physical soil state and straw incorporation. A fully validated methodology of tillage for assessing the effective use of fuel is still missing. In this regard, an appropriate choice of tractor and equipment regime is required for correct soil preparation.

This article explores how shallow tillage may be desirable to break up the residues and create new pores between the soil aggregates, successfully adapting to future climate changes by adjusting specific management practices. The task of the paper is to define the soil aggregate sizes that crumple and incorporate plant residues after various tillage options using regime combinations of different implements. In this study, the fuel consumption dependencies required to achieve the desired level of soil tillage by a disc harrow and spring tine cultivator were determined on different soil types.

Materials and methods

The treatments were performed on oilseed rape stubble, whose height was 20±2 cm, on loam and clay loam soils. The experiment for evaluation and comparison of performances was made on different soils because the soil structure formation and residue incorporation depend on soil type. For the measurements of soil penetration resistance, we used a Standard ASABE penetrometer with an iron cone with a nominal diameter of 11.28 mm and an angle of 60°. The mean penetration resistance at 10 cm was 1.05±0.05 MPa on loam and 1.25±0.06 MPa on clay loam soil. The water content of the soil depth 0–10 cm in loam was 17.5±1.0%, and in clay loam, it was 18.6±1.1%. Differences in soil conditions are explained by naturally different physical properties of the soil. The soil texture on clay loam was 27% clay, 23% sand, and 50% silt; on loam, it was 40% sand, 20% clay, and 40% silt. The field experiment was performed on 4 August 2021. Precipitation in July was 33 mm, and in August, it was 175 mm. The soil was very dry in July, but the precipitation began on 2 August with 9.8 mm; on 3 August, it was 2.8 mm. At the time of the study, the soil was sufficient humid, there was a normal physical condition exchange *i.e.*, and usually existing soil state without negative deviations. The temperature on the day of the field experiment was a minimum of 10°C and a maximum of 22°C. The experimental plots without wheeled soil were selected and used (Figure 1). Two reference tillage tools, five forward speeds, two depths, and two soils were used to determine the implements' tillage performances. The tillage depth was measured using a steel measuring tape with the undisturbed surface as a reference. The test to determine soil preparation was accomplished using a disc harrow and spring tine cultivator, at the tillage depths of 5 and 8 cm, at operating speeds of 1.4, 1.9, 2.5, 3.1, and 3.6 $m \cdot s^{-1}$. The disc harrow has 32 cone discs; the tilt angle of the discs was set at 15° and was not changed because it obtained positive results (Damanauskas *et al.,* 2019). The spring tine cultivator has 11 spring tines with chisel cutter wide wings. The disc harrow and spring tine cultivator were 4 m in working width. The construction of both units was similar, but there were differences in the working parts of each implement.

The post-harvest tillage must be accomplished with the lowest fuel consumption and work time required to achieve a sufficiently correct soil structure with stubble residue incorporation. Therefore, an equation was obtained for each implement type:

$$\left[\begin{array}{l} fuel\ \ (FC_{ha}) \rightarrow \min \\ quality\ \ (k_s, k_i) \rightarrow \max \end{array}\right] \rightarrow optimal\ \ regime \qquad (5)$$

The tractor 'Case IH 135' was equipped with an additional technique to evaluate fuel consumption and draft, which are indicators of tractor-implement match for shallow zone till. The engine rotation speed was fixed at 1600-1700 s^{-1}, and the tractor field operating speed was achieved by changing varied gears. Each regime mode of an implement was tested on loam and clay loam soil for three replications. Under investigation, the tillage direction for estimation of influences was parallel to the working direction of the combine harvester. Three soil samples from a tilled layer of each treatment of aggregate regime mode were taken for soil structure and plant residue incorporation assessment. The measurement of the soil structure is described in *The assessment of aggregate size fraction distribution* section, the assessment of the incorporation of plant residues is described in *The assessment of the incorporation of winter oilseed rape and plant residues into the soil* section, and fuel consumption and draft force measurements are described in *The measurements of the speed, draft force, and fuel consumption* section. The *Results* section presents the dependencies between fuel consumption and tillage quality in each regime process and soil type.

The assessment of aggregate size fraction distribution

With different combinations of the equipment regime mode, soil structure and incorporation of residues were investigated. The soil aggregate fraction volume proportion estimated the impact of implements on soil structure. A sieve set sorted the soil after each regime mode harrowing. The volume (m^3) of soil aggregate fractions, *i.e.*, fine, medium, and coarse, was determined (Figure 2). The ratio of the aggregate fractions was an indicator of soil quality and calculated

Figure 1. The estimation of tillage performances on winter oilseed rape stubble: A) tine cultivator; B) disc harrow.

Figure 2. The estimation of soil aggregate fractions after tillage of winter oilseed rape stubble.

according to the methodology provided in the literature (Slawiñski *et al*., 2011; Usowicz and Lipiec, 2017; Velykis and Satkus, 2018). The disc harrows and spring harrows loosened the soil layer to a certain depth, which was the implementation's working depth. A steel meter measured the loosened soil layer, *i.e*., working depth. The first harrowing regime depth was 5 cm, and the second was 8 cm. The loosened soil layers of both depths were sampled for three replications at descriptive places of each treatment and were sieved and divided into three aggregate fractions: fine <10 mm, medium 10-20 mm, and coarse >20 mm (Mueller *et al.,* 2013). The volume of aggregate fraction in each replication was measured, and the mean value was fixed as a reliable indicator for the illustrative structure of each treatment. The mean value data of the aggregate fraction volume deviation did not exceed 5 percent. The medium soil aggregate fraction (M_{medium}) has the highest aeration, water regime, and seed/soil contact, creating the best conditions for decomposition of seed germination and plant residues (Nugis *et al.,* 2016; Lipiec *et al.,* 2007). The fine aggregate fraction (M_{fine}) has weak aeration, is too dusty, and is more influenced by the environment; for example, the wind removes soil dust, and in the case of rain, a watertight layer is formed; when the soil dries, a soil crust is formed, which limits seed germination. Dusty soil is more noticeable with loam, and the soil crust is more noticeable on the clay loam. The coarse aggregates (M_{coarse}) form dry and hard clods that are almost impossible to crush. Such complex clod structure causes a low level of seed germination, bad soil contact with plant residues, and poor organic matter decomposition. The medium soil aggregate volume should be at least one-fifth of the overall soil volume after primary soil tillage for the best mineralisation and germination of scattered rape seeds. The soil structure ratio was calculated by the division of the proportion of medium soil aggregate fraction by the sum of the fine and coarse soil aggregate fractions, estimated as ks, which showed the significant differences in treatments between the regime mode combinations of disc harrow and spring tine cultivator:

$$k_s = \frac{M_{medium}}{M_{fine} + M_{coarse}} \qquad (6)$$

where M_{medium} denotes the medium soil aggregate fraction, M_{fine} denotes the fine soil aggregate fraction, and M_{coarse} denotes the coarse soil aggregate fraction. The bottom of the tilled soil depends on the parts of the working units, tillage depth, operating speed, and soil moisture conditions of their application. For example, when the top layer of soil is tilled with a cone disc harrow at 5 cm depth, the soil between the discs is not crushed, and the bottom of the tilled soil becomes uneven. Such uneven tillage can increase the likelihood of compacted soil, causing weak aeration. It was noticed that when k_s was lower than 0.1, the scattered rape did not germinate or was delayed because of weak soil and seed contact. Since it is just a primary post-harvest harrowing, the soil needs further preparation for crop sowing.

The assessment of the incorporation of winter oilseed rape and plant residues into the soil

Winter wheat is usually sown after winter rape in crop rotations; it is a factor that does not allow time for clearance of oilseed rape stem, mineralisation, and decomposition. The powerful winter rape stubble is a barrier to winter wheat sowing. This is the main reason why the quality of incorporation of residues into the soil is important for sowing the successive crops and the following year's yield. To assess plant residue incorporation quality, we used a weight method. All residues (winter rape stubble, straw, and other residues) were collected from the soil surface in a frame of 0.25 m^2 (50×50 cm) to determine the background of residues before tillage. The samples of residues were collected outside and inside the combine harvester tread tracks. All collected plant residues were dried and weighed. This total collected plant residue mass was marked as M_t. The incorporation of rape stubble depends on the soil texture; therefore, the experiment was done on two fields with different soil physical characteristics. The quality of incorporation was estimated by the ratio of plant residue mass before tillage and plant residue mass incorporated into the soil after tillage. Oilseed rape stubble and residues (upright and lying) were collected from the tilled soil surface after the tillage by the selected disc harrow and spring tine cultivator mode. The residues were dried, weighed, and marked as M_i. The ratio of incorporated plant residue mass and total residue mass is called the residue incorporation ratio, k_i. The ratio of residue incorporation (k_i) was calculated:

$$k_i = \frac{M_t - M_i}{M_t} \qquad (7)$$

where M_t denotes the total residue mass before tillage, and M_i denotes the visible unincorporated residue mass collected from the tilled soil surface.

The measurements of the speed, draft force, and fuel consumption

The following measurements were obtained: i) operating speed, by the original speed radar of the tractor connected to a data recorder; ii) draft force, using the standard towing fingers of the tractor; and iii) hourly fuel consumption ($L \cdot h^{-1}$), by the added fuel consumption gauge, fuel cooler, fuel filter, and air separator in the main fuel system of the engine. In addition, the calibration of signals from the towing fingers was obtained, as shown in Figure 3.

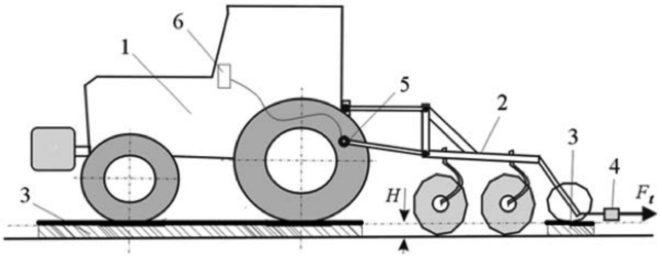

Figure 3. Calibration scheme of draft signal: 1- Case IH 135; 2- disc harrow; 3- pallet, the height of which is equal to the soil cultivating depth; 4- dynamometer; 5- loaded fingers; 6- data recorder.

The draft F_t was developed to such a value that the signals of the five towing fingers sensors would correspond to the signal limit recorded during the field tests.

The calibration of signals from the towing fingers was obtained from a dynamometer load cell (PCE-FB 50k). The towing fingers were loaded by the several values of draft force in the implement traction direction. The signal (voltage value) of the original load cell of the tractor's left and right fingers wrote to the data recorder. At the same time, the dynamometer showed the draft force in newtons. Indications from the recorder and dynamometer were in parallel. The specific draft (kNm^{-2}) was calculated as the draft force divided by the working depth and width of the implement. The fuel consumption data of the calibration test from the data recorder were imported into Microsoft Excel, and graphs were made. Hourly fuel consumption was measured by a fuel flow meter VZO4 OEM (Aquametro), which was fitted into the low-pressure fuel supply system of the CASE IH 135 tractor engine.

Additionally, a fuel cooling radiator, filter, and air separator were installed to ensure the work fluency of the fuel flow meter. The data recorder 'SKRT-21 Lite' recorded signals from the fuel flow meter. Fuel consumption per hectare was calculated only for the technological process of stubble tillage; the headland turns of the unit were omitted here. The engine rotation speed of the tractor was measured by using signals from the tractor's electricity generator. The built-in speed radar of the tractor was used for measuring operating speed. The thrust fingers, speed signal, and engine speed wireless were connected to the installed instrument system data recorder 'SKRT-21 Lite' with the software 'SKRT-MANAGER'. Fuel consumption per hectare FC was calculated according to the following equation ($L \cdot ha^{-1}$):

$$FC = \frac{FC_h}{0.36 \cdot \tau \cdot v \cdot W} \tag{8}$$

where FC_h is hourly fuel consumption ($L \cdot h^{-1}$), W is the working width of the implement (m), τ is the utilisation rate of the working width and time, and v is the operating speed ($m \cdot s^{-1}$).

Results and discussion

Dependence of soil structure at post-harvest shallow tillage

The soil structure is influenced by tillage; therefore, it is important to evaluate the impact of implement on forming soil quality. Pires *et al*. (2017) reported that soil structure is one of the main indicators of soil characteristics. The soil porous system is directly linked to water retention, movement, root development, and gas diffusion, and the conditions for all soil biotas are related. Various scenarios of the post-harvest tillage processes were obtained with the spring tine cultivator and compact disc harrow by changing the tillage depth and operating speed. The results showed that additional fuel consumption is needed to obtain a high quality of soil structure. Decreasing the tillage depth of the disc harrow caused untilled soil between the discs and an uneven soil bottom. Even though a lower draft force was required for disc harrowing compared to spring tine harrowing, the tillage was inappropriate at shallow depth. Because of this, a spring tine cultivator with wide wings, which covered all the width of the surface and left no untilled soil, was the best choice for achieving better soil structure level at a low depth. It was found that the working parts of the implement influenced the soil structure and its aggregate size proportions: on the loam soil, there was too much of the fine aggregate fraction, and in the clay loam soil, there was too much of the coarse aggregate fraction. The spring tine cultivator with wide cutting wings generally caused the most significant proportion of coarse aggregates. It was observed that different results in loam and clay loam soils were obtained using the same regime modes of both implements. The operating speed was the main factor influencing the soil aggregate structure ratio. By changing the speed, it was possible to adjust the soil structure.

The soil structure ratio (k_s) on loam soil increased from 0.12 to 0.145 when the operating speed increased from 1.4 to 2.5 $m \cdot s^{-1}$ and began to decline when the operating speed increased from 2.5 to 3.6 $m \cdot s^{-1}$ by working with a disc harrow at 5 cm depth. The soil structure ratio k_s was slightly higher when the working depth was set at 8 cm (Figure 4A).

The results show that when harrowing with the spring tine cultivator on loam soil at 5 cm depth, the soil structure ratio increased from 0.105 to 0.167 when the operating speed changed from 1.4 to 3.6 $m \cdot s^{-1}$. The soil structure ratio (k_s) on clay loam increased from 0.14 to 0.17 when the operating speed changed from 1.4 to 3.0 $m \cdot s^{-1}$ and began to decline when the operating speed was changed from 3.0 to 3.6 $m \cdot s^{-1}$ by working with the disc harrow at 5 cm depth, and it was slightly higher at 8 cm (Figure 4B). Harrowing with the spring tine cultivator, the soil structure ratio on clay loam increased from 0.1 to 0.2 when the operating speed changed from 1.4 to 3.6 $m \cdot s^{-1}$, at 5 cm depth. The soil structure ratio was lower when the tillage depth was set at 8 cm.

The spring tine cultivator formed an acceptable soil structure ratio on loam and clay loam at high speed. Stubble tillage with the spring tine cultivator reached the best soil structure ratio level (k_s=0.22) on clay loam when the tillage depth was 5 cm and speed 3.6 $m \cdot s^{-1}$. Tillage with the disc harrow reached its maximum and best soil structure ratio level (k_s=0.17) on clay loam when the tillage depth was 8 cm, the operating speed was 2.5 $m \cdot s^{-1}$; a number of fine soil aggregates was observed more after the disc harrow than after the spring tine cultivator mainly on loam soil. Too many coarse soil aggregates were formed on clay loam at low operating speed. In this case, the large course soil aggregates amount was 30 % higher than at high operating speeds. The soil structure ratio k_s reached an acceptable value at operating speeds higher than 2.5 $m \cdot s^{-1}$. The tillage depth did not cause significant differences in the soil structure aggregate ratio. A better soil aggregate ratio was obtained at an 8 cm depth in the loam soil; however, the treatments on clay loam soil showed a better soil aggregate ratio when the tillage depth was 5 cm with both implements. This can be explained by the fact that the discs and tines blades invert the hard soil from a deeper layer and form coarse aggregate fraction on clay loam soil. The formation of the fine aggregate fraction at a lower tillage depth in the loam soil at all operating speeds was more detectable. The coarser soil aggregate fraction was formed at 8 cm tillage depth and was more noticeable in clay loam soil at a lower operating speed. The soil structure ratio depended more on the operating speed and implement type than on the tillage depth. As the operating speed increases, the soil milling intensifies, and the particles brush each other more rapidly on the loam soil. According to the results demonstrated in Figure 4, the changing operating speed considerably impacts the soil aggregate ratio. The soil structure ratio (k_s) evaluation shows that it is necessary to use different tractor speed regimes or equipment choices on different soil types, which is especially relevant for the correct soil preparation in the same field with different soil types. After observing the results, it is recommended to work at a higher operating speed and tillage depth on loam soil to obtain a better soil structure. The tine cultivator chopped soil into too many coarse clods at a slower speed and deeper tillage. The disc harrow cut the ground better and left it finer than the cultivator. This was more obvious on clay loam soil. The furrow formation on the surface was observed with the spring tine cultivator and more on clay soil and with greater depth. The formation of aggregates also depended on soil moisture; during this research period, soil moisture was in middle conditions. According to Arvidsson (2004, 2010), the smallest aggregates were formed by a disc harrow on dry soil when the moisture content was less than 15%, and for the spring tine cultivator, the smallest aggregates were formed when the soil moisture was more than 20%.

Dependences of incorporation of rape stubble and plant residue

The post-harvest tillage processes can be evaluated in different ways; one of them is by incorporating plant residues into the soil. Incorporating rape stubble and plant residues into the soil can induce decomposition and increase mineralisation. Continuous shallow straw application and mineralisation significantly increase soil biological activity over several years. Changes in such soils are evident: an increase in organic matter and earthworms, an improvement in the structure of the soil in the upper layer, a decreased soil hardness, and a less rapid deterioration of soil physical properties (reduced risk of crusting). The mineralisation of blended rape stubble is faster than upright not inserted into the soil (Kriaučiūnienė *et al.,* 2018). Both implements had significant differences in plant residue incorporation quantity. Rapeseed stubble has solid stalks with heavy roots, which complicated the work. The results showed that more inversion of soil and depth is needed to obtain suitable incorporation of stubble. Because the selected post-harvest tillage depth was comparatively small at only 5 cm and 8 cm, the incorporation of residues depended on the operating speed, not the depth.

The spring tine cultivator cut rape roots well without leaving upright stubble. The disc working parts better covered the stubble into a soil layer but left furrows of upright stubble. Better stubble incorporation was determined on loam soil than on clay loam soil and at a higher operating speed in both soils. Decreasing the tillage depth of the disc harrow caused upright stubble. Even if a lower draft force is needed for the disc harrow compared to the spring tine harrow, the incorporation quality was low with a reduced depth. Because of this, a spring tine cultivator with wide wings, which covered all the surface width and left no untilled soil, was the best choice for cutting the roots and covering the surface with rape stubble even at a low depth. The spring tine cultivator working parts did not invert the soil, leaving the stubble unincorporated and lying on the surface. The incorporation of plant residues was better with the disc harrow when the operating speed was higher than average, and the cutting of stubble by the spring tine was the best at all speeds. After the treatments on both loam and clay loam soils at low operating speed and small depth, the level of incorporation quality was weak, and a large part of all plant residues remained on the surface then with the treatments at high operating speed, only the disc harrows ensured that the plant residues were almost invisible. With the increase in tillage depth and operating speed from 1.4 to 3.6 m·s^{-1}, the residue incorporation ratio ki increased in all cases of both harrows and soils (Figure 5). The residue incorporation ratio reached the highest value k_i –0.98 with tillage performed with the disc harrow at a depth of 8 cm and an operating speed higher than 3.0 m·s^{-1} on loam soil (Figure 5A); when used at a low operating speed the residue incorporation ratio was low, only 0.8-0.85. With tillage of loam soil with the spring tine cultivator, incorporation of residues was weak: at a depth of 8

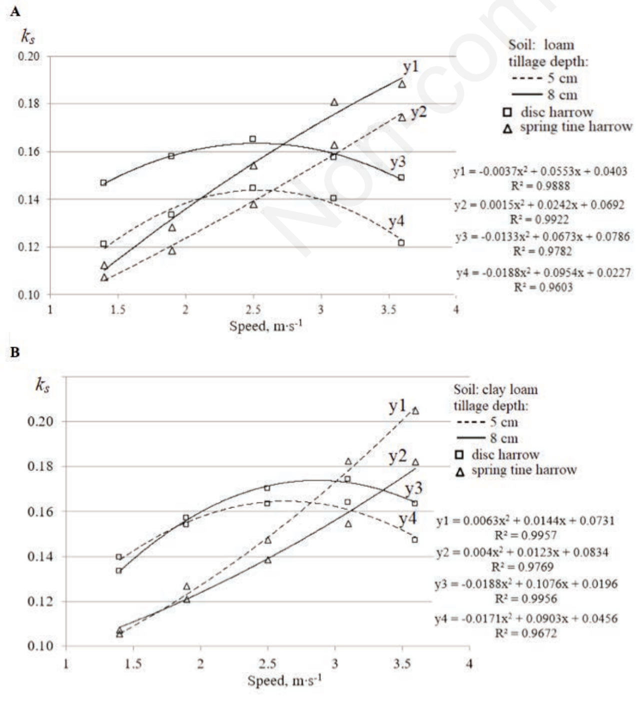

Figure 4. Dependence of soil aggregate structure ratio (k_s) on speed on (A) loam and (B) clay loam soil.

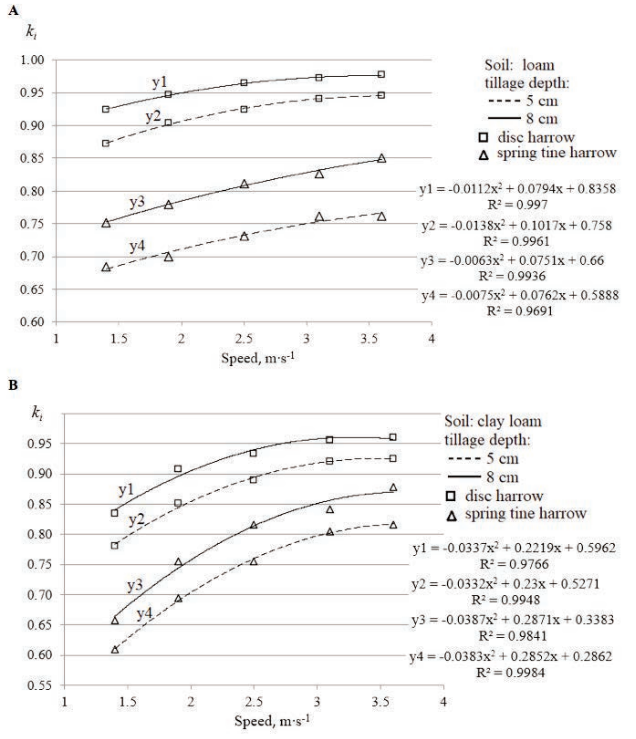

Figure 5. Dependence of incorporation ratio (k_i) on the speed at different depths on (A) loam soil and (B) clay loam soil.

cm and an operating speed higher than 3.0 m·s^{-1}, the residue incorporation ratio was only 0.75-0.8, substantially lower than with the disc harrow. In the treatments on clay loam soil (Figure 5B), raising the speed of the disc harrow from 1.4 to 3.6 m·s^{-1} and the tillage depth from 5 to 8 cm, the residue incorporation ratio coefficient increased from 0.8 to 0.96. The coefficient ki reached the highest value of 0.96 when the tillage depth of the disc harrow was 8 cm and the operating speed was 3.0 m·s^{-1}. The residue incorporation ratio was low when tillage was performed on clay loam soil with the spring tine cultivator at a low operating speed.

After raising the speed from 1.4 to 3.6 m·s^{-1} and tillage depth from 5 to 8 cm, the residue incorporation ratio coefficient increased from 0.6 to 0.86. The coefficient ki reached the highest value of 0.86 when the tillage depth of the spring tine cultivator was 8 cm, and the operating speed was 3.6 m·s^{-1}. The incorporation ratio (k_i) evaluation shows that the way to regulate the incorporation level of rape straw and other plant residues is by changing the operating speed. When the operating speed reached its maximum value, the incorporation ratio of residues reached the highest point. Different results of the incorporation ratio of residues into loam, and clay loam soil were obtained using the same equipment. The incorporation ratio of residues into loam soil was about 20% higher than treatments on clay loam soil; there is an option to work at lower speeds on loam soil than in clay loam soil. The optimal incorporation level of stubble increases soil biological activity because many worms and other soil organisms, including bacteria, appear on the surface of the soil, increasing the mineralisation and quality of soil properties and preventing soil from hardening. Moreover, the stubble on the surface protects the soil from harmful environmental impacts such as drafts, rainfall, and wind. When working with the disc harrow, a lot of stubble furrow remained upright, which does not enable mineralisation and is a barrier for seeding machines; in the meantime, the spring tine cultivator cut all the stubble and laid it on the surface or incorporated it deeper into the soil.

Dependence of draft on disc and spring tine harrows in different soil types

The draft force required to pull an implement is essential to determine the hourly fuel consumption of a tractor. McLaughlin *et al*. (2004) noticed that the mean draft for the disc harrow implement was 5.0 kNm^{-1} for a shallow zone till. The same tendency was stated by Arvidsson (2004). He established that the specific draft strongly correlated to soil cohesion but not penetration resistance, and the draft increased with decreasing soil water content. The draft force depends on implement adjustments and operating speed at an accessible stubble tillage level definable as the tractor drawbar resistance. Various trials of the post-harvest tillage quality levels and different draft demands were obtained by changing the implement, the tillage depth, and operating speed. The dependence of the draft on the desired level of soil structure and residue incorporation ratio was found. Specifically, the draft was generally the lowest for the disc harrow and the highest for the spring tine cultivator.

The draft increases with increasing speed and tillage depth on either implement. The results of the draft force presented in Figure 6A show the dependence on operating speed obtained by harrowing at 5 cm depth. With an increased operating speed from 1.4 to 3.6 m·s^{-1}, the draft force of the disc harrows increased by 3 kN on loam soils and by 3.5 kN on clay loam soil. The forward speed of the tools, the soil moisture content, and the soil cone index are among the critical parameters that influence the draft force of the cultivators. Hendrick (1988) obtained the draft force results for loamy, loamy-clayey, and clayey soils, reported as 520 + 49.2S, 480 + 48.1S, and 527 + 36.1S, respectively (S is tool speed in m·s^{-1}), of chisel ploughs and field cultivators in hard soil when the blades were working at 8.26 cm depth at 1.5-3 m·s^{-1} forward speed. From Hendrick's (1988) equations, we can see that the traction force when working in different soils differed little; this is in line with the results in this study. Safdari (2008) performed a mechanical and dynamic analysis of the cultivator shank using the finite element method. For his purpose, the draft force applied to the cultivator shank was measured at 15 cm depth; then, the force-time diagram was plotted. His measurements showed that the average draft force values at the speeds of 0.88, 1.6, and 2.5 m·s^{-1} were 234.7, 325, and 655.05 N, respectively. The results of Safdari showed a more than twofold increase in draft force, as the speed was increased twofold at 15 cm depth. The results of this research are in proportion to Safdari (2008). It was found that when comparing the spring tine to the disc harrow, the draft force increased by 3-3.5 kN at all operating speeds independent of soil type.

The results presented in Figure 6B show the draft force dependence on operating speed obtained by harrowing at 8 cm depth on both soils. It can be stated that when increasing the tillage depth from 5 to 8 cm at all modes, the draft force increased only 0.25 kN with both implements; thus, the draft force did not increase significantly. Higher differences in draft force independent of implement type were obtained at higher operating speeds on clay loam soil. The draft force was higher by 0.3 kN on clay loam soil than on loam soil at all operating speed variations with the same implement. The research results showed that the draft force increased mainly by the increasing operating speed because a higher operating speed demands a higher soil cutting force and higher inertia force, especially on clay loam soil. A similar account of the draft forces and speed and depth of the discs was proposed by Sahu and Raheman (2006). The research of Naderloo *et al*. (2009) confirmed that the operating speed had a more noticeable effect on the draft than the depth; it found that the optimum operating speed was about 1.75 m·s^{-1} on clay loam soil. Arvidsson (2010) stated that, on average, the specific draft was significantly higher for all chisel treatments than the disc treatments.

Dependence of fuel consumption on harrows type in different soil types

The fuel consumption of the tractor required to pull the implement is proportional to the resistance force its power requirement. A common practice is to use a reduced tillage system, tilling a shallow zone. The extensive ranges in implement draft, fuel consumption, and tractor efficiency indicate that substantial energy savings can be obtained by selecting energy-efficient tillage implements and the proper operating condition parameters of the tillage. Other authors' studies of conventional tillage systems deep zones have shown high expenditures for mouldboard tillage. For example, according to Bowers (1992), the average fuel consumption with mouldboard deep ploughing is 17.49±2.06 L·ha^{-1}, and that with chisel ploughing is 10.20±1.50 L·ha^{-1}, while the no-till planter requires 4.02±1.03 L·ha^{-1}. Koller (1996) reported that the fuel consumption was 49.40 L·ha^{-1} for mouldboard ploughing, 31.30 L·ha^{-1} for chisel ploughing, and 13.40 L·ha^{-1} for the no-till.

This research established that fuel consumption could be reduced by decreasing the working depth; it ranged only to 5.0 L·ha^{-1} for the shallow zone tillage and fluctuated depending on soil type. As the data show, a decrease in the depth of soil cultivation did not significantly affect agronomic parameters of the soil; that is, it is possible to work at a depth of 5 cm. The depth of cultivation can be reduced at high speeds; such modes are especially recommended on clay soils. The hourly fuel consumption increased due to the tillage depth, operating speed, soil, and implement type. It was found that hourly fuel consumption was more reliant on operating speed, as the movement of the tractor itself requires higher fuel content, and more energy is needed to overcome the inertial soil cutting forces. When the tillage was performed with the disc harrow, and the speed was increased from 1.4 to 3.6 m·s–1, the hourly fuel consumption increased from 9.3 to 16.8 L·h–1 in loam soil (Figure 7A) and from 9.8 to 17.6 L·h–1 in clay loam soil at the 5 cm tillage depth (Figure 7B). When the disc harrow was compared to the spring tine cultivator, the hourly fuel consumption increased 2-5 L·h–1 on loam soil and 2-6 L·h–1 on clay loam soil. The hourly fuel consumption was from 11 to 24 L·h–1 on loam and from 12 to 25 L·h–1 on clay loam, depending on the depth and operating speed. The research can confirm that the consumed hourly fuel consumption directly relates to the resistance of the implement, which depends on the soil type: on the clay loam soil, it was 1.0 L·h–1 higher than on loam soil.

The consumption optimisation of the working regime of the tractor implement is better reflected in fuel consumption per hectare. We obtained the fuel consumption differences on two types of soil treatments at various regimes using the disc harrow and spring tine cultivator. The fuel consumption per hectare increased with increased tillage depth but decreased with increased operating speed.

The results in Figure 8A illustrate that it is possible to till the stubble on loam soil with fuel consumption from 3.4 to 5.6 L·ha–1, depending on the selected tool and working mode. The results in Figure 8B illustrate that it is possible to make tillage stubble on the clay loam soil with fuel consumption from 3.6 to 5.9 L·ha–1 depending on the selected work mode. With the disc harrow, the fuel consumption was the lowest and fluctuated around 4 L·ha–1; when using the spring tine harrow, the fuel consumption ranged around 5 L·ha–1. Fuel consumption per hectare was reduced by increasing operating speed to 3.1 m·s–1. The fuel consumption then began to increase at a faster operating speed due to the inefficien-

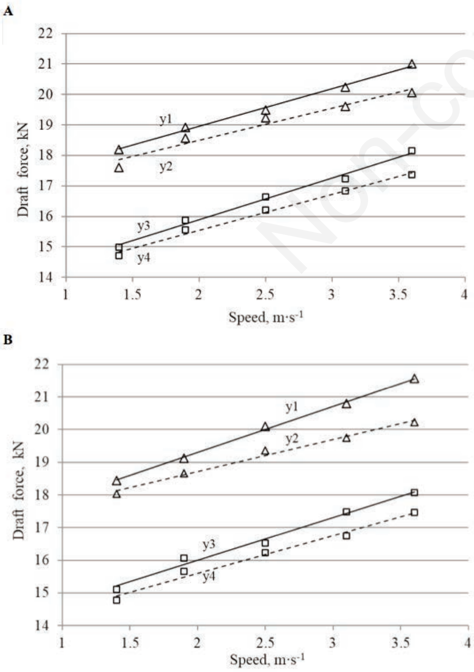

Figure 6. A) Dependence of draft force on the speed at (A) 5 cm and (B) 8 cm soil tillage depth.

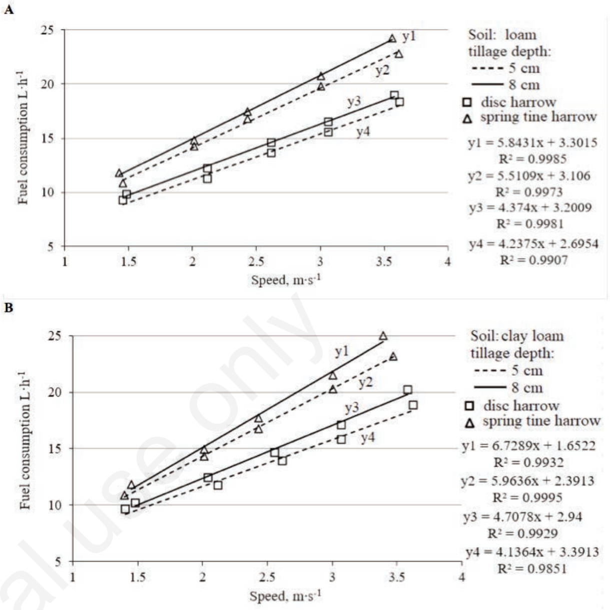

Figure 7. A) Dependence of hourly fuel consumption on the speed at different depths on (A) loam soil and (B) clay loam soil.

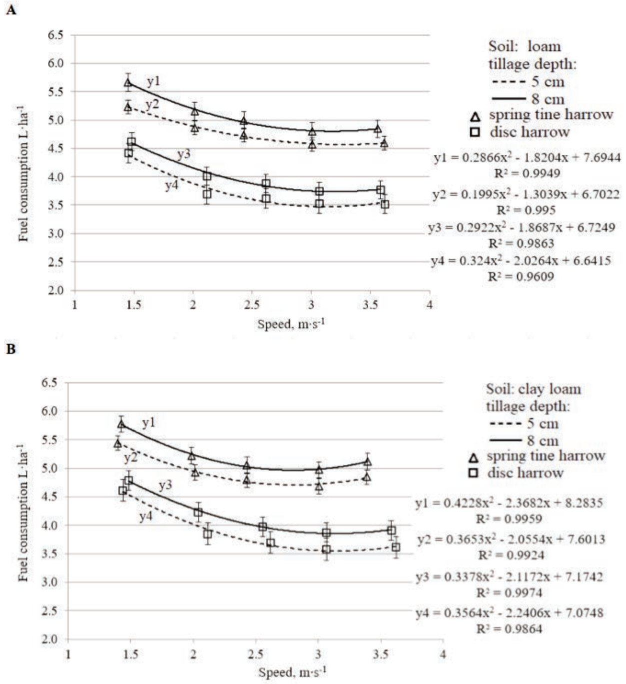

Figure 8. A) Dependence of fuel consumption on the speed at different depths on (A) loam soil and (B) clay loam soil.

Table 1. Summary of results.

Exchangeable factor	Range	Increase in fuel consumption
Speed	From min to max (1.4 to 3.6 m s^{-1})	1.0 L·ha^{-1}
Depth	From 5 cm to 8 cm	0.25 L·ha^{-1}
Soil type	Loam to Clay (resistance)	0.25 L·ha^{-1}
Type of implement	Disc harrow to spring tine	1.0 L·ha^{-1}

cies of the tractor engine regime under overloaded conditions. The results presented in Table 1 illustrate the differences obtained by changing the factor parameters from the lowest to the highest and soil resistance.

Conclusions

The results of the post-harvest tillage study may provide helpful indications for the appropriate choices of a tractor's working regime and implement setting, to optimise energy requirement on different soils, thereby reducing costs.

- Based on the results, the soil structure ratio k_s varied from 0.11 to 0.17 after disc harrowing tillage on loam and clay soils; the soil structure ratio k_s varied from 0.10 to 0.20 on both soils with spring tine cultivator. The best soil structure ratio was obtained with the disc harrow at an operating speed of 2.5-3.0 m·s^{-1} and the tillage depth on loam and clay loam of 8 cm. The best soil structure ratio was obtained with the spring tine cultivator at an operating speed of 3.0-3.6 m·s^{-1} and the tillage depth on loam of 8 cm and clay loam of 5 cm. The fuel consumption for the highest quality of soil structure ratio on loam soil was 3.8 L·ha^{-1} and on clay loam soil 4.0 L·ha^{-1}, with the disk harrow. The fuel consumption of the spring tine cultivator for the highest quality of soil structure ratio on loam soil was 4.8 L·ha^{-1} and on clay loam soil 5.0 L·ha^{-1}.

- The residue incorporation ratio varied from 0.60 to 0.96 on both implements on loam and clay loam soils. The best plant residue incorporation was obtained with the disc harrow at an operating speed from 3.0 to 3.5 m·s^{-1} and a tillage depth on loam and clay loam soil of 8 cm. The incorporation of the spring tine cultivator was worse; the residue incorporation ratio varied from 0.60 to 0.86 on both loam and clay loam soils. The fuel consumption for the highest quality of residue incorporation on loam soil was 3.8 L·ha^{-1} and on clay loam soil 4.0 L·ha^{-1}, with the disk harrow. The fuel consumption of the spring tine cultivator for the highest quality of residue incorporation on loam soil was 4.8 L·ha^{-1} and on clay loam soil 5.0 L·ha^{-1}.

- According to these findings, the tillage depth can be reduced to reduce fuel consumption, but the speed cannot be reduced. The choice of operating speed influenced fuel consumption, ranging from 3.5 to 5.7 L·ha^{-1} on loam soil and from 3.7 to 5.9 L·ha^{-1} on clay loam soil. The fuel consumption differences were 0.25 L·ha^{-1} at the same regime mode of implement, depending on soil type.

- Sufficient stubble tillage quality level can be reached when the disc harrow operating speed is 3.1 m·s^{-1}, with a tillage depth of 8 cm on loam and 5 cm on clay loam soil, which enables the minimal fuel consumption per hectare of 3.75 L·ha^{-1}. A sufficient stubble tillage quality level can be reached when the spring tine harrow operating speed is 3.5 m·s^{-1}, with a tillage depth of 5 cm on loam and clay loam soil; with this regime, the fuel consumption is 4.6 L·ha^{-1}.

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