

# Effects of working depth and wheel slip on fuel consumption of selected tillage implements

G. Moitzi<sup>1\*</sup>, H. Wagentristsl<sup>2</sup>, K. Refenner<sup>2</sup>, H. Weingartmann<sup>1</sup>,  
G. Piringer<sup>1</sup>, J. Boxberger<sup>1</sup>, A. Gronauer<sup>1</sup>

(1. *University of Natural Resources and Life Sciences (BOKU); Department of Sustainable Agricultural Systems; Division of Agricultural Engineering, Peter Jordan-Strasse 82; A-1190 Vienna;*

2. *University of Natural Resources and Life Sciences (BOKU); Department of Crop Science; Experimental Farm Gross Enzersdorf, Schlosshoferstraße 31; A-2301 Gross Enzersdorf*

**Abstract:** Rising fossil fuel prices are leading to an increasing awareness of energy efficiency in plant production. Tillage in particular can consume large amounts of fuel. For four tillage implements (reversible mouldboard plough, short disc harrow, universal-cultivator, subsoiler), this study quantifies the effect of different working depths on fuel consumption, wheel slip, field capacity and specific energy consumption. A four-wheel drive tractor (92 kW) was equipped with a data-acquisition system for engine speed, vehicle speed, wheel speed and fuel consumption. Fuel consumption was measured in the fuel system with an integrated high-precision flow-meter. The results show that the area-specific fuel consumption increased linearly with working depth for both the mouldboard plough and the short disc harrow, but disproportionately for the subsoiler. Wheel slip was found to increase fuel consumption and decrease field capacity performance at all depths. The influence of the engine speed was shown in a separate experiment with a universal-cultivator. Increasing the engine speed from 1,513 r min<sup>-1</sup> to 2,042 r min<sup>-1</sup> results in an increase of 80% for the fuel consumption rate (L/h) and 35% for the area-specific fuel consumption (L/ha). Future measurement of drawbar pull will allow a more detailed analysis of the energy efficiency losses at the engine, the transmission, and at the wheel/soil interface.

**Keywords:** fuel consumption, wheel slip, mouldboard plough, subsoiler, universal-cultivator, short disc harrow

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## 1 Introduction

Reducing fuel consumption in cropland agriculture is a complex and multifactorial process, where farm management plays a key role (Safa et al., 2010).

Conventional tillage with ploughs is one of the most energy-consuming processes in plant production (Stout, 1990; Kalk, 1981). Mouldboard ploughs, tined implements and disc implements are the main implement types for primary tillage (Arvidsson et al., 2004). The

intensity of tillage depends on the number of tillage operations, power transmission (active by PTO or passive by drawbar power), implement geometry, and depth of operation (Godwin, 2007; McKeyes, 1985; Loibl, 2006). Compared to conventional tillage systems, fuel consumption can be significantly reduced with conservation tillage systems (Mileusnić et al., 2010; Moitzi et al., 2009; Tabatabaefar et al., 2009). Tillage with a high degree of soil disturbance, e.g. ploughing or cultivating, contributes greatly to soil tillage erosion (Lobb et al., 1999; Sheng et al., 2007). The fuel consumption of soil tillage operations varies widely and can be reduced through proper matching of tractor size, operating parameters, tillage implement (McLaughlin et

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Corresponding author: Gerhard Moitzi, Email: [gerhard.moitzi@boku.ac.at](mailto:gerhard.moitzi@boku.ac.at)

al., 2008).

Of the average fuel consumption for ploughing (25 L ha<sup>-1</sup>), only 5 L ha<sup>-1</sup> of the fuel energy is used for the drawing of the plough (Kutzbach, 1989), while the remaining fuel consumption is due to efficiency losses in the engine, transmission, and wheel/soil interface (Jahns and Steinkampf, 1982; Schreiber et al., 2004). The term “fuel” is used here exclusively to denote diesel fuel. Additional, soil related, parameters, such as soil texture and organic matter content, influence fuel consumption in soil tillage (McLaughlin et al., 2002; Moitzi et al., 2009). Depending on the soil consistency the fuel consumption increases by 0.5 to 1.5 L ha<sup>-1</sup> per centimetre of ploughing depth (Kalk and Hülsbergen, 1999; Filipović et al., 2004; Moitzi et al., 2006). Moreover, wheel slip as a measure of traction affects field performance and fuel consumption (Jenane et al., 1996; Moitzi et al., 2006). The improvement of the drawbar pulling efficiency through an all-wheel drive reduced wheel slip during ploughing by 50% and during cultivating by 67% in comparison to a two-wheel drive and resulted in fuel

savings of 2 L ha<sup>-1</sup> (Moitzi et al., 2006). The working depth in tillage processes also had a large influence on fuel consumption and wheel slip.

This paper will determine the effect of working depth and wheel slip on fuel consumption and field capacity. Specifically, the effect will be measured during ploughing (mouldboard plough), stubble field skimming (short disc cultivator and universal-cultivator), and subsoiling (subsoiler with fixed tines) in a in a typical cereal-growing region in Eastern Austria.

## 2 Materials and methods

### 2.1 Experimental setup

The experiments (Table 1) were conducted on arable fields at the research station Gross Enzersdorf (Lower Austria; 48° 15' N/ 16° 37' E) of the University of Natural Resources and Life Sciences Vienna. The site is situated in a semi-arid region with an average precipitation of 546 mm and average temperature of 9.8°C. The silty loam soil belongs to the soil type calcic CHERNOZEM.

**Table 1 Overview of experimental set-up**

	Ploughing	Stubble field skimming	Subsoiling
Soil tillage device	4 furrow reversible mouldboard plough	Short disc harrow (SDH); Universal-cultivator (UC)	Subsoiler
Adjusted mean working depth (cm)	18, 20, 35	SDH: 8, 10, 13; UC: 13, 15	20, 30, 33, 40, 45
Date of experiments	3 November, 2005	31 July, 2008	2 October, 2008
Previous crop	Corn	Winter rapeseed	Corn
Mean water content in the soil (gravimetric)	14.3% (0-30 cm)	18.3% (0-20 cm)	16.9% (0-40 cm)
Mean dry bulk density	1.35 g cm <sup>-3</sup>	1.40 g cm <sup>-3</sup>	1.39 g cm <sup>-3</sup>

Before the experiment was carried out, each field was probed with soil sample rings (height: 4.8 cm; radius: 3.5 cm; volume: 184.73 cm<sup>3</sup>) to a depth of 30 cm for the ploughing experiment, 20 cm for the experiment with short disc harrow and universal-cultivator, and 40 cm for the experiment with the subsoiler, respectively. The soil samples were dried in an oven (105°C, 12 h) and afterwards the mean water content (gravimetric) and mean dry bulk density were calculated.

The mean working depth of the mouldboard plough was set by measuring the vertical distance between furrow ground and unploughed soil. For the short disc harrow, universal cultivator and subsoiler the mean

working depth was calculated by the difference between the vertical distance of the implement-frame to the soil surface in the tillage process and the vertical distance of the implement-frame to a concrete surface.

### 2.2 Specifications for soil tillage implements

Table 2 shows the technical data of the soil tillage implements according to manufacturers' specifications.

### 2.3 Tractor and measuring equipment

For all experiments a four-wheel drive tractor (Steyr 9125, CNH, St. Valentin, Austria) with a rated engine power of 92 kW (DIN) was used. The four stroke diesel engine with direct injection and exhaust turbo supercharger has six cylinders (vertical in line) with a total

**Table 2** Technical data of the mouldboard plough, short disc cultivator, universal-cultivator and subsoiler

Four furrow reversible Mouldboard Plough – two-way-rear mounted		
Technical working width, m	1.70	
Weight, kg	1210	
Adjustable working depth, cm	15 - 30	
Depth adjustment	Rear wheel	
Manufacturer	<i>Heger, Hohenruppersdorf, Austria</i>	
Short Disc Harrow (Catros™)		
Technical working width, m	3.00	
Number of discs	2 × 12	
Spacing between discs, cm	25	
Disc diameter, cm	46	
Weight, kg	1770	
Adjustable working depth, cm	3–12	
Depth adjustment	Wedge ring roller	
Manufacturer	<i>Amazone, Hasbergen, Germany</i>	
Universal-Cultivator (Cenius™)		
Technical working width, m	3.00	
Number of spiral spring tines	13	
Tool width, cm	7.50	
Number of discs	8	
Disc diameter, cm	46	
Weight, kg	2160	
Adjustable working depth, cm	5 - 30	
Depth adjustment	Wedge ring roller	
Manufacturer	<i>Amazone, Hasbergen, Germany</i>	
Subsoiler (Cultiplow™)		
Technical working width, m	3.00	
Number of fixed tines	4	
Width of subsoiler wing, cm	34	
Weight, kg	773	
Adjustable working depth, cm	20 - 50	
Depth adjustment	Roller harrow	
Manufacturer	<i>Agrisem International, Ligne, France</i>	

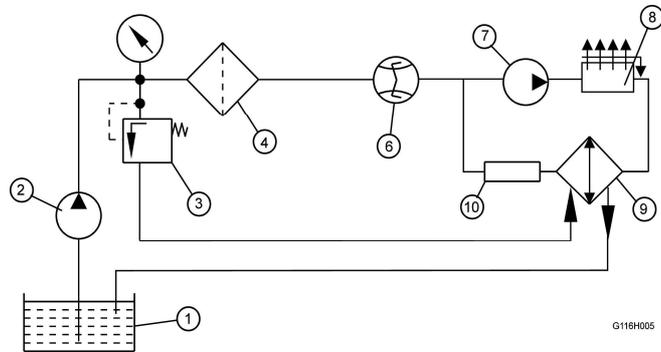
displacement of 6,596 cm<sup>3</sup>. The transmission (Steyr-Power-4, 40 km h<sup>-1</sup>) is a fully synchronous multistep powershift with 4×6 gears. The main power take-off performance test according ISO R500-1991, type I (DIN 9611) indicated – at maximum power (95 kW with an engine speed of 1,800 r min<sup>-1</sup>) – an hourly fuel consumption of 27.2 L h<sup>-1</sup> and a specific fuel consumption of 241.5 g kWh<sup>-1</sup>, with an equivalent crankshaft torque of 379.9 Nm. The maximum equivalent crankshaft torque was 556.3 Nm at 1,200 r min<sup>-1</sup> (OECD-Test-Report, 1988). The kerb weight was

6,220 kg and was ballasted with a front ballast of 830 kg. Front tires were radial 540/65 R 28, inflated to 1.6 bar, and the rear tires were radial 650/65 R 38 at 1.8 bar.

During the experiments, the tractor's transmission was set at gears that were adjusted to the implement used: For ploughing, the tractor was operated at the third gear/second power shift; with the short disc harrow, at fourth gear/second power shift; with the universal cultivator, at third gear/fourth power shift (third gear/third power shift for the experiment varying the engine operating point); and with the subsoiler at second

gear/first power shift.

For the measurement of the fuel consumption a high-performance flow meter (PLU 116H, AVL 2005, List, Graz, Austria) with a proportional–integral (PI) controller was installed in the fuel system of the tractor (Figure 1).



1. Fuel tank 2. Pre-pump 3. Pressure control with manometer 4. Pre-filter. 6 Flow-meter PLU 116H 7. Pump 8. Fuel injection pump 9. Fuel/fuel-heat exchanger 10. Glass sight gauge for fuel recirculation control

Figure 1 Fuel consumption monitoring system (AVL 2005)

The volumetric fuel consumption was continuously measured with a measurement precision uncertainty of 0.3% with a negligible pressure drop between inlet and outlet ( $\Delta p=0$ ). Additionally an air bubble releaser and heat exchanger (between fuel inlet and fuel outlet) were installed in the fuel measurement system. The digital rectangular signal was logged with a scan rate of 1 Hz. The consumption flow rate ( $L h^{-1}$ ) is calculated according Equation (1).

$$Q = \frac{f \cdot 3.6}{K_D} \quad (1)$$

where,  $Q$  is flow rate,  $L h^{-1}$ ;  $f$  is frequency, Hz.

According to the calibration protocol  $K_D$  was  $161.99 \text{ cm}^3$ . The factor 3.6 in Equation (1) is a dimensionless conversion factor. All signals in Table 3 are recorded with a multi-channel data logger (Squirrel Datenlogger 2020) with a scan rate of 1 Hz.

**Table 3 Process parameters and their measurements**

Process parameters	Sensor and signal output
Vehicle speed ( $v$ )	<i>Radar sensor</i> , generates a rectangular signal ( $130 \text{ pulses m}^{-1} = 27.8 \text{ Hz/(km h}^{-1})$ )
Wheel speed ( $v_0$ )	<i>Transmission sensor</i> (inductive transducer), generates a 0.4 - 3.8 V AC signal
Engine speed ( $n_E$ )	<i>Inductive sensor</i> generates a rectangular 0 - 12 V AC signal
Fuel consumption rate ( $Q$ )	<i>Flow meter</i> (PLU 116 H), generates a digital rectangular signal between 22 - 2800 Hz

## 2.4 Process parameters

The process parameters were determined using a variety of sensors (Table 3).

For the calculation of the wheel slip ( $s$ ) the parameters “wheel speed” ( $v_0$ ) and “vehicle speed” ( $v$ ) are required (Equation (2)).

$$s = \frac{v_0 \uparrow v}{v_0} \cdot 100 \quad (2)$$

where,  $v_0$ : wheel speed,  $\text{km h}^{-1}$ ;  $v$ : vehicle speed,  $\text{km h}^{-1}$ ;  $s$ : wheel slip, %.

The theoretical field capacity ( $C_{theo}$ ,  $\text{ha h}^{-1}$ ) does not account for wheel slip and is defined as:

$$C_{theo} = w \cdot v_0 \cdot 0.1 \quad (3)$$

where,  $w$  is technical working width, m.

The effective field capacity ( $C_{eff}$ ,  $\text{ha h}^{-1}$ ) accounts for wheel slip by replacing wheel speed  $v_0$  with vehicle speed  $v$ :

$$C_{eff} = w \cdot v \cdot 0.1 \quad (4)$$

The area-specific fuel consumption ( $Q_{A1}$ ,  $L \text{ ha}^{-1}$ ) with slip is defined as:

$$Q_{A1} = Q / C_{eff} \quad (5)$$

where,  $Q$  is fuel consumption rate,  $L h^{-1}$

The area-specific fuel consumption ( $Q_{A2}$ ,  $L \text{ ha}^{-1}$ ) without wheel slip is calculated with the theoretical field capacity:

$$Q_{A2} = Q / C_{theo} \quad (6)$$

The area-specific fuel consumption with slip ( $Q_{A1}$ ) is calculated with the vehicle speed ( $v$ ), whereas the fuel consumption without slip ( $Q_{A2}$ ) is calculated with wheel speed ( $v_0$ ). Their difference indicates the fuel amount which is lost due to the slip between wheel and soil. Both area-specific fuel consumption parameters do not include fuel consumption during turning at the headland. Therefore, they allow a comparison of soil tillage devices regardless of field shape and field size.

The specific soil displacement energy ( $J \text{ kg}^{-1} \text{ soil}$ ) was calculated by dividing the energy content of the consumed fuel by the mass of moved soil. The lower heating value of 36 MJ/L from diesel fuel (Kraftstoffverordnung 2013) was used for calculation of the energy content of the consumed fuel. The mass of moved soil per hectare was computed by the mean bulk

density (Table 1) and the measured mean working depth. The fuel consumption as a function of working depth was fitted both with a linear and with a quadratic function. The function with the highest coefficient of determination ( $R^2$ ) was selected for interpolation (Figures 2, 3 and 5).

### 3 Results and discussion

#### 3.1 Mouldboard plough

Mouldboard ploughs are used in conventional tillage systems, where the furrow slice is turned in an angle of about 139°. The measured fuel consumption rate shows a diminishing increase with increasing working depth (Figure 2), which is the result of shifting the partially loaded engine's operating point closer to the full load range. The engine speed was relatively constant at the different working depths (Table 4), and at partial engine load, the specific fuel consumption ( $\text{g kWh}^{-1}$ ) decreases with increasing power demand. The area-specific fuel consumption ( $Q_A$ ) is the quotient of fuel consumption rate and field capacity (Equations (5) and (6)). It also exhibited a possibly diminishing increase with working depth. The area-specific fuel consumption with wheel slip  $Q_{A1}$  was approximated slightly more accurately with a quadratic model ( $R^2 = 0.991$ ) than with a linear model ( $R^2 = 0.978$ ). Linear functions for this parameter were found in Kalk and Hulsbergen (1999) and Filipovic et al.

(2004). The slope of the  $Q_{A1}$  curve is  $0.348 \text{ L ha}^{-1}$  per cm working depth. The y-intercept of  $Q_{A1}$  in the linear model (Figure 2),  $6.48 \text{ L ha}^{-1}$ , is the basic consumption which results mainly from the rolling resistance between tyre and soil surface. The wheel slip increases from 3.34% at 18 cm working depth to 6.12% at 35 cm working depth (Table 4), which is a result of increased drawbar power demand. For the working depth of 35 cm, this slip between wheel and soil consumes  $1.1 \text{ L ha}^{-1}$  of the total area-specific fuel consumption  $Q_{A1}$  of  $18.29 \text{ L ha}^{-1}$ .

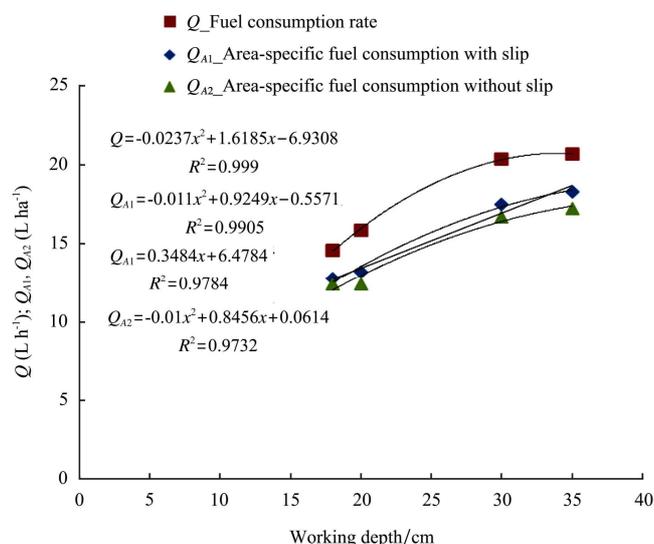


Figure 2 Fuel consumption rate ( $\text{L h}^{-1}$ ) and area-specific fuel consumption ( $\text{L ha}^{-1}$ ) as a function of working depth for ploughing

**Table 4 Process parameters for ploughing with the mouldboard plough at different working depths (gear adjustment: 3. gear and 2. power shift)**

Process parameters	Unit	Working depth (cm), Mean ± Std. Dev.			
		18 (n*=408)	20 (n*=399)	30 (n*=415)	35 (n*=445)
Fuel consumption ( $Q$ )	$\text{L h}^{-1}$	14.61 ± 1.61	15.85 ± 1.71	20.36 ± 1.63	20.67 ± 2.18
Engine speed ( $n_E$ )	$\text{r min}^{-1}$	1732 ± 68	1873 ± 68	1804 ± 60	1773 ± 153
Vehicle speed ( $v$ )	$\text{km h}^{-1}$	6.69 ± 0.28	7.01 ± 0.39	6.80 ± 0.30	6.62 ± 0.67
Wheel speed ( $v_0$ )	$\text{km h}^{-1}$	6.91 ± 0.28	7.51 ± 0.43	7.18 ± 0.30	7.05 ± 0.68
Slip (s)	%	3.34 ± 1.34	6.03 ± 2.03	5.68 ± 1.53	6.12 ± 1.87
Effective field capacity ( $C_{eff}$ ) with slip	$\text{ha h}^{-1}$	1.14	1.19	1.16	1.13
Theoretical field capacity ( $C_{theo}$ ) without slip	$\text{ha h}^{-1}$	1.17	1.28	1.22	1.20
Fuel consumption ( $Q_{A1}$ ) with slip	$\text{L ha}^{-1}$	12.82	13.32	17.55	18.29
Fuel consumption ( $Q_{A2}$ ) without slip	$\text{L ha}^{-1}$	12.49	12.38	16.69	17.23
Specific energy	$\text{J (kg soil)}^{-1}$	185	172	152	136

Note: \* number of measured values.

#### 3.2 Short disc harrow

Short disc harrows are widely used for stubble field

skimming. The measured fuel consumption increased from  $6.53$  to  $8.40 \text{ L ha}^{-1}$  with increasing working depth

from 8 to 13 cm (Table 5, Figure 3). The mean engine speed ranged from 1,711 to 1,733 r min<sup>-1</sup>, the vehicle-speed from 8.10 to 8.22 km h<sup>-1</sup>, the effective field capacity was 2.43-2.50 ha h<sup>-1</sup>. Wheel slip increased from 3.4% to

6.0% with increasing working depth. A raised implement without skimming (= 0 cm working depth) results in a basic fuel consumption of 2.85 L ha<sup>-1</sup>, which is mainly caused by the rolling resistance in the soil/tyre interface.

**Table 5 Process parameters for stubble field skimming with a short disc harrow at different working depths (gear adjustment: 4. gear and 2. power shift)**

Process parameters	Unit	Working depth (cm), Mean ± Std. Dev.			
		0 (n*=120)	8 (n*=337)	10 (n*=168)	13 (n*=150)
Fuel consumption (Q)	L h <sup>-1</sup>	7.14 ± 0.82	16.11 ± 0.86	17.74 ± 1.00	20.40 ± 0.31
Engine speed (n <sub>E</sub> )	r min <sup>-1</sup>	1768 ± 19	1711 ± 38	1725 ± 19	1734 ± 30
Vehicle speed (v)	km h <sup>-1</sup>	8.35 ± 0.05	8.22 ± 0.21	8.21 ± 0.11	8.10 ± 0.18
Wheel speed (v <sub>0</sub> )	km h <sup>-1</sup>	8.35 ± 0.04	8.51 ± 0.21	8.58 ± 0.09	8.60 ± 0.15
Slip (s)	%	0.03 ± 0.69	3.40 ± 0.84	4.33 ± 0.99	6.00 ± 0.81
Effective field capacity (C <sub>eff</sub> ) with slip	ha h <sup>-1</sup>	2.50	2.47	2.46	2.43
Theoretical field capacity (C <sub>theo</sub> ) without slip	ha h <sup>-1</sup>	2.51	2.55	2.57	2.58
Fuel consumption (Q <sub>A1</sub> ) with slip	L ha <sup>-1</sup>	2.85	6.53	7.20	8.40
Fuel consumption (Q <sub>A2</sub> ) without slip	L ha <sup>-1</sup>	2.85	6.31	6.89	7.91
Specific energy	J (kg soil) <sup>-1</sup>		198	173	153

Note: \* number of measured values.

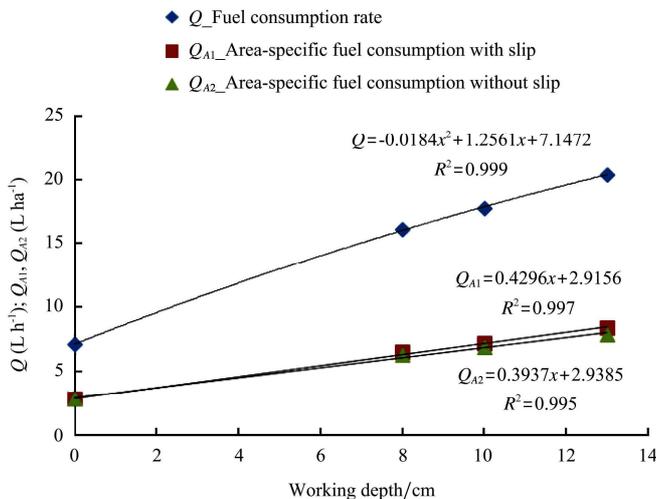


Figure 3 Fuel consumption rate (L h<sup>-1</sup>) and area-specific fuel consumption (L ha<sup>-1</sup>) as a function of working depth for stubble field skimming with short disc harrow

### 3.3 Universal-cultivator

The universal cultivator is an alternative device for stubble field skimming. The influence of the working depth on the process parameters of the universal-cultivator are shown in Table 6. At a working depth of 13 cm the area-specific fuel consumption with slip for the universal-cultivator is lower than with the short disc harrow (6.78 L ha<sup>-1</sup> vs. 8.40 L ha<sup>-1</sup>).

**Table 6 Process parameters at stubble field skimming with a universal-cultivator at different working depths (gear adjustment: 3. gear and 4. powershift)**

Process parameters	Unit	Working depth (cm), Mean ± Std. Dev.		
		0 <sup>1</sup> (n*=120)	13 (n*=100)	15 (n*=127)
Fuel consumption (Q)	L h <sup>-1</sup>	7.14 ± 0.82	17.03 ± 0.54	20.45 ± 0.56
Engine speed (n <sub>M</sub> )	r min <sup>-1</sup>	1768 ± 19	1720 ± 14	1718 ± 48
Vehicle speed (v)	km h <sup>-1</sup>	8.35 ± 0.05	8.37 ± 0.08	7.88 ± 0.25
Wheel speed (v <sub>0</sub> )	km h <sup>-1</sup>	8.35 ± 0.04	8.56 ± 0.06	8.16 ± 0.23
Slip (s)	%	0.03 ± 0.69	2.02 ± 0.83	3.47 ± 1.16
Effective field capacity (C <sub>eff</sub> ) with slip	ha h <sup>-1</sup>	2.50	2.51	2.36
Theoretical field capacity (C <sub>theo</sub> ) without slip	ha h <sup>-1</sup>	2.51	2.57	2.45
Fuel consumption (Q <sub>A1</sub> ) with slip	L ha <sup>-1</sup>	2.85	6.78	8.63
Fuel consumption (Q <sub>A2</sub> ) without slip	L ha <sup>-1</sup>	2.85	6.63	8.35
Specific energy	J (kg soil) <sup>-1</sup>		131	145

Note: \* number of measured values; <sup>1</sup>data from the short disc harrow (Table 5).

Figure 4 shows the effect of an increased engine speed during cultivation at 15 cm. Without changing the gear adjustment (3. gear and 3. powershift), the engine speed was increased stepwise from 1,513 to 1,733 r min<sup>-1</sup>, and then to 2,042 r min<sup>-1</sup>. The corresponding hourly fuel consumption rate rose by 80% from 13.3 L h<sup>-1</sup> with

1,513 r min<sup>-1</sup> to 23.6 L h<sup>-1</sup> with 2,042 r min<sup>-1</sup> and the area-specific fuel consumption (L ha<sup>-1</sup>) increased by 35%. This is explained by two effects: on the one hand the higher engine speed and vehicle speed result in a higher field capacity, but on the other hand it causes higher specific fuel consumption. The strategy of maximizing field performance by increasing the wheel speed (so-called high speed farming) is therefore not advisable from the viewpoint of energy conservation. This has been confirmed by authors Filipović et al. (2004). According to investigations by Kichler et al. (2011), operating at fast speeds in deep tillage increased draft, fuel consumption, axle torque and field performance. With regard to energy efficiency, the optimal vehicle speed depends on matching the implement to the tractor,

and a good match can achieve substantial energy savings (McLaughlin et al., 2008). An indicator for fuel-efficient engine operation is the engine speed, which is for most engines at 70%-80% of the nominal engine speed, that is, between 1,300 and 1,700 r min<sup>-1</sup>. The “gear up, throttle down” strategy proposed by Grisso and Pitman (2001) is a practical approach for saving fuel, even though it is limited to lighter field operations. The idea is to operate tractors in a higher gear when pulling lighter loads, thus achieving lower engine speeds and lower fuel consumptions while maintaining the ground speed. However, the “gear up, throttle down” strategy is limited by incomplete combustion of diesel fuel (black exhaust fumes) and reduced engine lubrication and cooling.

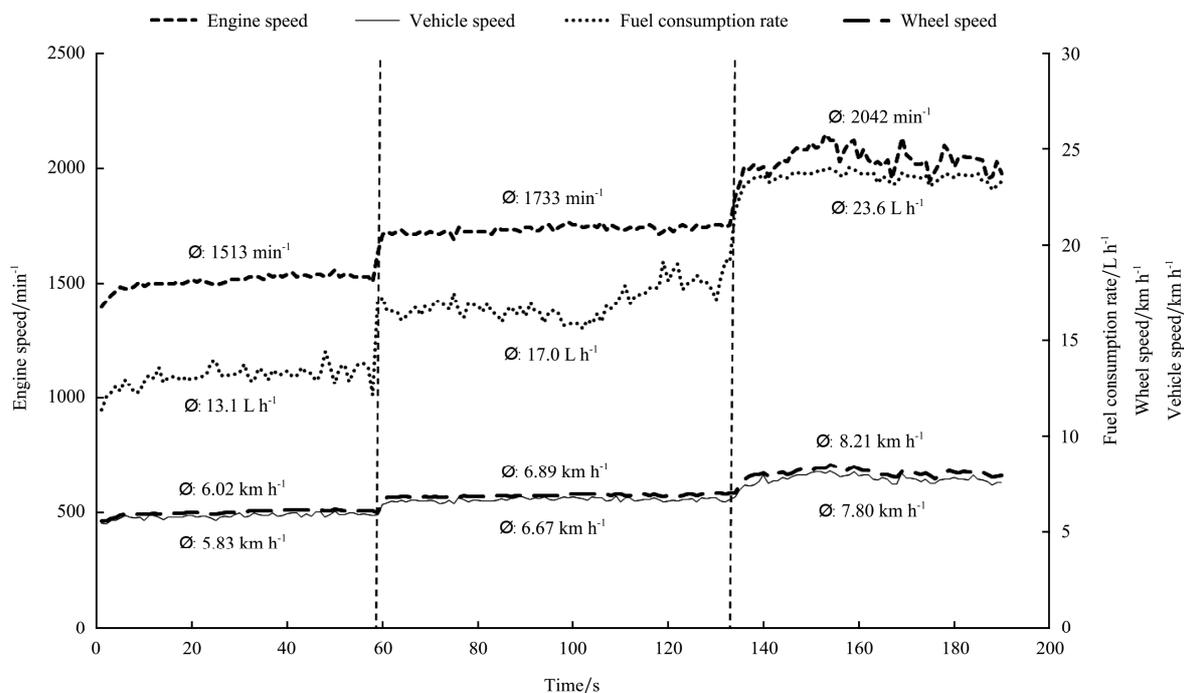


Figure 4 Influence of the engine operating point (controlled via engine speed) on fuel consumption rate, wheel speed, and vehicle speed. Working depth: 15 cm. Gear adjustment: 3. gear and 3. powershift

### 3.4 Subsoiler

Mechanical subsoiling is an energy-intensive mechanical approach for mitigating harmful soil compaction (Moitzi et al., 2008). The progressive increase of the fuel consumption rate in Figure 5 is the result of the changed engine operating point with higher specific fuel consumption (g kWh<sup>-1</sup>). The area-specific fuel consumption rose from 8.70 L ha<sup>-1</sup> at a working depth of 20 cm to 18.47 L ha<sup>-1</sup> at 45 cm (Table 7,

Figure 5), with a quadratic expression giving a better fit than a linear fit. The mean engine speed varied between 1,691 and 1,720 r min<sup>-1</sup>, the vehicle-speed decreased with increasing working depth, from 3.41 to 2.96 km h<sup>-1</sup>, and the effective field capacity decreased as well, from 1.02 to 0.89 ha h<sup>-1</sup>. Wheel slip increased from 4.3% to 16.4% with working depth. The fuel consumption caused by the slippage was 3.02 L ha<sup>-1</sup> at a working depth of 45 cm.

**Table 7 Process parameters for subsoiling at different working depths (gear adjustment: 2. gear and 1. powershift)**

Process parameters	Unit	Working depth (cm), Mean ± Std. Dev.				
		20 (n*=15)	30 (n*=30)	33 (n*=13)	40 (n*=15)	45 (n*=22)
Fuel consumption ( <i>Q</i> )	L h <sup>-1</sup>	8.90 ± 0.49	11.41 ± 0.71	11.87 ± 0.84	14.32 ± 0.85	16.43 ± 0.70
Engine speed ( <i>n<sub>E</sub></i> )	r min <sup>-1</sup>	1711 ± 13	1721 ± 38	1700 ± 28	1690 ± 21	1691 ± 29
Vehicle speed ( <i>v</i> )	km h <sup>-1</sup>	3.41 ± 0.09	3.39 ± 0.12	3.31 ± 0.14	3.17 ± 0.13	2.96 ± 0.16
Wheel speed ( <i>v<sub>0</sub></i> )	km h <sup>-1</sup>	3.56 ± 0.05	3.60 ± 0.07	3.55 ± 0.05	3.53 ± 0.05	3.55 ± 0.04
Slip ( <i>s</i> )	%	4.29 ± 2.29	5.84 ± 3.35	6.93 ± 3.22	10.06 ± 3.99	16.38 ± 4.51
Effective field capacity ( <i>C<sub>eff</sub></i> ) with slip	ha h <sup>-1</sup>	1.02	1.02	0.99	0.95	0.89
Theoretical field capacity ( <i>C<sub>theo</sub></i> ) without slip	ha h <sup>-1</sup>	1.07	1.08	1.07	1.06	1.07
Fuel consumption ( <i>Q<sub>A1</sub></i> ) with slip	L ha <sup>-1</sup>	8.70	11.21	11.97	15.05	18.47
Fuel consumption ( <i>Q<sub>A2</sub></i> ) without slip	L ha <sup>-1</sup>	8.32	10.55	11.14	13.53	15.45
Specific energy	J (kg soil) <sup>-1</sup>	109	94	91	95	103

Note: \* number of measured values.

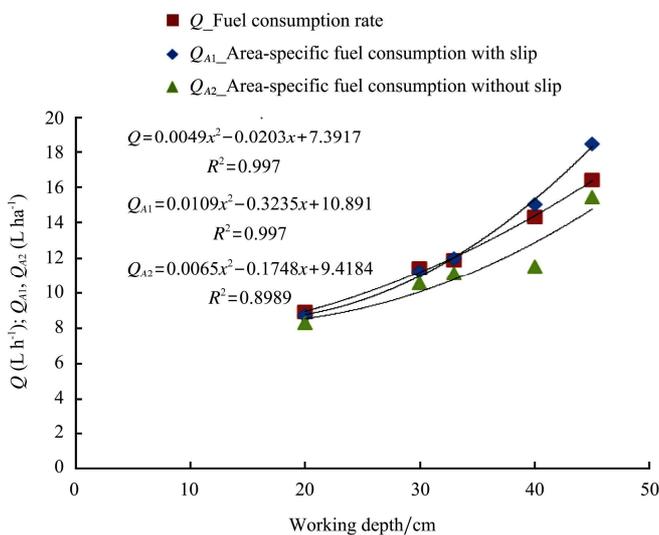


Figure 5 Fuel consumption rate (L h<sup>-1</sup>) and area-specific fuel consumption (L ha<sup>-1</sup>) as a function of working depth for subsoiler

### 4 Conclusions

Fuel consumption of tillage with a given implement is greatly affected by the working depth. The slip in tillage processes is an important factor for analysis of fuel consumption. With increasing working depth, the drawbar pull rises and also the slip. The result is an increased fuel consumption rate (L h<sup>-1</sup>) and area-specific fuel consumption (L ha<sup>-1</sup>). The area-specific fuel consumption increases linearly with working depth for a mouldboard plough and a short disc harrow. For subsoiling the area-specific fuel consumption increases

quadratically with working depth.

A more detailed analysis of the efficiency in the tractor-implement combination would require measuring the drawbar power to pull (kW), which is the product of drawbar pull (kN) and vehicle speed (km h<sup>-1</sup>). This would allow a detailed investigation of the energy efficiency losses at the engine, transmission, and wheel/soil interface, but was beyond the scope of this investigation.

A very efficient way of saving fuel is to choose an appropriate driving strategy, which implies operation close to the optimal engine operating point. It is more fuel efficient to operate an implement with a smaller tractor at a “good load” than with a larger tractor at a “bad load” for a certain vehicle speed.

The field measurements under realistic conditions and results calculated from these data will be useful for determining environmental impacts of crop cultivation, for example in life cycle assessments (LCA), and also for assessing the economic efficiency of different soil tillage systems under the specific climate and soil conditions (semi-arid climate, silty loam soil) of this study.

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