Effects of tillage systems and mechanization on work time, fuel and energy consumption for cereal cropping in Austria

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Abstract: The machinery stock, fuel consumption and work time are crucial economic factors for the profit potential in the arable farming sector. The influence of five soil tillage systems (two conventional tillage systems and three conservation tillage systems) and two tractor sizes (92 kW-tractor and 59 kW-tractor) on work time, fuel and energy consumption was measured in the semi-arid region in Austria. The tractors were equipped with a high-performance flow meter and a radar sensor to measure the fuel consumption (L h^{-1}) and working speed (km h^{-1}). The conventional tillage with mouldboard plough has the highest working time and fuel consumption rate. The replacement of plough with a cultivator, reduces the work time and fuel consumption for soil tillage as well as the energy consumption per moved soil matter to more than 50% roughly. The highest saving effects (more than 85%) were achieved with the direct drilling without soil tillage system. A well loaded engine in a small tractor with small implements is more fuel efficient than a worse loaded engine in a "big tractor". An adjusted tractor-implement combination, which is well implemented in the 59-kW mechanization, decreases the fuel consumption to up to 30% and 46%. Due to lower field capacity in the 59-kW mechanization, the work time is higher between 2.4% and 11.7%.

Keywords: fuel consumption, mechanization, tillage system, work time

Citation: Moitzi G., Szalay T., Schüller M., Wagentristl H., Refenner K., Weingartmann H., Liebhard P., Boxberger J., and Gronauer A.. 2013. Effects of tillage systems and mechanization on work time, fuel and energy consumption for cereal cropping in Austria. Agric Eng Int: CIGR Journal, 15(4): 94－101.

1 Introduction

Energy efficiency awareness continues to gain more importance in the crops production sector because of the increasing energy costs (Boxberger et al., 2008). In accordance with "Factor Five" from Von Weizsäcker (2009), the agricultural sector has in areas of irrigation, heating, drying crops, lighting, building design, refrigeration, fertilizer and pesticide use and conservation tillage the potential to achieve a factor 10-100 improvements in resource productivity. Crop farming has become increasingly mechanized, requiring significant energy inputs at particular stages of the production cycle to achieve optimum yields. Energy is used directly as fuel or electricity to operate machinery and equipment. In conventional tillage systems with ploughing, more than 50% of the total fuel consumption is usually required for soil preparation and seeding alone

Received date: 2013-08-02 **Accepted date:** 2013-09-05

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for wheat cropping (Moitzi et al., 2009). The total fuel consumption during soil preparation is mainly influenced by soil texture and type.

In addition to this, the fuel consumption rises proportionally with the depth of ploughing (Moitzi et al., 2006; Kalk and Hülsbergen, 1999). Soil related parameters, such as soil texture and organic matter content, influence fuel consumption in soil tillage (McLaughlin et al., 2002). Depending on the soil consistency the fuel consumption increases by 0.5 to 1.5 L ha^{-1} per centimetre of ploughing depth (Filipović et al., 2004; Moitzi et al., 2006; Kalk and Hülsbergen, 1999).

The total drawbar power required in soil tillage depends mainly on the working depth. Approximately 100 m^3 or 150 t ha^{-1} (soil density: 1.5 kg dm^{-3}) must be moved if one centimetre soil is tilled (Boxberger et al., 2008). Soil tillage systems can be classified based on the tillage intensity and soil covering with residue. Loibl (2006) suggested a classification in which the conventional tillage system is differed in soil turning and non-soil turning systems, depending on the soil coverage with residues (-15% or -560 kg residues ha^{-1}: soil turning with plough, 15%-30% or 560 kg-1120 kg residues ha^{-1}: non-turning with cultivator). The conservation tillage systems leave more than 30% residue cover on the surface and are classified in "mulch tillage", "ridge tillage" and "no tillage". The deposition of organic residues on the surface reduces run-off and promotes infiltration through macro-pores by earthworms (Brunotte and Sommer, 2009). In addition, the bearing capacity in the top and subsoil can be improved, which reduces the risk of soil compaction by applying conservation tillage.

Investigations by Eitzinger and Formayer (2004) show that the soil water storage capacity in conservation tillage systems in the semi-arid regions of Austria is higher than on soil-turning systems. The conventional cropping systems with plough are still common in the humid and semi-humid region of Austria. One of the reason for this fact is the increased infection risk by plant diseases (*Fusarium graminearum* and *Fusarium culmorum* resulting in followed mycotoxin-contamination in cereals) on the soil surface in non-turning tillage systems (Brunotte, 2007).

The shift from soil tillage systems with plough to non-turning tillage systems reduces the direct energy input and working time (Dutzi, 2008; Brunotte and Sommer, 2009). These economic benefits are the main reasons why conservation tillage systems are practised in the semi-arid regions.

The direct energy input in plant production via fuel is also affected by the kind of tractor-device combination. The total fuel consumption per hour increases if the tractor engine is over dimensioned in relation to the required performance for power take off operation or draw power operation (Moitzi et al., 2008).

The main aim of the presented experiment is to evaluate the influence of five soil tillage systems and two tractor sizes on the work time and fuel consumption in the semi-arid region of Austria.

2 Materials and methods

2.1 Experimental site

The field experiments took place at the experimental farm of the University of Natural Resources and Life Science (BOKU) in Gross-Enzersdorf (Lower Austria; 48°15′N/16°37′E). The climate at the experimental site is characterised with an average temperature of 9.8°C and rainfall of 546 mm respectively, typical for semi-arid regions. The soil (silty loam of *Chernozem*) is well suited for arable cropping.

A long-term soil tillage trial since 1996 was the basis for the measuring of the fuel consumption and field performance with different soil implements. The aim of this trial was to analyse the effect of five different soil tillage systems on soil and cropping related parameters. Each tillage system is designed in randomized plots in a fourfold repetition. The size of plots (60 m×24 m) enabled cultivation with the machines, which are normally used on arable farms and are flat.

2.2 Tillage systems with operations

2.2.1 Operations with the 92 kW-tractor

The stubble field skimming was conducted after harvesting the corn and the measurements for soil tillage, seedbed preparation and seeding at the end of October 2005 with a 92 kW-four-wheel-tractor (Steyr 9125; exhaust turbo supercharger; 6 cylinders with a displacement of 6.600 cm^3, mechanically acting gear box with 4 step power shift: 24 forward and reverse speeds). The operated machines with the process parameters are shown in the Table 1.

Table 1 Tillage systems with operations for the 4WD-tractor (92 kW)

Conventional Tillage		Conservation Tillage		
With mould board plough	With heavy cultivator (20 cm)	With heavy cultivator (10 cm)	Integrated Tillage[1)]	No Tillage
Heavy cultivator Stubble cultivation *w**: 3 m d_{avg}*: 5 cm v_{avg}*: 9.5 km h-1	Heavy cultivator Stubble cultivation *w*: 3 m d_{avg}: 5 cm v_{avg}: 9.5 km h^{-1}	Heavy cultivator Stubble Cultivation *w*: 3 m d_{avg}: 5 cm v_{avg}: 9.1 km h^{-1}	Heavy cultivator Stubble cultivation *w*: 3 m d_{avg}: 5 cm v_{avg}: 9.5 km h^{-1}	
2×4 Mouldboard plough *w*: 1.6 m d_{avg}: 25 cm v_{avg}: 6.7 km h-1	Heavy cultivator *w*: 3 m d_{avg}: 20 cm v_{avg}: 7.5 km h^{-1}	Heavy cultivator *w*: 3 m d_{avg}: 10 cm v_{avg}: 9.5 km h^{-1}	Heavy cultivator *w*: 3 m d_{avg}: 20 cm v_{avg}: 7.5 km h^{-1}	
Power harrow *w*: 3 m d_{avg}: 10 cm v_{avg}: 3.2 km h-1				
Seeding machine *w*: 3 m d_{avg}: 3 cm v_{avg}: 8.5 km h-1	Seeding machine *w*: 3 m d_{avg}: 3 cm v_{avg}: 8.2 km h^{-1}	Seeding machine *w*: 3 m d_{avg}: 3 cm v_{avg}: 8.6 km h^{-1}	Seeding machine *w*: 3 m d_{avg}: 3 cm v_{avg}: 8.2 km h^{-1}	Direct drilling machine with disc coulters *w*: 3 m d_{avg}: 2 cm v_{avg}: 8.6 km h^{-1}

Note: **w*: working width; *d_{avg}: average working depth; *v_{avg}: average working speed. [1)] Every four years a 2×4 mouldboard plough was used.

2.2.2 Operations with the 59 kW-tractor

After corn harvesting in September 2007 stubble field skimming was done with the heavy cultivator and the soil tillage, seedbed preparation and seeding took place around mid October 2007. The operations were conducted with a 59 kW-four-wheel-tractor (Steyr 8090; exhaust turbo supercharger; 4 cylinders with a displacement of 3.456 cm^3, mechanically acting gear box with 2 step power shift: 16 forward and reverse). The operated machines with its process parameters are shown in the Table 2.

The heavy cultivator (3 m and 2.6 m) was equipped with wing blades, which were mounted on two bars. Cracker rolls were combined with the cultivator. In the "integrated tillage system" a mouldboard plough was used instead of a cultivator every four years.

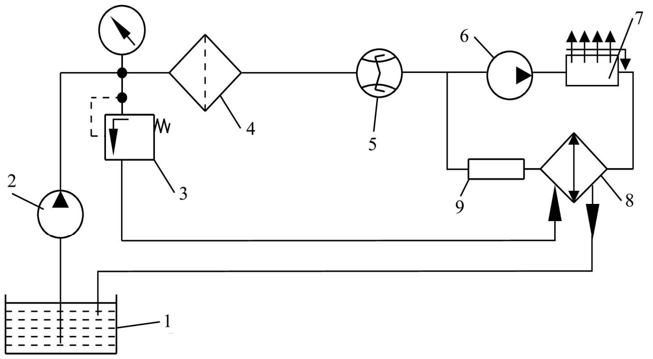
Table 2 Tillage systems with operations for the 4WD-tractor (59 kW)

Conventional Tillage		Conservation Tillage		
With mouldboard plough	With heavy cultivator (20 cm)	With heavy cultivator (10 cm)	Integrated Tillage[1)]	No Tillage
Heavy cultivator Stubble cultivation *w**: 2.6 m d_{avg}*: 5 cm v_{avg}*: 9.0 km h^{-1}	Heavy cultivator Stubble cultivation *w*: 2.6 m d_{avg}: 5 cm v_{avg}: 9.0 km h^{-1}	Heavy cultivator Stubble cultivation *w*: 2.6 m d_{avg}: 5 cm v_{avg}: 9.0 km h^{-1}	Heavy cultivator Stubble cultivation *w*: 2.6 m d_{avg}: 5 cm v_{avg}: 9.0 km h^{-1}	
2x3 Mouldboard plough *w*: 1.2 m d_{avg}: 25 cm v_{avg}: 6.5 km h^{-1}	Heavy cultivator *w*: 2.6 m d_{avg}: 20 cm v_{avg}: 7.2 km h^{-1}	Heavy cultivator *w*: 2.6 m d_{avg}: 10 cm v_{avg}: 8.7 km h^{-1}	Heavy cultivator *w*: 2.6 m d_{avg}: 20 cm v_{avg}: 8.8 km h^{-1}	
Power harrow *w*: 3 m d_{avg}: 10 cm v_{avg}: 5.0 km h^{-1}				
Seeding machine *w*: 3 m d_{avg}: 3 cm v_{avg}: 7.8 km h^{-1}	Seeding machine *w*: 3 m d_{avg}: 3 cm v_{avg}: 9.1 km h^{-1}	Seeding machine *w*: 3 m d_{avg}: 3 cm v_{avg}: 9.1 km h^{-1}	Seeding machine *w*: 3 m d_{avg}: 3 cm v_{avg}: 9.1 km h^{-1}	Direct drilling machine with disc coulters *w*: 3 m d_{avg}: 2 cm v_{avg}: 7.9 km h^{-1}

Note: **w*: working width; *d_{avg}: average working depth; *v_{avg}: average working speed. [1)] Every four years a 2×4 mouldboard plough was applied.

2.3 Measurement and calculation of the process parameters

For the measurement of the fuel consumption a high-performance flow-meter (PLU 116H; AVL®) with a proportional-integral (PI)) controller was integrated in the fuel system of the tractor (Figure 1, Table 3).



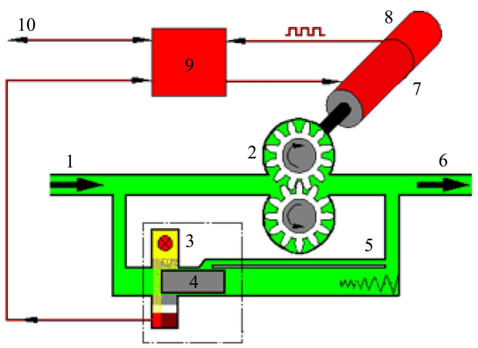
1. Fuel tank 2. Pre-pump 3. Pressure control with manometer 4. Pre-filter 5. Flow-meter PLU 116H 6. Pump 7. Fuel injection pump with runback 8. Fuel/fuel-heat exchanger 9. Glass sight gauge for runback control

Figure 1 Fuel consumption monitoring system (AVL 2005)

Table 3 Technical data for the flow-meter PLU 116H (AVL 2005)

Items	Parameters
Nominal Measurement rage	0.3 – 60 L h^{-1}
Digital output	Square-wave signal opto-decoupled
Frequency output	Approx. 12 – 2800 Hz
Measuring error	0.3%
Supply voltage	11 – 16 V/DC

The volumetric fuel consumption was continuously measured without pressure drop between inlet and outlet (Δp=0) in Figure 2.



1. Inlet
2. Gear counter
3. Piston Scan
4. Measuring piston
5. Overflow channel
6. Outlet
7. Servometer
8. Pulse generator
9. PI regulator
10. Digital output

Figure 2 Measuring principle of the AVL PLU 116H flow meter with servo-controlled displacement counter (Δp = 0)

An air bubble releaser and heat exchanger (between inlet and outlet fuel) was also additionally installed in the fuel measurement system for realising constant flow condition.

The digital rectangular signal was logged with a scan rate of 1 Hz. The consumption flow [L h^{-1}] was calculated using Equation (1).

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

where, Q: fuel flow, L h^{-1}; f: frequency, Hz; K_D: digital calibration factor, cm^{-3}; according calibration protocol: 161.99 cm^{-3}.

The working speed (v) was measured via the radar-sensor (Dickey-John®). The measured squarewave frequency is proportional to velocity (27.8 Hz per 1 km h^{-1}) and was logged also with a scan rate of 1 Hz. A multi-channel datalogger (Squirrel Datenlogger 2020®) was used for the signal recordings.

In dependance on the working speed and technical width of the device, a datafile for a working procedure for one plot could be created which contained about 1500 and 2000 values each for working speed and fuel consumption. The speed and fuel consumption values, which are measured during turning events at the headland were deleted manually.

The work time (Equation (2)) was calculated from the reciprocal value of the theoretical field capacity (Equation (3)). The non-consideration of the headland values allows a direct comparison without bias caused by the size and shape of the field.

$$WT = \frac{1}{C_{theo}} \quad (2)$$

$$C_{theo} = w \times v_{avg} \times 0.1 \quad (3)$$

where, WT: work time, h ha^{-1}; C_{theo}: theoretical field capacity, ha h^{-1}; w: implement working width, m; v_{avg}: average working speed, km h^{-1}.

The fuel consumption [L ha^{-1}] was calculated according to Equation (4) and does not consider the fuel consumption during turning events at the headland.

$$Q_{field} = Q \times WT \quad (4)$$

where, Q_{field}: fuel consumption, L ha^{-1}.

The parameters in Table 4 were used for the calculation of the fuel consumption induced CO_2-emission and energy consumption per tonne of moved soil.

Table 4 Basic data for Diesel fuel

Heat-value /kWh kg^{-1}	Density at 20°C/kg L^{-1}	Fossil CO_2-emission /kg CO_2 per kg Diesel	Fossil CO_2-Emission /kg CO_2 per L Diesel
11.87	0.83	3.153	2.617

3 Results

3.1 Work time

Between 0.39 and 2.81 h ha^{-1} work time is needed for soil tillage and seeding for wheat cultivation (Figure 3). The soil tillage system has a greater effect on the work time than the tractor size. The shift from soil turning to non-soil turning with a heavy cultivator in the conventinal tillage system decreases the work time to about 50%. Ploughing is the main work time consumer in soil tillage. The difference in power harrow (3 m) which was operated with the 92 kW and 59 kW-tractor, is caused by the different working speed (3.2 km h^{-1} resp. 5.0 km h^{-1}) of the tractors. The overall higher worktime requirement with the 59 kW tractor of 2.4% to 11.7% for the soil tillage system is caued by the smaller working width for same machines (mouldboard plough, heavy cultivator). More than 85% of the working time could be saved through the application of direct drilling without soil tillage system.

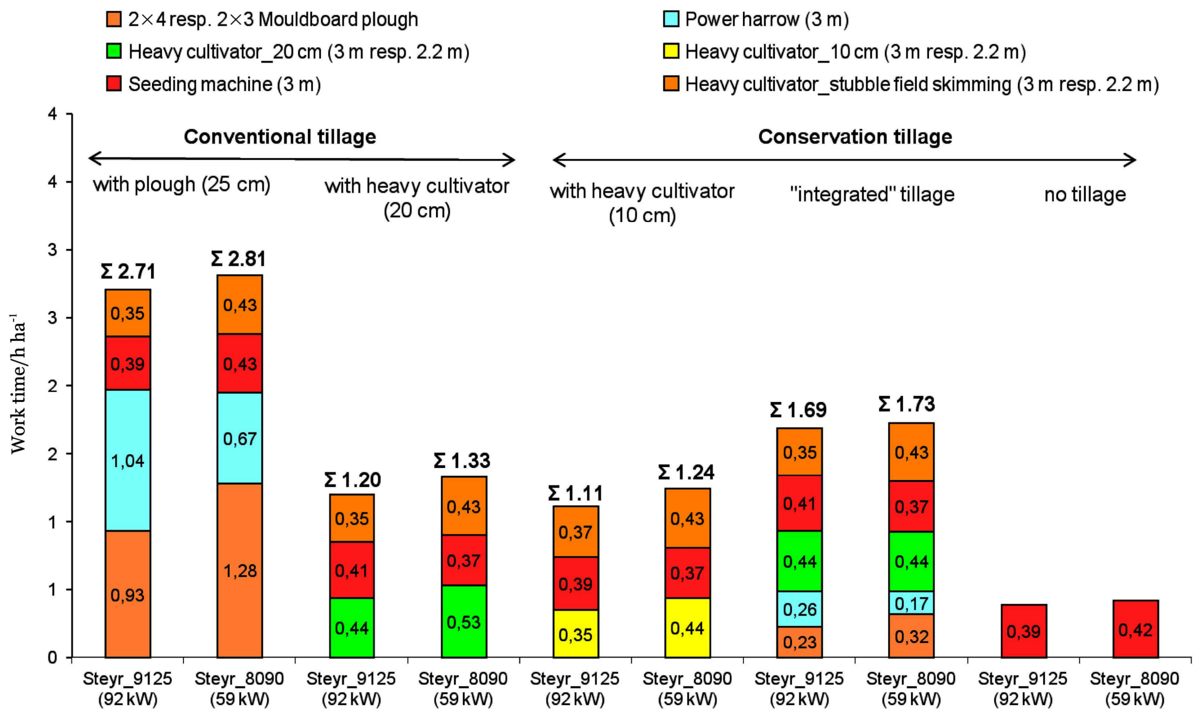


Figure 3 Average work time for different tillage processes in dependence of mechanization and soil tillage system. A mouldboard plough instead of a cultivator is used every four years in the "integrated" tillage system

3.2 Fuel and energy consumption

The fuel consumption (L ha^{-1}) is a combined parameter, which is calculated by the working time and hourly fuel consumption (Equation 4). There is a correlation between work time (Figure 3) and fuel consumption (Figure 4). Furthermore, the highest saving effects (more than 85%) were realized with direct drilling without soil tillage (Figure 4). The differentiation between the 92 kW and 59 kW-tractor for operations, which are caused by the interaction of field capacity (ha h^{-1}) and fuel consumption (L h^{-1}) are large. The overall fuel consumption (L ha^{-1}) for the 59 kW-tractor are between 30% and 46% lower than for the 92 kW-tractor. Two main factors are responsible for this effect: Firstly, the average fuel consumption for a high engine load in the case of 92-kW tractor is 21 L h^{-1} and 14 L h^{-1} for the 59 kW-tractor. Secondly, the higher fuel consumption for the 92 kW-tractor is caused by higher specific fuel consumption (L kWh^{-1}) which results from a suboptimal engine operating point through the smaller drawpower requirement for certain operations (e.g. shallow cultivation).

The specific fuel consumption (L kWh^{-1}) decreases with increasing engine load (Uppenkamp and Fröba, 2008). Especially in the partial load area, a reduced engine speed increases the engine load, in which the absolute fuel consumption decreases at constant power.

The fuel consumption in soil tillage is usually expressed in litre per hectare. It is a relative parameter, which does not consider the working depth. The expression of the fuel consumption on the moved soil bulk describes the energy input per soil matter. Figure 5 shows the calculated energy consumption based on the fuel consumption (Figure 4) and working depth (Table 1 and Table 2) for the soil with mean bulk density (0-30 cm) of 1.50 g cm^{-3}.

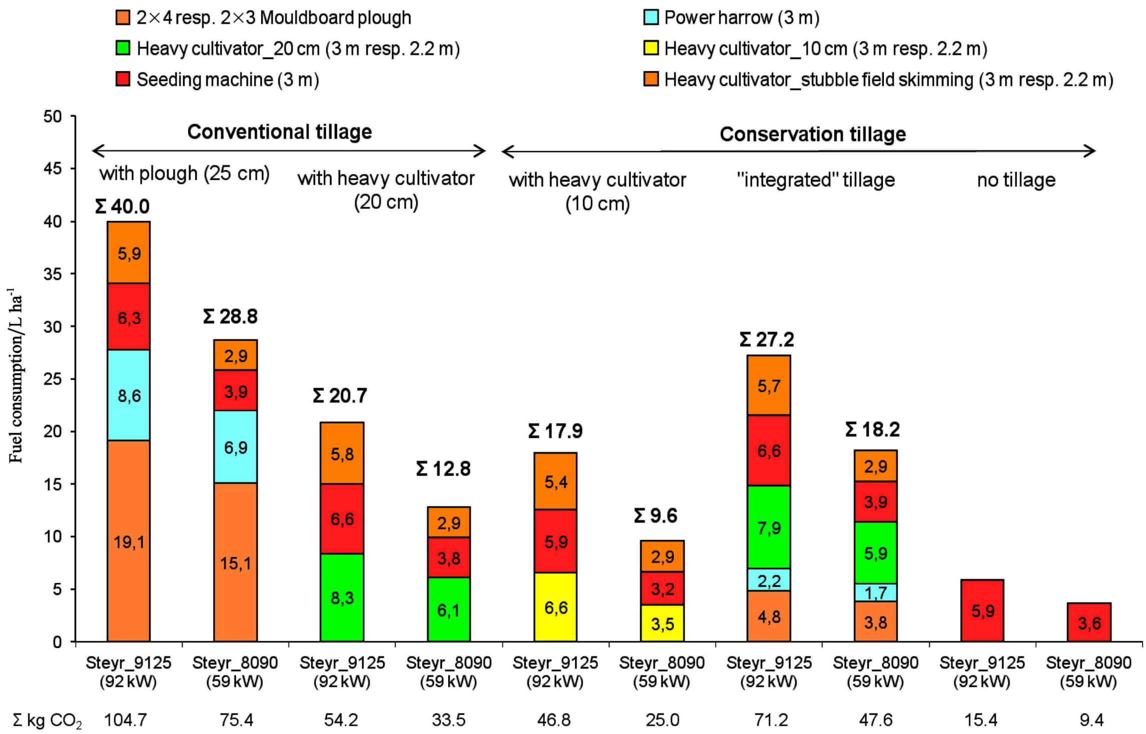


Figure 4 The average fuel consumption with total CO_2-emission for different tillage processes in dependence of mechanization and soil tillage system. A mouldboard plough instead of a cultivator is used every four years in the "integrated" tillage system

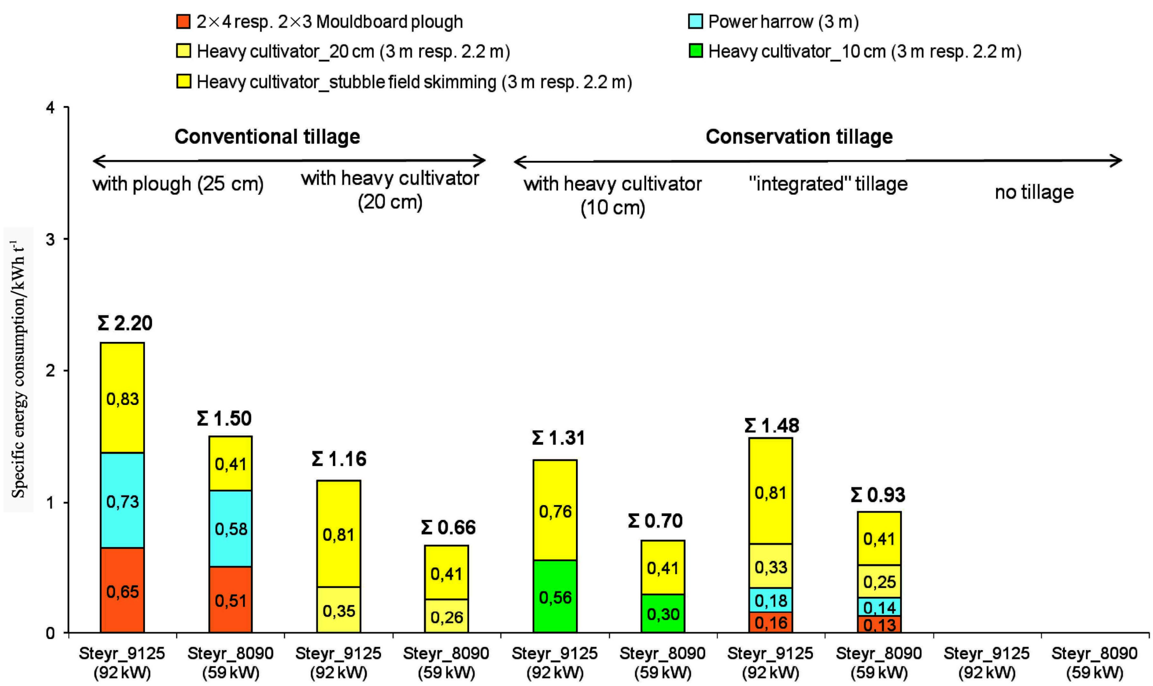


Figure 5 Specific energy consumption per Tonne moved soil bulk. Seeding is not considered. A mouldboard plough instead of a cultivator is used every four years in the "integrated" tillage system

It is 32% to 47% more efficient to move one tonne soil with the 59 kW-tractor than with the 92 kW-tractor. Ploughing with a 2×3 mouldboard plough and 59 kW-tractor is 21.5% more efficient than an 2×4 mouldboard plough with 92 kW-tractor. The power harrow (3 m) causes a higher energy input per soil matter than a plough. Operated with an 59 kW tractor the moved soil (10 cm) needs 20.5% less energy for power harrow than with an 92 kW tractor. Stubble field skimming with a "smaller" mechanisation (59 kW, 2.2 m) reduces the energy consumption in average by 50% in comparison to the "larger" tractor (92 kW, 3 m).

4 Discussion

The machinery stock, fuel consumption and work time requirement are crucial economic factors for the profit potential in the arable farming sector. There are 3 main terms measurements: short-term, mid-term and long-term measurements for the reduction of fuel consumption (Uppenkamp and Fröba, 2008). Short term measurements are immediately accomplishable, no additional investments is needed and it's done using either for example an engine operating in a reduced engine speed or through the adaption of implements to the tractor and field conditions. Mid-term measurements may require investments and a change in the soil tillage system. The concept of "conservation tillage" aims at cost reduction with the sustainable effect of soil conservation (Brunotte and Sommer, 2009). The substitution of ploughing through cultivation with a heavy cultivator has a considerable effect on the fuel and work-time. The saving effects are more than 50% (Figure 3 and 4) in this case. An adjusted tractor-implement combination, which was well materialized in the 59-kW mechanization, decreases the fuel consumption between 30% and 46% at the expense of a higher work time between 2.4% and 11.7%. In cases of the same machine (power harrow 3 m, seeding machine 3 m) the 92 kW-tractor engine was not well loaded in comparison to the 59 kW-tractor. An indicator for fuel-efficient engine operation is the engine speed, which is for most engines at 70%-80% of the nominal engine speed. The "gear up, throttle down" strategy by Grisso and Pitman (2001) is a practical approach for saving fuel in field operations. 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.

A higher working speed with 92 kW-tractor would reduce the fuel consumption differences but not eliminate it completely. In the case of machines with different working width (plough and heavy cultivator), the operation with the 59 kW-tractor is more fuel efficient than with the 92 kW-tractor.

The reduced work time of 0.35 h ha^{-1} with 2×4 mouldboard ploughing operated with a 92 kW-tractor caused in comparison to the 2×3 mouldboard plough operated with a 59 kW-tractor an additional fuel consumption of 4 L ha^{-1}.

5 Conclusions

The following conclusions can be drawn from the experiments with different tillage systems and tractors.

- The conventional tillage system with plough showed the highest work time (h ha^{-1}), fuel consumption (L ha^{-1}) and energy consumption per moved soil matter (kWh t^{-1}).
- The replacement of plough through a cultivator reduced the work time and fuel consumption for soil tillage as well as the energy consumption per moved soil matter about more than 50%.
- The integrated soil tillage with alternating plough application in the crop rotation reduced the potential negativ effects of long term cultivating (increased weeding etc.).
- The tractor-implement combination influenced via working speed and working width, the work time and fuel consumption.
- A tractor-implement combination operated in a high engine load had a great potential in reducing fuel consumption
- A well loaded "small tractor" with small implements are more fuel efficient than a worse loaded "big tractor".

Acknowledgements

Appreciation is extended to the staff of the experimental station Gross-Enzersdorf from the University of Natural Resources and Life Science (BOKU), Vienna.

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