Effect of cereal stubble management on the combine harvester performance and energy requirements

Tapani Jokiniemi[1*], Pasi Suomi [2], Raimo Linkolehto [2], Jukka Ahokas[1]

(1 Department of Agricultural Sciences, University of Helsinki, Koetilantie 5, P.O. Box 28, FI-00014 University of Helsinki, Finland; 2 Natural Resources Institute Finland (Luke), Vakolantie 55, FI-03400 Vihti)

Abstract: Combine harvesting is one of the most energy consuming field operations in arable farming. The power demand of combine harvester depends strongly on the mass flow through the machine, and one approach to reduce the energy consumption is thus increasing the stubble height in harvesting. In this study, the energy saving possibilities by increased stubble height and different straw management in cereal harvesting were examined. In addition to combine harvesting, the mulching of the tall stubble with a tractor powered rotary mower after the harvest was investigated. The results indicated an energy saving of 22%–24% in combine harvesting of spring wheat "Quarna" when the stubble height was increased from 13 cm to 35 cm, and 17% with 13 cm stubble when the combine chopper was inactivated. When mulching of the tall (35 cm) stubble as a separate work was included in the analyses, the total energy consumption was increased by ca. 10% compared to the short (13 cm) stubble. It was concluded that increasing the stubble height offers potential for energy savings in cereal harvesting, as long as the tall standing stubble does not complicate the following cultivation operations. With proper management, the magnitude of combined energy consumption of harvesting and mulching the long stubble can be comparable to the short stubble in combine harvesting.

Keywords: combine harvesting, cereal, stubble height, energy, fuel consumption, stubble mulching

Citation: Jokiniemi, T., Suomi, P., Linkolehto, R. , J. Ahokas. 2015. Effect of stubble management on the energy consumption and performance of cereal harvesting. Agric Eng Int: CIGR Journal, 17(4): 64-72.

1 Introduction

Combine harvesting is one of the most energy consuming field operations in agriculture cereal crop production. It is the second largest single direct energy input of the field machinery after primary tillage, and in reduced tillage or no-till systems it may even be the largest one (Mikkola and Ahokas, 2009). Diesel fuel consumption in combine harvesting varies usually from ca. 8-10 L/ha to more than 20 L/ha, depending on the harvested crop, yield level, harvesting technology and the weather conditions (Jokiniemi et al., 2012; KTBL, 2014). Due to the high energy inputs and continuously improving energy efficiency requirements in agriculture, the energy saving possibilities in combine harvesting are worth investigating.

Several methods have been suggested to improve the efficiency of combine harvesters, many of them requiring technical modifications. The major part of the combine engine power is consumed by the hydrostatic drive train, and intensive research about replacing the current system with electric propulsion systems have been conducted lately (Bernhard & Schreiber, 2005; Aumeret et al., 2008). Straw chopper is another significant power consumer, and several studies have been conducted to optimize the operation of the chopper (Bognár and Szendrö, 2004; Korn et al., 2012; Schwartz et al., 2011). Efficiency of the combine harvester can also be improved without technical modifications by optimizing the engine load with suitable ground speed and throughput management (Wacker and Böttinger, 2007; Wei et al. 2007).

Another approach to reduce the energy consumption and thus improve the efficiency of the combine is

Received date: 2015-05-28 **Accepted date:** 2015-09-29

***Corresponding author: Tapani Jokiniemi,** Department of Agricultural Sciences, University of Helsinki, Koetilantie 5, P.O. Box 28, FI-00014 University of Helsinki, Finland.Email: tapani.jokiniemi@helsinki.fi.

decreasing the amount of material other than grain (MOG) that the machine has to process. From this point of view, the optimal cutting header solution might be the stripper header, which usually uses rotating drum and fingers to strip the ears from the plants and thus minimizes the amount of MOG in the threshing equipment. According to Tado et al. (1998), a stripper header can increase combine capacity by 50%–100% with lower energy requirement compared to the conventional cutting header. Strakšas (2006) reported a fuel saving of 40% when a combine equipped with a stripper header was compared to the conventional system.

Similar effects on the amount of MOG in the threshing system can be achieved without technical modifications by increasing the stubble height. Špokas and Steponavičius (2010) studied the effect of increased stubble height on the technological parameters of combine harvester. They discovered that increasing the stubble height from 100 to 200 mm decreased the fuel consumption of Claas Lexion 540C combine harvester by 4.7 L/h and increased the capacity by 0.84 ha/h. This was concluded to be a result from decreased mass flow through the combine, as well as the higher moisture of the straw close to the soil surface. Also Kehayov et al. (2004) detected fuel consumption savings up to 30% when the cutting height of wheat was increased. According to Tado et al. (1998), an increase of 50%–90% in the combine field and throughput capacity can be achieved by this method.

However, increasing the stubble height may complicate the following cultivation operations, as large amount of unchopped plant residue remains on the field. In no-till farming the tall, standing stubble is usually found favourable, as it protects the soil from wind, preserves the moisture and helps winter crops to survive by collecting snow to the soil surface (Aase and Siddoway, 1980). Additionally, when a heavy plant residue is chopped to the soil surface, it may disturb the seeding of the next plant, causing some of the seeds to be left on the surface amongst the residue, instead of entering the soil (Laine, 2006). Very tall stubble, on the other hand, may increase the hairpinning-effect, where the plant residue is pushed into the bottom of the sowing furrow when a disk coulter is used for seeding (Doan et al. 2005; Rainbow and Derpsch 2011). Even in conventional cultivation method with ploughing as primary tillage, the tall stubble does not necessarily cause problems. Strakšas (2006) noted in his study with a combine stripper header, that even when stubble was not mulched, the amount of straw that remained on the soil surface after ploughing was only 0.24%–0.60% of the total amount of straw, and it did not cause any problems in the following cultivation operations.

When chopping of the standing stubble is nevertheless considered necessary, for example due to the requirements of the following cultivation operations, one option is to mulch it after the harvesting. While the time window for combine harvesting is usually limited, the stubble mulching after the harvesting is not so time critical. Benefits of the enhanced harvesting capacity may still dominate over additional workload, even though one extra work phase is added.

Aim of this study was to evaluate the energy requirements and capacity of cereal harvesting operation when the stubble height in combine harvesting was increased. Mulching the tall stubble was also included in the analysis, as it may sometimes be required by the following cultivation operations. Target was to inspect the achievable energy savings in practical working conditions, as well as to examine the performance and energy use of the combine harvester and stubble mulcher combination. Additionally, the effect of inactivating the chopper on the combine harvester’s fuel consumption was studied to reflect the situation when the straw is collected for litter or energy.

2 Materials and methods

2.1 Theoretical inspection

According to Srivastava et al. (2006), the rotary power requirement of combine harvester can be estimated by the

Equation (1). The machine specific constants a, b and c for combine harvester in the Equation (1) are adapted from the ASAE standard D497. Due to the differences in the machine design, adjustments and crop conditions, the range for machine specific constants is ±50%.

$$P_{rot} = a + bw + cC_m \qquad (1)$$

Where P_{rot} is the rotary power requirement, kW, a is machine specific constant, 20 kW, w is the working width of the machine, m, b is machine specific constant, 0 kW/m, c is machine specific constant, 3.6 kWh/t, and C_m is the field capacity in material basis, t/h.

Equation (1) shows the obvious effect that the material throughput (field capacity) has on the combine power requirement, and it can thus be used to estimate the effect of the stubble height on the machine energy consumption. As the coefficient b for the machine working width w is zero for combine harvester, the power requirement depends only on the idling power a and the combine throughput (field capacity) C_m. The throughput consists of the grain, the straw and the chaff that flow through the machine. Besides the stubble height, the amount of MOG depends on the grain variety and growing season conditions. Špokas and Steponavičius (2010) reported of grain-to-straw ratios of 0.77–1.06 with several winter wheat varieties. Moisture contents in their study were 18% (w.b.) for straw and 14% (w.b.) for grain. If the grain-to-straw ratio is assumed to be for example 1.0 at the harvest moisture and the length of the stem is 70 cm, Equation (1) predicts an energy saving of 18% with an output of 10 t/h of grain, when the stubble height is increased from 10 cm to 40 cm. The effect of the chaff was ignored in this calculation, and the properties of the stem were assumed to be equal from the foot to the ear. When grain-to-straw ratio decreases, the energy savings due to the taller stubble increases. As the range for the constants in the Equation (1) is large (± 50%), this simple calculation gives only a rough estimation about the power requirements. However, it shows the magnitude of the achievable energy savings with the increased stubble height in combine harvesting.

2.2 Test machinery and measuring system implementation

The combine harvester used in the study was Sampo Rosenlew C6. Technical specifications of the combine are presented in Table 1. The electronic engine management in modern agriculture machinery enables fuel consumption measurements without additional flow meters, as the fuel consumption information can be captured from the engine CAN-bus. According to Udompetaikul et al. (2011) the reliability of the fuel consumption information from the CAN-bus is very good and it can be used as sole method for fuel consumption measurements. Also Jokiniemi et al. (2015, manuscript in preparation) found the reliability of the CAN-bus fuel consumption information satisfactory with an average error of –0.9 L/h. However, the precision of the data was good and it is thus well suited for internal comparisons.

Table 1 Combine harvester specifications

Feature	Value
Engine power, kW	136
Cutting width, cm	420
Threshing cylinder diameter, cm	50
Threshing cylinder width, cm	111
Number of straw walkers, pcs	5
Walker area, m^2	4.8
Total sieve area, m^2	3.4
Grain tank volume, m^3	4.2
Weight, kg	9 195

Data acquisition in the current study was conducted from a custom-made CAN-bus with a National Instruments NI USB-8473 CAN-bus interface and a PC data acquisition application programmed with LabView software. The engine bus of the combine was connected to the custom-made bus via a CAN bridge. Engine fuel rate (L/h) was captured from the engine bus and written to the custom bus. Yield mass flow (kg/s) was recorded from the combine sensors to a laptop PC via serial port. Additionally, a Garmin 19x NMEA 2000 GPS receiver was installed on the combine and connected to the custom CAN-bus to record the machine movements at the field as well as the speed information. The accuracy of the GPS receiver was < 3 meters for position (95 % typical) and, more importantly, 0.2 km/h for speed. Sampling frequency for all the data was 5 Hz and it was collected and stored on a laptop PC, which was installed in the cabin of the combine.

The equipment used for the stubble mulching was Valtra T163eV tractor and Spearhead Multicut 460 rotary mower. Tractor engine power was 125 kW and highest torque 740 Nm, and it was equipped with Versu-transmission, which offered five powershift gears and four speed ranges with automatic shifting function. The Spearhead rotary mower had three cutting rotors, all of which had three horizontally rotating blades, with a total working width of 460 cm. The side units of the mulcher were foldable for road transportation periods. The structure of the mulcher can be seen from Figure 2. Data collection in the stubble mulching was similar to combine harvesting: the fuel consumption was captured from the tractor CAN-bus and tractor ground speed and position were measured with the Garmin 19x NMEA 2000 GPS receiver. The data acquisition system was altogether identical to the combine harvester.

Figure 2 Rotary mower used for mulching the stubble

2.3 Test procedure

The field trials were conducted at the Vakola Cropinfra research platform (latitude 60° 26.994', longitude 24° 20.975') of the Natural Resources Institute Finland in autumn 2014. A level field was chosen for the trials to avoid the effect of slopes on the results. Also the uniformity of the crops in the field was taken into account when the test plot was chosen. The test crop was spring wheat variety "Quarna", and the total height of the crops was on average 72 cm.

The trial procedure included three test plots and two replications for each. One test plot consisted of three travels from one edge of the field to another using full cutting width of the combine. The acreage of the test plots was between 0.25 and 0.31 ha. Two stubble heights (13 and 40 cm) were used, as it may be assumed that the effect of the stubble height on the combine harvester fuel consumption is relatively linear as long as the engine load remains constant. The test members were as follows:

1. Short stubble. The pointer of the combine header height was set to 20 cm, which the experienced combine operator determined as a safe limit to prevent stones from rising to the header. This setting resulted in practice an average stubble height of 13 cm.
2. Tall stubble. The header height pointer was set to 40 cm. This was determined as the upper limit for the header height to ensure that all the wheat ears were collected, as the crops were somewhat deteriorated after a long rainy period. The stubble height with this setting was in average 35 cm.
3. Short stubble without the chopper. The pointer was again set to 20 cm, but the chopper of the combine was inactivated. This setting reflected a situation when the straw was to be baled after harvesting.

The ground speed of the combine was attempted to keep optimal at all times during the tests. In practice this was done by keeping the yield losses at the same, acceptable level on each test plot with the aid of the yield loss monitor. This resulted higher speeds in the tall stubble test, which was also expected through smaller total crop mass flow. After harvesting each test plot, the grain was unloaded from the combine grain hopper into a trailer, which was then weighed with a scale. The mass of the grain in each trial was calculated by the difference in the subsequent weighings. Once the harvesting was done, the tall stubble test plots were mulched to examine the total energy consumption and the performance of the combine harvester and rotary mower combination.

2.4 Data analysis

Headland turns and unloading were first filtered out from the initial data and only continuous harvesting work was analysed. The fuel consumption captured from the combine bus was converted to area- and grain mass specific units (L/ha and L/t) by using the mean values for fuel consumption readings and the GPS speed and the duration of the harvest work. The area needed for the calculations was received from the speed and the cutting width of the combine. Standard deviation and single factor Anova-analysis were used in the area specific fuel consumption to examine the variation in the data. The yield data was received from the weighing results and the yield monitor of the combine, and the results were calculated with both of these values. Standard deviation was applied to examine the error between the yield level sensor data and weighing. Finally, the energy savings for tall stubble and operation without the chopper, compared to the short stubble, were calculated. The fuel consumption in stubble mulching was calculated consistently, using the fuel consumption data from the tractor CAN-bus, the GPS speed information and the working width of the mower.

3 Results and discussion

3.1 Combine harvester performance and energy requirements

The test drive pattern and the yield map of the test field, based on the combine yield sensor and GIS-information, are presented in Figure 3. The yield level was relatively stable on the part of the field where the harvesting trials were conducted. However, some variation in the yield inside the test area still existed. Therefore the results were calculated in both acreage- and yield basis (L/ha and L/t).

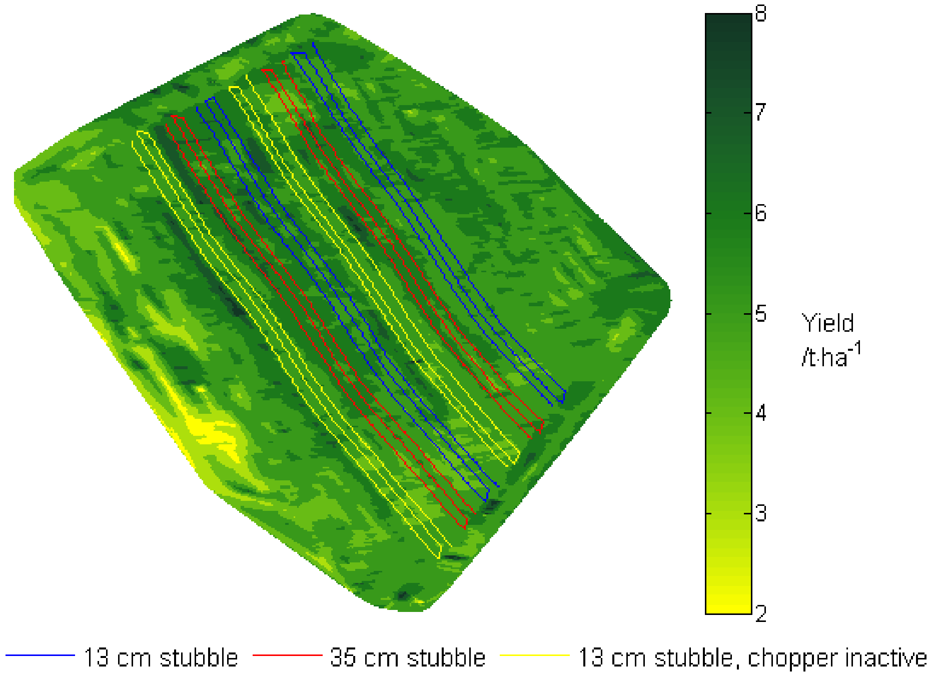

Figure 3 Yield map of the test field and the test drive pattern

Average acreage- and yield mass specific fuel consumption rates for each trial are presented in Figure 4. The fuel consumption pattern is very similar in both cases, which implies that the yield variation between individual trials was not very significant. The tall (35 cm) stubble produced the lowest fuel consumption in both area- and yield based analysis. Even the fuel consumption with the chopper inactivated was slightly higher than that of the tall stubble. The energy savings with the 35 cm stubble compared to the 13 cm stubble were in average 25% (2.4 L/ha) in area based analysis and 22% (0.44 L/t) in yield mass based analysis. The corresponding figures for 13 cm stubble with the chopper inactivated were 17% (1.56 L/ha and 0.33 L/t) with both analysis methods. Standard deviation of 10% -20% in the area specific fuel consumption indicates that there was relatively large variation in the fuel consumption measurement data. This was caused by the natural variation in the grain culture, as shown also in the Figure 3. However, according to the Anova-analysis the difference in the area specific fuel consumption between the short and tall stubble was highly significant (p-value = 0.000).

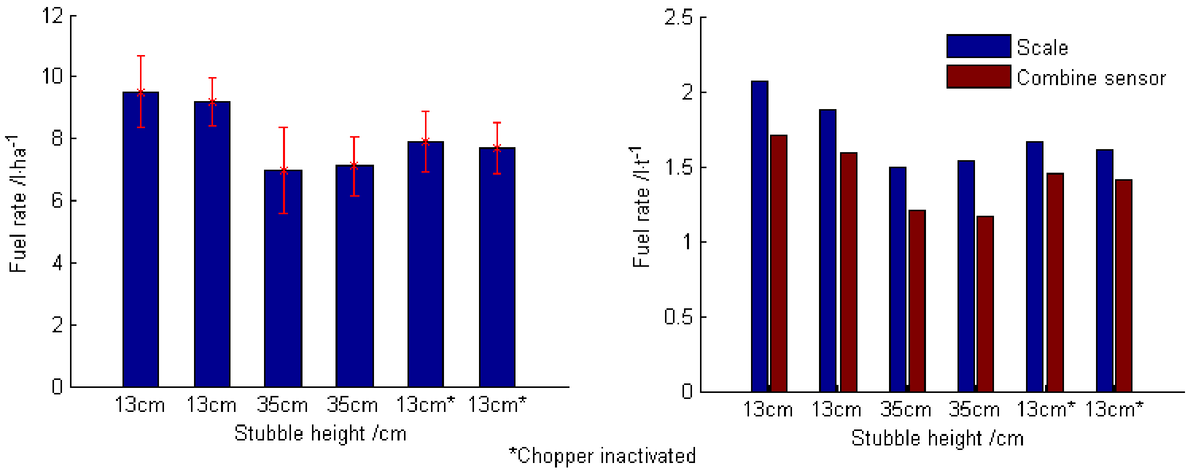

Figure 4 effect of stubble height on combine harvester specific fuel consumption

Figure 4 also reveals a significant difference in the yield mass based fuel rate between the results from weighing and those received from the combine yield level sensor. The average error in the results from the yield level sensor, compared with those from weighing, was 0.26 L/t with a standard deviation of 0.07 L/h. The relatively small standard deviation implies that the precision of the combine yield monitor is good, and the poor accuracy is most likely a matter of calibration. Due to the good precision, the data from the combine yield monitor can thus be used for internal comparison.

Combine speed and capacity with different stubble height and straw management are presented in Figure 5 and Figure 6. The mass flow at the combine threshing drum decreases when the stubble height increases. As the load on the cleaning and especially on the separation sections reduces consistently, the ground speed can be increased without increasing the yield losses or overloading the threshing drum. Capacity of the combine increases respectively with the ground speed (Figure 6). Area based capacity increased in average 27% (0.44 ha/h) and the yield mass based capacity 24% (1.88 t/h) with 35 cm stubble compared to 13 cm. Figures 5 and 6 indicate that the capacity of the combine with chopper inactivated was almost equal to normal operation with short stubble. Inactivating the chopper had thus little effect on the harvesting capacity.

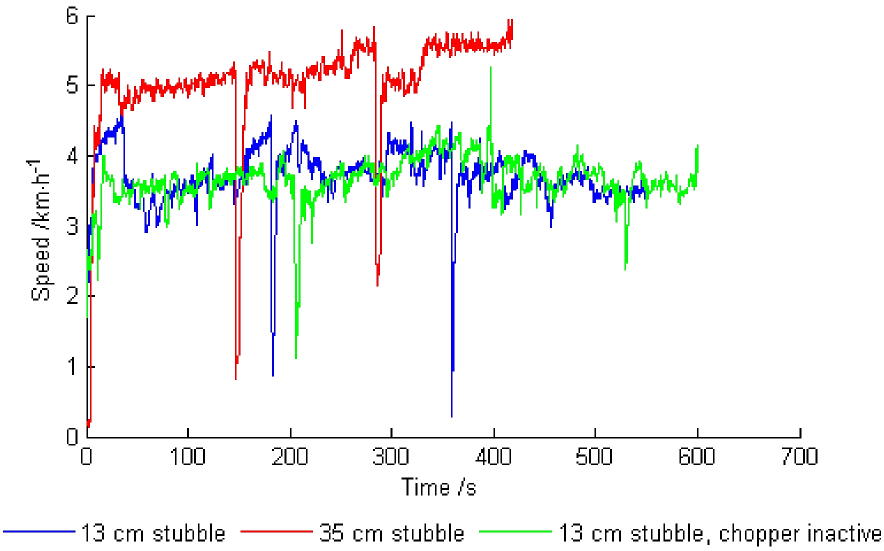

Figure 5 Example of combine speed with different stubble heights

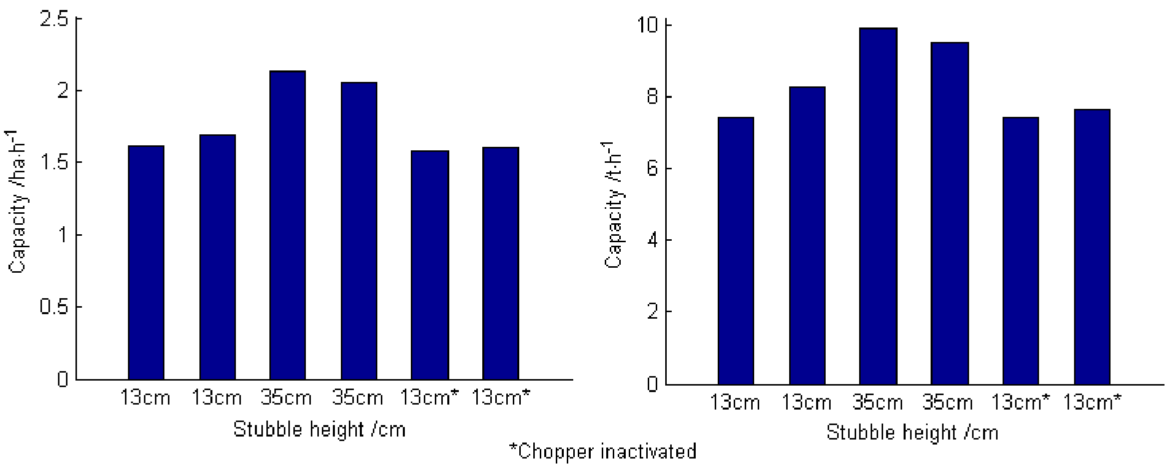

Figure 6 Effect of stubble height and straw management on the combine capacity in area and yield mass basis

3.2 Mulcher performance and energy requirements

Fuel consumption in stubble mulching was in average 20.7 L/h and speed was 14.0 km/h. When the total working width of 4.6 m is utilized, the acreage specific fuel consumption will thus be 3.2 L/ha and capacity 6.5 ha/h, if the headland turns are ignored. However, turning at the headlands is not necessary with this type of machine, but the work can be done by circulating the field. The energy consumption and labour input of the combine harvester and stubble mulcher combination are presented in Figure 7. Additional energy is required for baling the straw when the chopper was inactivated. However, when the straw is collected, some intended use for it exists, and the energy consumption of baling should be allocated for this use, instead of grain production.

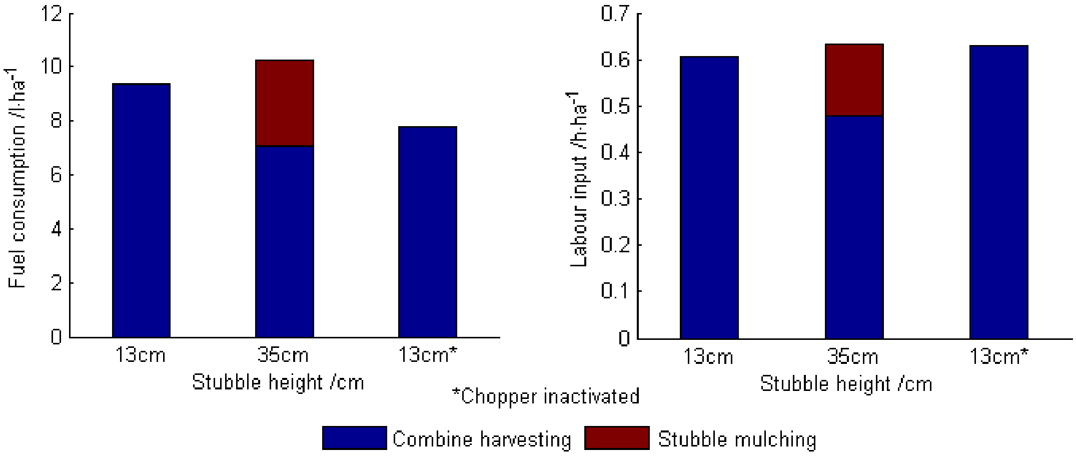

Figure 7 Effect of stubble height and straw management on energy requirements of combination of combine harvester and mulcher

Total fuel consumption was ca. 10% higher with high stubble and mulching compared to the short stubble with chopper. Also the total labour input was ca. 4% higher. Thus, the results indicate that mulching the tall stubble after harvesting is not a favourable method in terms of energy use. However, when mulching the stubble is not necessary, increasing the stubble height in combine harvesting can offer potential for remarkable energy savings. It must also be noted that the relation of implement and tractor sizes has an effect on the fuel consumption. The tractor used in this study was somewhat oversized for the mower, which may have increased the fuel consumption in stubble mulching. With a tractor of proper size, less energy would be used to propulsion of the tractor, and also the engine load would be on a more favourable area considering the fuel efficiency, resulting lower acreage specific fuel consumption in stubble mulching.

4 Conclusions

Results indicate that significant energy savings can be achieved by reducing the stubble height in cereal harvesting. When the stubble height in combine harvesting was increased from 13 cm to 35 cm, energy savings of 22%–25% were obtained, while the capacity of the combine harvester increased by 24%–27%. When separate mulching of the tall stubble was included in the analysis, the overall energy consumption increased by ca. 10% compared to the short stubble without mulching. The combine harvester and separate stubble mulcher combination was not hence favourable considering the energy use. However, stubble mulching should be done only when required by the following field operations. Additionally, while the time window for the harvesting is usually narrow, mulching can be performed also in poorer weather conditions. With proper management the energy consumption of the combine harvester and stubble mulcher combination in tall stubble can thus be close to that of short stubble without mulching, but with increased capacity for the time critical harvesting task.

When the chopper of the combine harvester was inactivated, the energy consumption of harvesting reduced 17%. In practice, when the chopper is not used, the aim is to bale the straw either for litter or for energy. As the utilization of the straw improves the overall energy balance of the cereal farming operations, offers reduced energy consumption in combine harvesting further benefit for this activity.

Acknowledgements

This study was funded by the foundation of Marjatta and Eino Kolli.

References

Aase, J.K. and F.H.Siddoway. 1980. Stubble height effects on seasonal microclimate, water balance and plant development of no-till winter wheat. *Agricultural meteorology,* 21(1): 1-20.

ASAE D497.7. 2011. Agricultural machinery management data. *American Society of Agricultural and Biological Engineers*. 8 p.

Aumer, W., M.Lindner, , M.Geißler, , T.Herlitzius, and G. Bernhardt,. 2008. Conceptual comparison of electrical and hydrostatic propulsion in combine harvesters. *Landtechnik,* 63(2): 88-89.

Bernhard, B. and M.Schreiber. 2005. Experimental comparison of ground drives for combine harvesters. *Landtechnik,* 60(2): 82-83.

Bognár, J. and P.Szendrö. 2004. Chopping fibrous materials. Energetical investigation of dynamic processes. *Landtechnik,* 59(2): 82-83.

Doan, V., Y.Chen and B.Irvine. 2005. Effect of oat stubble height on the performance of no-till seeder openers. *Canadian Biosystems Engineering,* 47(2): 37-44.

Jokiniemi, T., A.Suokannas and J.Ahokas. 2015. Energy consumption in agriculture transportation operations. *Submitted*.

Jokiniemi, T., H.Rossner and J.Ahokas. 2012. Simple and cost effective method for fuel consumption measurements of agricultural machinery. *Agronomy research,* 10(1): 97-107.

Kehayov, D., Ch.Vezirov and At.Atanasov. 2004. Some technical aspects of cut height in wheat harvest. *Agronomy Research,* 2(2): 181-186.

Korn, C., J.Fehrmann, T.Herlitzius, M.Flanhardt and A.Acimas. 2012. Development of a straw chopper for combines for increased working width. *Landtechnik,* 67(1): 11-16.

KTBL, Kuratorium für Technik und Bauwesen in der Landwirtschaft. 2014. Fuel consumption calculator. http://daten.ktbl.de/dieselconsumption/home.html. (Accessed 15.11.2014).

Laine, A. 2006. Olki toimii katteena kevätviljan suorakylvössä. *Koetoiminta ja käytäntö,* 63(3): 13-14.

Mikkola, H. and J.Ahokas. 2009. Energy ratios in Finnish agricultural production. *Agricultural and Food Science,* 18(3-4): 332-346.

Rainbow, R. and R.Derpsch. 2011. Advances in No-Till Farming Technologies and Soil Compaction Management in Rainfed Farming Systems. In *Rainfed Farming Systems*, ed. P. Tow, I. Cooper, I. Partridge and C. Birch, ch. 39, 991-1014. Netherlands: Springer.

Schwartz, M., T.Zährl, D.Gottlieb and S.Böttinger. 2011. Power requirement at the combine chopper. *Landtechnik,* 66(4): 272-275.

Špokas, L. and D.Steponavičius. 2010. Impact of wheat stubble height on combine technological parameters. *Journal of Food, Agriculture and Environment,* 8(2): 464-468.

Strakšas, A. 2006. Development of a stripper-header for grain harvesting. *Agronomy Research,* 4(1): 79-89.

Srivastava, A.K.,C.E. Goering, R.P.Rohrbach and D.R.Buckmaster. 2006. Machinery selection and management. In *Engineering Principles of Agricultural Machines*, ed. A.K. Srivastava, ch.15, 525-551. St. Joseph, Michigan: ASABE.

Tado, C.J.M., P.Wacker, H.D.Kutzbach and D.C.Suministrado. 1998. Development of stripper harvesters: a review. *Journal of Agricultural Engineering Research,* 71(2): 103-112.

Udompetaikul, V., S.K.Upadhyaya and B.Vannucci. 2011. The effect of tire inflation pressure on fuel consumption of an agricultural tractor operating on paved roads. *Transactions of the ASABE,* 54(1): 25-30.

Wacker, P. and S.Böttinger. 2007. Combine harvesters – state of the art. *Landtechnik,* 62(4): 216-217.

Wei, Q., Q.Zhang and Z.Mao. 2007. Power efficiency analysis of combine harvester in field operation. ASABE paper no. 071027, St. Joseph, Mich.: ASABE.