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Analysis of different corn stover harvest systems

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Corn stover, with an accruing amount of approximately 3.8 Mt dry matter per year, is a possible substrate for biogas production in Germany. However, using corn stover in the future will require knowledge about corn stover yield and suitable corn stover harvest systems. This study aimed to quantify, using field experiments, the harvest rates and losses of corn stover harvesting for eight harvest systems and various harvest conditions over the course of two years. From an average corn stover yield potential of 103.2 dt ha^{-1}, 55.6 dt ha^{-1} of dry matter were windrowed and 46.8 dt ha^{-1} were harvested; as such, the harvest losses (56.4 dt ha^{-1}) were higher than the harvested corn stover yield. Harvest rates of 41.4 to 49.1% were observed for the harvest systems examined, and significant differences were observed between the windrowing technologies but not between the corn stover harvesting technologies. A longer field retention time for the corn stover had a mainly negative impact on the harvest rate, while different varieties of corn had no impact on the rate. With regard to quality, the dry matter content and ash content of the corn stover were, on average, 50.4% and 7.0%, respectively.

Keywords
Corn stover yield, windrowing technologies, harvest rate, harvest residues, raw ash content

Bioenergy is an important renewable energy source and accounts for 75% of renewable energies globally (IEA 2015) as well as 59% in Germany (FNR 2015). However, the amount of land available for the production of biomass feedstock is limited; as such, there are competing uses, especially with food production. Aside from improving the yield of biomass, the amount of available bioenergy can be increased, without using more land, by harvesting currently unused potential biomass such as agricultural crop residues. Such residues could be a significant source of bioenergy, though its use would need to be limited so that enough organic matter like stover and green manure is left in order to maintain soil functions (Anton and Steinicke 2012).

Corn stover, which is an agricultural by-product, is the third most important crop residue, regarding quantity and energy content in the world, after rice and wheat straw; approximately 204 Mt dry matter (DM) of it are produced annually (Kim and Dale 2004). This makes it a suitable feedstock for bioenergy purposes, and its potential has been investigated for numerous different regions (Pavliska et al. 2012, Jiang et al. 2012, Cosic et al. 2011, Scarlat et al. 2010). Corn for grain (including corn-cob-mix) was cultivated on 455,500 ha in Germany in 2015 (Statistisches Bundesamt 2016). Between 2006–2015, the average annual grain yield in Germany was 96.2 dt ha^{-1} with a corn moisture of 14% (Statistisches Bundesamt 2016); by assuming that the average proportion of corn stover to harvested grain is 1:1 - which is the assumption usually made in literature (Shinners et al. 2012; Sokhansanj et al. 2002; Leask and Daynard 1973) – the total amount of corn stover produced annually in Germany

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can be said to be 3.8 Mt DM. Until now, corn stover has been left on the field to produce humus and return nutrients to the soil; this is the only significant use of corn stover in Germany. In other soil-climate regions, such as in the United States, corn stover has already been used to produce bioenergy, in particular ethanol; many studies have investigated this production process (Qiang and Thomsen 2012, Zuo and Yang 2011, sheehan et al. 2003, Sokhansanj et al. 2002), but not much is known about its utilization in biogas plants. Initial trials which have used corn stover as a biogas substrate have achieved a high specific methane yield, with an average of 318 l CH_4 per kg organic dry matter (ODM) being produced under standardised conditions at a laboratory scale (Fleschhut et al. 2015). Djatkov et al. (2015) achieved a similar yield under standardised conditions (301 l CH_4 (kg ODM)$^{-1}$. Corn stover, therefore, seems to be a promising substrate for biogas plants; it is particularly promising in Germany as the country has 8,726 biogas plants and an installed electrical power of 3,905 MW (Fachverband Biogas e.V. 2016).

To make extensive use of corn stover as feedstock, we first need to know what the available and usable biomass potentials are. These factors are influenced by environmental and agronomical parameters which determine the yield of the grain and the corn stover. However, its biomass potential is most influenced by the performance of harvest and storage technology along with technical restrictions related to corn stover harvest. The harvesting of corn stover, however, has various effects on the fertility of a soil; e. g., it has an effect on both the humus and nutritional content of soil and on a soil's physical and biological parameters (Karlen et al. 2011, Blanco-Canqui and Lal 2009, Lindstrom 1986). For this reason, an accurate quantification of harvest losses should be done in order to be able to estimate the ecological impact and calculate thereupon sustainable harvest rates.

The efficiency and performance of a number of different corn stover harvest systems have already been investigated (Vadas and Digman 2013, Sokhansanj et al. 2010, Petrolia 2008). Harvest technologies can be divided into intermitted and combined, or single-, two-, and multi-pass procedures according to the number and combination of steps within the harvest chain (threshing, windrowing, and harvesting).

For single-pass systems, the corn stover or different fractions of the residuals are harvested simultaneously with grain by using a modified combine harvester in which the grain and non-grain fractions are separated and processed in separate streams. In this case, the size of the corn stover is reduced by shredders within the combine harvester. Afterwards, the corn stover is collected in storage wagons or is processed into bales by a towed baler (Shinners et al. 2009, Hoskinson et al. 2007, Shinners et al. 2007a). Aside from only a single harvest operation being needed, this system results in only a small amount of losses and a low raw ash content due to low soil contamination of the harvested corn stover. However, the load and attrition of the combine harvester are increased, and the efficiency of the grain harvest is reduced (Vadas and Digman 2013). Shinners et al. (2012 and 2007a) found that the single-pass procedure was 39 % less efficient than a conventional grain harvest which did not involve corn stover collection.

The grain and corn stover are generally harvested separately to avoid the area efficiency of a grain harvest being significantly reduced. In two-pass systems, grain threshing and corn stover windrowing can be done in a single field operation, while the windrowed stover is harvested separately. To do this, a modified corn header is used (Straeter 2011, Shinners et al. 2012), which has a pick function for the corn ears alongside a windrowing function which produces corn stover windrows underneath the combine harvester; husks and cobs also fall from the straw walkers and sieves on the formed windrows. Shinners et al. (2012) found that the area efficiency was reduced only by 9% for this two-pass system, because apart from the corn ears, no further parts of the residual crop passed the combine harvester. If the windrowing and harvesting steps are performed separately, three passes are required to harvest both the grain and the corn stover. If a shredder is used before the windrowing, then four or more passes may be necessary. After windrowing, the corn stover windrows are harvested with balers or more rarely with forage harvesters or loader wagons, depending on the type of utilization and storage facilities.

The harvest system used plays an important role in determining the yield and quality of the obtained corn stover. Shinners et al. (2007b) determined that corn stover yields of 54 dt ha^{-1} were obtained on average by three- and four-pass systems (i.e. a shredder was equipped with a windrow forming system or a shredder and a rotary rake) which were combined with a forage harvester, which was equivalent to a harvest rate of 55% of the available corn stover. Sokhansanj et al. (2002) investigated corn stover yields of 54 dt ha^{-1} and 59 dt ha^{-1} for a three-pass system which had 78 dt ha^{-1} and 119 dt ha^{-1} of corn stover available, respectively; the harvest rate was, on average over two years, 60%.

A two-year experiment in Wisconsin compared different corn stover harvest systems; in this experiment, Shinners et al. (2012) investigated the highest possible harvest rates of the available corn stover and the highest corn stover DM yields (61 and 65 dt ha^{-1}, respectively) in a single-pass system; the corresponding harvest rates were found to be between 67 to 71%. The same conditions were used to find the corn stover yields of a two-pass system (i.e. windrowing of the corn stover during grain threshing, followed by a corn stover harvest with a forage harvester) and these were between 41 to 48 dt DM ha^{-1} (which amounted to a corresponding harvest rate of 41 to 56%). A four-pass system was also examined (which involved the threshing, shredding, windrowing and harvesting of corn stover with a forage harvester), and a yield of 38 to 46 dt DM ha^{-1} was obtained (which equated to a harvest rate of 41 to 46%). It was assumed in this experiment, that the amount of available corn stover was equal to the amount of grain. The ash contents were between 4.9 to 9.8% of the DM, depending on the harvest system; the proportion of raw ash also increased significantly as more field passes were conducted (Vadas and Digman 2013). Golub et al. (2012) conducted calculations for a number of different corn stover harvest systems (two- and multi-pass systems), and they found corn stover yields of 62 to 71 dt DM ha^{-1}, which was equivalent to a harvest rate of 60 to 68%.

The majority of studies related to corn stover yield and the quality of different harvest systems have mostly been conducted in the United States, though some have been conducted in Serbia as well. The prevailing climatic conditions in these regions allow corn stover to have a greater DM content, and they are qualitatively different from corn stover produced in Central European countries. Womac et al. (2005) determined that the DM content of corn stover in the southeastern part of the United States was 59 to 76% when harvested early (with a grain moisture of approximately 25%) and 78 to 89% when harvested later (with a grain moisture of approximately 15%). If the moisture content is higher, the corn stover is often left to dry in the field before being harvested and stored so that it can be processed into dry bales (Shinners et al. 2007b).

The moisture content of grain and corn stover in Germany is higher owing to the country's climate. To conserve the corn stover which will be used in biogas plants, the most favourable method is ensiling. Because of this, a lower DM content is sought at harvest time; this requires the use of a different harvesting process than ones used in other climate regions. At present, three-pass systems are being looked at. Single-pass systems, meanwhile, are not currently available in Germany and Central Europe, except so called ‘aftermarket solutions’ which are not distributed commercially by producers. Research findings on harvest systems and the technical restrictions of corn stover harvesting are not directly transferable to the different conditions in Germany. In most studies, the amount of corn stover available after a grain harvest is simply estimated (i.e. it is derived from the grain yield), or the harvest losses are estimated. This means that the values for the harvest rates and harvest residues could be inaccurate.

For corn stover to be used in both Germany and similar soil-climate conditions, the suitability of different harvest systems needs to be investigated; in particular, they need to provide an exact quantification of the harvest rates and harvest losses. Because there are losses in every step of the corn stover harvesting process, the mass balance of corn stover yields across the process chain needs to be precisely investigated.

The use of corn stover in biogas plants requires corn stover with a low raw ash content; furthermore, corn stover with low DM is preferable as this would aid ensiling, which would play a crucial role. For these reasons, the objectives of the present research were to analyse different harvest systems under various conditions in field experiments and to evaluate the success and quality of a corn stover harvest by means of the corn stover yield, DM content and ash content.

Materials and methods

Field experiments to analyse, assess and compare the various corn stover harvest systems were carried out at a practical scale in the years 2014 and 2015 at Grub, a research station of the Bavarian State Research Centre for Agriculture (county of Erding in southern Bavaria). This location is 494 m above sea-level; the annual average rainfall is 864 mm, and the annual average air temperature is 9.0 °C. The experimental sites in both years were next to each other, so that almost homogenous local characteristics could be assumed (i.e. marshy soil, and the soil type was loess loam).

In large-scale plots of at least 0.063 ha, corn was sown (date of sowing: 24.04.2014 and 23.04.2015; seed rate: 9 plants per m^2; row distance: 0.75 m). The widths of the plots were adapted so that they would match the width of the single windrowing technologies, and each plot width corresponded to a multiple of the width of the combine harvester (6 m); as such, the widths of the plots were 6, 9 and 12 m. After reaching threshing ripeness (i.e. maximum grain moisture of 35%) all plots were harvested with an 8-row combine harvester (Claas Lexion 670). For the corn stover harvest systems, two- and three-pass systems were tested. Altogether, eight harvest variants (factor 1: four windrowing technologies in combination with factor 2: two different harvest technologies: a forage harvester and a forage loader wagon) were tested under various harvest conditions (factor 3: two field retention times in 2014 and three varieties in 2015). All variants were tested in 64 large-scale plots, and they were repeated four times in a split-plot design with complete blocks. The field retention time and the varieties were randomly chosen for the main plots, and the different windrowing technologies were randomly assigned to each split plot within each main plot.

Harvest systems

For the two-pass system, which is able to simultaneously harvest the grain and windrow the stover, the 'Mais Star* Collect' (Carl Geringhoff Vertriebsgesellschaft mbH & Co.KG, Germany) was fitted onto the combine harvester. It is a modified corn header with special blades with angular knife bars, which could powerfully chop the corn stover and direct it toward a collecting tray underneath the corn header without touching the ground. Inside the collecting tray an auger transported the corn stover to the center of the corn header and dropped it as a windrow underneath the combine harvester. The threshed cobs and husks were placed on top of the windrow at the back of the combine harvester. For the trials, an 8-row Mais Star* Collect was used and the harvesting speed was around 4.3 to 4.5 km h^{-1}.

A 'BioChipper' (BioG GmbH, Austria), a 'Schwadhäcksler UP-6400' (Uidl Biogas GmbH/Agrinz Technologies GmbH, Austria), a 'Merge Maxx 900' (2014) and a 'Merge Maxx 902' (2015) (Kuhn S.A., France) were tested as the intermitted procedures which were used after conventional grain harvesting had been done (combine harvester: Claas Lexion 670; corn header: Capello Quasar), and they required three passes for the grain and corn stover harvest. The BioChipper and the Schwadhäcksler UP-6400 are modified shredders with an additional windrowing function. By means of a rotating shaft with flails, additional parts of the stubble are shredded above the ground, depending on the setting of working depth; as a result, the corn stover is chopped and picked up via the air suction produced by the flail shaft. Afterwards, the corn stover is delivered by conveyor to one side of the machine and forms a windrow. The working width of the BioChipper and the Schwadhäcksler UP-6400 was 6 and 6.4 m, respectively; this meant that with two runs, back and forth, the corn stover of 12 m working width and 12.8 m, respectively, was swathed to a double-windrow. Under trial conditions, the average working speed was 5 to 6 km h^{-1}.

Using the Merge Maxx 900/902, the corn stover was collected by the pick-ups without being made any smaller, and it was guided onto the conveyor belts by windguard tines. The delivery options for the Merge Maxx 900/902 are diverse either left or right side or centrally, and for the working width of 9.1 m, delivery was chosen to be done centrally. The working speed in the trials was around 7 km h^{-1}.

The windrowed corn stover was harvested with a forage harvester (Claas Jaguar 960, 3 m pick-up width) and a forage loader wagon (Krone ZX 400 GL, 2.1 m pick-up width and Claas Cargos 8400, 2.0 m pick-up width).

Harvest condition variations

In real-world conditions, corn stover is spread on a field after a grain harvest for a longer period of time (i.e. several days) before windrowing and harvesting are done. This is the reason that in 2014 the influence of a longer field retention time was tested and compared with a shorter field retention time. For the short field retention time, the corn stover was harvested within 15 to 30 h after the grain harvest, whereas for the longer field retention time, two days elapsed between the grain harvest and windrowing, and they were left for a further one and a half to two days when the forage harvester and forage loader wagon were used for harvesting (Table 1). The Mais Star* Collect connects the threshing and windrowing steps into a single pass. It is therefore necessary to consider the fact that for this variant a longer field retention time could only have an effect on the corn stover harvest conducted by the forage harvester or forage loader wagon (i.e. it cannot have an effect on the windrowing step).

Table 1: Temporal overview of the harvesting procedure (threshing, windrowing and harvesting) of corn stover in 2014 (two different field retention times) and 2015 (three different corn varieties); the grey-coloured backgrounds indicate variants which were used over both years.

	Day 1	Day 2	Day 3		Day 4	Day 5
2014	**27.10.**	**28.10.**	**29.10.**		**30.10.**	**31.10.**
	threshing ***long field retention time*** (LG 32.58 variety) 1)		threshing ***short field retention time*** (LG 32.58 variety) 1)	windrowing of all plots 2)	harvesting ***short field retention time*** with forage harvester/forage loader wagon	harvesting ***long field retention time*** with forage harvester/forage loader wagon
2015	**28.09.**	**29.09.**	**30.09.**		**01.10.**	**02.10.**
		threshing ***SY Talisman/ KWS 9361*** variety 1)	threshing ***LG 32.58*** variety (short field retention time) 1)	windrowing of all plots 2)	harvesting ***LG 32.58*** variety with forage harvester/forage loader wagon	harvesting ***SY Talisman/ KWS 9361*** variety with forage loader wagon

1) Use of windrowing technology Mais Star* Collect
2) Use of windrowing technologies BioChipper, Schwadhäcksler UP-6400 and Merge Maxx 900/902

The LG 32.58 (S 250/K 250; German maturity system, S = silage maize; K = grain maize) corn variety, which has medium early maturity, was grown in 2014 and 2015; the medium early variety, SY Talisman (S 220/K 230), which matures a little bit earlier, and the medium late maturing KWS 9361 (S 290/K 280) variety were tested on half of the plots in 2015 (instead of having a longer field retention time) in order to get a wider range of different amounts and moisture content of corn stover. To investigate the harvesting performance under equal conditions over two years (i.e. same variety, same field retention time, harvesting with a forage harvester as well as with a forage loader wagon), we aimed to harvest the corn stover of variety LG 32.58 within 15 to 30 h in 2015, too.

The date when the corn stover was harvested was determined by the optimal harvest time of the grain, which was set to be at a maximum grain moisture content of 35 % in our study. The harvest was begun on 27 October 2014; however, owing to an unusually warm growing season in 2015, it was on 29 September in that year (Table 1). There was almost no rain during the harvest in both years.

Yield and quality parameters

The objective of the research was to investigate the corn stover yields produced by different harvest systems. Therefore, based on the amount of corn stover available after the grain harvest, the corn stover yields and harvest losses were examined after the corn stover windrowing and harvest, depending on the different harvest systems used.

To determine the corn stover yield potential, i.e. all above ground plant residues remaining on the field after grain harvest, twenty plants (= 2.3 m^2) from eight randomly selected sub-plots of every replication of the trial (taking into account field retention time/variety, as well as the windrowing technology) were manually harvested (the height at which they were cut was directly above ground level) just preceding the grain harvest; the plants were divided into grains and residual parts (i. e. corn stover) by using a stationary thresher (LD 350, Wintersteiger AG, Austria); the mass and DM content of both fractions were subsequently determined. This allowed us to incur almost no losses.

To assess the harvest losses during an entire pass, the windrowed corn stover yield was quantified after processing of the four windrowing technologies. In order to do this, the amount of corn stover in a partial area of the windrow of every plot (windrow width × 1 m) was collected by hand. By considering the DM content of the corn stover and the working widths of each windrowing technology, the windrowed corn stover yield, in dt ha^{-1}, could be calculated.

In order to determine the harvested corn stover yield, the windrowed corn stover of every sub-plot (0.036 ha) was harvested with a forage harvester or a forage loader wagon. The sub-plots which were chosen were in the centre of the large-scale plots to exclude any undesired effects resulting from the driving of the combine harvester and the windrowing technologies. The amount of harvested corn stover in each plot was unloaded into large boxes and weighed with a floor scale (ELC3, Dini Argeo s. r. l., Italy, measurement uncertainty: up to 0.008 %). While unloading the corn stover, a representative mixed sample, based on 20 to 30 random items, was picked to examine the moisture of the corn stover. From this mixed sample, three random samples were taken and used to determine the exact DM content.

The harvest rate denoted as a percentage, was calculated by the ratio of the harvested corn stover yield to the corn stover yield potential. The harvest losses were calculated as the difference between the corn stover yield potential and the harvested corn stover yield, and losses incurred during the harvest when using a forage harvester or a forage loader wagon were the result of the difference between the windrowed corn stover yield and the harvested corn stover yield.

The ash content (VDLUFA 1976), which is a measure of the contamination of the corn stover with soil during a harvest, was determined for all of the random samples.

Finally, based on the harvested corn stover yield and ash content, the organic corn stover DM yield (ODM yield) was calculated. This yield serves as the basis for the production of methane.

Statistical analyses

All factors were tested in a split-plot design using a multi-factorial analysis of the variance. The main effects, as well as the interaction effects, were tested for statistical significance. For the comparison of the factor levels, the Student-Newman-Keuls (SNK) method was used as a multiple comparisons procedure at the 95 % significance level. Statistical analyses were done using the statistical software, SAS 9.3 (SAS Institute Inc., USA).

Results

Lossless DM grain yields were, on average, 115.9 dt ha^{-1} in 2014 (only LG 32.58 variety) and 122.2 dt ha^{-1} for all three varieties in 2015, and they were 115.7 dt ha^{-1} for the LG 32.58 variety in 2015 (Figure 1). The corn stover yield potential (all above-ground plant residues remaining on the field after the grain harvest) amounted to a DM yield of 97.6 dt ha^{-1} in 2014 and 115.8 dt ha^{-1} in 2015, and it was 108.4 dt ha^{-1} for the LG 32.58 variety in 2015. The cultivation of different varieties in 2015 caused a stronger variation in both parameters than in 2014. The difference between the grain yield and the corn stover yield potential was 18 dt ha^{-1} in 2014, but only 6 dt ha^{-1} for all three varieties and it was 7 dt ha^{-1} for the LG 32.58 variety in 2015; so the difference was greater in 2014 than in 2015. The grain to corn stover proportion was 1 : 0.84 (2014) and 1 : 0.95 (2015).

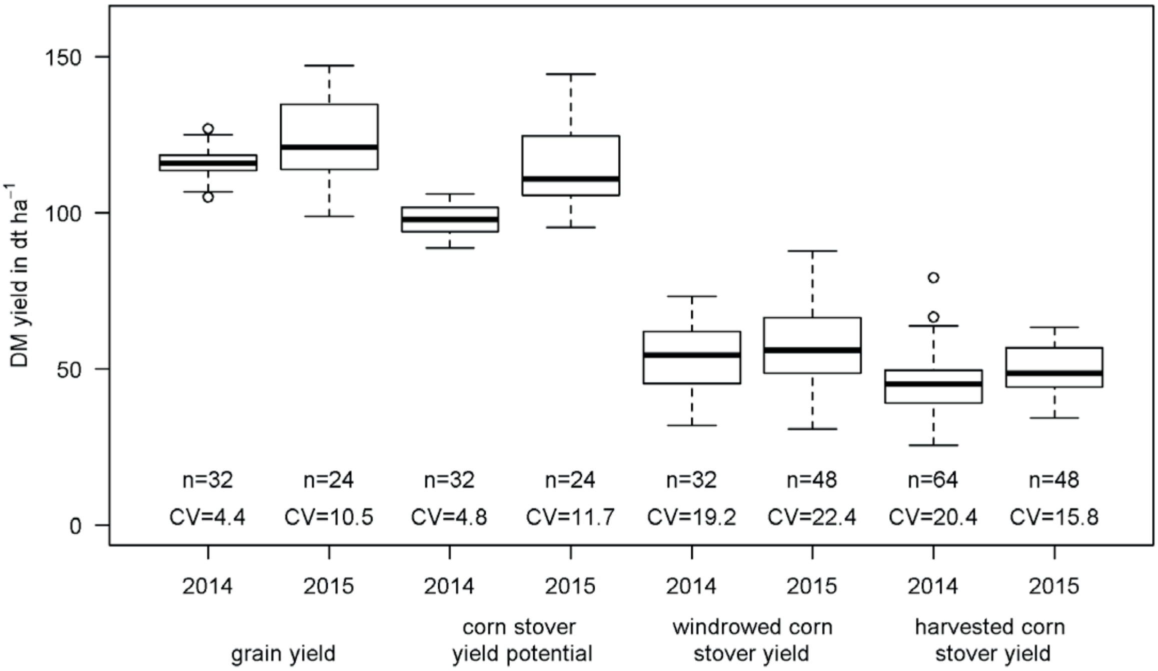

Figure 1: DM yields in dt ha^{-1} of grain and corn stover after the threshing, windrowing and harvesting steps in 2014 and 2015 (averaged over all of the field retention times/varieties and harvest systems); n = number of observations; CV = coefficient of variation in %; boxplots: brackets = highest and lowest value of the non outside observations (max. 1.5 interquartile ranges), bar = median

On average, 53.1 and 57.2 dt ha^{-1} of corn stover were windrowed for all harvest systems and harvest conditions in 2014 and 2015. Therefore, 46 and 51 % of the corn stover yield potential was not windrowed, respectively. Harvesting with the forage harvester and the forage loader wagon caused additional losses, which were similar in both years: 14 % (2014) and 13 % (2015) of the windrowed corn stover yield was lost. Consequently, the total harvested corn stover yield which could subsequently be used was 45.6 and 49.6 dt ha^{-1}, respectively. The harvest rate (harvested corn stover yield/corn stover yield potential) was 46.7 % (2014) and 42.8 % (2015). The higher level of grain yield and corn stover yield potential in 2015 resulted in a slightly higher windrowed and harvested corn stover yield. The coefficients of variation of the windrowed as well as harvested corn stover yields were between 15.8 and 22.4 % and had a wide variation.

For the variants which remained constant over both years (Table 1, variety LG 32.58, harvest after a short field retention time), the windrowed corn stover yields were, on average, 55.6 and 55.5 dt ha^{-1} in 2014 and 2015, respectively, and the harvested corn stover yields were, on average, 47.4 and 46.1 dt ha^{-1}, respectively and therefore almost identical in both years. However, there were differences in the yield and quality produced by the different harvest systems (Table 2). While the BioChipper, the Schwadhäcksler UP-6400, and the Merge Maxx 900/902 windrowed similar corn stover yields (51.7 to 53.8 dt ha^{-1}), the Mais Star* Collect tended to result in higher windrowed corn stover yields, being 64.8 dt ha^{-1} ($p = 0.0712$). The Mais Star* Collect also had the highest harvested corn stover yield, 50.7 dt ha^{-1}; however, it also had the highest losses for the final harvest step with the pick up, caused by harvest with a forage harvester and a forage loader wagon; these losses were 14 dt ha^{-1} or 22 % of the windrowed corn stover yield. When the corn stover was harvested by the forage harvester or the forage loader wagon after using the the BioChipper and Merge Maxx 900/902, similar losses (11 and 9 %, respectively) were caused and therefore equal corn stover yields of 46.4 and 47.4 dt ha^{-1} were reached. Comparatively high losses of 11 dt ha^{-1}, or 21 % of the windrowed corn stover yield, were detected during the harvests with the forage harvester and the forage loader wagon, when the corn stover had been windrowed with the Schwadhäcksler UP-6400. As a consequence, the Schwadhäcksler UP-6400 had the lowest corn stover yield, being 42.7 dt ha^{-1}; the windrowed corn stover yields, however, were similar to those obtained with the BioChipper and Merge Maxx 900/902.

Table 2: Yield and quality parameters of the tested harvest systems (mean ± standard deviation; averaged over 2014 and 2015 for the variants which had a short field retention time and the LG 32.58 variety. The different lower case letters indicate significant differences between the windrowing technologies, and the different capital letters indicate significant differences between the forage harvester and the loader wagon; comparison of means based on the Student-Newman-Keuls-test, $\alpha = 0.05$; n = number of observations)

	Windrowed corn stover DM yield in dt ha^{-1}	**Harvested corn stover DM yield in dt ha^{-1}**	**DM content of corn stover in %**	**Ash content of corn stover in % DM**	**Organic corn stover DM yield in dt ha^{-1}**
	n = 8	**n = 16**	**n = 16**	**n = 16**	**n = 16**
BioChipper	52.1 ± 9.6 a	46.4 ± 5.0 ab	52.5 ± 9.9 a	7.4 ± 2.2 a	42.9 ± 4.5 ab
Schwadhäcksler UP-6400	53.8 ± 10.0 a	42.7 ± 4.6 b	51.6 ± 11.5 a	7.6 ± 1.6 a	39.4 ± 4.3 b
Mais Star* Collect	64.8 ± 12.7 a	50.7 ± 7.1 a	46.5 ± 11.0 b	5.7 ± 1.1 b	47.8 ± 6.8 a
Merge Maxx 900/902	51.7 ± 10.1 a	47.4 ± 8.5 ab	51.1 ± 9.8 a	7.1 ± 2.1 a	43.9 ± 7.8 ab
p-value	0.0712	0.0111	0.017	0.0077	0.0035
	-	**n = 32**	**n = 32**	**n = 32**	**n = 32**
Forage harvester	-	46.1 ± 6.8 A	49.4 ± 10.3 A	7.0 ± 1.9 A	42.9 ± 6.4 A
Forage loader wagon	-	47.4 ± 7.2 A	51.4 ± 10.9 A	6.9 ± 2.0 A	44.2 ± 6.9 A
p-Value	-	> 0.1	> 0.1	> 0.1	> 0.1

The forage harvester and forage loader wagon had similar losses on an average of all windrowing technologies; the systems had statistically equal corn stover yields of 46.1 and 47.4 dt ha^{-1}, respectively. The harvest rates differed significantly when using different windrowing technologies, and over the course of the two years the averages were 41.4 % for the Schwadhäcksler UP-6400, 45.0 % for the BioChipper, 45.9 % for the Merge Maxx 900/902, and 49.1 % for the Mais Star* Collect. There were clear differences between the harvest rates in 2014 and 2015 (48.6 and 42.5 %, respectively) based on the different corn stover yield potentials (97.6 dt ha^{-1} in 2014 and 108.4 dt ha^{-1} in 2015), even though they had similar harvested corn stover yields.

With regard to the quality parameters, DM content and ash content, only the system using the Mais Star* Collect differed from the other windrowing technologies. Corn stover harvest with the Mais Star* Collect led to both a significantly lower DM content (46.5 %) and ash content (5.7 %), while the other windrowing technologies were roughly equal to one another (DM contents of 51.1 to 52.5 %; ash content of 7.1 to 7.6 %). Unlike the windrowing technology, the harvest technology had no influence on the overall DM and ash contents. The ODM yield of corn stover in 2014 (43.7 dt ha^{-1}) and 2015 (43.3 dt ha^{-1}) were almost similar, and the only real difference was between the Mais Star* Collect, which exhibited the highest ODM yield (47.8 dt ha^{-1}), and the Schwadhäcksler UP-6400, which exhibited the lowest ODM yield (39.4 dt ha^{-1}).

The difference in the corn stover yield was not only owing to the different windrowing technologies but also owing to the influence of the various harvest conditions. Longer field retention times, both – before windrowing as well as during the harvesting process – reduced the harvested corn stover yields significantly ($p = 0.0499$) from 47.4 to 43.9 dt ha^{-1}; significant interaction ($p = 0.0088$) between the windrowing technologies and the field retentions times were also observed (Table 3). For the BioChipper the corn stover yield was significantly lower when the corn stover harvest was delayed; the reduced amount was 11 dt ha^{-1}. The Schwadhäcksler UP-6400 and Mais Star* Collect, meanwhile, only seemed to be affected negatively by the longer field retention time. For the Merge Maxx 900/902, the opposite, but not statistically significant, effect was observed. These relationships also occurred for the windrowed corn stover yields, although a statistical certainty was not achieved. For the Mais Star* Collect, only the final harvest of the windrowed corn stover was influenced by the longer field retention time, whereas no difference was observed in the amount of windrowed corn stover after both the long and short field retention times. When a longer field retention time was used, the difference between the highest yield (55.6 dt ha^{-1}) and lowest yield (35.0 dt ha^{-1}) was 20.6 dt ha^{-1}; for the short field retention time, this difference was only 7.4 dt ha^{-1}.

Table 3: Corn stover yields of the different windrowing technologies as a function of the field retention time in 2014 (mean ± standard deviation; the different letters indicate significant differences between the windrowing technology x field retention time combinations; comparison of means based on the Student-Newman-Keuls-test, α = 0.05; n = number of observations)

		Windrowed corn stover DM yield in dt ha^{-1} n = 4			Harvested corn stover DM yield in dt ha^{-1} n = 8		
Long field retention time	**BioChipper**	42.8	± 7.3	a	35.0	± 2.6	d
	Schwadhäcksler UP-6400	43.6	± 8.2	a	38.9	± 8.8	cd
	Mais Star* Collect	58.4	± 5.5	a	46.0	± 4.6	bc
	Merge Maxx 900/902	57.5	± 6.2	a	55.6	± 12.7	a
Short field retention time	**BioChipper**	55.1	± 13.7	a	46.0	± 5.9	bc
	Schwadhäcksler UP-6400	54.1	± 10.7	a	43.6	± 4.8	bc
	Mais Star* Collect	58.1	± 11.8	a	49.1	± 4.3	ab
	Merge Maxx 900/902	55.3	± 8.5	a	51.0	± 9.5	ab
p-values							
Windrowing technology		> 0.1			< 0.0001		
Field retention time		> 0.1			0.0499		
Windrowing technology x field retention time		> 0.1			0.0088		

During the harvest, the selected three varieties had slightly different values for their corn stover yield potentials and somewhat significantly different values for the DM content of the harvested corn stover (Table 4). Despite these differences, the windrowed corn stover yields of the different varieties did not significantly differ. For the individual windrowing technologies, there were significant differences (p = 0.0020) in the windrowed corn stover yields. Regarding the harvested corn stover yields, statistically significant differences between specific combinations (windrowing technology x variety) were found; this can be explained by the significant effect of the windrowing technologies (p = 0.0049) and not by the significant interactions (p > 0.1). The highest harvested corn stover yield, 58.8 dt ha^{-1}, was achieved by the Mais Star* Collect with the KWS 9361 variety. The harvested corn stover yields obtained by the Schwadhäcksler UP-6400 and Merge Maxx 900/902 were significantly reduced when the LG 32.58 variety was cultivated (41.8 and 43.7 dt ha^{-1}, respectively). When averaged over the different windrowing technologies, it was found that the variety had no significant effect on the yield of the harvested corn stover.

Table 4: Corn stover yields of the different windrowing technologies as a function of the crop variety in 2015 (mean ± standard deviation; the different capital letters indicate significant differences between the varieties, and the different lower case letters indicate significant differences between the windrowing technology x variety combinations; comparison of means based on the Student-Newman-Keuls-test, α= 0.05; n = number of observations)

				Windrowed corn stover DM yield in dt ha^{-1} n = 4			Harvested corn stover DM yield in dt ha^{-1} n = 4		
Variety	corn stover DM yield potential in dt ha^{-1} n = 8	DM content of corn stover in % n = 8							
LG 32.58	108.4 ± 5.4 A	59.5 ± 5.8 AB	BioChipper	49.2	± 1.8	a	46.7	± 4.0	ab
			Schwadhäcksler UP-6400	53.6	± 10.9	a	41.8	± 4.3	b
			Mais Star* Collect	71.4	± 11	a	52.4	± 8.9	ab
			Merge Maxx 900/902	48.0	± 11.5	a	43.7	± 5.8	b
SY Talis-man	114.8 ± 13.0 A	65.4 ± 6.3 A	BioChipper	53.2	± 9.1	a	54.4	± 5.6	ab
			Schwadhäcksler UP-6400	56.3	± 20.5	a	51.2	± 9.6	ab
			Mais Star* Collect	67.7	± 8.2	a	51.3	± 6.7	ab
			Merge Maxx 900/902	55.2	± 12.8	a	46.6	± 7.9	ab
KWS 9361	124.3 ± 16.0 A	53.6 ± 4.4 B	BioChipper	59.0	± 9.8	a	51.9	± 7.9	ab
			Schwadhäcksler UP-6400	46.4	± 9.1	a	48.4	± 8.6	ab
			Mais Star* Collect	70.1	± 6.4	a	58.8	± 2.4	a
			Merge Maxx 900/902	55.9	± 14.4	a	47.6	± 10.7	ab
p-Value									
Variety	0.0728	0.0030	windrowing technology	0.0020			0.0049		
			variety	> 0.1			> 0.1		
			windrowing technology x variety	> 0.1			> 0.1		

Discussion

Yield structure and harvest rates

High yields were achieved in both years with grain DM yields of more than 115 dt ha^{-1}. Although grain yields were generally very low in the research region in 2015 because of the dry season (average grain DM yield in Bavaria in 2015 was 70.9 dt ha^{-1}, Bayerisches Landesamt für Statistik 2016), in 2015 an almost identical yield as in 2014 was achieved on the experimental site.

The corn stover yield potential remained below the grain yield in both years, and it was strongly influenced by the annual effects unlike the grain yields. Despite constant grain yields, the calculated grain to stover proportion varied. Because yields of both fractions were determined by manual-harvest, we can assume that the yield measurements were lossless. It is possible that the grain yields were overestimated by this method, which means that the grain to stover proportion based on the threshed grain yield will be restricted. Nevertheless, it became clear that the residual plant biomass was strongly depending on the growing conditions and other influences, such as the harvest date (Pordesimo et al. 2004) or the level of yield (Scarlat et al. 2010). Estimating the available corn stover yield by using a grain to stover proportion of 1 : 1 which is often assumed for simplification, is a rather rough indicator for the available and potentially harvestable mass of corn stover after threshing. This assessment was also made by Sokhansanj et al. (2002). The determination of the corn stover yield potential and the precise understanding of the yield physiology of the residual parts of the crop are necessary for accurately calculating the harvest residue after a corn stover harvest.

The harvested corn stover yields were 47.4 and 46.1 dt ha^{-1} (LG 32.58 variety and harvest after the short field retention time) in 2014 and 2015, respectively, and the harvest residues were larger than the harvested corn stover yields in both years. The proportion of the harvest residue is the sum of the remaining standing stubble, the mass of the corn stover which is not collected by the windrowing technology, and the additional losses when the windrowed corn stover is harvested; the biggest losses are caused by technical limitations during windrowing. In the present study, the harvested corn stover yields were slightly below those obtained by Shinners et al. (2007b), who measured yields of 54 dt ha^{-1} and were, in part, considerably lower than the yields obtained by Sokhansanj et al. (2002), who had achieved corn stover yields between 54 to 59 dt ha^{-1}. The values were also much lower than those of Golub et al. (2012), who had gotten yields between 62 to 71 dt ha^{-1}. Conversely, they were above the harvested corn stover yields of Shinners et al. (2012), who had gotten 38 to 48 dt ha^{-1} for the different harvest systems they had tested. Shinners et al. (2012) found higher yields for a two-pass system than for a multi-pass system, which is what the present study found.

It is not appropriate to directly compare the harvest rates because the harvest rates are considerably influenced by the corn stover yield potential. Hence, for similar harvested corn stover yields, there were sometimes large differences between the harvest rates owing to the differences in the corn stover yield potential. Further uncertainties with the harvest rates can exist if the corn stover yield potential is estimated from the mass of the grain. It is also difficult to compare the results of other studies if different harvest systems were used and other harvest conditions existed.

Influence of the harvest system on yield and quality

Both parameters, the windrowed corn stover yield as well as the harvested corn stover yield, had a high variation in both years (Figure 1), and an effect of the windrowing technology was detected on the harvested corn stover yield for the variants which were used over both years (Table 1). There were, however, no significant differences in the corn stover potential between the plots of the four windrowing technologies, and so the assumption of equal starting conditions seems to be justified. Statistically significant differences were only detected between the Mais Star* Collect and Schwadhäcksler UP-6400, with the difference in yield being 8 dt ha^{-1} (Table 2). For the windrowed corn stover yields, differences of between 11 to 13.1 dt ha^{-1} were found between the Mais Star* Collect and the three other windrowing technologies. However, these differences in yield were not significant, as indicated by the high standard deviation. The small-scale measurement of this parameter (windrow with x 1 m) was problematic because the success of windrowing depends on how the vehicle is driven; increasing the length of the measurement may improve the results. The windrowed corn stover yield is the sum of the corn stover which was windrowed as well as a certain proportion of the corn stover which had already been at the place of the windrow before the windrowing occurred. For this reason, the proportion of the windrow width and the working width of each windrowing technology has an influence on the mass of the windrowed corn stover. For windrowing technologies whose windrow width has a larger proportion of the working width (for example 36 % for the Mais Star* Collect, but only 12 % for the BioChipper; data not shown), the amount of corn stover which is in the windrow before windrowing is higher. This could explain the higher windrowed corn stover yields of the Mais Star* Collect than the other windrowing technologies. Consequently, measurements of the windrowed corn stover yields are adversely affected, and as a result, this parameter is only suitable for being used to assess the success of a windrowing process to a limited degree.

The proportion of the harvested corn stover yield to the windrowed corn stover yield was highest for the Merge Maxx 900/902, at 91 %, and smallest for the Mais Star* Collect, at 78 %; this suggests that the windrowing technology had an effect on the subsequent harvest, irrespective of the success of the windrowing process. The possible reasons for this are the windrow width and the height of the stubble. The Mais Star* Collect had significantly higher stubble and broader width (data not shown) than the other windrowing technologies, and so this allows greater losses to occur during the corn stover harvest. Another potential reason for the different proportion of harvested to windrowed corn stover yield between the BioChipper (89 %) and Schwadhäcksler UP-6400 (79 %) – despite similar windrowed corn stover yield and stubble high – is the chop length of the windrowed corn stover. Windrowing with the Schwadhäcksler UP-6400 resulted in the shortest chop length, and this seems to have been a disadvantage for the following corn stover harvest with a pick-up.

Apart from the corn stover yields which were achieved, the different quality parameters play an important role in enabling a comprehensive analysis of the different harvest systems. In order to densify the corn stover enough so that it can be stored in a silo and to ensure that ensiling is successful, corn stover with a high DM content has to be avoided. While the DM content of the residual crop (whole plant without grain) was 36.9 % (in 2014) and 34.2 % (in 2015) on average immediately before threshing, these were 41.4 % (in 2014) and 59.4 % (in 2015) after the corn stover harvest. A difference of approximately 20 % between the two years of the experiment can be attributed to the weather conditions during the harvest. The drying of the corn stover while spread in the field was owing to the early harvest – which was one month earlier in 2015 than in 2014 – as well as the higher day-time temperatures and higher wind velocity in 2015. Compared with these, the effect of the windrowing technology on the DM content was at a maximum of 6 %, which is only of minor importance. The significantly lower DM content of the corn stover harvested by the Mais Star* Collect can be explained by the immediate windrowing of the corn stover during the grain harvest. In this way, the field drying of the corn stover was less than for a separate windrowing pass.

The average ash content was 7.0 %, which indicates that the contamination with soil was lower than when harvesting wilted grass from grassland (Thurner et al. 2015), which is also used as a biogas substrate. Therefore, the ash content of the corn stover can be considered to be unproblematic. However, in both years, there had been hardly any rain during the harvest, and this has to be considered. The ash content of our study was in the range found by Shinners et al. (2012), who had gotten 5.8 to 9.8 % for DM. As had earlier been described by Vadas and Digman (2013) and Shinners et al. (2012), our study was also able to show a clear link between soil contamination and the number of passes. Thus, with the Mais Star* Collect, a significant lower ash content was measured than for the three-pass systems. Because the mass of the ash has an influence on the yield of the harvested corn stover and is undesirable for both ensiling and utilization in biogas plants, the ODM yield should be used to compare different harvest systems. However, the same differences were observed for the ODM yield as for the harvested corn stover yield.

There were no differences between the forage harvester and forage loader wagon with respect to the measured yield and quality; this is likely because of the similar way in which the two harvest (i. e. by pick-up).

Influence of the different harvest conditions on harvest performance

A four-day delay in corn stover harvesting after grain harvest is considered realistic for practical conditions due to labour economical reasons; however, this led to significantly reduced corn stover yields in the trial. The effect this had on the individual windrowing technologies was different for each technology (Table 3). If the corn stover is spread on the field after the grain harvest, it is assumed that the corn stover will be compressed owing to the ongoing field retention time and storage density will increase as a result. Because the BioChipper and Schwadhäcksler UP-6400 use a suction effect, longer field retention could complicate the corn stover pick-up during a windrowing pass; this may explain the sometimes significantly reduced corn stover yields for the BioChipper and Schwadhäcksler UP-6400 under these conditions. In contrast, the Mais Star* Collect is coupled with the grain harvest of the combine harvester, and for this reason the delay in the harvest only influences the following harvest of the windrowed corn stover (Table 1). As expected, the windrowed corn stover yields in the short and long field retention times did not differ for the Mais Star* Collect, and only an insignificant difference was found for the harvested corn stover yields. The Merge Maxx 900/902 achieved even higher corn stover yields, windrowed yields and harvested yields, when a longer field retention time was used. It is conceivable that a higher storage density improves crop flow, which benefits the pick-up of the Merge Maxx 900/902. Because this effect was not significant and a high standard deviation was detected, the difference might also be owing to experimental error.

Changes in the physical nature of the corn stover can not only be caused by different field retention times but also by the selection of the variety when growing corn for grain. The main features, influenced by the genotype, are the amount of corn stover and DM content which can lead to different corn stover qualities in a corn stover harvest. Different corn stover qualities were achieved with the varieties chosen by the present study. Despite a great increase in the DM content during the harvest, after the harvest there were still some significant differences in the DM content, with a difference of almost 12 % between the SY Talisman variety, which had the earliest maturity, and the KWS 9361 variety, which had matured the latest (Table 4). Because there was no significant difference between the residual biomass of the three varieties, the variation of the corn stover quality caused by the variety was rather low. Furthermore, the variety influences the moisture content, amount of corn stover and other features pertinent to stover quality; therefore, it is rather difficult to measure the discrete effect of moisture content and corn stover amount on the harvest rate. These reasons may be why it was not possible to clearly quantify the effect on the windrowed and harvested corn stover yields.

As expected, there seems to be a positive correlation between the corn stover yield potential and the harvested corn stover yield. On an average for the windrowing technologies, the highest harvested yield (51.6 dt ha^{-1}) was measured for the KWS 9361 variety which had the highest corn stover yield potential and lowest harvested yield (46.1 dt ha^{-1}) was detected for the LG 32.58 variety which had the lowest corn stover yield potential. The corn stover harvest of the SY Talisman and KWS 9361 varieties was done over four days due to the experimental design, and therefore the harvest losses might be greater for these than when harvesting was performed immediately after grain threshing, as it had been for LG 32.58. However, the harvested yields of LG 32.58 were not higher in 2015, although the corn stover yield potential was higher in 2015 than in 2014. Sokhansanj et al. (2002) found only a small difference, 5 dt ha^{-1}, in the harvested corn stover yield, despite a big difference (41 dt ha^{-1}) between the corn stover yield potential of two years; this suggests that there is only a weak correlation between the corn stover yield potential and the harvested corn stover yield.

Furthermore, it was shown for the windrowing technologies BioChipper and Schwadhäcksler UP-6400 that the highest corn stover yields were from the SY Talisman variety, which had the lowest DM content. There may be a link here to the corn stover moisture and storage density (in a similar manner as in their relationship to the field retention time) owing to the suction effect of these windrowing technologies. However, the Mais Star* Collect achieved higher yields when the KWS 9361 variety, which had the highest moisture content, was grown. In this windrowing technology, corn stover is thrown into a collecting tray underneath the corn header during grain threshing; therefore, losses might be higher when the corn stover is drier. The smallest variation of the harvest rate due to the variety selected was observed for the Merge Maxx 900/902. An isolated change in both parameters could result in a clearer effect and will be able to supply new information for machine-specific optimal harvesting conditions.

In general, note that the weather conditions during a corn stover harvest may vary substantially. In this study, the weather during the harvest was very good in both years. Bad weather conditions, especially rainfall, can cause similar, but even stronger, effects than those simulated by the field retention time and variety selection. An estimation of the harvest performance for various weather conditions or for other soil-climate regions is not immediately possible.

Conclusions

A huge amount of corn stover is produced when corn is grown, and it could be attractive for the purposes of generating energy. However, there are technical restrictions when harvesting corn stover, which means that the usable mass of corn stover is limited. Although the corn stover yield potential is 103.2 dt ha^{-1}, only 55.6 dt ha^{-1} of the corn stover can be windrowed and 46.8 dt ha^{-1} finally harvested. Although there is a significant amount of corn stover which can be used, as for a harvest rate of 45 %, the harvest residue still exceeds the harvest yield. However, from an ecological point of view, the impact of such a low corn stover harvest rate on humus and nutrient recovery to soil is weakened, too. Knowledge of harvested corn stover yields, and especially of harvest residue, is essential for a valid assessment of the ecological effect of using corn stover as a biomass feedstock. Estimating the corn stover yield potential and harvest residue using a grain to stover proportion of 1 : 1 is less suitable because the corn stover yield potential can vary strongly, and as such the grain to stover proportion is not consistent.

Regarding the entire harvesting operation, the windrowing step causes the greatest harvest losses. Consequently, it is perhaps the most important factor to increasing the usable amount of corn stover. Agronomic, as well as breeding-related improvements, can only make a minor contribution to increasing the usable amount. Our analysis of the different harvest systems has shown that windrowing technology has a significant influence on the harvested corn stover yield, whereas the harvesting method (i.e. with a forage harvester and forage loader wagon) does not. Currently available windrowing technologies are mostly new technological developments; the potential for optimization has not yet been fully exploited, and therefore harvest rates could be increased in future. Aside from the choice of harvest system, the prevailing conditions or corn stover quality can influence the performance of a harvest as well. Longer field retention times after the grain harvest were found to mainly have a negative impact on the harvest rates, while the use of different varieties had no influence. It is still not clearly understood how much of an impact different weather conditions have on harvest rates. Further research will need to define the major influences on harvest performance for the different harvest systems, with the aim of optimizing these systems. It should also be examined as to what corn stover yields are possible when using newly developed harvest systems, like the Strohmax 5000 (M & R/Maschinen- und Fahrzeughandel GmbH, Germany); this system also picks up corn stover through a rotating flail shaft but feeds it directly into the forage harvester after passing the screw conveyor.

An average ash content of 7.0 % was found, which indicates that soil contamination in corn stover is unproblematic. DM content was found to be 50.4 % on average, and this was primarily owing to the weather conditions during the harvest. There were significant differences between the two-pass and three-pass harvest systems for the quality parameters.

A comprehensive analysis of corn stover harvest systems requires further parameters besides the ones investigated in this study. The essential criteria are, for example, area productivity and the cost effectiveness of the harvest systems. Mechanical strain or wear of the gathering technology also plays a role which might be correlated to the stubble height after the windrowing step. However, for this investigation the trial was not large enough. Regarding corn stover quality, there are perhaps further influences of the harvest system on the proportion of harvested corn stover fractions and therefore perhaps on the chemical composition of the corn stover. Furthermore, studies on chop length could provide better knowledge about compressibility in a silo and fermentation in a biogas plant.

References

Anton, C.; Steinicke, H. (Hrsg.) (2012): Bioenergy – chances and limits. Statement. Deutsche Akademie der Naturforscher Leopoldina, Halle (Saale)

Bayerisches Landesamt für Statistik (2016): GENESIS-Online Datenbank. Erntestatistiken. https://www.statistikdaten.bayern.de/genesis/online?operation=previous&levelindex=3&levelid=1469684203407&step=3, accessed on 28 July 2016

Blanco-Canqui, H.; Lal, R. (2009): Corn Stover Removal for Expanded Uses Reduces Soil Fertility and Structural Stability. Soil Science Society of America Journal 73(2), pp. 418–426, http://dx.doi.org/10.2136/sssaj2008.0141

Cosic, B.; Stanic, Z.; Duic, N. (2011): Geographic distribution of economic potential of agricultural and forest biomass residual for energy use: Case study Croatia. Energy 36(4), pp. 2017–2028, http://dx.doi.org/10.1016/j.energy.2010.10.009

Djatkov, D.; Viskovic, M.; Rajcetic, J.; Golub, M.; Martinov, M. (2015): Investigation on possibilities of biomethane production from corn stover in Vojvodina. In: Kovačev, I. (Hrsg.): Proceedings of the 43rd International Symposium on Agricultural Engineering. Actual Tasks on Agricultural Engineering, 24th–27th February 2015, Opatija, Croatia, Croatia, pp. 635–644

Fachverband Biogas e.V. (2016): Biogas Segment Statistics 2014/2015. http://www.biogas.org/edcom/webfvb.nsf/id/de_branchenzahlen, accessed on 28 July 2016

Fleschhut, M.; Ostertag, J.; Thurner, S.; Eder, J. (2015): Körnermaisstroh für die Biogasproduktion. In: Biogas in der Landwirtschaft. Stand und Perspektiven, FNR/KTBL-Kongress vom 22. bis 23. September 2015 in Potsdam. Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL), Darmstadt, S. 328

FNR (2015): Basisdaten Bioenergie Deutschland 2015. Fachagentur Nachwachsende Rohstoffe e.V. https://mediathek.fnr.de/broschuren/bioenergie/biogas/basisdaten-bioenergie.html, accessed on 7 May 2016

Golub, M.; Bojic, S.; Djatkov, D.; Mickovic, G.; Martinov, M. (2012): Corn Stover Harvesting for Renewable Energy and Residual Soil Effects. Agricultural Mechanization in Asia Africa and Latin America 43(4), pp. 72–79

Hoskinson, R.; Karlen, D.; Birrell, S.; Radtke, C.; Wilhelm, W. (2007): Engineering, nutrient removal, and feedstock conversion evaluations of four corn stover harvest scenarios. Biomass and Bioenergy 31, pp. 126–136, http://dx.doi.org/10.1016/j.biombioe.2006.07.006

IEA (2015): Renewables Information. International Energy Agency, Paris

Jiang, D.; Zhuang, D.; Fu, J.; Huang, Y.; Wen, K. (2012): Bioenergy potential from crop residues in China. Availability and distribution. Renewable and Sustainable Energy Reviews 16(3), pp. 1377–1382, http://dx.doi.org/10.1016/j.rser.2011.12.012

Karlen, D.; Birell, S.; Hess, J. (2011): A five-year assessment of corn stover harvest in central Iowa, USA. Soil and Tillage Research 115–116, pp. 47–55, http://dx.doi.org/10.1016/j.still.2011.06.006

Kim, S.; Dale, B. (2004): Global potential bioethanol production from wasted crops and crop residues. Biomass and Bioenergy 26(4), pp. 361–375, http://dx.doi.org/10.1016/j.biombioe.2003.08.002

Leask, W.; Daynard, T. (1973): Dry matter yield, in vitro digestibility, percent protein, and moisture of corn stover following grain maturity. Canadian Journal of Plant Science 53, pp. 515–522

Lindstrom, M. (1986): Effects of residue harvesting on water runoff, soil erosion and nutrient loss. Agriculture, Ecosystems & Environment 16, pp. 103–112, http://dx.doi.org/10.1016/0167-8809(86)90097-6

Pavliska, O.; Theuretzbacher, F.; Bauer, A.; Amon, B.; Amon, T.; Kaul, H. (2012): Efficient utilization of lignocellulosic crop residues for biogas production using an optimized process chain. In: 20th European Biomass Conference and Exhibition. Conference 18–22 June 2012, exhibition 18–21 June 2012, Milano, ETA-Florence Renewable Energies, Florence, pp. 673–678

Petrolia, D. (2008): The economics of harvesting and transporting corn stover for conversion to fuel ethanol. A case study for Minnesota. Biomass and Bioenergy 32(7), pp. 603–612, http://dx.doi.org/10.1016/j.biombioe.2007.12.012

Pordesimo, L.; Edens, W.; Sokhansanj, S. (2004): Distribution of aboveground biomass in corn stover. Biomass and Bioenergy 26(4), pp. 337–343, http://dx.doi.org/10.1016/S0961-9534(03)00124-7

Qiang, Z.; Thomsen, A. (2012): Fuel Ethanol Production from Wet Oxidised Corn Stover by S. Cerevisiae. Materials for Environmental Protection and Energy Application, PTS 1, 2 343-344, pp. 963–967

Scarlat, N.; Martinov, M.; Dallemand, J.-F. (2010): Assessment of the availability of agricultural crop residues in the European Union: Potential and limitations for bioenergy use. Waste Management 30(10), pp. 1889–1897, http://dx.doi.org/10.1016/j.wasman.2010.04.016

Sheehan, J.; Aden, A.; Paustian, K.; Killian, K.; Brenner, J.; Walsh, M.; Nelson, R. (2003): Energy and Environmental Aspects of Using Corn Stover for Fuel Ethanol. Journal of Industrial Ecology 7(3-4), pp. 117–146, http://dx.doi.org/10.1162/108819803323059433

Shinners, K.; Adsit, G.; Binversie, B.; Digman, M.; Muck, R.; Weimer, P. (2007a): Single-pass, split-stream harvest of corn grain and stover. Transactions of the ASABE 50(2), pp. 355–363

Shinners, K.; Bennett, R.; Hoffman, D. (2012): Single- and two-pass corn grain and stover harvesting. Transactions of the ASABE 55(2), pp. 341–350, http://dx.doi.org/10.13031/2013.41372

Shinners, K.; Binversie, B.; Muck, R.; Weimer, P. (2007b): Comparison of wet and dry corn stover harvest and storage. Biomass and Bioenergy 31(4), pp. 211–221, http://dx.doi.org/10.1016/j.biombioe.2006.04.007

Shinners, K.; Boettcher, G.; Hoffman, D.; Munk, J.; Muck, R.; Weimer, P. (2009): Single-Pass Harvest of Corn Grain and Stover: Performance of Three Harvester Configurations. Transactions of the ASABE 52(1), pp. 51–60, http://dx.doi.org/10.13031/2013.22143

Sokhansanj, S.; Mani, S.; Tagore, S.; Turhollow, A. (2010): Techno-economic analysis of using corn stover to supply heat and power to a corn ethanol plant – Part 1: Cost of feedstock supply logistics. Biomass and Bioenergy 34(1), pp. 75–81, http://dx.doi.org/10.1016/j.biombioe.2009.10.001

Sokhansanj, S.; Turhollow, A.; Cushman, J.; Cundiff, J. (2002): Engineering aspects of collecting corn stover for bioenergy. Biomass and Bioenergy 23(5), pp. 347–355, http://dx.doi.org/10.1016/S0961-9534(02)00063-6

Statistisches Bundesamt (Destatis) (2016): Wirtschaftsbereiche - Feldfrüchte und Grünland. https://www.destatis.de/DE/ZahlenFakten/Wirtschaftsbereiche/LandForstwirtschaftFischerei/FeldfruechteGruenland/Tabellen/FeldfruechteZeitreihe.html, accessed on 22 May 2016

Straeter, J. (2011): Cornrower System of stover harvest. ASABE Paper No. 1110596, http://dx.doi.org/10.13031/2013.37239

Thurner, S.; Scheiber, P.; Heizinger, V.; Hoffmann, D. (2015): Grasanwelkguternte: Ladewagen oder Häckselkette - Ein Verfahrensvergleich. In: Forum Pflanzenbau live, Agritechnica 2015, https://www.agritechnica.com/fileadmin/downloads/2015/Programm/Forum_1/F1-13-11-1300_Thurner.pdf, accessed on 29 July 2016

Vadas, P.; Digman, M. (2013): Production costs of potential corn stover harvest and storage systems. Biomass and Bioenergy 54, pp. 133–139, http://dx.doi.org/10.1016/j.biombioe.2013.03.028

VDLUFA (1976): Band III Die chemische Untersuchung von Futtermitteln (Engl.: Chemical Analysis of Feedstuffs). Verband Deutscher Landwirtschaftlicher Untersuchungs- und Forschungsanstalten, VDLUFA-Verlag, Darmstadt

Womac, A.; Igathinathane, C.; Sokhansanj, S.; Pordesimo, L. (2005): Biomass moisture relations of an agricultural field residue: corn stover. Transactions of the ASAE 48(6), pp. 2073–2083, http://dx.doi.org/10.13031/2013.20084

Zuo, Z.; Yang, X. (2011): Ethanol Production from Corn stover Using Soaking Pretreatment. Advanced Materials Research 171–172, pp. 261–265, http://dx.doi.org/10.4028/www.scientific.net/AMR.171-172.261

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