IMPACT OF BLADE ANGLE ON MISCANTHUS HARVESTING ENERGY REQUIREMENT

J. D. Maughan, S. K. Mathanker, T. E. Grift, A. C. Hansen, K. C. Ting

ABSTRACT. *Miscanthus is emerging as a promising feedstock for domestic biofuel production. However, inefficiencies of the machinery that is used for harvesting bioenergy crops such as miscanthus currently prohibit commercial production. The performance of a mower-conditioner used to harvest miscanthus was evaluated, and modifications to the disk head were made to allow the machine to operate more efficiently. It was also hypothesized that the harvest energy requirement of the mower-conditioner in miscanthus could be reduced by increasing the blade oblique angle. Blades with oblique angles of 20° and 30° were manufactured and fitted to the disk mower-conditioner. When combined with data collected from a real-time yield sensing system, the data collected regarding the machine performance resulted in point-specific and overall machine energy consumption information. The 30° oblique angle resulted in a 27% reduction in the energy requirement, with an energy consumption of 13.5 MJ Mg^{-1} as compared to 18.5 MJ Mg^{-1} for the conventional straight (0°) blades. Further studies are needed to examine the overall life of the angled blades as well as the feasibility of their application to other crops harvested by disk mower-conditioners, such as hay and forage.*

Keywords. *Biomass, Blade angle, Cutting energy, Energy consumption, Forage, Harvesting, Machinery management, Miscanthus, Mower-conditioner, Precision agriculture, Yield sensing.*

Bioenergy crops are an important solution to reduce oil and gas imports by increasing the potential for production of renewable energy in the U.S. They are also becoming an important way to support agriculture, rural economies, and new industries such as biorefineries due to an increasing amount of biomass potentially available for domestic energy consumption. Estimates place the amount of biomass currently used and potentially available at 473 million tons DM in 2012 and over 1 billion tons DM by 2030, and the total domestic energy consumption from biomass at greater than 4% as of 2009 (USDOE, 2011). *Miscanthus × giganteus*, hereafter referred to as miscanthus, is a sterile, high-yielding C4 grass that has received much attention in Europe, and more recently in the U.S. (Jorgensen, 2011), as a biomass feedstock to produce cellulosic ethanol. Studies performed on experimental plots at three different University of Illinois Agricultural Research and Education Centers have shown that 12 million ha of U.S. farmland, with an average yield of 30 Mg ha^{-1}, could grow enough biomass to produce 132 billion L (35 billion gal) of ethanol (Heaton et al., 2008).

One major concern with producing miscanthus and other biomass crops is the economic sustainability of the bioenergy feedstock (Giampietro et al., 1997; Heaton et al., 2010). The transportation and harvest costs of miscanthus account for a major portion of the total cost within the feedstock supply chain (Khanna et al., 2008; Miao et al., 2012). The harvest costs, including mowing-conditioning and baling as major components, account for up to 69% of the cost of delivered miscanthus (Khanna et al., 2008). This raises the issue of how to improve harvest techniques as a method of reducing the costs associated with producing miscanthus. Modern hay harvesting machines are currently used, but they must be operated at a slower travel speed than in hay crops because of the density and toughness of miscanthus stems (Anderson et al., 2011). Research institutions are investigating harvesting systems and equipment for cutting, conditioning, windrowing, and baling as a means of improving machine efficiency (Johnson et al., 2012).

The development of bioenergy crops for use as a replacement for oil and gas imports has made necessary the evaluation of conventional hay and forage harvest equipment as a means of harvesting these crops. This equipment, which has not changed dramatically since its development (Stone and Gulvin, 1977), may require some modifications and additions to be useful in harvesting energy crops such as miscanthus (Anderson et al., 2011). Such additions may include yield monitoring and sensing systems, which are not currently widely available for forage equipment. Mathanker et al. (2014a) have developed a "look-ahead" type yield sensing system that converts the bending resistance of the miscanthus stems to a measure of miscanthus yield. They also explored the use of LIDAR to meas-

Submitted for review in August 2013 as manuscript number PM 10373; approved for publication by the Power & Machinery Division of ASABE in June 2014.

The authors are **Justin D. Maughan, ASABE Member,** Graduate Student, **Sunil K. Mathanker, ASABE Member,** Postdoctoral Research Associate, **Tony E. Grift, ASABE Member,** Associate Professor, **Alan C. Hansen, ASABE Member,** Professor, and **K. C. Ting, ASABE Fellow,** Professor and Head, Department of Agricultural and Biological Engineering, University of Illinois, Urbana, Illinois. **Corresponding author:** Alan Hansen, 338 Agricultural Engineering Sciences Building, 1304 W. Pennsylvania Ave., Urbana, IL 61802; phone: 217-333-2969; e-mail: achansen@illinois.edu.

  ISSN 2151-0032 DOI 10.13031/trans.57.10373

ure the swath volume at the rear of the mower-conditioner as a measure of yield (Mathanker et al., 2014b). Research regarding the amount of cutting energy expended when harvesting miscanthus has shown that modifications to the cutting components will reduce the energy consumption of the harvester (Johnson et al., 2012; Liu et al., 2012; Mathanker and Hansen, 2014).

Much research has been done to evaluate the cutting of grass stems and the performance of mowing systems such as those contained in mower-conditioners, specifically the power required to operate such machines. The power requirements of mower-conditioners vary greatly, depending on the cutting components, machine parameters such as width and speed, as well as the characteristics of the cutting components, such as blade sharpness (Tuck et al., 1991). A mower-conditioner with a sickle cutterbar will require 4.5 kW m^{-1} as compared to 8.0 kW m^{-1} for a disk mower-conditioner (ASABE, 2011). A sickle cutterbar cuts the crop material by means of reciprocating knife sections and a countershear. For a rotary machine, the crop material itself supplies the support force to cut the stalk (Srivastava et al., 2006a). The impact cutting action, as well as the air pumping action that is performed by the rotary cutterheads, account for the differences in the energy consumption. Another reason may be that the crop is not only cut by the blades but also accelerated during impact.

Blades typically available for use on rotary mowers are of a rectangular shape, usually with a slight twist to avoid crop drag against the underside of the blade after cutting has occurred (fig. 1). Due to the design of rotary cutting platforms and the twist in the blade, the blades are either "left" or "right," for use on either a clockwise or counter-clockwise rotating cutterhead. Each blade is reversible, meaning that it has two cutting edges; however, only one edge is used at a time for cutting the plant material. To use the other cutting edge, the blade must be flipped over on the cutting head. The blades that are commonly used have an oblique angle of 0°. The oblique angle is the angle between the axis along the length of the blade and the cutting edge of the blade. A complete description of cutting mechanics and geometry is provided by Srivastava et al. (2006a).

The energy consumption of the impact cutting action of a mowing machine may be reduced by increasing the blade oblique angle. This is because the force required to cut the plant material is reduced when the material is cut progressively as the blade enters the plant stem at an angle relative to the direction of blade travel, versus being cut all at once with a straight cut (Srivastava et al., 2006a). Laboratory studies were performed by Johnson et al. (2012) in which blade angles of 0°, 30°, and 60° were studied. A single blade with provisions to change the oblique angle was affixed to an arm on a pivot and was accelerated into a miscanthus stem. The data collected from this experiment indicated that a blade oblique angle of 60° had lower cutting energy than a straight blade angle of 0°. The straight cut required an average of 8.4 M J ha^{-1} as compared to 5.6 MJ ha^{-1} for the 60° oblique cut (Johnson et al., 2012). These results were in agreement with observations by Persson (1987) that the greater the blade oblique angle, the greater the possible reduction in energy. However, it has been suggested that the optimum blade angle is in the range of 15° to 30° (O'Dogherty and Gale, 1986).

Figure 1. Blade typical of those available for use on a rotary mower (New Holland part no. 87029587).

Based on the research performed by Johnson et al. (2012), a single disk-cutter setup was used to field test the effect of blade angles on one cutter head of a mower-conditioner (Maughan et al., 2014). The cutter head was instrumented to obtain torque and speed data, and was fitted with two blades. The researchers modified commercially available straight blades to obtain the oblique angles to be used in the experiment. The blade oblique angles used were straight (0°), 30°, and 40°. The blade oblique angle of 60° was not used because the type of blade used in the single disk-cutter study could not be modified to that angle without changing other important characteristics, such as blade length. The single disk-cutter apparatus was propelled through a stand of mature miscanthus to collect data on the performance of the blades. Maughan et al. (2014) indicated that the highest energy consumption of 46.1 MJ ha^{-1} occurred when the straight blade was used, and the lowest energy consumption of 9.1 MJ ha^{-1} occurred when the 40° oblique angle blade was used. The results of the single disk study indicated that an analysis of the performance of blades with increasing oblique angles on a full-scale mower-conditioner could show a reduction in energy consumption.

The purpose of this study was to reduce the machine energy requirement of a mower-conditioner operating in field conditions when harvesting miscanthus. The machine energy requirement was defined, for the purposes of this study, as the amount of energy required for the mower-conditioner to cut and condition miscanthus while traveling through the field. It was also referred to as energy consumption. Field conditions in this study were defined as traveling at a reasonable field speed and harvesting a nearly full swath width of miscanthus. It was hypothesized that an increase in blade oblique angle would result in an overall reduction of the machine energy consumption. The specific objectives of this study were to: (1) evaluate the energy requirement of the mower-conditioner for cutting miscanthus in field conditions, (2) develop blades with an oblique angle greater than 0° that could be fitted to a mower-conditioner, and (3) determine the significance of the blade oblique angle with regard to the overall machine energy requirement.

MATERIALS AND METHODS

In order to investigate the machine system energy, several tasks were completed. First, a "look-ahead" type yield sensor was developed as a means of detecting crop yield before cutting. A full description of the development and analysis of the yield sensing system was reported by Mathanker et al. (2014a). Information used to determine the harvest energy of the mower-conditioner was collected from CAN (Controller Area Network) messages on the machine during the harvest season, while a data logger system simultaneously recorded the CAN information and yield sensor information.

HARVEST EQUIPMENT

The commercially available equipment that was used to harvest miscanthus consisted of a New Holland self-propelled H8080 mower-conditioner with a model 750 HD Specialty rotary disc head (fig. 2). A 168 kW engine that produced a rated torque of 729.2 Nm was the power unit on the H8080 mower-conditioner. The 750 HD Specialty disc head had a cutting width of 4.7 m and 12 discs with a maximum speed of 3000 rpm. Each disc had two blades affixed to it for cutting the crop. A New Holland BB9080R large square baler equipped with New Holland's baler yield monitor system was also used. The baler was powered by a John Deere 7930 tractor.

Due to the large volume of crop material that must pass through the mower-conditioner, several modifications had been made to the disc header, as shown in figure 3. These modifications included a smaller diameter auger to convey crop material to the center of the header for conditioning, crop lifters to propel the crop material away from the discs, and fingers in the center of the auger to propel the crop material into the conditioning rolls. The chevron-design, intermeshing molded rubber conditioning rolls were replaced with slatted-steel conditioning rolls to provide more aggressive crop conditioning and enable more efficient material pickup when baling. The mower-conditioner was instrumented to evaluate the energy consumption of the machine per Mg miscanthus.

Figure 2. New Holland H8080 self-propelled mower-conditioner with 750 HD Specialty rotary disc head.

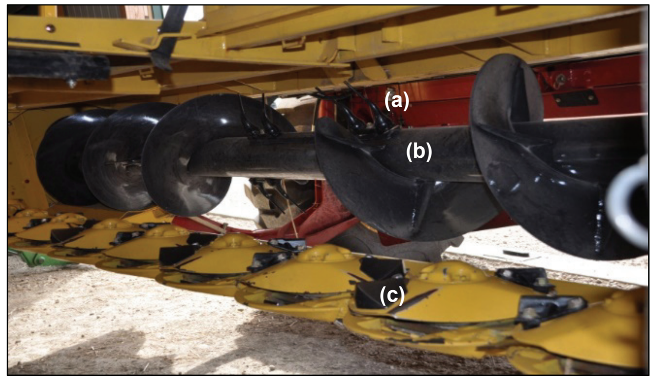

Figure 3. Modifications performed on 750 HD Specialty rotary head (conditioning rolls removed for the picture): (a) fingers on auger, (b) smaller diameter auger, and (c) lifters to propel crop away from discs.

CUTTING EXPERIMENTS

Similar to the lab-scale study (Johnson et al., 2012) and the limited-scale field study with one cutting disk (Maughan et al., 2014), three different blade oblique angles (0°, 20°, and 30°) were evaluated using a commercial machine with 12 cutting disks, as shown in figures 2 and 3. A blade oblique angle of 40° was not used because any blade wear that occurred would change the length of the blade, thereby changing parameters that determine the energy consumption of the mower-conditioner. The 0° blades were purchased at a local New Holland dealer (New Holland part no. 87029587), while the 20° and 30° blades were custom manufactured by Kondex Corporation (Lomira, Wisc.) specifically for this experiment (fig. 4). The 30° blades had only one cutting surface, so they were not reversible like the original blades. The 20° angle was selected because it was found that these blades could be reversible and still have a significant amount of material at the blade tip. The effects of the blade angle on blade life were not considered in this experiment.

To evaluate the cutting energy based on the blade oblique angle, five plots of mature miscanthus were selected at the Energy Biosciences Institute (EBI) Energy Farm in Urbana, Illinois (40.065707° N, -88.208714° W), so that there could be five samples for each of the three blade configurations. Four of the plots were identical in size and shape, had an average area of 0.69 ha (1.70 ac), and were

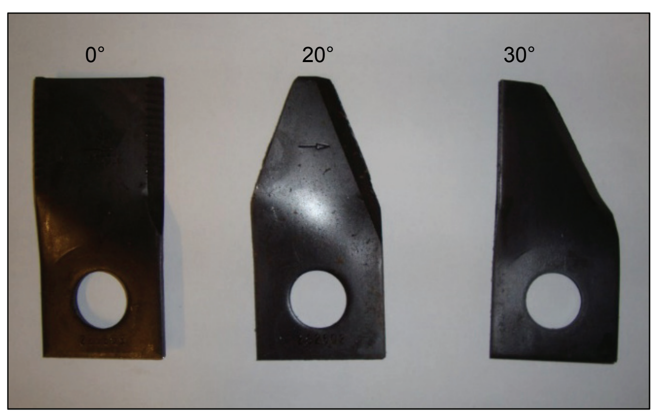

Figure 4. Blades used in cutting experiments on mower-conditioner.

Table 1. Variables collected by data logger system.

Variable	Sample Rate (Hz)
Time (HHMMSS.000)	1
Latitude (degrees, minutes, decimal minutes)	1
Longitude (degrees, minutes, decimal minutes)	1
GPS speed (km h^{-1})	1
Course (degrees relative to true north)	1
GPS fix type (ok, bad, invalid, GPS, DGPS, RTK fixed, and RTK float)	1
Loop time (ms)	1
Program error status	1
Engine speed (rpm)	1
Percent torque (of rated)	1
Wheel-based speed (km h^{-1})	1
Yield sensing system voltage	1000

120 m long. The fifth plot was 3.53 ha (8.72 ac) and was 188 m on each side. The plots were divided into three equal-sized subplots, with each subplot assigned a different blade treatment and each plot receiving all three treatments. The mower-conditioner was first outfitted with a new set of straight (0° oblique angle) blades to begin the cutting experiment. The end rows of each plot were cut first, using the straight blades, and then each subplot was harvested with the assigned blade treatment of 0°, 20°, or 30°.

The data logger system was set up to collect the data shown in table 1. The sample rate and length of time of operation resulted in the collection of a large amount of data that included segments of operation with no cutting, such as when traveling to and from a field, when turning at the end of a pass, or when avoiding an obstacle in the field. These data were excluded, leaving only the data associated with the mower-conditioner traveling at field speed with the disk head engaged and with a sufficient amount of miscanthus standing to register a value on the yield sensing system. Some data were also excluded due to one or more of the variables failing to be recorded for a single data point. The variables listed in table 1 were used to find the energy consumption of the mower-conditioner and the yield of the miscanthus, with a precise location and time affixed to each data point.

Data Processing

The data processing included sorting the raw data to find usable final data, and analysis of that data to generate machine and field performance results. The raw data collected from the data logger were processed using Microsoft Excel 2010. The values collected from the yield sensing system were used to predict the miscanthus yield, as described by Mathanker et al. (2014a). The rest of the data were processed and sorted to be able to calculate the energy requirement of the mower-conditioner for harvesting miscanthus.

The GPS readings were collected in degrees and decimal minutes. To aid in sorting and analyzing the data, each latitude-longitude pair was converted to an *x-y* coordinate pair using the coordinate transformation described by Srivastava et al. (2006c). The coordinate transformation was performed by using the southwest corner of each plot as the reference corner. The coordinates of this point were then used to determine the displacement of each data point. Figure 5 shows a swath pattern map that was created using this method.

To achieve the objective of evaluating the machine energy requirement of the mower-conditioner while operating in field conditions, information was needed for determining the actual field efficiency of the machine. Field efficiency is the ratio of the productivity of a machine operating in field conditions to the theoretical maximum productivity and accounts for the failure to utilize the maximum width of the machine, any time losses that occur due to operator capability or habit, and any field characteristics (ASABE, 2006).

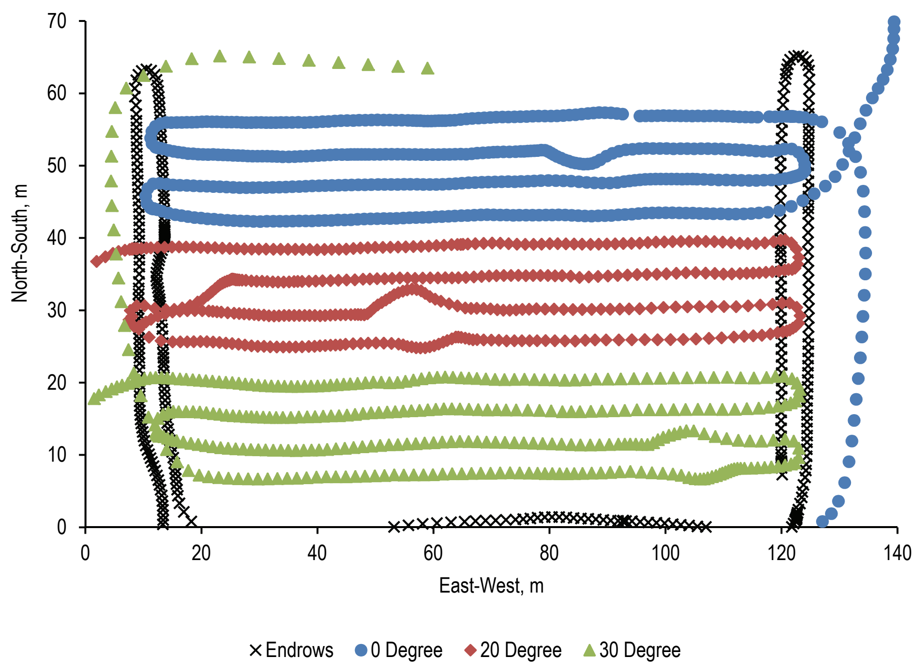

Figure 5. Swath pattern map after coordinate conversion showing distances (in meters) and area cut with each blade angle.

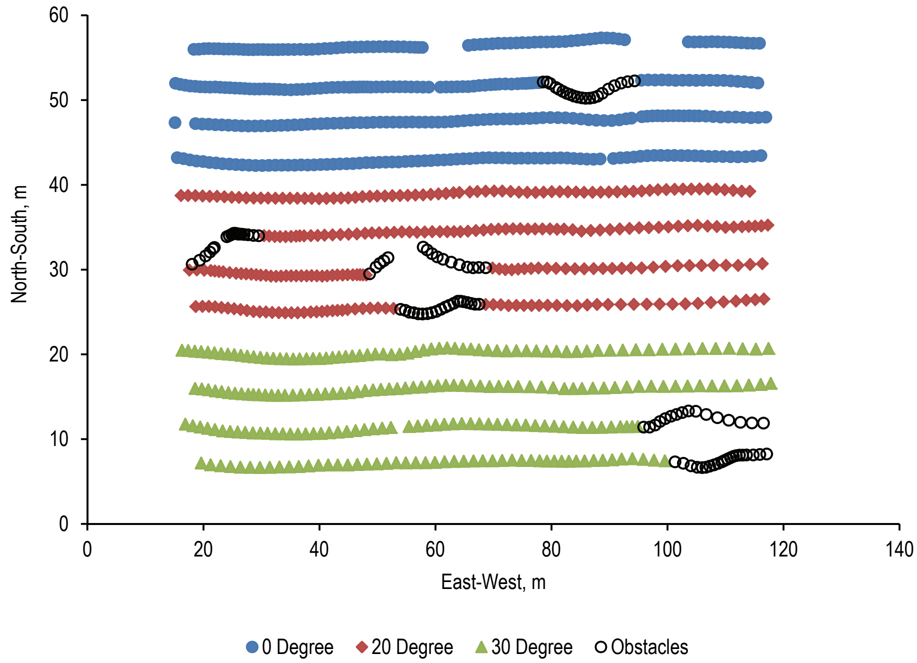

Figure 6. Swath map of final sorted data. Data that were collected while avoiding obstacles in the field are included to show the swath path.

The process of determining the field efficiency of the mower-conditioner included finding the data points representing the time spent turning as well as any data collected while avoiding obstacles in the field. Normally, obstacles encountered in the field result in a reduction in the field efficiency of the machine. However, in this study, the data collected while avoiding obstacles were eliminated from the analysis because these obstacles were the experimental equipment and observation points located at several points mid-field. Such observation points and equipment would not normally exist in a miscanthus field. A swath map of the final data used for determining the energy consumption of the miscanthus is shown in figure 6. The data collected while avoiding obstacles are included to show the swath path and to show that some other data points that were collected while operating in field conditions were later eliminated by the sorting process. The sorting process eliminated these other data points either because the yield sensing system measured the miscanthus yield as less than 0 Mg ha^{-1} or because there was an error in the location information for the data points.

Determining Machine Performance and Energy Consumption

The final sorted data were imported into new worksheets to find the machine energy consumption for each data point. The final information needed to determine the field efficiency was generated by using the turning information and the effective swath width, according to the procedure outlined by Srivastava et al. (2006b). The swath width was estimated from the average distance between each pass. The *y*-values for each pass were averaged together and then subtracted from the previous pass. The widths for each pass within a treatment were averaged together to determine the overall effective swath width per treatment.

The theoretical field capacity (ha h^{-1}) of the mower-conditioner, or theoretical area capacity, was calculated in order to determine the field efficiency of the machine. Field capacity is a function of the speed of the harvester, maximum width of the machine, and yield of the crop, or the amount of land or crop that is processed within a given amount of time, and therefore can be expressed as either area capacity or material capacity (ASABE, 2005). The crop yield is not used to determine the theoretical area capacity. The field efficiency is then determined by finding the ratio of the performance of the machine for the operating conditions within the field, rather than the effective time for performing the operation when accounting for the turning time and effective machine width, and the theoretical area capacity (ASABE, 2006).

The data that were collected included engine speed (rpm) and percent torque. The percent torque value that was recorded was the percentage of the rated torque that the engine was producing. The actual torque was found by multiplying the percent torque value by the torque at rated speed. From the actual torque value and engine speed, the actual power for each data point was determined.

The values collected from the yield sensing system were used to determine the instantaneous yield in Mg ha^{-1}, which was then used to help determine the energy consumption per unit weight of the crop. The miscanthus yield was predicted from the yield sensing system as described by Mathanker et al. (2014a), after accounting for the calibration procedure. The calibration procedure was performed in the same way; however, different incremental weights were used for the calibration in this study than previously, so the sensed yield data were transformed to enable use of the logarithmic model developed by Mathanker et al. (2014a). This provided an accurate measure of the actual crop yield, as well as a method for developing a yield map of the mis-

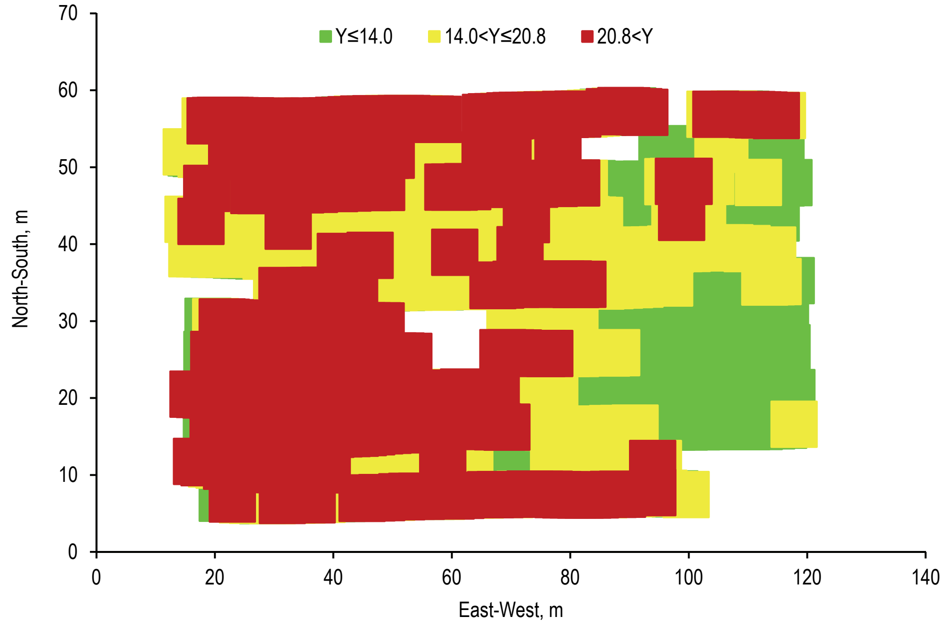

Figure 7. Miscanthus yield map generated from yield sensing system on mower-conditioner for plot B4 at the EBI Energy Farm in Urbana, Illinois. Yield values (*Y*) are in Mg ha^{-1}.

canthus harvest. The yield data were divided into three different yield ranges, as shown in figure 7.

The effective material capacity could be determined as a function of the crop yield, machine speed, maximum machine width, and field efficiency (ASABE, 2006). Each data point collected by the data logger system was represented by an area (ha) and by a crop yield (Mg). Therefore, the point-specific performance of the mower-conditioner could be determined. The final step in determining the machine performance was to find the point-specific energy consumption (MJ Mg^{-1}) of the mower-conditioner by converting the mower-conditioner power units from kW to a measure of energy (MJ):

$$E_m = \frac{P}{C_m} \times K_m \quad (1)$$

where

E_m = energy consumption, material basis (MJ Mg^{-1})
P = power (kW)
C_m = effective material capacity (Mg h^{-1})
K_m = units constant (3.6)

The energy consumption calculated in this manner, on a per unit material basis, was the instantaneous measure of the energy consumption of the mower-conditioner at any given moment. It was then possible to determine the effect of varying the blade oblique angle on the energy consumption of the mower-conditioner through statistical analysis. The statistical analysis was performed using SAS (SAS Institute, Inc., Cary, N.C.). A linear regression model was used to analyze the data, with the least squares method and a Tukey-Kramer adjustment. Specifically of interest in the statistical analysis was the correlation between crop yield and energy consumption, and the difference in energy consumption of the mower-conditioner by varying the blade oblique angle.

Results and Discussion

Yield Sensing for Determining Energy Consumption

For this study, the purpose of the yield sensing system was to determine the yield as a measure of the energy consumption of the harvest machine per Mg of biomass. A full analysis of the training data and validation of the yield sensing system is reported by Mathanker et al. (2014a), who also stated that the correlation between the yield sensing system and the actual yield as measured by the baler yield monitor system was $R^2 = 0.80$.

The yield sensing system provided a reasonable measure of yield for calculating the material energy consumption, or energy consumption per Mg of biomass, of the mower-conditioner. The relationship between the crop yield and the machine energy consumption was found to be exponential with $R^2 = 0.85$. When the crop yield is low, the energy consumption of the mower-conditioner per Mg of biomass is very high, and the energy consumption decreases exponentially as the crop yield increases. This may be partially due to the fact that the machine operator may not be able to harvest a thinner crop at a higher travel speed due to inexperience, habit, field conditions, or the maximum machine speed being reached.

The yield sensing system performed according to expectations and provided point-specific yield data that could be used to determine the point-specific energy consumption of the mower-conditioner. Further refinement is necessary to make the system more durable and more accurate. However, the system shows promise as a method of determining crop yield for measuring energy consumption.

Cutting Experiment Results

The energy consumption of the mower-conditioner was evaluated while operating in field conditions, and the data were analyzed to show how the energy consumption could be reduced. Statistical analysis of the preprocessed and sorted data indicated that there was a difference in the energy consumption of the mower-conditioner based on the oblique angle of the cutting blades (table 2). The mower-conditioner, operating in normal field conditions and fitted with conventional straight blades, required an average of 18.5 MJ Mg^{-1} while harvesting miscanthus. This represented the energy consumption over all five subplots assigned to the 0° blade treatment. Subsequent analysis of the different treatments showed that the 30° angle blades provided a 27% reduction in overall machine energy consumption, requiring only 13.5 MJ Mg^{-1}, while the 20° angle blades required 15.9 MJ Mg^{-1}, which is a 14% overall reduction. This is comparable to the 32% reduction found by Maughan et al. (2014) between 0° and 30°. Overall, the cutting experiments conducted during the 2013 harvest season were comparable to previous findings (Persson, 1987; Johnson et al., 2012; Maughan et al., 2014) regarding the energy savings that could be obtained by increasing the blade oblique angle.

The significance of the effect of the blade oblique angle on the machine energy consumption was quantified with statistical analysis. The significance of the differences between these means is presented in table 3. With $\alpha = 0.05$, the difference between the 0° and 30° angles is significant ($p = 0.01$), while the difference between the 0° and 20° angles is not significant ($p = 0.13$). From these results, it was concluded that the energy consumption is reduced when the 30° blades are used in place of the 0° blades, although it may not be reduced when using the 20° blades. The difference between the 20° and 30° angle is also not significant ($p = 0.16$). A similar study on a large production scale could further verify these findings and suggest methods for a greater reduction of the energy requirement.

Further considerations regarding the energy savings that could be achieved with a change in the blade oblique angle must include how the change in blade angle affects the overall life of the blade. The 20° blade contains 17% less material than the conventional 0° blade, while the 30° blade contains only 7% less material due to having only one cutting edge. This reduction in the amount of material in the blade poses a potential for the angled blades to wear out sooner than the conventional blades. Similarly, since the 30° blades are not reversible, the potential for more frequent blade replacement may also be increased. The effect of blade angle on the rate at which the angled blades need to be replaced, as compared to the straight blades, was not explored in this study. It may be important to know if the savings associated with the reduced energy requirement outweigh the costs associated with replacing the angled blades.

SUMMARY AND CONCLUSIONS

The energy consumption of a mower-conditioner was evaluated, and modifications were made to reduce the energy consumption of the machine when harvesting miscanthus. The "look-ahead" yield monitor system was tested to measure the biomass yield just prior to the crop being cut. The yield information was then used to determine point-specific and overall energy consumption of the mower-conditioner, in MJ Mg^{-1} of miscanthus, while operating in typical field conditions. Blades with oblique angles of 20° and 30° were developed and fitted to the mower-conditioner in turn, and the energy reduction varied from 18.5 MJ Mg^{-1} with the 0° blades to 15.9 MJ Mg^{-1} with the 20° blades and 13.5 MJ Mg^{-1} with the 30° blades. Overall, this was a 14% reduction with the 20° blades and a 27% reduction with the 30° blades. Statistical analysis revealed that only the reduction due to the 30° oblique angle was significant ($p = 0.01$).

The results support the original hypothesis that the energy consumption of the mower-conditioner could be reduced by increasing the blade oblique angle. Further work is needed to determine the effect of changing the blade oblique angle on the life of the blade, and to determine if the energy savings achieved by increasing the blade oblique angle outweigh any costs associated with the manufacturing and replacement of the angled blades. The application of increasing the blade oblique angle to reduce the harvesting energy requirement may also be extended to other crops that are harvested with a disk mower-conditioner, such as hay and forage.

ACKNOWLEDGEMENTS

This project was funded by the Energy Biosciences Institute through a program entitled "Engineering Solutions for Biomass Feedstock Production." Special thanks go to Neal Stoffel of Kondex Corporation for manufacturing the angled blades, and Tim Mies and Collin Reeser of the EBI Energy Farm for managing and carrying out the harvest procedures.

Table 2. Estimates of energy consumption by blade angle (least squares means) showing probabilities and 95% confidence limits.

Angle	Estimate (MJ Mg^{-1})	Standard Error	DF	t-Value	Pr > |t|	Lower Limit	Upper Limit
0°	18.50	1.08	8	17.14	<0.0001	16.00	20.99
20°	15.90	1.11	8	14.32	<0.0001	13.34	18.46
30°	13.48	1.09	8	12.39	<0.0001	10.97	15.99

Table 3. Differences in energy consumption by blade angle (least squares means) showing probabilities and 95% confidence limits.

Angle 1	Angle 2	Estimate of Difference (MJ Mg^{-1})	Standard Error	DF	t-Value	Pr > |t|	Lower Limit	Upper Limit
0°	20°	2.60	1.54	8	1.68	0.1311	-0.96	6.16
0°	30°	5.01	1.53	8	3.28	0.0112	1.49	8.54
20°	30°	2.42	1.55	8	1.56	0.1576	-1.16	5.99

References

Anderson, E., Arundale, R., Maughan, M., Oladeinde, A., Wycislo, A., & Voigt, T. (2011). Growth and agronomy of *Miscanthus × giganteus* for biomass production. *Biofuels, 2*(2), 167-183. http://dx.doi.org/10.4155/bfs.10.80.

ASABE. (2005). S495.1: Uniform terminology for agricultural machinery management. St. Joseph, Mich.: ASABE.

ASABE. (2006). EP496.3: Agricultural machinery management. St. Joseph, Mich.: ASABE.

ASABE. (2011). D497.7: Agricultural machinery management data. St. Joseph, Mich.: ASABE.

Giampietro, M., Ulgiati, S., & Pimentel, D. (1997). Feasibility of large-scale biofuel production: Does an enlargement of scale change the picture? *Bioscience, 47*(9), 587-600. http://dx.doi.org/10.2307/1313165.

Heaton, E. A., Dohleman, F. G., & Long, S. P. (2008). Meeting U.S. biofuel goals with less land: The potential of miscanthus. *Global Change Biol., 14*(9), 2000-2014. http://dx.doi.org/10.1111/j.1365-2486.2008.01662.x.

Heaton, E. A., Dohleman, F. G., Miguez, A. F., Juvik, J. A., Lozovaya, V., Widholm, J., Zabotina, O. A., McIsaac, G. F., David, M. B., Voight, T. B., Boersma, N. N. & Long, S. P. (2010). Miscanthus: A promising biomass crop. *Advances in Botanical Research,* Vol. 56, 75-137.

Johnson, P. C., Clementson, C. L., Mathanker, S. K., Grift, T. E., & Hansen, A. C. (2012). Cutting energy characteristics of *Miscanthus ×giganteus* stems with varying oblique angle and cutting speed. *Biosystems Eng., 112*(1), 42-48. http://dx.doi.org/10.1016/j.biosystemseng.2012.02.003.

Jorgensen, U. (2011). Benefits versus risks of growing biofuel crops: The case of miscanthus. *Current Opinion in Environ. Sustainability, 3*(1-2), 24-30. http://dx.doi.org/10.1016/j.cosust.2010.12.003.

Khanna, M., Dhungana, B., & Clifton-Brown, J. (2008). Costs of producing miscanthus and switchgrass for bioenergy in Illinois. *Biomass and Bioenergy, 32*(6), 482-493. http://dx.doi.org/10.1016/j.biombioe.2007.11.003.

Liu, Q., Mathanker, S. K., Zhang, Q., & Hansen, A. C. (2012). Biomechanical properties of miscanthus stems. *Trans. ASABE, 55*(4), 1125-1131. http://dx.doi.org/10.13031/2013.42231.

Mathanker, S. K., & Hansen, A. C. (2014). Harvesting system design and performance. In Y. K. Shastri, A. C. Hansen, & L. F. Rodriguez, & K. C. Ting (Eds.), *Biomass Feedstock Production Engineering* (pp. 85-139). New York, N.Y.: Springer.

Mathanker, S. K., Hansen, A. C., Grift, T. E., & Ting, K. C. (2014a). Sensing miscanthus stem bending force for maximizing throughput rate in a disk mower-conditioner. *Trans. ASABE, 57*(1), 5-12. http://dx.doi.org/10.13031/trans.57.10121.

Mathanker, S. K., Maughan, J. D., Hansen, A. C., Grift, T. E., & Ting, K. C. (2014b). Sensing miscanthus swath volume for maximizing baler throughput rate. *Trans. ASABE, 57*(2), 355-362. http://dx.doi.org/10.13031/trans.57.10167.

Maughan, J. D., Fehrenbacher, B. M., Mathanker, S. K., & Hansen, A. C. (2014). Impact of cutting speed and blade configuration on energy requirement for miscanthus harvesting. *Appl. Eng. Agric., 30*(2), 137-142. http://dx.doi.org/10.13031/aea.30.10161.

Miao, Z. W., Shastri, Y., Grift, T. E., Hansen, A. C., & Ting, K. C. (2012). Lignocellulosic biomass feedstock transportation alternatives, logistics, equipment configurations, and modeling. *Bioproducts Biorefining, 6*(3), 351-362. http://dx.doi.org/10.1002/bbb.1322.

O'Dogherty, M. J., & Gale, G. E. (1986). Laboratory studies of the cutting of grass stems. *J. Agric. Eng. Res., 35*(2), 115-129.

Persson, S. (1987). *Mechanics of Cutting Plant Material.* St. Joseph, Mich.: ASAE.

Srivastava, A. K., Goering, C. E., Rohrbach, R. P., & Buckmaster, D. R. (2006a). Chapter 11: Hay and forage harvesting. In *Engineering Principles of Agricultural Machines* (pp. 325-340). St. Joseph, Mich.: ASABE. http://dx.doi.org/10.13031/2013.41473.

Srivastava, A. K., Goering, C. E., Rohrbach, R. P., & Buckmaster, D. R. (2006b). Chapter 15: Machinery selection and management. In *Engineering Principles of Agricultural Machines* (pp. 525-552). St. Joseph, Mich.: ASABE. http://dx.doi.org/10.13031/2013.41477.

Srivastava, A. K., Goering, C. E., Rohrbach, R. P., & Buckmaster, D. R. (2006c). Chapter 6: Precision agriculture. In *Engineering Principles of Agricultural Machines* (pp. 123-138). St. Joseph, Mich.: ASABE. http://dx.doi.org/10.13031/2013.41468.

Stone, A. A., & Gulvin, H. E. (1977). *Machines for Power Farming* (3rd ed.). New York, N.Y.: Wiley.

Tuck, C. R., Odogherty, M. J., Baker, D. E., & Gale, G. E. (1991). Laboratory studies of the performance characteristics of mowing mechanisms. *J. Agric. Eng. Res., 50*(1), 61-80. http://dx.doi.org/10.1016/S0021-8634(05)80006-X.

USDOE. (2011). U.S. billion-ton update: Biomass supply for a bioenergy and bioproducts industry. ORNL/TM-2011/224. Oak Ridge, Tenn.: U.S. Department of Energy, Oak Ridge National Laboratory.