IMPROVING THE THROWING EFFECTIVENESS OF AN UPWARD-CUTTING FORAGE HARVESTER

K. J. Shinners, M. Stelzle, R. G. Koegel

ABSTRACT. *An upward-cutting, cut-and-throw, forage harvester was previously shown to reduce specific energy requirements by 30 to 34%, but it also had a 27% shorter throwing distance than a conventional, cut-and-blow, forage harvester. The upward-cutting, cut-and-throw, forage harvester was modified to improve the throwing/blowing characteristics while maintaining the specific energy advantage. By increasing the open area in the sidewalls of the cutterhead housing, the air speed through the discharge spout was increased from 8.6 to 21.5 m/s, which significantly improved throwing distance. A video method was used to observe that cut material was engaged with the cutterhead knife for a significant fraction of a revolution, such that the crop left the cutterhead in a wide, nonconcentrated pattern. A throwing countersurface mounted below and perpendicular to the knife improved particle release. The throwing distance improved and the energy requirement increased with a smaller relief dimension from the countersurface to the knife tip. With a 9-mm relief, 9- and 12-knife cutterheads produced mean throwing distances 4 and 11% shorter, respectively, than a cut-and-blow harvester harvesting alfalfa; and 6 and 14% shorter, respectively, than a cut-and-blow harvester harvesting corn. The 9-knife cutterhead produced a throwing distance closer to that of the cut-and-blow harvester than the 12-knife cutterhead due to greater air velocity in the spout. With a 9-mm relief, 9- and 12-knife cutterheads resulted in specific energy requirements 21 and 24% lower, respectively, than a cut-and-blow harvester harvesting alfalfa; and 14 and 25% lower, respectively, than a cut-and-blow harvester when harvesting corn. The 12-knife cutterhead produced greater specific energy reductions than the 9-knife cutterhead due to lower peak cutting and mat compression loads.*
Keywords. *Forage harvesters, Energy requirements.*

Generally the specific energy requirements of a forage harvester are very high, and therefore the power needed to drive the forage harvester can sometimes determine the size of tractor used on the livestock oriented farm. The specific energy for forage harvesting can reach 3.5 kWh/t (O'Dogherty, 1982). The crop unit and other drive train losses require 20% of the total power. The cutterhead which compresses and cuts the crop accounts for 40% of the total power, and the remaining 40% of the total power consumed by the forage harvester is used by the blower/impeller conveying system (Blevins and Hanson, 1956; O'Dogherty, 1982; Persson, 1987; Shinners et al., 1990).

The most commonly used conveying system is a flywheel impeller/blower fed by an auxiliary cross-auger or spinner. Blevins and Hanson (1956) subdivided the power required by a blower into three areas: particle movement or kinetic energy, friction energy, and air movement. Friction energy accounts for a large portion of the required power. The friction loss for these crops is even greater when gum accumulation occurs at certain moisture contents (Finner, 1966; Shinners et al., 1990).

Due to its relatively low bulk density, the forage can easily be affected by cross winds. Therefore, to keep the forage moving in a certain direction, the material must be supported by an airstream which is usually created with an auxiliary blower/impeller. To transport the forage in a concentrated stream into the hauling unit, the direction of the combined air and crop stream must be changed along a curved surface, in general a 90° directional spout. Chancellor (1960) estimated that up to 50% of the crop's kinetic energy is lost in the 90° elbow. For this reason, blowers on forage harvesters must be driven at sufficient speeds to overcome the frictional losses at the band and along the spout and still be able to blow the forage to the far end of a large transportation unit. Totten and Millier (1966) determined the theoretical efficiency of the blower to be between 25 and 30%.

By using the kinetic energy imparted by the cutterhead for transporting the crop, the inefficient blower can be eliminated. Downward-cutting, cut-and-throw, forage harvesters are based on this concept. The material is fed into the cutterhead unit by means of feed rolls. The cutterhead shears down into the incoming mat of material as it passes the shearbar. The cut material then is accelerated by the cutterhead to the peripheral speed of the knives. In order to redirect the flow of material vertically, a housing is placed under the cutterhead. Unfortunately, the chopped and accelerated material produces friction losses while it is dragged along the cutterhead housing until it is thrown into the directional spout. Very often the

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The authors are **Kevin J. Shinners**, ***ASAE Member Engineer***, Associate Professor, and **Michael Stelzle**, Graduate Research Assistant, Dept. of Agricultural Engineering, University of Wisconsin, Madison; and **Richard G. Koegel**, ***ASAE Member Engineer***, Research Agricultural Engineer, USDA-ARS U.S. Dairy Forage Research Center, Madison, Wis.

downward-cutting, cut-and-throw, forage harvester does not impart sufficient velocity to wilted legumes and grasses to fill large forage wagons. The adjustment of the clearance between cutterhead knives and housing is critical for proper throwing action and this adjustment is time consuming. For these reasons, the popularity of the downward-cutting, cut-and-throw, forage harvester has decreased.

An approach to eliminate both the blower of a cut-and-blow forage harvester and the friction along the cutterhead housing of a downward-cutting, cut-and-throw, forage harvester is to use the kinetic energy of an upward-cutting cutterhead in a cut-and-throw forage harvester (Shinners et al., 1991). With this concept the knives cut up into the mat of forage and the chopped material is immediately launched upward into a directional spout. This eliminates the frictional loss at the cutterhead housing, because the material is no longer dragged along the housing.

The Swedish National Machinery Testing Institute (SNMTI) tested a commercial machine with such a configuration. It had a 480-mm-diameter cutterhead operating at 1500 rpm, resulting in a tip velocity of 38 m/s. This machine required 30% less power than a harvester with a flywheel cutterhead and 41% less power than a cut-and-blow forage harvester with a cylinder cutterhead (SNMTI, 1985).

The National Grassland Research Institute of Japan developed and tested an upward-cutting cylindrical type cut-and-throw forage harvester (Yoshihara et al., 1983). It had a 610-mm-diameter cutterhead operating at 1120 rpm, which developed a tip velocity of 36 m/s. This machine required 30% less power than a conventional downward-cutting cylindrical type cut-and-throw forage harvester when harvesting corn (Yoshihara et al., 1983).

The Department of Agricultural Engineering at the University of Wisconsin-Madison modified a downward-cutting, cut-and-throw, forage harvester into an upward-cutting, cut-and-throw, forage harvester. It had a 610-mm-diameter cutterhead operating at 975 rpm which developed a tip velocity of 31 m/s. This machine required 34% less specific energy than a conventional cut-and-blow forage harvester (Shinners et al., 1991).

Shinners et al. (1991) noted that the throwing distance of the upward-cutting, cut-and-throw, forage harvester was not sufficient. This particular machine threw the chopped forage a 27% shorter distance than a conventional cut-and-blow forage harvester. The SNMTI also noted that the upward-cutting, cut-and-throw, forage harvester had only "adequate" throwing performance while other machines had "good" or "excellent" throwing performance (SNMTI, 1985).

The overall objective of this research was to increase the throwing distance of an upward-cutting forage harvester without adversely affecting the energy benefits already achieved. Specific research objectives were to:

- Develop a means to visualize the particle movement from the cutterhead.
- Improve the particle movement from the cutterhead by developing throwing aids.
- Improve the air movement through the cutterhead and spout.

Machine Description and Test Procedures

Machine Description

Modifications were made to a New Holland model 717 cut-and-throw forage harvester to invert the feed roll and cutterhead components so that the geometric relationship between the feed rolls, shear bar, and cutterhead remained as they were in the original machine. By driving the feed rolls and cutterhead in the opposite rotational direction, the knives entered the mat of uncut material from below and threw the material upward out of the machine. The feed roll throat area was 49 350 mm^2, cutterhead width was 445 mm, cutterhead diameter was 610 mm, and cutterhead speed was 1000 rpm. The cutterhead originally had 9 knives, but a new cutterhead with 12 knives was used in later research.

Video Method for Determining Particle Movement from Cutterhead

To improve the throwing performance of the upward-cutting, cut-and-throw, forage harvester, it was important to determine the particle movement from the cutterhead. With the spout removed, a strobe lamp was used to produce a standing picture of a single knife at the shearbar. When material was run through the forage harvester, the particle movement after the cutting action was seen. By using a video camera in a dark environment, particle movement from the cutterhead was recorded. The throwing performance of the cutterhead was then investigated by viewing the tape with a high resolution video tape player.

With this method, it was estimated that about 65% of the cut crop was thrown directly from the cutterhead by impact. The other 35% of the cut crop slid downward along the knife and was not immediately released from the knife, resulting in a nonconcentrated stream which was undesirable for good throwing performance (fig. 1). Based on these results, it was concluded that one reason for the lower than desired throwing performance was the poor

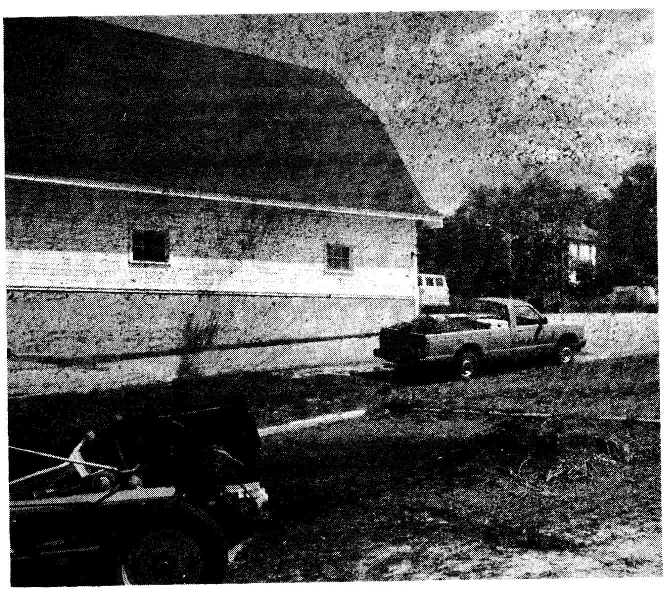

Figure 1–Nonconcentrated crop stream from cutterhead without throwing countersurfaces.

release of the cut material from the knives of the cutterhead.

In order to prevent the cut crop from sliding down the back side of the knife, a throwing countersurface was added to the knife. This device was a plate mounted inboard and perpendicular to the knife (fig. 2). The addition of the countersurface was designed to improve the throwing distance in two ways by: (1) improving the crop release from the knife preventing the cut material from sliding down the knife, and (2) compressing the cut crop so that it would rebound from the countersurface with a greater velocity than the knife. The throwing countersurface greatly improved the release of the crop such that the material left the cutterhead in a concentrated stream (fig. 3).

Twelve-knife Cutterhead

Initial research with the nine-knife cutterhead indicated that throwing distance was improved by smaller countersurface relief and greater air velocity in the spout (sections 3.1 and 3.3). Smaller countersurface relief also resulted in greater energy requirements (section 3.1). By adding additional knives to the cutterhead and maintaining the same feed rate and cutterhead speed, the amount of material cut and compressed per knife would be decreased, and the energy needed would then be reduced. This would allow smaller countersurface relief for improved throwing performance without adversely affecting energy requirements. A new cutterhead was designed and fabricated with 12 knives, 12 radially mounted air pumping paddles, air openings in the cutterhead end disks (27% open area), and 12 adjustable throwing countersurfaces with a design relief of 9 mm.

Determination of Throwing Distance

Throwing distance was determined for the experimental upward-cutting cut-and-throw machine, a conventional downward-cutting cut-and-throw harvester (New Holland 717), and a conventional cut-and-blow harvester (John Deere 3950). Throwing distance was determined inside a closed facility to avoid wind influence on the throwing performance. The material used for these tests was harvested with a mower-conditioner two days in advance, allowed to field wilt for one day, hand collected, and transported to the test facility the day before the test. In this way, the moisture content of the material was more uniform throughout the test. Since the throwing performance of the forage harvesters changes with different feed rates, the feed rate needed to be the same for all tests. The test material was weighed and then evenly distributed on a conveyor. Loading the same amount of material and driving the conveyor with the same speed insured a constant feed rate of approximately 25 t/h with alfalfa and 20 t/h with corn. Conveyor limitations limited feedrates to these values.

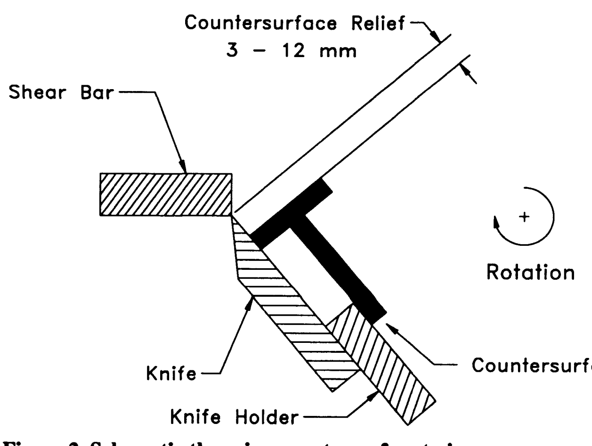

Figure 2–Schematic throwing countersurface to improve crop release from the knife.

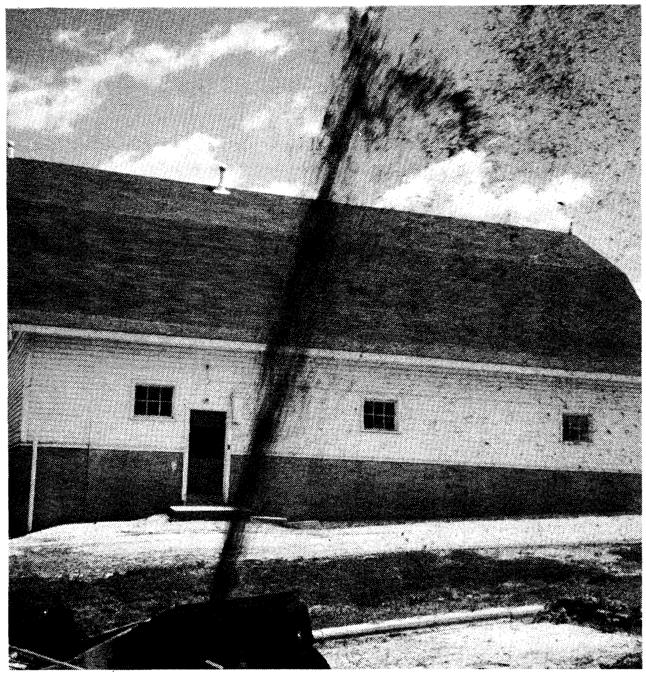
Figure 3–Concentrated crop stream from cutterhead with throwing countersurfaces.

The conveyor fed the material directly into the pick-up and auger (alfalfa) or the feed rolls (corn) of the test machines. In order to conduct a consistent test of the throwing distances, the deflector cap at the end of the spout of each machine was set horizontal and the difference in height of the spouts was held within 30 mm. Additionally, the length of arc of contact between the crop and the spouts (1420 mm) was made similar for all machines by the addition of an extension to the spout of the cut-and-blow harvester. In all tests the cutterhead speed of both cut-and-throw machines was about 1000 rpm. The blower speed of the cut-and-blow machine was also kept at 1000 rpm while its cutterhead operated at 850 rpm.

A plastic strip was placed at ground level behind each machine in order to capture the material. The plastic strip was 16.5 m long and was subdivided into 11 sections of 1.5 m. The start of the plastic strip was placed directly below the pivot point of the deflector at the end of the spout of all machines. For each experimental condition, four replicates were conducted. Moisture and particle samples were taken after each replicate (*ASAE Standards*, 1993a, b).

After each test, the mass of material on each section of the plastic strip was determined. The percentage of the total mass of the chopped material in each section produced a material distribution curve with a geometric mean and standard deviation. The average of the geometric mean throwing distance and geometric standard deviation of the replicate tests of each machine was used to compare the throwing performance of the forage harvesters. The geometric mean throwing distance and geometric standard deviation were calculated from equations 1 and 2. The midpoint throwing distance for each section of the plastic strip (x_{ai}) was the distance from the pivot point of the spout deflector to the midpoint of that section. The log-normal distribution was chosen for three reasons: (1) the log transformation provided a normal distribution, (2) the mean and median have identical values with this distribution, and (3) the geometric mean and standard deviation completely define the distribution.

$$x_{gm} = \log^{-1}\left(\frac{\sum (M_i \cdot \log x_{ai})}{\sum M_i}\right) \qquad (1)$$

$$s_{gm} = \log^{-1}\left[\frac{\sum\left[M_i\left((\log x_{ai})-(\log x_{gm})\right)^2\right]}{\sum M_i}\right]^{-1/2} \qquad (2)$$

x_{gm} = geometric mean throwing distance (m)
s_{gm} = geometric standard deviation (unitless)
M_i = mass in each section (percent of total)
x_{ai} = midpoint throwing distance of each section (m)

Determination of Machine Specific Energy Requirements

The energy requirements for harvesting alfalfa were found in field tests as well as with the throwing distance tests. Since corn heads were not available for the different forage harvesters, the energy requirements for processing corn were only determined in combination with the throwing distance tests.

During field tests, all the chopped material from the forage harvester was collected in a side-dumping forage box with a weighed container (Kraus et al., 1993). The machine feed rate was determined by dividing the material mass by the test duration. Different feed rates were obtained by choosing different travel speeds along the windrow. Feed rates varied from approximately 10 to 17 t/h. For each test, a sample for moisture content and particle size analysis were taken. Since most field tests lasted a whole day, the crop moisture content changed during the day. Therefore, the feed rate of each test run was adjusted using a moisture content adjustment factor (*ASAE Standards*, 1993c).

A torque transducer was mounted between tractor pto and drive shaft of the forage harvester. The torque transferred to the forage harvester and the pto speed were measured and stored with a portable, programmable datalogger every 0.1 s. After each test, an average of the collected data points was stored by the datalogger. Power requirements were determined from these data. Specific energy was determined by dividing the required power by the moisture adjusted feed rate.

For field tests, six replicates per experimental condition were conducted. For throwing distance tests, four replicates per experimental condition were conducted.

Determination of Spout Air Velocity

Modifications were made to the cutterhead and its housing to improve air flow characteristics. The open area in the sides of the cutterhead housing was increased from 9 to 32%. Radially mounted fan-type blades and three openings were added on both side discs of the 12-knife cutterhead. The air speed was measured just before the curved portion of the spout with the experimental forage harvester driven at pto speed. Velocity was measured with a pitot-tube and a manometer.

Experimental Conditions and Statistical Analysis

Independent variables considered during evaluation of specific energy requirements included countersurface relief (3, 6, and 9 mm), number of cutterhead knives (9 and 12), cutterhead speed (1000 and 1350 rpm), and feed rate (approximately 11 and 22 t/h). Independent variables during evaluation of throwing performance included countersurface relief, number of cutterhead knives, and open area in the cutterhead housing (0, 23, and 32% open area).

Statistical analysis was conducted using a one-way analysis of variance. If similar experiments conducted on different days were combined for analysis, two-way analysis of variance was used.

Results

Throwing Distance and Specific Energy Requirement with a Nine-knife Cutterhead

When harvesting alfalfa, increasing the countersurface relief reduced the throwing distance and the specific energy requirements (table 1). Compared to the cut-and-blow harvester, the experimental harvester threw 13% farther with a 3-mm relief, the same distance with a 6-mm relief and 7% shorter with a 12-mm relief. Compared to the conventional cut-and-blow harvester, the experimental harvester needed 25% less specific energy with a countersurface relief of 12 mm, 16% less with a 6-mm relief, and 10% less with a 3-mm relief.

When harvesting corn, there was no significant difference in the geometric mean throwing distance for the three countersurface relief dimensions tested (table 1). The experimental upward-cutting harvester threw the crop 6 to 7% shorter than the conventional cut-and-blow harvester. The experimental upcut harvester threw 12% farther than the conventional cut-and-throw harvester. Compared to the conventional cut-and-blow harvester, the experimental harvester needed 21% less specific energy with a countersurface relief of 12 mm, 8% less with a 6-mm relief, and 1% less with a 3-mm relief. The throwing distance geometric standard deviation for both the cut-and-blow and experimental harvester were similar, indicating that both machines produced similar dispersion in the throwing pattern.

During most throwing distance tests, the deflector cap at the end of the spout of each machine was fixed horizontally. To determine the maximum throwing distance of each machine, the deflector caps were positioned in a manner so that they would not interfere with the natural crop stream given by the trajectory of the spouts. With corn, the experimental machine threw 4% farther and with less dispersion than the cut-and-blow forage harvester (table 2). The feed rate was approximately 20 t/h for all machines.

During field tests harvesting alfalfa, the experimental machine with a cutterhead speed of 1000 rpm and a

Table 1. Throwing distance and specific energy requirements with alfalfa and corn, three countersurface reliefs, and 9-knife cutterhead operating at 1000 rpm

Machine Configuration/ Countersurface Relief	Moisture Content (% w.b.)*	Mean Length-of-Cut (mm)	Moisture-adjusted Feed Rate (t/h)	Geometric Mean Throwing Distance (GMTD) (m)	Difference in GMTD from Cut-and-Blow (%)	Throwing Distance Geometric Standard Deviation	Moisture Adjusted Specific Energy (MASE) (kWh/t)	Difference in MASE from Cut-and-Blow (%)	Replicates
				Alfalfa					
Cut-and-blow	55.3_{ab}	12.6_{bc}	25.1_b	8.3_b	—	1.194_a	1.65_a	—	4
Cut-and-throw	56.3_{ab}	11.9_{ab}	25.3_b	7.2_d	–13	1.163_b	1.61_a	–2	4
Exp. upcut/12 mm	56.7_b	13.7_c	24.4_{ab}	7.7_c	–7	1.200_a	1.24_d	–25	4
Exp. upcut /6 mm	55.0_a	12.8_{bc}	24.5_{ab}	8.3_b	0	1.188_a	1.39_c	–16	4
Exp. upcut/3 mm	56.3_{ab}	10.9_a	23.9_a	9.4_a	13	1.194_a	1.49_b	–10	4
LSD (P = 0.05)	1.5	1.6	1.0	0.3		0.018	0.08		
				Corn					
Cut-and-blow	67.7_a	11.0_a	20.2	10.6_a	—	1.274_a	1.70_a	—	4
Cut-and-throw	67.0_a	10.8_a	19.9	8.8_c	–17	1.272_a	1.46_c	–14	4
Exp. upcut/12 mm	68.0_a	10.8_a	20.0	9.9_b	–7	1.283_a	1.35_d	–21	4
Exp. upcut/6 mm	70.0_b	10.6_a	19.8	10.0_b	–6	1.269_a	1.56_b	–8	4
Exp. upcut/3 mm	66.7_a	10.6_a	19.8	9.9_b	–7	1.267_a	1.69_a	–1	4
LSD (P = 0.05)	1.8	0.6	0.5	0.6		0.031	0.10		

* Averages with different subscripts are statistically different at the 95% level.

countersurface relief of 6 mm required 18% less specific energy than the cut-and-blow harvester (table 3). When operated at the faster cutterhead speed of 1350 rpm, the experimental machine required 7% greater specific energy than the cut-and-blow harvester. This result indicates that increasing the throwing distance by increasing knife tip speed would be an inefficient approach. When the countersurface relief was reduced to 3 mm with the cutterhead operated at 1000 rpm, the experimental machine required 12% less specific energy than the cut-and-blow harvester (table 3).

Tables 2 and 3 show a significant difference in the mean length-of-cut between cut-and-blow and upward-cutting cut-and-throw harvesters. Both machines were set to a theoretical length of cut of 9.5 mm. The results in table 3 show that the cut-and-blow harvester cut the crop to a length closer to the theoretical length of cut. The upward-cutting cut-and-throw harvester produced crop particles which were longer than the theoretical length of cut when operated at 1000 rpm. It is possible that some fraction of the energy difference between the machines could be attributed to the difference in actual length of cut.

Table 2. Maximum throwing distance with corn, 12-mm countersurface relief and 9-knife cutterhead operating at 1000 rpm

Machine Configuration/ Countersurface Relief	Moisture Content (% w.b.)*	Mean Length-of-Cut (mm)	Geometric Mean Throwing Distance (GMTD) (m)	Difference in GMTD from Cut-and-Blow (%)	Throwing Distance Geometric Standard Deviation	Replicates
Cut-and-blow	66.7	10.6_a	11.7_b	—	1.334_a	4
Cut-and-throw	63.3	11.9_b	9.9_c	–15	1.261_b	4
Exp. upcut/12 mm	64.3	10.8_a	12.2_a	4	1.271_b	4
LSD (P = 0.05)	3.1	0.4	0.1		0.024	

* Averages with different subscripts are statistically different at the 95% level.

In order to determine the relationship between energy requirements and countersurface relief, the spout and the shielding from the cutterhead housing were removed to avoid any friction that could add to the energy consumption of the experimental machine. The experiment was run with no countersurfaces and with countersurfaces at 3- and 6-mm relief. The experiment was conducted with two feed rates, the second double that of the first. The specific energy requirements increased with smaller countersurface relief (table 4). At the higher feed rate the difference in energy requirements from larger to smaller relief was greater than at the lower feed rate.

The effect of countersurface relief on throwing distance and energy requirements can be explained as follows. Initially, the first layers cut move down the knife until they contact the countersurface. With a continuing cutting action the space between countersurface and uncut material is filled with cut material. This material becomes compressed until the relief space is filled. Assuming that the cut material is not squeezed out between the countersurface and the uncut mat, the cutting of the remaining mat occurs by shearing of the already cut crop stems rather than the knife tip. The greater amount of uncut mat which is cut by stem-to-stem shearing adds to the greater energy consumption with smaller countersurface relief. Also, because the compression force acting on the cut mat must be higher with a smaller relief, greater energy consumption results.

Since the compression energy is stored in the cut mat as potential energy and released after complete cutting in the form of kinetic energy, the rebound effect of the compressed mat is much greater with a smaller countersurface relief. The greater spring effect improves

Table 3. Specific energy requirements for harvesting alfalfa in field tests with a 9-knife cutterhead at two countersurface relief settings

Machine Configuration/ Cutterhead Speed	Moisture Content (% w.b.)*	Mean Length-of-Cut (mm)	Moisture-adjusted Feed Rate (t/h)	Moisture-adjusted Specific Energy (MASE) (kWh/t)	Difference in MASE from Cut-and-Blow (%)	Replicates
			6-mm Countersurface Relief			
Cut-and-blow	49.7_a	8.1_a	$11.2a_b$	1.89_b	—	12
Cut-and-throw	52.9_b	9.0_b	10.3_a	1.67_c	−12	12
Exp. upcut / 1000 rev/min	64.7_d	10.1_c	11.9_b	1.55_d	−18	12
Exp. upcut / 1350 rev/min	62.5_c	8.4_a	10.6_a	2.02_a	7	12
LSD (P = 0.05)	1.7	0.5	1.2	0.10		
			3-mm Countersurface Relief			
Cut-and-blow	54.8_a	9.2_a	14.3_b	1.90_a	-	36
Exp. upcut / 1000 rev/min	59.2_b	11.1_b	13.2_a	1.67_b	−12	36
LSD (P = 0.05)	1.3	0.7	0.8	0.07		

* Averages with different subscripts are statistically different at the 95% level.

the release of the chopped material from the knife and is, therefore, beneficial for improving throwing distance. Because smaller relief allows only a small portion of the mat to be in contact with the knife, a greater portion of the mat can be thrown out immediately because the particle path is not disturbed by the knife. This effect also improves the particle release and results in a greater throwing distance for the smaller relief dimension.

Throwing Distance and Specific Energy Requirement with a 12-knife Cutterhead

The addition of throwing countersurfaces improved the throwing performance of the nine-knife cutterhead. However, the achieved energy savings did not reach earlier results of 30 to 34% less energy for the upward-cutting, cut-and-throw, forage harvester compared to a conventional cut-and-blow forage harvester (Shinners et al., 1991). There was also a contradictory result in that, while better throwing distance was achieved with smaller countersurface relief, greater energy requirements also resulted. The 12-knife cutterhead was an attempt to reach the desired energy savings while keeping the throwing distance comparable to that of a conventional cut-and-blow forage harvester. Changing the countersurface relief from 9 to 6 mm did not increase the throwing distance with the 12-knife cutterhead as it had with the 9-knife cutterhead (table 5). In this test, the upward-cutting cut-and-throw harvester threw 13% shorter than the cut-and-blow harvester. However, the upward-cutting cut-and-throw machine threw 8% farther than the conventional cut-and-throw machine. The test also showed that with a decrease of the countersurface relief the specific energy requirements increased (table 5). The experimental machine with a 9-mm relief required 23% less specific energy than the cut-and-blow machine and 22% less than the cut-and-throw machine. Also, the energy requirement increased slightly when the countersurface relief was reduced from 9 to 6 mm.

The 12-knife cutterhead with a 9-mm relief threw 5% farther than the 9-knife cutterhead with a 12-mm relief (table 5). The experimental machine with the 12-knife cutterhead threw the crop 11% shorter than the cut-and-blow machine. Compared to the conventional cut-and-throw machine, the experimental machine with the 12-knife cutterhead threw the crop 24% farther. The experimental harvester with the 12-knife cutterhead and 9-mm relief produced the greatest dispersion in the throwing distance (table 5).

Since the 12-knife cutterhead had a smaller relief than the 9-knife cutterhead, higher specific energy requirements might have been expected. However, the 12-knife cutterhead needed 6% less specific energy than the 9-knife cutterhead (table 5). By adding three knives and maintaining a constant feed rate and cutterhead speed, the amount of material per cut was decreased and, therefore, the energy needed to compress and shear the crop mat was less with the 12-knife cutterhead than with the 9-knife cutterhead. When several tests were combined and analyzed by two-way analysis of variance, the throwing distance of the experimental machine harvesting alfalfa with the 12-knife cutterhead was 11% less than that of the

Table 4. Cutting and throwing energy requirements for harvesting alfalfa with an upward cutting 9-knife cutterhead operating at 1000 rpm, shielding and spout removed

Countersurface Relief	Moisture Content (% w.b.)*	Moisture-adjusted Feed Rate (t/h)	Moisture-adjusted Specific Energy (MASE) (kWh/t)	Difference in MASE from No Countersurfaces (%)	Replicates
		Low Feed Rate			
No countersurfaces	57.3_a	11.6_a	1.30_c	—	4
6 mm	57.8_a	11.2_a	1.42_b	9	4
3 mm	57.0_a	11.4_a	1.47_a	13	4
LSD (P = 0.05)	1.0	0.5	0.03		
		High Feed Rate			
No countersurfaces	57.3_a	23.0_b	1.21_c	—	4
6 mm	57.8_a	21.8_a	1.49_b	23	4
3 mm	57.0_a	22.0_a	1.68_a	39	4
LSD (P = 0.05)	1.0	0.6	0.13		

* Averages with different subscripts are statistically different at the 95% level.

Table 5. Throwing distance and specific energy requirements with alfalfa and cutterhead operating at 1000 rpm

Machine Configuration/ Countersurface Relief	Moisture Content* (% w.b.)	Mean Length-of-Cut (mm)	Moisture-adjusted Feed Rate (t/h)	Geometric Mean Throwing Distance (GMTD) (m)	Difference in GMTD from Cut-and-Blow (%)	Throwing Distance Geometric Standard Deviation	Moisture-adjusted Specific Energy (MASE) (kWh/t)	Difference in MASE from Cut-and-Blow (%)	Replicates
12-knife Cutterhead with two Countersurface Reliefs									
Cut-and-blow	58.0_b	12.3_a	26.7_a	10.9_a	—	1.215_b	1.93_a	—	4
Cut-and-throw	57.3_b	12.2_a	27.2_a	8.8_c	–19	1.189_a	1.90_a	–2	4
12 knives / 9 mm	57.3_b	12.1_a	26.3_a	9.5_b	–13	1.240_c	1.49_c	–23	4
12 knives / 6 mm	54.7_a	12.8_a	27.5_a	9.5_b	–13	1.210_b	1.56_b	–19	4
LSD (P = 0.05)	0.9	1.0	1.6	0.2		0.015	0.06		
9-knife Cutterhead with 12-mm Relief and 12-knife Cutterhead with 9-mm Relief									
Cut-and-blow	71.0_a	12.6_a	24.5_a	10.3_a	—	1.171_a	1.61_a	—	4
Cut-and-throw	72.0_b	13.0_a	24.2_a	7.4_d	–28	1.176_a	1.39_b	–14	4
12 knives / 9 mm	72.0_b	13.9_a	23.7_a	9.2_b	–11	1.225_c	1.14_d	–29	4
9 knives / 12 mm	70.7_a	13.0_a	24.6_a	8.7_c	–16	1.191_b	1.21_c	–25	4
LSD (P = 0.05)	0.5	1.7	2.2	0.3		0.014	0.07		

* Averages with different subscripts are statistically different at the 95% level.

cut-and-blow harvester, but 12% farther than the conventional cut-and-throw harvester (table 6). The experimental machine reduced the specific energy required to harvest alfalfa by 24% compared to the cut-and-blow machine and by 17% compared to the cut-and-throw harvester (table 6).

When harvesting corn, the experimental machine with a 9-mm countersurface relief threw 14% shorter than the conventional cut-and-blow machine and 23% farther than the conventional cut-and-throw machine. Considering the specific energy requirements, the experimental machine needed 25% less specific energy than the conventional cut-and-blow machine and 20% less than the cut-and-throw machine (table 6).

The 12-knife cutterhead was also tested in two field tests with a countersurface relief of 9 mm and a cutterhead speed of 1000 rpm (table 7). The experimental upward-cutting, cut-and-throw, forage harvester needed 30% less specific energy than the conventional cut-and-blow forage harvester and 19% less than the conventional cut-and-throw harvester when harvesting alfalfa (table 7).

Table 6. Throwing distance and specific energy requirements with 12-knife cutterhead with 9-mm relief operating at 1000 rpm

Machine Configuration	Moisture Content* (% w.b.)	Mean Length-of-Cut (mm)	Moisture-adjusted Feed Rate (t/h)	Geometric Mean Throwing Distance (GMTD) (m)	Difference in GMTD from Cut-and-Blow (%)	Throwing Distance Geometric Standard Deviation	Moisture-adjusted Specific Energy (MASE) (kWh/t)	Difference in MASE from Cut-and-Blow (%)	Replicates
Alfalfa									
Cut-and-blow	59.6_a	11.8_a	26.0_a	10.4_a	—	1.193_a	1.78_a	—	9
Cut-and-throw	59.2_a	12.1_a	26.2_a	8.3_c	–20	1.183_a	1.63_b	–8	9
Exp. upcut	60.7_a	12.1_a	25.6_a	9.3_b	–11	1.215_b	1.36_c	–24	9
LSD (P = 0.05)	0.7	0.7	1.2	0.3		0.014	0.04		
Corn									
Cut-and-blow	63.3_a	12.1_a	24.1_a	12.5_a	—	1.334_b	1.81_a	—	4
Cut-and-throw	65.7_a	15.5_a	22.1_a	8.8_c	–30	1.261_a	1.69_b	–7	4
Exp. upcut	64.0_a	13.6_a	22.9_a	10.8_b	–14	1.271_a	1.35_c	–25	4
LSD (P = 0.05)	1.5	4.7	1.4	0.6		0.024	0.01		

* Averages with different subscripts are statistically different at the 95% level.

Table 7. Specific energy requirements for harvesting alfalfa, field tests, 9-mm countersurface relief, and 12-knife cutterhead operating at 1000 rpm

Machine Configuration	Moisture Content* (% w.b.)	Mean Length-of-Cut (mm)	Moisture-adjusted Feed Rate (t/h)	Moisture-adjusted Specific Energy (MASE) (kWh/t)	Difference in MASE from Cut-and-Blow (%)	Replicates
Cut-and-blow	60.5_a	10.7_a	17.3_a	2.00_a	—	12
Cut-and-throw	63.7_b	12.1_a	15.8_a	1.73_b	−14	12
Exp. upcut	64.8_b	11.5_a	15.9_a	1.40_c	−30	12
LSD (P = 0.05)	2.6	1.4	2.6	0.07		

* Averages with different subscripts are statistically different at the 95% level.

Effect of Air Velocity on Throwing Distance

Increasing the percent open area in the cutterhead housing created greater air velocity and improved throwing performance with the nine-knife cutterhead (table 8). The maximum air velocity achieved by the nine-knife cutterhead with countersurfaces was 11% greater than the maximum achieved with the previous cutterhead design (Shinners et al., 1991).

Air velocity decreased as the open area around the circumference of the 12-knife cutterhead was reduced by the addition of more components (18.6 m/s without knives or countersurfaces, 13.2 m/s with knives and countersurfaces). The circumferential open area was approximately 36 and 12% for the 9- and 12-knife cutterhead, respectively, whereas air velocity was 21.5 and 13.2 m/s for the 9- and 12-knife cutterhead, respectively. This reduction in air velocity was probably due in great part to the reduction in circumferential open area. The addition of openings in the cutterhead discs and the radial air pumping paddles with the 12-knife cutterhead did have a significant effect on the air velocity. Closing the openings in the sides of the cutterhead discs reduced the air velocity by 31% (13.2 m/s with disks open, 9.1 m/s with disks closed).

The maximum achieved air speed of 22.1 m/s was less than the 31.8 m/s tip speed of the cutterhead knifes. It was evident that air movement inside the cutterhead and through the spout, even at speeds lower than the tip speed of the knives, helped to support the crop stream and improve the throwing performance. It is probable that the air movement reduces the rate of deceleration of the crop stream by reducing the magnitude of air drag on the cut particles.

Table 8. Throwing distance and air velocity in spout with alfalfa, 9-knife cutterhead, no countersurfaces, with several size openings in the cutterhead housing

Machine Configuration/ Open Area	Air Velocity in Spout (m/s)	Geometric Mean Throwing Distance (GMTD) (m)	Difference in GMTD from Cut-and-Blow (%)
Cut-and-blow	22.7	6.0	—
Exp. upcut/ 0%	8.6	3.9	−35
Exp. upcut/ 23%	Data not available	5.2	−13
Exp. upcut/ 32%	21.5	5.6	−7

Note: Because only one replicate was conducted, no statistical analysis was possible.

Comparison of Throwing Distance with Earlier Research

The research reported here used the same conventional cut-and-throw and the cut-and-blow harvesters as used by Shinners et al. (1991). The experimental upward-cutting harvester was used with the exception of the countersurface throwing aids and cutterhead housing modifications described earlier. The use of these constant base machines allows a comparison of throwing distance improvement. Without throwing countersurfaces and cutterhead housing modifications, the experimental harvester with the nine knife cutterhead threw 27% shorter than the cut-and-blow harvester and 20% shorter than the conventional cut-and-throw harvester (table 9). With the addition of countersurfaces and greater air inlet area, the experimental harvester with the nine-knife cutterhead and 9-mm relief threw only 4% shorter than the cut-and-blow machine and 11% farther than the conventional cut-and-throw machine. The throwing distance with the 12-knife cutterhead and 9-mm relief was 11% shorter than the one achieved with the cut-and-blow machine and 12% farther than with the conventional cut-and-throw machine.

The 9-knife cutterhead with 9-mm countersurface relief produced a geometric mean throwing distance closer to that of the cut-and-blow harvester than the 12-knife cutterhead with a similar relief. It was felt that this result was due in great part to the 39% reduction in air velocity from the 9- to the 12-knife cutterhead. Increasing the diameter of the 12-knife cutterhead to create a circumferential open area similar to that of the 9-knife cutterhead would probably result in a higher air velocity to support the crop stream through the spout. Increasing the air velocity in this manner to a level similar to that of the 9-knife cutterhead probably would improve the throwing performance of the 12-knife cutterhead to throwing distances similar to that of a cut-and-blow machine while maintaining the achieved specific energy savings of 25 to 30%.

Conclusions

- Increasing the open area in the sides of the cutterhead housing improved the throwing performance by increasing the air velocity with the 9-knife cutterhead.
- The 9-knife cutterhead created greater air velocity in the spout than the 12-knife cutterhead (21.5 vs. 13.2 m/s, respectively) due to greater circumferential open area (36 vs. 12%, respectively).
- Throwing countersurfaces mounted perpendicular and inboard to the knife improved the throwing performance by facilitating rebound and improving release of the crop from the cutterhead, both of which helped to create a concentrated crop stream from the machine.
- A smaller relief dimension from the countersurface to the knife tip increased throwing distance by improving crop release and creating greater rebound. However, a smaller relief also increased specific energy requirements by increasing cutting and compression energy.
- With a 9-mm relief, the 9- and 12-knife cutterheads produced a mean throwing distance 4 and 11% shorter, respectively, than a cut-and-blow harvester

Table 9. Average throwing distances with alfalfa, 9-knife cutterhead without countersurfaces, 9-knife cutterhead with countersurfaces at 9-mm relief and 12-knife cutterhead with countersurfaces at 9-mm relief, all operating at 1000 rpm

	1990* Upcut Harvester 9-knife Cutterhead No Countersurfaces		1992 Upcut Harvester 9-knife Cutterhead With Countersurfaces – 9 mm Relief		1993 Upcut Harvester 12-knife Cutterhead With Countersurfaces – 9 mm Relief	
Machine Configuration	Geometric Mean Throwing Distance (GMTD) (m)	Difference in GMTD from Cut-and-Blow (%)	Geometric Mean Throwing Distance (GMTD) (m)	Difference in GMTD from Cut-and-Blow (%)	Geometric Mean Throwing Distance (GMTD) (m)	Difference in GMTD from Cut-and-Blow (%)
Cut-and-blow	7.7	-	8.3	-	10.4	-
Cut-and-throw	7.0	-9	7.2	-13	8.3	-20
Exp. upcut	5.6	-27	8.0	-4	9.3	-11

* After Shinners et al., 1991.

when harvesting alfalfa (8.0 vs. 8.3 m and 9.3 vs. 10.4 m, respectively). With a 9-mm relief, the 9- and 12-knife cutterheads produced a mean throwing distance 6 and 14% shorter, respectively, than a cut-and-blow harvester when harvesting corn (10.0 vs. 10.6 m and 10.8 vs. 12.5 m, respectively). The 9-knife cutterhead produced a throwing distance closer to that of the cut-and-blow harvester than the 12-knife cutterhead due to greater air velocity in the spout.

- With a 9-mm relief, the 9- and 12-knife cutterheads reduced specific energy requirements by 21 and 24%, respectively, compared to a cut-and-blow harvester when harvesting alfalfa (1.30 vs. 1.65 kWh/t and 1.36 vs. 1.78 kWh/t, respectively). With a 9-mm relief, the 9- and 12-knife cutterheads reduced specific energy requirements 14 and 25%, respectively, compared to a cut-and-blow harvester when harvesting corn (1.46 vs. 1.70 kWh/t and 1.35 vs. 1.81 kWh/t, respectively). The 12-knife cutterhead produced greater specific energy reductions compared to the cut-and-blow harvester than the 9-knife cutterhead due to lower peak cutting and mat compression loads.

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