FORAGE HARVESTER ORIENTATION MECHANISM TO REDUCE PARTICLE SIZE VARIATION

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ABSTRACT. *A third set of feed rolls, one of which contains a cam-actuated combing mechanism, was placed between the normal feed rolls and the cutterhead of an experimental forage harvester. This mechanism was intended to orientate stems of forage, such as alfalfa, before being commutated by the cutterhead and thereby reduce particle size variation. When the 1:1 combing ratio was used as a control, the combing mechanism reduced the percent longs, shortened the geometric mean length, and lowered the geometric standard deviation of the particle size distribution. Increasing the combing ratio was beneficial up to the limit of 3:1. The percent longs were reduced by up to 48%, the geometric mean length was reduced by up to 29%, and the geometric standard deviation was reduced by up to 15% with a combing ratio of 3:1. However, the control forage harvesters consistently produced chopped material with fewer percent longs, shorter geometric mean length, and lower geometric standard deviation than the experimental machine. This may have been at least partially due to non-uniform feeding from the pick-up of the experimental machine. Net specific energy requirements of the combing mechanism and clean-off roll were less than 0.24 kWh/t.* ***Keywords.*** *Forage harvesters, Combining mechanism.*

With the forage harvester and its complementary equipment, silage production can be almost completely mechanized. The chief objective in chopping material to be stored as silage is to reduce the materials to lengths that can be handled by an impeller-blower and moved in a pipe along with an air stream. With silage, additional important reasons for chopping are to facilitate packing for exclusion of air, to facilitate removal from the silo, to make feeding easier, and to improve digestibility (Kepner et al., 1978).

In many cases the high power requirement of the forage harvester dictates the size of the power unit which must be available for forage production. This may significantly influence capital costs as well as energy costs.

The energy breakdown of a cylinder-type forage harvester has been divided as 40% for the cutterhead, 40% for conveying by the blower, and 20% for the pick-up and drive train (Blevins and Hansen, 1956; O'Dogherty, 1982; Persson, 1987). Shinners et al. (1991) modified a cut-and-throw harvester by reversing the direction of rotation of the cutterhead such that the knives entered the mat of incoming material from below and directly threw the material from the cutterhead, thus eliminating the need for a blower. This modification reduced specific energy requirements by 25 and 34% compared to conventional cut-and-throw and cut-and-blow configurations, respectively.

If the auxiliary blower can be eliminated, the cutterhead is the machine component which requires the majority of the energy and thus requires research for further energy reduction. The energy consumed by the cutterhead can be divided into the following categories (Okokon and Finner, 1983): (1) shearing the incoming mat of forage, (2) acceleration of the chopped forage to the speed of the knives, (3) recompression of the forage mat with each knife pass, (4) friction of the forage with the housing, and (5) air movement. Kraus (1989) estimated that these factors could be divided as follows: (a) shearing – 22%, (b) acceleration – 21%, (c) recompression – 21%, (d) friction – 26%, and (e) air pumping – 10%.

One method to reduce the energy requirement of the cutterhead is to increase the theoretical length-of-cut. This reduces the recompression and shearing energies because the material is sheared less often.

To increase the theoretical length-of-cut, the variance of the chopped length must be considered, which ultimately affects the ability of the material to be conveyed and properly stored. Typically, the theoretical length-of-cut (TLC) is set such that the mean actual length-of-cut (ALC) is small enough for the material to be conveyed with an air stream and also provide good packing and unloading characteristics in storage. The TLC is usually 33% less than the ALC (O'Dogherty, 1982). This means that the forage is being cut more often than necessary for good conveying or storage properties. If the ALC were to approach the TLC, the TLC could be reset to a greater length thus reducing the energy required by the cutterhead.

Forages, such as alfalfa, can enter the cutterhead disoriented. The stems can enter perpendicular to the axis of the cutterhead, parallel to the axis, or at any angle in-

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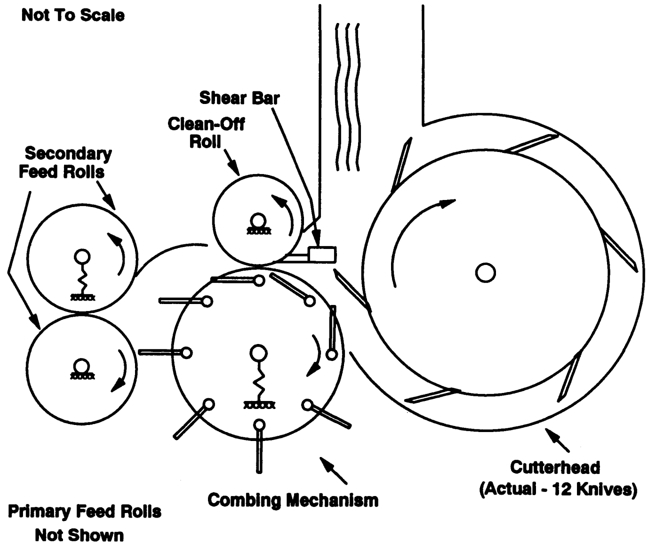

Figure 1–Experimental combing mechanism with upward cutting cutterhead.

between. This results in the ALC longer than the TLC. Although there have been efforts to reduce the ALC by the use of recutter screens, this is very energy intensive. There is a need to reduce the randomness of forage stem orientation as forage enters the cutterhead such that the ALC approaches the TLC. An orientation process is one approach which might allow for a longer TLC without unacceptable long lengths in the final chopped material.

The overall objective of this research was to develop and evaluate a mechanism for orientating forages, such as alfalfa, in order to obtain a smaller chop length variation. The specific objectives were: (1) to develop and fabricate a system for orientating forage before a forage harvester cutterhead, including a feedroll assembly, a combing mechanism, and an upward cutting cutterhead assembly; and (2) to evaluate the performance of the system in terms of mean particle size, particle size distribution, and specific energy requirements.

MACHINE DESCRIPTION

A combing mechanism and associated clean-off roll was designed to be placed between the feed rolls and cutterhead of a forage harvester (fig. 1). The combing mechanism had eight tine bars with two to three tines per bar. Each bar was cam actuated in order to facilitate retraction of the tines from the forage such that wrapping would be prevented. The mechanism had a width of 520 mm, a maximum tine path diameter of 370 mm, and a tine diameter of 10 mm. The cross bars were allowed to pivot so the tines would exit the mat of material in a vertical fashion similar to the tines of a mower-conditioner reel or the pick-up tines of a windrow pick-up. A cam and follower mechanism was used to turn the tine bars. A coil spring was used to retract the tines after they passed through the mat of forage, and to resist the centrifugal force which tended to lift the follower off the cam. Attached to the cam was a timing arm, which allowed the position at which the tines exited the material to be changed by rotating the cam relative to the tine bars.

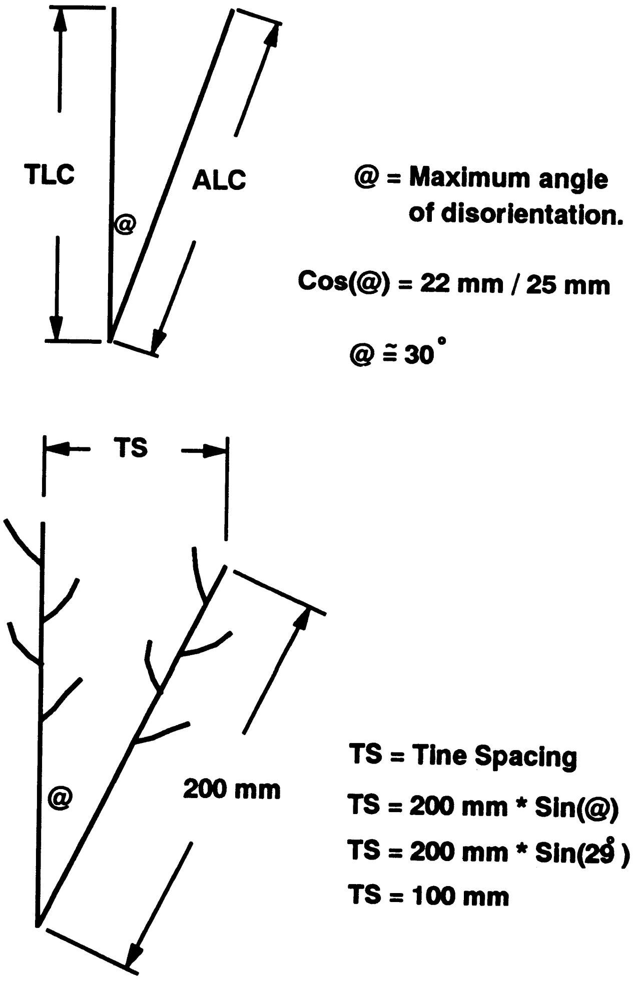

Figure 2–Analysis conducted to determine tine spacing.

The combing mechanism was designed to orient the forage stems by having the tines rake through the forage while the material was pinched between the secondary feed rolls. Once the material traveled far enough to become "disengaged" from the feed rolls, the combing mechanism, in conjunction with the clean-off roll, conveyed the orientated material into the cutterhead. In order to achieve a high degree of orientation, a large number of tines could be used. However, it was felt that the power required to orientate the material might be directly proportional to the number of tines used. In order to determine the maximum allowable tine spacing, some assumptions were made. It was assumed that a 25-mm length-of-cut was the maximum that could be easily moved by an impeller blower, facilitate packing in the silo, and not lead to problems unloading the silo. Another assumption was that the TLC could be set to 22 mm without obtaining unacceptable amounts of material longer than the 25 mm maximum. It was assumed for the analysis that the average straight length of an alfalfa stem was 200 mm. Figure 2 provides an analysis of the tine spacing. From the analysis, it was found that the maximum tine spacing was approximately 100 mm. However, the tines were placed 200 mm apart on each of the tine bars and staggered to give a lateral spacing of 100 mm between adjacent tine bars. The combing mechanism was covered

Table 1. Cutterhead specifications for field-going forage harvester

Diameter (mm)	Width (mm)	Number of Knives	Speed (rev / min)
710	520	12	956

Table 2. Combing mechanism specifications for field-going forage harvester

Roll Diameter (mm)	Tine Path Diameter (mm)	Width (mm)	Speed for TLC = 27 mm (rev / min)	Speed for TLC = 17 mm (rev / min)
280	370	520	360	226

Table 3. Clean-off roll specifications for field-going forage harvester

Diameter (mm)	Width (mm)	Speed for TLC = 27 mm (rev / min)	Speed for TLC = 17 mm (rev / min)
140	520	720	452

Table 4. Secondary feed roll specifications for field-going forage harvester

	TLC = 27 mm	TLC = 17 mm
Diameter (mm)	155	
Width (mm)	480	
Speed for combing ratio of 1:1 (rev / min)	645	405
Speed for combing ratio of 1.5:1 (rev / min)	430	270
Speed for combing ratio of 2:1 (rev / min)	323	203
Speed for combing ratio of 3:1 (rev / min)	215	135
Speed for combing ratio of 4:1 (rev / min)	161	101

with a housing to keep material out of the mechanism and to allow a clean-off roll to run against the combing mechanism.

The combing mechanism and associated clean-off roll were originally placed between the feed rolls and a cutterhead in a stationary test stand. The feed rolls, input feed apron, feed roll gear box, and cutterhead were taken from a Fox Model SPF forage harvester. The feed roll gear box had three gear ranges available and was incorporated to provide easy changes in feed roll speed which resulted in different combing ratios. The combing ratio was defined as the linear speed of the tine tips divided by the linear speed of the material as it exited the secondary feed rolls.

Using the knowledge gained with the test stand during initial testing, the orientating mechanism was then integrated into a Fox Model IF546 field-going forage harvester. The experimental machine was designed to use an upward cutting cut-and-throw cutterhead, the subject of previous research (Shinners et al., 1991). On this machine, the clean-off roll was fixed and the combing mechanism was allowed to float in order to accommodate different mat thicknesses. The speed of the combing mechanism and clean-off roll relative to the speed of the cutterhead was assumed to dictate the TLC. Tables 1 through 4 provide pertinent information concerning the machine components.

PROCEDURE

STATIONARY TEST STAND

The forage used in this part of the research consisted of fresh third cutting alfalfa. The test stand was fed by placing randomly oriented forage on the test stand feed apron or on an elevator which fed the feed apron. The feed rates for these initial tests averaged 2.0 t/h. The chopped forage was thrown onto the floor by the cutterhead, then swept together, mixed thoroughly, and sampled for measurement of particle size and moisture. A stationary feed roll and cutterhead assembly with machine components similar to the experimental test stand, except for the combing mechanism and clean-off roll, was used as a control. Four replicates were conducted with the stationary test stand. Combing ratios of 1, 2.2, 3, and 4.6:1 were used, along with the control, for a total of five experimental conditions. A 9.5-mm TLC was used for all tests.

Particle size was determined for three sub-samples per experimental condition with the sample mass ranging from 300 to 700 g. The particle size analysis was conducted in accordance with ASAE Standard S424 (*ASAE Standards*, 1991). Moisture content was determined for each trial by drying a 100-g sample in a 103° C oven for 24 h in accordance with ASAE Standard S358.2 (*ASAE Standards*, 1991).

Power requirements of the combing mechanism and clean-off roll were determined using the experimental test stand. A torque transducer was placed in the drive line between the combing mechanism and the power source. Torque and speed measurements were taken at a frequency of 10 Hz. An average for both torque and speed were recorded for each trial. These measurements, along with the start and end time of each trial were recorded with a Campbell Scientific 21X datalogger. Four replications were conducted at combing ratios of 1, 2.2, 3, and 4.6:1. Fourth cutting alfalfa was placed on an elevator in a randomly oriented fashion such that the elevator fed the material onto the test stand's feed apron at a feedrate of approximately 3.2 t/h.

FIELD-GOING MACHINE

The field-going machine was first tested in the laboratory. Forage used in this part of the research consisted of wilted second cutting alfalfa. The material was cut by a sickle-type mower-conditioner and placed in a windrow. The wilted material was collected by hand. The forage harvester was fed by placing a given amount of material on an elevator in a randomly oriented fashion. The elevator conveyed material onto the feed apron of the forage harvester at an average feed rate of 6.8 t/h. For each trial, the chopped material was thrown onto a tarp, swept up, and placed in plastic bags. After all trials were completed, the bags of chopped forage were emptied and thoroughly mixed. Particle size of six sub-samples per experimental condition was determined with the mass of each sub-sample between 300 and 1000 g. Particle size analysis was done in accordance with ASAE Standard S424 (*ASAE Standards*, 1991). Moisture content was determined by drying a 100-g sample per trial in a 103° C oven for 24 h in accordance with ASAE Standard S358.2 (*ASAE Standards*, 1991). A stationary feed roll and cutterhead assembly, without a combing mechanism and clean-off roll, was used as a control. Combing ratios of 1, 2, 3, and 4:1 were used, along with the control, for a total of five experimental conditions. Six replicates per

Table 5. Geometric mean length (GML) of alfalfa particles from stationary test stand

Experimental Conditions		GML (mm)
Combing ratio – 1.0:1		17.4 a
– 2.2:1		17.9 a
– 3.0:1		15.6 b
– 4.6:1		17.8 a
Control		16.9 a
LSD (P = 0.05)		1.2
TLC – 9.5 mm	Number of observations – 12	

* Averages with different suffixes are significantly different at the 95% level.

Table 6. Geometric mean length (GML), percent longs (PL), and geometric standard deviation (GSD) of alfalfa particles from field-going forage harvester in laboratory tests

Experimental Conditions	GML (mm)	PL (%)	GSD
Combing ratio – 1.0:1	26.8 a	40.6 a*	2.97 a
– 2.0:1	24.6 b	38.5 a	2.77 b
– 3.0:1	22.5 c	34.6 b	2.81 b
– 4.0:1	22.6 c	34.4 b	2.80 b
Control	20.6 d	26.4 c	2.75 b
LSD (P = 0.05)	1.6	3.5	0.10
TLC – 27 mm	Number of observations – 30		

* Averages with different suffixes are significantly different at the 95% level.

experimental condition were conducted. A 27 mm TLC was used for all trials.

After the experimental machine had undergone preliminary tests, it was taken to the University of Wisconsin West Madison Agricultural Research Station for field trials. Two other forage harvesters were used for comparison during the field trials. One was a pull-type cut-and-blow forage harvester, and the other forage harvester was a modified cut-and-throw harvester described by Shinners et al. (1991). All three forage harvesters were operated with the TLC of 17 mm.

Either third or fourth cutting alfalfa was used. The combing ratios used were 1, 1.5, 2, and 3:1 and 1, 1.5, and 3:1 for third and fourth cutting, respectively. Three and five replicates per experimental condition were conducted for third and fourth cutting, respectively. The crop was cut by a sickle-type mower-conditioner, placed in windrows, allowed to wilt for one day, and then harvested after the dew was gone the next day. At times, raking two or four windrows together was required to have sufficient feed rate. The feed rates used were 8.6 and 12.3 t/h for third and fourth cutting, respectively. Each trial ranged from approximately 30 to 90 m in length. The chopped material was blown into a container placed on a trailer behind the forage harvester. The total mass of the material harvested for each trial ranged from 113 to 386 kg.

A sub-sample of material was collected after each trial. From each of these sub-samples, six particle-size sub-samples and three moisture sub-samples were taken. The procedures for moisture and particle size measurement were as previously described.

Experiments were also conducted to determine the overall power requirement of the experimental machine. Fourth cutting alfalfa was cut by a sickle-type mower-conditioner, placed in windrows, allowed to wilt for one day, raked, and then harvested after the dew was gone the next day. Combing ratios of 1, 1.5, and 3:1 were used, along with the two control forage harvesters, for five experimental conditions. Performance of the forage harvesters was quantified by pto torque, pto speed, and material feed rate. The first two parameters were measured and recorded with a torque transducer and a datalogger at a frequency of 10 Hz. The torque transducer was placed between the tractor and the harvester so that total machine power could be calculated. The machine feed rate was determined by weighing the quantity of forage chopped during a trial and dividing by trial time. Elapsed time was recorded by the datalogger. Machine specific energy was calculated by dividing the required power by the feed rate. In order to decrease data scatter due to differences in crop moisture between trials, the machine specific energy and feed rate were adjusted using moisture compensation equations as outlined in ASAE Engineering Practice EP502 (*ASAE Standards*, 1991).

Initially, the performance of the combing mechanism was quantified only by the geometric mean length (GML). During a later experiment, the performance was also quantified by the geometric standard deviation (GSD) and percent of total material remaining on the top screen of the particle size separator, defined here as percent longs (PL).

Statistical analysis was conducted using a two-way analysis of variance where the effects of replicates conducted on different days with different feed rates were removed by blocking. The least significant difference (LSD) presented in the tables indicates a 5% probability of no significant difference.

RESULTS

Initial experiments with the stationary test stand indicated that the combing mechanism could produce a geometric mean length closer to the TLC (table 5). At a combing ratio of 3:1, the geometric mean length was 8% less than that with the control system. However, combing ratios of 2.2 and 4.6:1 did not produce a lower geometric mean length than the control system. Feed rates used in this portion of the research were low (2 t/h) which may have attributed to the inconsistent results. With low feed rates, there appeared to be insufficient clamping force on the mat of material between the secondary feed rolls. This allowed the combing mechanism to pull stems free from the pinch point rather than orienting the stems.

Laboratory tests with the field-going experimental forage harvester indicated that the control system produced less percent longs and a shorter geometric mean length than the experimental harvester (table 6). This might be attributed to cutterhead and knife differences between the control and experimental harvesters. Also, the experimental machine used the upward cutting cutterhead configuration while the control used the conventional downward cutting configuration which may have partially attributed to this result.

If the 1:1 combing ratio was considered the control, since no combing took place with this ratio, the combing mechanism reduced the percent longs, shortened the geometric mean length, and lowered the geometric standard deviation. The 3:1 and 4:1 combing ratios produced about the same level of performance, suggesting a practical limit for the combing ratio might lie between the 2.2:1 and the 3:1 ratios.

When the machines were tested under field conditions, the control harvesters produced chopped material with lower percent longs, shorter geometric mean length, and

Table 7. Geometric mean length (GML), percent longs (PL), and geometric standard deviation (GSD) of alfalfa particles from field-going forage harvester tests with third cutting alfalfa

Experimental Conditions	GML (mm)	PL (%)	GSD
Combing ratio – 1.0:1	16.6 a *	23.2 a	2.92 a
– 1.5:1	14.8 b	18.1 b	2.64 b
– 2.0:1	13.8 b	14.8 bc	2.67 b
– 3.0:1	14.7 b	17.4 b	2.60 b
Control - 1	13.7 bc	13.3 c	2.62 b
Control - 2	11.7 d	8.6 d	2.39 c
LSD (P = 0.05)	1.0	2.6	0.08
TLC – 17 mm	Number of observations – 18		

* Averages with different suffixes are significantly different at the 95% level.

lower geometric standard deviation than the experimental harvester (tables 7 and 8). This again might be attributed to design differences between the three machines. For instance, knife design, cutterhead speed, feed roll gripping force, etc., were all different for the three machines. Also, the geometric mean length was shorter than the TLC for the control harvesters. No explanation could be found for this unusual result.

Using the 1:1 combing ratio as the control, the combing mechanism reduced the percent longs, shortened the geometric mean length, and lowered the geometric standard deviation. Increasing the combing ratio appeared to be beneficial up to the limit of 3:1. The percent longs were reduced by up to 48%, the geometric mean length was reduced by up to 29%, and the geometric standard deviation was reduced by up to 15% for the fourth cutting (table 8).

During all trials with the experimental harvester, the cutterhead, combing mechanism, and clean-off roll rotational speeds were kept constant for a given TLC. The speed of the primary and secondary feed rolls were changed to obtain different combing ratios, with higher ratios coming from slower feed roll speeds. It was assumed that the speed of the combing mechanism and the clean-off roll relative to the cutterhead speed controlled the TLC. One explanation considered to explain the results was that possibly the speed of the secondary feed rolls at least partially controlled the TLC and that the slower speeds of these feed rolls used for the higher combing ratios actually reduced the TLC. If this were true, then the reduced percent longs and shorter geometric mean length produced by the use of the combing mechanism might at least be partially due to this phenomenon. However, it is believed that the geometric standard deviation, which is an index of the spread of the particle size distribution, would be unaffected by changes in the TLC.

Table 8. Geometric mean length (GML), percent longs (PL), and geometric standard deviation (GSD) of alfalfa particles from field-going forage harvester tests with fourth cutting alfalfa

Experimental Conditions	GML (mm)	PL (%)	GSD
Combing ratio – 1.0:1	18.8 a*	27.4 a	3.04 a
– 1.5:1	16.6 b	21.2 b	2.79 b
– 3.0:1	13.3 c	14.2 c	2.57 c
Control – 1	12.0 d	11.7 d	2.62 c
Control – 2	11.5 d	10.3 d	2.54 d
LSD (P = 0.05)	0.5	1.4	0.05
TLC – 17 mm	Number of observations – 30		

* Averages with different suffixes are significantly different at the 95% level.

Table 9. Energy requirements of combing mechanism and clean-off roll for the stationary test stand

Combing Ratio	Gross Specific Energy (kWh / t)	Net Specific Energy (kWh / t)
1.0:1	0.14 a*	0.05 a
2.2:1	0.25 b	0.13 b
3.0:1	0.38 c	0.24c
4.6:1	0.51 d	0.14 b
LSD (P = 0.05)	0.02	0.05

* Averages with different suffixes are significantly different at the 95% level.

For the speed of the secondary feed rolls to have at least partially dictated the TLC, two events would have had to occur. First, the mat of material would have had to slip at the combing mechanism/clean-off roll pinch point. If slippage did occur here, it was believed that feeding and drivetrain problems would have occurred. However, feeding and drivetrain problems did not exist during these trials. Second, the crop length would have had to have been considerably longer than the distance from the secondary feed roll pinch point to the shear bar. This distance was 430 mm on the field-going machine. Because many of the tests reported here were conducted using third or fourth cutting alfalfa, it was felt that the crop length was less than this distance. Therefore, it was felt that the assumption that the speed of the combing mechanism and clean-off roll relative to the cutterhead speed dictated the TLC was valid and the reduction in the particle size parameters was due to the orientation produced by the combing mechanism.

Net specific energy requirements (gross power - empty power) of the combing mechanism and the clean-off roll increased with combing ratio (table 9). A combing ratio of 3:1 required about five times the net specific energy of that required for a combing ratio of 1:1. Total machine specific energy for the experimental forage harvester was similar for 1:1 and 3:1 combing ratios, but less for the 1.5:1 combing ratio (table 10). The gross specific energy requirements at the 1.5:1 combing ratio was similar to that of the upward cutting control (2) harvester.

Observations in field tests indicated that the pick-up and feed apron mechanisms of the experimental harvester did not result in uniform flow of forage into the feed rolls. Rather, material would build-up at the interface between the pick-up and the feed apron until the feed rolls grabbed the mass and fed it to the combing mechanism. This occurred at slow feed roll speeds associated with high combing ratios. It is believed that at least part of the reason that the experimental machine did not produce the same level of particle size distribution as the control harvesters

Table 10. Moisture adjusted total machine energy requirements for the field-going experimental forage harvester and the control forage harvesters

Experimental Conditions	Feed Rate (t / h)	Gross Specific Energy (kWh / t)	Moisture Content (% wet basis)
Ratio – 1.0:1	13.1 a*	1.55 a	62.6
Ratio – 1.5:1	14.1 a	1.40 b	63.2
Ratio – 3.0:1	12.7 a	1.53 ab	62.1
Control – 1	15.0 a	1.71 c	61.0
Control – 2	12.4 a	1.42 b	56.6
LSD (P = 0.05)	4.3	0.14	

* Averages with different suffixes are significantly different at the 95% level.

was due to the non-uniform manner in which this harvester was fed. Plans are under way to modify the pick-up and feed roll mechanisms on this machine. This modification will include utilization of: (a) a pick-up with auger feed fingers, (b) a feed roll assembly that does not include a feed apron, and (c) stronger feed roll springs. These modifications should improve the feeding characteristics thereby improving crop orientation.

CONCLUSIONS

- When the 1:1 combing ratio was used as a control, the combing mechanism reduced the percent longs, shortened the geometric mean length and lowered the geometric standard deviation of the particle size distribution.
- Increasing the combing ratio was beneficial up to the limit of 3:1. The percent longs were reduced by up to 48%, the geometric mean length was reduced by up to 29%, and the geometric standard deviation was reduced by up to 15% with a combing ratio of 3:1.
- The control forage harvesters consistently produced chopped material with fewer percent longs, shorter geometric mean length, and lower geometric standard deviation than the experimental machine.
- Net specific energy requirements of the combing mechanism and clean-off roll were less than 0.24 kWh/t with the stationary test stand. The combing mechanism had no significant effect on gross energy requirements with the field-going experimental harvester.

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