3-2002

A Reduced–Cost Mechanized System for Handling and Curing Mechanically–Harvested Burley Tobacco

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Abstract. *An experimental system was tested in which mechanically harvested burley tobacco plants placed onto steel slotted receivers were retrieved from a field, transported to a field curing structure, and placed onto the structure for air curing by a single worker. The system consisted of a tractor–towed, trailer mechanism that engaged and hoisted loads of approximately 360 burley plants of approximately 1 Mg mass. Ten slotted steel rails, 3.05 m long, holding 36 notched plants were placed onto parallel wooden beams suspended at a height of 2.13 m by wooden posts set in the ground. Burley tobacco was cured in this configuration covered by polyethylene.*

Time–and–motion experiments showed that the system could retrieve tobacco from the field and place it onto a curing structure adjacent to the field at the rate of 0.1 to 0.18 ha/h. Replicated experiments also showed that the system operated with negligible leaf loss due to handling. Finally, experimental results showed that leaf grade index decreased with time that filled tobacco rails were left lying on the ground after being harvested and prior to being retrieved. This study further indicated that the estimated cost of the proposed harvesting system compares favorably with systems that require several manual laborers.

Keywords. *Burley tobacco, Mechanical harvesting, Field curing structures*

Harvesting burley tobacco has remained a labor–intensive process since colonial days. Mature plants, approximately 2 m tall and 3 kg mass, are impaled onto wooden sticks and hung in barns or other structures for air curing. Various mechanisms have been developed in recent years to reduce or eliminate manual operations in burley harvesting. Some have received limited acceptance by growers, but their impact has been marginal.

Burley tobacco production is controlled by a system in which landowners are assigned quotas. This climate of limited production, along with the availability of migrant workers for harvesting, has resulted in very little incentive for growers to invest in mechanical harvesting systems. However, consolidation of production quotas to fewer growers and rising labor wages may yet provide a climate for adoption of the most cost–effective mechanical harvesting systems.

To that end, the work described in this article was initiated. Our major goal was to adapt essential mechanical components of a fully automated, high capacity harvesting system developed and tested by Wells et al. (1990a, b) in a medium capacity system that uses inexpensive field curing structures. The objectives of this study were: to design, fabricate, and test a mechanism for retrieving slotted steel rails filled with notched burley plants and placing them onto field curing structures with one worker; to evaluate various retrieval scenarios with regard to quality of cured leaf; and, to estimate and evaluate the cost of the proposed system in comparison with other harvesting systems.

Review of Literature

Conventional harvesting of burley tobacco consists of laborers cutting plants at their base and impaling them onto a 1.5–m wooden stick. Once five to six tobacco plants are impaled on a stick, the stick is laid in the field, with the leaf tips lying northward, for two to three days for wilting and corresponding weight loss. Tobacco is then picked up from the ground, loaded onto wagons, and transported to traditional curing barns. Inside a barn, the sticks of tobacco are lifted up and hung on tier rails and air curing is complete in six to eight weeks.

Conventional cutting and housing of burley tobacco can be considered as separate operations. It takes 65 worker h/ha to cut tobacco and 92 worker h/ha to move it from fields to curing barns (Nutt et al., 1990). Thus, 157 strenuous labor hours are required to harvest a hectare of tobacco.

Engineers have tried to overcome the hardships of harvesting burley tobacco by developing mechanical systems to transport and house tobacco. Yoder and Henson (1974) developed a system in which one worker operated a front–end tractor loader to move portable curing frames filled with conventional sticks from the field to a specially–modi-

Article was submitted for review in April 2001; approved for publication by the Power & Machinery Division of ASAE in December 2001.

The work reported in this article (no. 01–05–4) was conducted by the Kentucky Agricultural Experiment Station and was supported by a grant from Philip Morris USA. Mention of trade names does not necessarily imply endorsement by the Kentucky Agricultural Experiment Station.

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  ISSN 0883–8542

fied open–interior curing barn in which the frames were stacked. Curing frames were constructed of wood or steel and could be stacked two or three high in a curing barn. The combined cost of these frames and open–interior barns was higher than that of conventional curing barns.

Transportation of the frames to a barn was accomplished by placing the frames on standard flatbed wagons using a tractor–mounted front–end loader. The frames were then moved to barns and unloaded by the same tractor. This process was very efficient with the relocation of tobacco plants occurring just after being cut in the field. However, the time required to transport and place the empty frames in the field was a detriment to farmer adoption of this system. Also, the frames had to be stored in curing barns when empty, precluding the use of barns for other storage purposes.

Mechanical harvesting aids have been developed to cut and place tobacco plants in the field on traditional sticks of nominal dimension of $4 \times 4 \times 100$ cm. Casada et al. (1972) developed one of the first mechanical stick harvesting mechanisms that involved a machine cutting and placing tobacco plants onto sticks. A more recent mechanism that harvested in this manner was Duncan's floating spear mechanism (Duncan et al., 1999). This mechanism cut and conveyed plants up a conveyor and impaled them on a floating spear. Traditional sticks positioned at the end of the floating spear received impaled plants pushed from the spear by a conveyor. Once a stick was filled, it was released from the mechanism and placed on the ground.

Mechanical aids have also been designed to accommodate farmers in the transporting and housing of the traditional stick tobacco as well. Duncan's cable hoist system was developed to hoist rails of tobacco that held traditional sticks into a barn (Duncan et al., 1996). This one–person system utilized specially designed trailers, rails, and barns to house burley tobacco.

Casada et al. (1987) developed a harvesting system that also used portable frames to cure tobacco. A tractor–drawn harvester was developed to notch, cut, and convey plants to a platform towed behind the tractor. Notches were cut diagonally from the axis near the base ends of the stalks. The notched tobacco was conveyed to a platform where two or three workers hung it on a specially designed wire–strung wooden frame.

These special wire–strung frames were moved with a tractor–mounted front–end loader. Once filled, a frame was removed from the platform and then replaced by an empty one. Filled frames were removed from the field and covered with plastic. The major advantage of the portable frames was the speed at which tobacco was harvested. The harvesting capacity of this system, using six workers, was approximately 0.8 ha/day.

Wells et al. (1990a) developed a completely automated harvesting system for harvesting burley tobacco. This system required only two workers to operate the entire harvesting process, from cutting the plant to positioning the frames for curing. The harvester cut plants at ground level and engaged them near the base of the stalk with special opposed roller chains having pointed attachment links. The plants were conveyed up an incline and inverted. Plants were then notched on each side of the stalk and placed into slotted rails in all–metal portable curing frames. The frames were then dispensed and unloaded by the harvester. The portable curing frames were equipped with folding legs and each held 450 plants.

One worker operated the harvester, while a second delivered empty curing frames using a tractor–mounted front–end loader. Labor time required to harvest burley tobacco was reduced 80 to 85% by the automated system as compared with conventional hand harvesting methods. Only 50% of this time was spent actually harvesting, the other time was spent turning, off–loading frames, reloading frames, making repairs, and correcting malfunctions. The effective maximum harvesting capacity measured for the system was approximately 1.21 ha per day. Bridges et al. (1997) showed that, owing to the initial cost of the harvester and the portable carrying frames, the annual cost of this system compared favorably with other systems only for relatively large crops, i.e. $\geq$ 50 ha.

Yoder (1970) demonstrated through experimentation that curing tobacco under plastic–covered structures results in substantial benefits, as well as some limitations, when contrasted with traditional air curing barns. Single–tiered, single–row portable curing structures were used to test such curing variables as film color, density of tobacco in frame, and height of stick rail. Two densities, 194 and 258 cm^2 per stalk, two film colors (black and clear), and two stick rail heights (1.83 and 2.13 m) were evaluated in portable curing structures and compared with tobacco cured in a conventional curing barn. There was no significant difference in the quality of tobacco cured under the plastic when compared to the tobacco cured in a conventional barn.

Duncan (1995) described how to build and use a post–row system much like a cantilever system developed by Walton et al. (1985). Traditional sticks were used in this system and density per stick was not a factor in the study. Duncan recommended that frames be covered before any rainfall with black 6–mil plastic. The plastic was wide enough to drape over the sides and cover most of the tip leaves. Several strands of baler twine were pulled snugly over the plastic and tied to the posts to hold the plastic down during windy occasions. The sides were made so that they could be rolled up if needed for enhanced drying at any time.

Many tobacco–harvesting techniques have been developed and producers have adopted some of the components. However, no mechanical harvesting system has yet received widespread acceptance by producers. Such harvesters have not been accepted because of insufficient capacity or excessive cost. Compared with conventional manual methods, the mechanical harvesters do not substantially reduce labor requirements per ha of tobacco harvested. While the automated system reduces labor by 80%, its high investment cost is apparently unacceptable to growers as long as migrant laborers are available for conventional harvesting in available and accessible curing barns.

A system has been proposed that combines the proven technology of notching, inverting, and inserting plants into slotted rails with the affordability of field curing structures. Such a system will be less expensive than the automated system developed by Wells et al. (1990a) and seems capable of substantially improving labor productivity. An essential component of such a system is a mechanical means of retrieving metal rails filled with tobacco from the field and placing them onto field curing structures.

Machine Design, Development, and Fabrication

Proposed Solution

A mechanical burley tobacco harvesting system has been proposed that would use the technological features of the automated system described by Wells et al. (1990a,b), but reduce cost by simplifying mechanical components and replacing portable steel curing frames with wooden two–beam structures. The system envisions a harvester that cuts, inverts and notches plants such as the harvester described by Wells et al. (1990a,b); however, notched plants would be placed in slotted steel rails as illustrated in figure 1. The harvester would likely be tractor–mounted to utilize propulsion and power for harvesting.

The steel rail shown in figure 1 would be approximately 3 m in length and each holds 35 to 40 plants. The harvester would fill such rails and store a group of approximately 10 in a magazine. The harvester would unload such groups on a grass–covered area adjacent to a field. Figure 2 shows such a group of filled steel rails deposited on the ground.

The first step in developing this system was to design and test a mechanism to retrieve slotted rails filled with notched tobacco plants from a field in groups of 10 and to transport them to post–row curing structures constructed near the field. The mechanism would then place the groups of filled rails on the structure for curing.

Curing Structure

The two–beam curing structures used in this study were constructed of 5.1– × 10.2–cm beams attached to both sides of 10.2– × 10.2–cm posts. The posts supported the beams at the quarter points and were set in the ground at a depth of 61 cm.

The distance between the support rails were 290 cm. The rails were loaded so that there was 15.2 cm of free rail left on each end of the rail (no tobacco within 15.2 cm). At that spacing, the inside distance between two hanging beams was 285 cm. With 15.2 cm of free rail on each side, the operator had 5.1 cm of clearance on each side of the rails to clear the curing structure beams with the hanging tobacco.

Prototype Design

The prototype transporter illustrated in figure 3 consisted of a vertical mast rising from an axle with a cantilever beam at its top extending rearward. A 12–V winch was attached to the top of the mast with the cable passing over a pulley

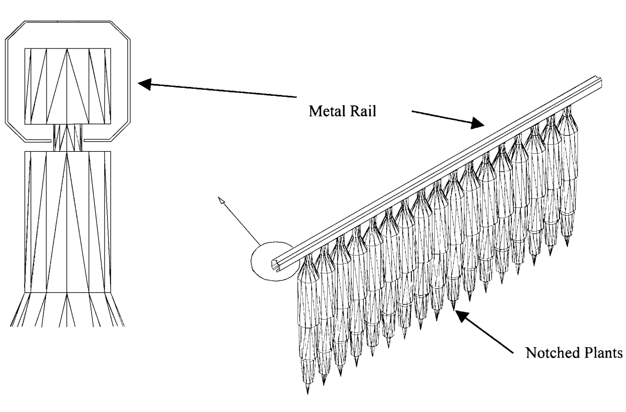

Figure 1. Diagram of notched plants in a steel rail.

Figure 2. Loaded tobacco rails laying on the ground ready for pick up.

at the end of the cantilever beam. The cable was attached to the center of a rectangular steel–carrying frame (305 cm long and 279 cm wide) that could be raised and lowered with the winch.

The carrying frame was designed to lift the 10 individual rails of tobacco. Figure 4 shows a piston–type attachment device hinged from the bottom of the carrying frame. Ten such devices on each side of the carrying frame spaced 30.5 cm apart attached the filled rails of tobacco to the carrying frame. At full extension under load, the attachment devices were 31.8 cm long and formed an angle with the vertical of 30 degrees (see fig. 4b). Thus, the horizontal component of the force applied to each end a rail maintained attachment during transport.

As the carrying frame was lowered and the slotted rails were placed on the field–curing structure, the attachment devices retracted to a minimum length of 21.6 cm and rotated upward. As the carrying frame continued to descend, the attachment devices continued to rotate upward until they were pushed from the ends of the rails and disconnected, then they were pulled further upward by the extension springs (fig. 4b). After all the devices were disconnected from the rails, the empty carrying frame was hoisted into a secure position beneath the cantilever beam for transport. Details of the design and fabrication of the retrieval/transporter are given by Camenisch (2000).

Experimental Methods

Tests were conducted to evaluate the prototype transporter at the University of Kentucky Animal Research Center near Versailles, Kentucky. The test plot for this harvesting system was a field planted in burley tobacco cultivar Tennessee 86. The two–beam curing structure was constructed on the grass–covered area adjacent to the tobacco field.

A John Deere 5210, 29.8–kW two–wheel–drive tractor was used to tow the transporter. During the testing, the tractor had no rear–wheel ballasting. The mass of the tractor without ballasting was 1928 kg. The tractor's electrical system was used to charge the 12–V battery that powered the winch on the transporter.

The fully automated tobacco–harvesting unit developed at the University of Kentucky (Wells et al., 1990a, b) was used to cut, notch, and hang tobacco stalks on the frames designed for that system. From there they were removed by hand and hung on the rails (fig. 1) attached to the carrying frame of the experimental transporter. Rails filled with freshly cut tobacco were approximately 102.5 kg in mass. Once the rails were filled, they were slowly lowered onto a grass–covered area as shown in figure 2.

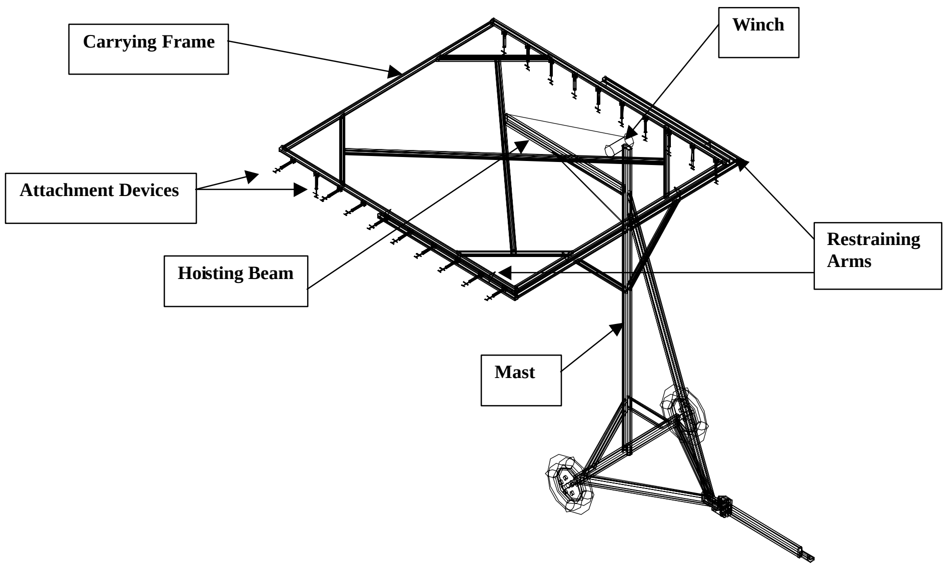

Figure 3. Diagram of retrieval/transport mechanism showing rectangular carrying frame hoisted to just beneath the horizontal beam and secured for transport by the restraining arms.

Harvesting and housing experiments began on 30 August 2000 and were completed on 18 September 2000. To determine the effect of the time that the filled rails were left on the ground prior to placement on the post–row structure upon leaf loss and cured leaf quality, three treatments were executed whereby groups of 10 filled rails (called loads) were left on grass–covered area for 0, 1, or 2 days. The 0–day treatment involved harvesting three loads of filled rails in the late morning and hanging them to the curing structure on the same day. The 1–day treatment involved harvesting one day and hanging the next day, while the 2–day treatment was hung the second day after harvesting. All treatments were replicated three times.

Retrieval/Transportation Tests

Each test consisted of an operator starting the tractor and trailer from or near the curing structure and then proceeding to the rails of tobacco on the ground. The trailer was positioned near filled rails of tobacco (fig. 2) and the carrying frame was lowered. The operator then connected each of the attachment devices on the carrying frame to the end of each of the rails in the load (fig. 5). The load was then raised and secured by the restraining arms (figs. 3 and 6). Next, the operator drove the transporter to the two–beam curing structure and positioned the transporter between two of the parallel support beams (fig. 7). Once the trailer and load were aligned, the operator lowered the carrying frame and filled

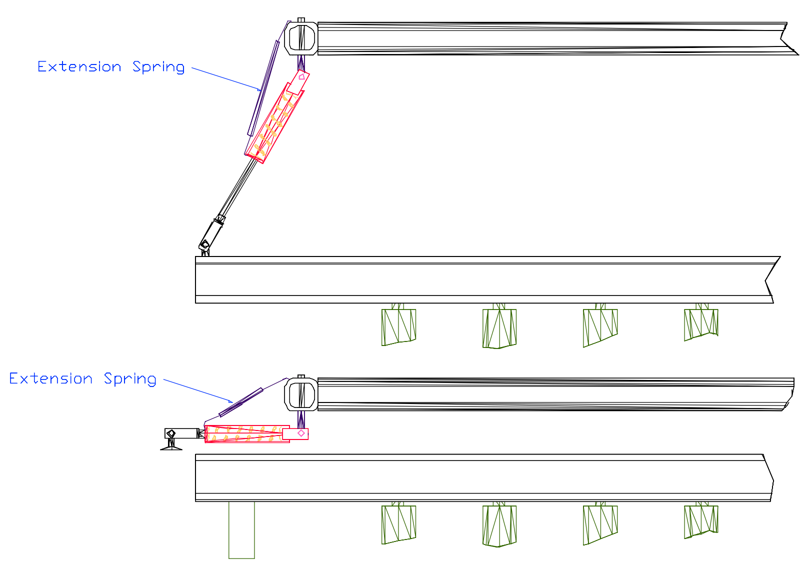

Figure 4. Piston–type attachment device: a) Extended, attaching end of rail to carrying frame as lifted; b) Retracted and detached from rail as carrying frame descends.

Figure 5. Manually connecting piston–type attachment devices on the carrying frame to the ends of filled rails lying on the ground.

Figure 7. Retriever/transporter placing rails of tobacco on a field curing structure.

rails onto the beams of the curing structure and the attachment devices automatically released the rails. The carrying frame was then raised back to its transport position beneath the cantilever beam. At this point, one of the transportation replications was complete.

All tests were videotaped and analyzed as nine activities: 1) traveling to the load, 2) positioning the trailer, 3) lowering the carrying frame, 4) attaching the rails, 5) raising the carrying frame, 6) traveling to the two–beam curing structure, 7) aligning the trailer, 8) lowering and unloading the rails, and 9) securing the carrying frame. The time required for each activity was recorded for each of the three replications of the three treatments.

Evaluation Of Cured Tobacco

Black 4–mil plastic was used to cover all tobacco placed on the curing structures. All treatments were covered one week after harvesting. One week after the last treatment was covered, plastic damaged by wind was replaced. Thereafter, the plastic covering remained intact until curing was complete.

To test the quality of the cured tobacco, random samples were taken from the different replications on 3 November 2000. One–stalk samples were taken from a randomly determined position within each of the 10 rails of tobacco comprising a replication of each treatment. Three replications of 10 stalks were also obtained from tobacco from the same plot that was harvested using the conventional cutting, placing on a stick, and curing in a conventional barn. Samples were placed in plastic for storage until they could be properly stripped and graded. On 8 November 2000, cured leaves were removed from the tobacco plants, separated into the three grades and tied in bundles. Each of the bundles were weighed and graded by a federal grader. Each federal leaf grade was a combination of group, color, and quality indices.

Figure 6. Retriever/transporter with load hoisted for transport.

Analysis and Results

General Observations

Testing of the transporter showed that it could easily be towed and manipulated as a two–wheeled trailer with a large load. Towing the trailer to loads of tobacco rails and reversing to align it with the hoisting device was completed in every test without difficulty. The loaded trailer was easily towed to the two–beam curing structure. Even with rough terrain, the rails stayed on the attachment units during jostling of the trailer and the load. Difficulty in using the trailer occurred while trying to align the trailer within the field curing structure for unloading. Sometimes several adjustments were required to align the trailer to place the rails on the two–beam structure.

Attaching the rails to the carrying frame, via the attachment unit, was simply accomplished during some tests and not in others. Some tests required the carrying frame to be moved several times after some rails were hooked to get the other rails aligned properly with the carrying frame. The quickest and easiest attachment occurred when all of the rails were aligned with the carrying frame at one time. To have the rails align properly with the attachment units of the carrying frame, they must be laid down at approximately 30.5–cm spacing (fig. 2). This configuration allowed the carrying frame to easily be attached to the rails with minimal lifting of the rails and no repositioning of the trailer.

Detaching the rails from the carrying frame was a very simple process. Most of the attachment units detached automatically each time a load was placed on the two–beam structure and several times all of the units detached automatically. However, during most tests one or two units would stick in the notches and not automatically release. These required manual assistance to release the rail. Although little time was required to release the rails, the operator was required to dismount the tractor and carry out this procedure by hand.

The two–beam curing structure remained intact during all of the tests and during the curing season. All of the rails were properly supported and there were no failures of any beams or posts.

The plastic sheet that covered the curing structure suitably protected the tobacco from the elements. However, because the plastic sheet only covered approximately 90 cm on each side of the curing structure, the lower portion of the tobacco on the outermost rails had wind and water damage. It was difficult to secure the plastic sheet along the sides of the two–beam structure. The sheets were tied to each of the posts to protect the plastic from wind damage.

The experiments described in the previous section were designed to determine the effect of time that loads of filled tobacco rails remained lying on the ground upon leaf loss, wilting and quality of cured leaves. The hypothesis was that time on the ground would increase wilting, reduce leaf loss, and improve cured leaf quality while not resulting in loss of marketable leaf weight. After several practice runs it was surprisingly noted that there was no leaf breakage in any of the trial loads. This unexpected result continued during all of the replicated tests, with absolutely no leaf breakage occurring when the tobacco was lowered on the ground or picked up.

There were some observations concerning differences in the treatments. When the first replication of the 2–day treatment was picked up, significant bacterial spoilage was evident in the middle of the load. The other two replications had some spoilage and felt warm in the middle of the loads. The temperature was approximately 35°C and it rained on the 1–day treatment while on the ground and during pick–up and transport. There was no observable evidence of bacterial spoilage in any of the replications. The control treatment was hand harvested on conventional sticks, left in the field for three days, and cured in a conventional barn.

Transport Data Analysis

Table 1 presents a compilation of means and standard deviations of activity times recorded during operation of the experimental transporter. The activities whose magnitude and variability had the most impact on transporter performance were: attaching the rails, transporting loads from field to curing structure, and positioning the transporter to unload rails onto the curing structure. The time required for the other activities showed little variation.

The activities with the greatest variation show where improvement can be made to increase the handling rate of the transporter. The variation in the time required to attach the rails was caused by some of the rails being oriented properly on the ground while others were badly disoriented. Much more time was required to attach the disoriented rails than those that were oriented properly. It should be noted, however, that both the mean and standard deviation of this activity were substantially influenced by one of the replications requiring 615 s to complete and the numbers in parentheses are the means and standard deviations of attachment time if that observation is omitted. We believe that a simple change in the design of the attachment devices on the carrying frame can substantially reduce the time required for this activity.

Table 1. Means and standard deviations of activity times associated with the experimental transporter.

Activity	Mean Time Per Load (s)	Standard Deviation (s)	Percent of Total
Travel to load	85	23	10
Position trailer to load	29	6	3.4
Lower carrying frame	43	8	5.1
Attach rails	242 (196)	156 (73)	28.5
Hoist carrying frame	76	27	8.9
Travel to field structure	149	77	17.6
Position trailer to unload	150	75	17.6
Lower rails onto structure	59	30	6.9
Raise carrying frame	17	5	2
Total	850 (804)	204 (129)	100

Variation in travel time arises from varying distances between locations of filled rails in the field and the curing structure and is therefore inevitable. Aligning the transporter in the curing structure was also characterized by substantial variation. This was due to the terrain and the inexperience of the operator. If the terrain was flat or the operator had become accustomed to aligning the trailer properly, this variation could have likely been substantially reduced. We will attempt to design a steering aid to assist operators in centering the transporter between support beams in the field–curing structure.

The average time required to transport 1 ha of tobacco from field to curing structure was approximately 11.7 h. At this rate, approximately 0.7 ha of tobacco could be harvested per 8–h day using this method. The minimum time required to transport and place 1 ha of tobacco on the curing structure was estimated as 6.2 h. At this rate, approximately 1.3 ha of tobacco would be transported per 8–h day. We hope to achieve the latter capacity with minimal modifications to the transporter and field curing structure.

Curing Data Analysis

Leaf grades consisting of group, color and quality indices were assigned to each of the replications by a federal grader and grade index values were computed using the method prescribed by Bowman et al. (1989). Leaf grade index was determined by

$$GI = G \times C - Q \qquad (1)$$

where

GI = leaf grade index ($11 \leq GI \leq 100$)
G = leaf group value ($2 \leq G \leq 5$)
C = leaf color value ($1 \leq C \leq 10$)
Q = quality value ($10 \leq Q \leq 50$)

Table 2 is a compilation of grade indices and sample mass determined for three leaf groupings within each treatment/replication. The values of GI range from very low (5) to moderately high (80). The mass of each sample was multiplied by the corresponding grade index and these products for the three leaf groupings per plant were summed and then divided by the total plant leaf mass to calculate a weighted grade index for each treatment/replication as shown in table 3. Means and variances for replicated

Table 2. Grades and weights for replications within each treatment.

		Grade Indices			Sample Mass (kg)		
Treatment	Repl.	Flyings	Lugs/ Leaf	Tips	Flyings	Lugs/ Leaf	Tips
Conventional	1	70	80	70	0.42	0.83	0.44
	2	70	80	70	0.41	0.89	0.56
	3	70	80	70	0.54	0.72	0.52
0–day	1	60	70	60	0.79	0.65	0.34
	2	60	70	60	0.88	0.47	0.35
	3	60	70	0	0.83	0.75	0.4
1–day	1	5	5	5	0.75	0.64	0.33
	2	60	70	60	0.85	0.62	0.24
	3	60	70	60	0.65	0.66	0.38
2–day	1	60	70	60	0.75	0.63	0.29
	2	10	70	10	0.78	0.5	0.5
	3	10	25	5	0.62	0.56	0.53

weighted grade indices for each treatment are given in table 4.

The mean values in table 3 indicate a strong trend in the treatments. The weighted average grade indices decrease with increasing time between harvest and retrieval of the tobacco, and of all mechanically–handled treatment means were less than that of the conventional method. The conventional mean grade index of 74.6 was the highest while that of the 2–day treatment (34.6) was the lowest.

An analysis of variance was performed to determine if there was significant difference between the treatment means. The calculated F–value was 2.14, which was smaller than the critical F–value of 4.07 for $\alpha = 0.05$. Thus, a significant difference among the treatment means could not be inferred at the $\alpha = 0.05$ level. However, table 4 shows that the variance within the 1– and 2–day treatments is much higher (1151 and 682, respectively) than the variance

Table 3. Sum of grade index × mass and weighted grade index for each treatment/replication.

Treatment	Repl.	Sum (GI × Mass)	Sum (GI × Mass)/ Total Plant Leaf Mass
Conventional	1	126.6	74.9
	2	138.8	74.8
	3	131.4	74.1
	Mean	132.3	74.6 a[a]
0–day	1	113.3	63.7
	2	107.3	62.8
	3	126.9	63.8
	Mean	115.8	63.4 ab
1–day	1	8.6	5
	2	108.6	63.6
	3	108.3	63.9
	Mean	75.2	44.2 ab
2–day	1	106.3	63.8
	2	47.8	26.8
	3	22.7	13.3
	Mean	58.9	34.6 b

[a] Treatment means designated by the same letter are not significantly different by the Fisher Least Significant Difference (LSD) test at $\alpha = 0.05$ (Freund et al., 1997).

Table 4. Means and variances of weighted grade index within treatments.

Groups	Count	Sum	Average	Variance
Conventional	3	223.7	74.6	0.20
0–day	3	190.2	63.4	0.31
1–day	3	132.6	44.2	1151
2–day	3	104	34.7	682

within the conventional and 0–day treatments (0.20 and 0.31, respectively). The variances within the 1– and 2–day treatments were high enough to raise the mean square within groups to a level that would make the calculated F–value very low.

An additional analysis of variance was performed using only the conventional and 0–day treatments. The calculated F–value in this case was much higher (732) which exceeded the critical F–value of 7.71 for $\alpha = 0.05$, which infers that there is a significant difference between the means of the conventional treatment and the 0–day treatment. After observing that the average weighted values of the 1– and 2–day treatments are lower than the 0–day treatment, it is logical to conclude that they too can be considered significantly different from the conventional treatment.

To further evaluate the difference between treatment means of the average weighted grade index values, a Fisher Least Significance Difference (LSD) test was performed as explained by Freund et al. (1997). The calculated Fisher LSD ($\alpha = 0.05$) was 34.9. The only treatment means that have a difference greater than or equal to 34.9 are the conventional and 2–day treatments, whose difference is 39.9. The 0– and 1–day treatments cannot be considered significantly different from any of the other treatments using this method.

After observing the trend in treatment means, it was noted that the grade index of the tobacco decreased as the number of days tobacco was left on the ground increased from 0 to 2 days. Therefore, to keep the amount of spoilage or heat damage to a minimum, tobacco should be picked up as soon as possible, preferably the same day that it is placed on the ground. To leave the tobacco on the ground overnight increases the risk of having spoilage and lower grade values.

Another key observation was that the spoilage occurred most significantly in the loads of tobacco that were transferred while it was raining. All of the loads were placed on the ground in dry conditions. However, the first replication of the 1–day test was picked up while it was raining. The rain stopped after that test so the other two loads (replications) were not exposed to rain during pick–up and transport. They were rained on only when they were lying on the ground. The load that was rained on while being transported received the lowest grades among all of those analyzed. Therefore, to reduce the risk of the combination of spoilage and water damaged, the tobacco should not be placed on the ground or picked up and transported during rainfall.

An analysis of variance was performed to determine if the harvesting treatments had any effect on the mass of the cured tobacco. The sum, average, and the variance of each of the treatments are shown below in table 5. All three have similar means indicating no discernable trend and all of the variances are low. The calculated F–value (1.11) is lower than the critical F–value (4.07), which infers that there is no significant difference ($\alpha = 0.05$) between the treatment means.

Table 5. Sums, means, and variances of masses of cured leaf samples for experimental treatments.

Groups	Count	Sum (kg)	Mean (kg)	Variance (kg)
Conventional	3	5.32	1.77	0.0068
1–day	3	5.48	1.83	0.021
2–day	3	5.13	1.71	0.00029
3–day	3	5.15	1.72	0.0034

Some of the difference between weighted grade indices of the conventional treatment versus the other treatments was attributed to some degradation of tobacco cured under the plastic caused by wind and rain. The plastic sheeting was used to cover only approximately 1 m along the sides of the structure. Thus, only a portion of the outside plants was exposed. This problem may be avoided by using sheeting that covers most of the sides, as well as the top of the tobacco in the field curing structures.

COST ANALYSIS

The annual cost of the proposed system was estimated for harvesting a 20–ha crop and included that of a harvester, transporter, two tractors, steel rails, and construction of a wooden post–row housing structure. The straight–line method was used to compute annual depreciation capital assets. Capital recovery cost was computed assuming 10% annual interest, and other annual fixed costs were estimated as 2% of initial cost. ASAE EP 496.2 (ASAE, 2000) was used to estimate tractor maintenance and fuel cost. Assuming a labor wage of $8 per worker hour, the total annual cost to harvest and house 20 ha of tobacco was estimated as $1,872 per ha. Camenisch (2000) gives details of the cost analysis.

The Catch22 model developed by Bridges et al. (1996) was used to analyze several different types of tobacco harvesting systems (Wells et al., 2000). Annual costs ranged from $1014 to $2400 per ha for systems utilizing conventional wooden sticks. The cost of the Powell system, utilizing notched plants hung on wire–strung frames was $2036 per ha, while the fully automated system cost $2945 per ha. Wells et al. (2000) assumed the initial cost of two tractors as $12,000 each and a labor wage of $6.00 per worker hour. Increasing these parameters to $30,000 and $8.00 per worker hour, respectively, would increase the annual costs of the various harvesting systems such that the estimated annual cost of the proposed system would compare more favorably. The proposed system is more expensive than some of the systems utilizing conventional sticks and manual operations. However, the proposed system may be a viable alternative for growers that have insufficient curing barn space and/or unreliable availability of laborers.

CONCLUSIONS AND RECOMMENDATIONS

The conclusions of this study are as follows:

- The transport unit developed and evaluated in this study was found to perform reliably and at an acceptable harvesting rate of 0.7 to 1.3 ha per 8–h day. The labor requirement (two persons) is much smaller than most other systems (four to six persons). The automated tobacco harvesting system developed by Wells et al. (1990a, b) is the only other tobacco harvesting system that can harvest tobacco at this rate with only two workers.
- No leaf loss was observed in the process of putting the tobacco on the ground or picking it up. Thus, the proposed harvester, and not the transporter, will cause the only leaf loss from this system.
- Experiments showed that the quality of tobacco harvested with the prototype system decreased as time between harvesting and retrieval (and hanging) increased. There was no appreciable water weight loss while the tobacco laid on the ground, thus it is imperative that the retriever/transporter be able to retrieve and hang tobacco on a field curing frame the same day as it is harvested.

Some recommendations are indicated to increase harvesting rates and to improve quality of cured tobacco. The variation within the activity of aligning the transporter between curing structure beams can be eliminating with an alignment aid that the operator can easily use. The harvester should be designed to lower filled rails uniformly at 30.5–cm spacing. Such uniformity would subsequently reduce the variation in the attachment activity and the mean time required to connect the attachment units to the filled rails on the ground. We plan to redesign the attachment devices to increase range of motion simplify the attachment.

A hydraulic winch should be used for hoisting the tobacco rails. Typical hydraulic winches have greater lifting capacities than electric winches and allow any tractor equipped with remote hydraulic connections to easily be attached to the transporter and operated.

Finally, the use of 6.1– versus 4.9–m plastic covering would probably eliminate some damage to tobacco caused by rain and wind.

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