



Narrow-Width Harvester for Switchgrass and Other Bioenergy Crops in Experimental Plots

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ABSTRACT

Greater capacity in field experimental research could be achieved by equipment that harvests high-yielding biomass energy crops within small plots. Versatility and cost-effectiveness would be enhanced if the harvester were adaptable to currently available equipment. A narrow-width biomass harvester for experimental plots was constructed to meet these objectives. The machine consists of a hydraulic drive, flail mower, support arm assembly, collection box and weighing platform, and electronic weighing system. The harvester is currently being powered with a 63.7 kW narrow specialty tractor with a 1.4-m outside tread width. The narrow tractor-flail was used to harvest 1.52-m swaths down the centers of 3.8 by 12.2 m plots of switchgrass (*Panicum virgatum* L.) so that a portion of the crop remained undisturbed for other measurements. The harvester could harvest dry switchgrass yields up to 20 Mg ha⁻¹ in 8.8-m plots before its collection box was filled. Other grasses and forages with shape and size characteristics similar to switchgrass would also likely be accommodated. Under normal conditions, three people can harvest 12 plots (20 m long) within 1 h including weighing the biomass, emptying the harvester, and bagging samples. The harvester can be attached to a tractor and made ready for harvesting, or removed to make the tractor available for other purposes, in about 1.5 h. Cost of materials for the harvester was <\$10,000.

NUMEROUS DESCRIPTIONS of small plot forage harvesters have appeared in the forage research literature over the past several decades (Howell, 1956; Kemp and Kalbfleisch, 1957; Hubbard and Willis, 1962; Paterson and Browning, 1962; Thompson and Heinrichs, 1963; Buker, 1967; Swallow, 1967; Allen et al., 1968; Collins et al., 1969; McCormick and Hoveland, 1971; Stubbendieck and Fenster, 1981; Barnes et al., 1984). Though useful, many of these systems are small and do not have sufficient power for harvesting switchgrass, miscanthus (*Miscanthus* spp.), and other high-yielding bioenergy crops.

More recently, automated harvesting and weighing systems, costing less than commercial equipment, have been developed that increased the efficiency of harvesting and expanded the number of forage grasses and legume species that can be harvested. Pearson and Robinson (1994) developed a weigh bin with an electronic weighing system that is designed to attach to the underside of a self-propelled commercial swather directly behind the hay conditioner. One person is needed to operate the harvester and collect data, and it can be converted quickly for harvesting commercial fields (Pearson, 2007). Another system is designed that consists of a weigh bucket and frame that attach to a tractor-pulled forage harvester (Pedersen and Moore, 1995).

The forage harvester described in this article represents another approach for automatically harvesting and weighing biomass from field experimental plots. In addition, the equipment described meets the following requirements: (i) low cost to fabricate (<\$10,000) compared with commercial equipment, (ii) sufficient power to harvest high-yielding bioenergy crops, (iii) narrow profile for harvesting within relatively small contiguous plots, (iv) wheel position that does not crush the forage before being cut, and (v) adaptability to currently available equipment requiring no modification.

DESIGN AND DESCRIPTION

The automated harvesting system was designed for a bioenergy crop experiment at the Columbia Plateau Conservation Research Center, Pendleton, OR. The machine consists of five major components: hydraulic drive, flail mower, support arm assembly, collection box and weighing platform, and electronic weighing system. The flail mower mounts to the front of a tractor and is pushed into the crop to be harvested. A rotating flail cuts and chops the forage, and propels it into a collection box on the weighing platform for weighing.

Flail Mower and Tractor Requirements

The experiment consisted of contiguous plots of switchgrass, winter wheat (*Triticum aestivum* L.), and spring mustard [*Brassica juncea* (L.) Czern.], but the harvester was only used for harvesting the switchgrass. We required the flail mower to cut a narrow swath down the centers of 3.8 by 12.2 m (12.5 by 40 ft) plots so that an area of switchgrass in a plot would remain undisturbed for other measurements. In addition, the tractor had to be narrower than the width of the flail mower so that no wheels would roll over the uncut forage. An unmodified Kubota model 8540

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Abbreviations: PTO, power takeoff.

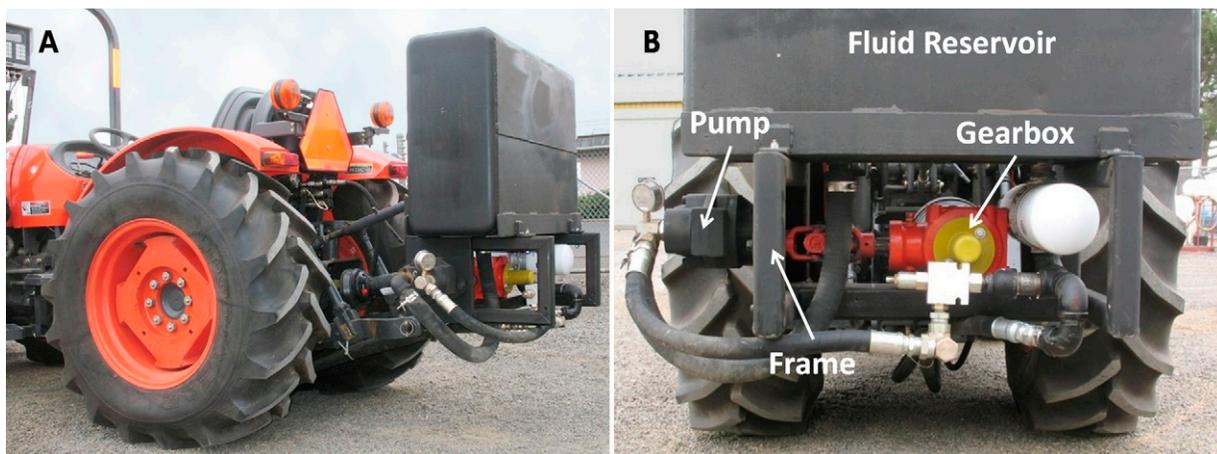


Fig. 1. (A) Hydraulic drive attached to the tractor's three-point hitch and (B) rear view of hydraulic drive with frame, hydraulic pump, fluid reservoir, and right angle gear box.

narrow tractor with 63.7 kW net engine power, front wheel assist, and outside tread width of 1.4 m met this requirement. Narrow specialty tractors are 30% narrower than standard tractors to fit between rows of vines and fruit trees. Though the harvesting system was designed for the narrow Kubota, the concept could easily be extended to other brands and models of specialty tractors.

In addition, the tractor needed to be strong enough to push and lift the front-mounted flail. Bolt holes had to be furnished in the middle of the tractor's undercarriage for attaching a loader bracket and connecting a hydraulic lift cylinder to the flail. Power requirements of at least 40 kW were required for flail and propulsion. One hydraulic remote was needed to operate the hydraulic lift cylinder for harvester head height adjustment. An independent power takeoff (PTO) clutch was required so that the operator could engage or disengage the flail while moving.

Hydraulic Drive

The hydraulic drive mounts to the rear of the tractor by means of two lift arm links, swing draw bar, and the top link of the tractor's Category II, three-point hitch (Fig. 1A). The system consists of a frame, hydraulic pump with double universal driveshaft and right angle gearbox, and hydraulic fluid reservoir mounted rigidly to the frame (Fig. 1B). The frame forms a box that is constructed from welded lengths of 6.4-mm (1/4-in)-thick A36 mild-steel square tubing (Fig. 2). Initially, the end of a forward support leg (45.7 cm long by 7.5 cm wide by 5 cm high) is welded at a right angle to each end of one cross member (65.9 cm long by 7.5 cm wide by 5 cm high). Angle iron (5.1 by 5.1 cm) is welded to the end of the forward support legs to form a right angle surface for bolting to the hitch. To extend the frame rearward, four longitudinal support members (45.7 cm long by 5 cm wide by 5 cm high) are welded at right angles to the two forward support legs. The lower longitudinal members are welded near the bottom of the two forward support legs and the upper members are welded 30.5 cm up from the bottom. Two rear support legs (30.5 cm long by 5 cm wide by 5 cm high) are welded at the opposite ends of the lower and upper support members. To form a platform for the hydraulic reservoir, one piece of angle iron (95.2 cm long by 5 cm high by 7.5 cm wide) is welded to the top of the pair of rear support members and another piece of the same size is bolted to the upper support members. One piece of channel (55.9 cm long by 15 cm wide by 5 cm high) is welded between the

left and right lower support members to form a platform for the right angle gearbox and hydraulic pump.

The hydraulic gear pump is a Model GM25B-2V77C-1F20B (Haldex and Barnes, Corp., Rockaway, NY) and is connected directly to the right angle gearbox by means of double universal joints and a driveshaft. The pump is bolted to a mounting plate with four bolts 12.7 mm (0.5 in) in diam. by 3.8 cm (1.5 in) long. The mounting plate is steel plate that is 30.5 cm long by 20.3 cm wide by 1.9 cm thick. It is welded onto the longitudinal member and forward support leg on the left side of the frame. The described hydraulic drive system was used with the Kubota tractor's PTO that has a rating of 57 kW at 9.0 Hz (540 rpm). The right angle 3:1 gearbox is a Model 2401 (Bondoli and Pavesi, Inc., Ashland, VA) and is coupled to the PTO shaft of the tractor to have an output speed of 27 Hz (1620 rpm). At this speed, the pump has a theoretical output capacity of 2.08 L s^{-1} . The three-point hitch is locked into position when the telescoping PTO shaft is horizontal with the gearbox.

The open hydraulic circuit allows fluid to flow continuously from the pump to the flail motor and return to the hydraulic

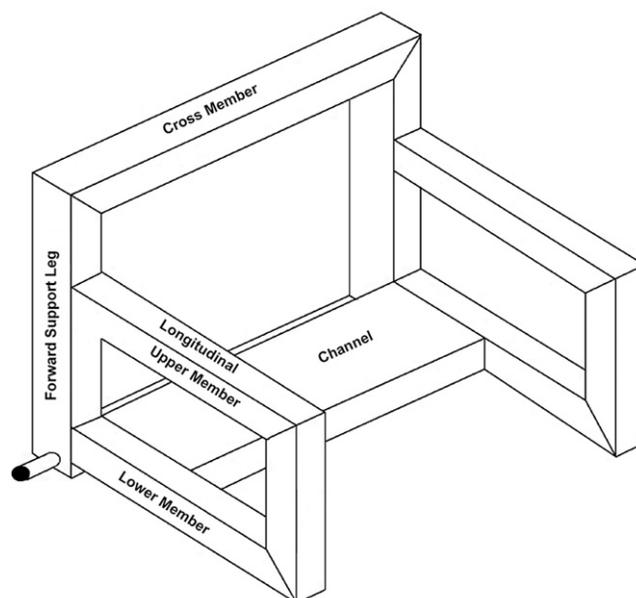


Fig. 2. Schematic diagram of frame used in construction of hydraulic drive.

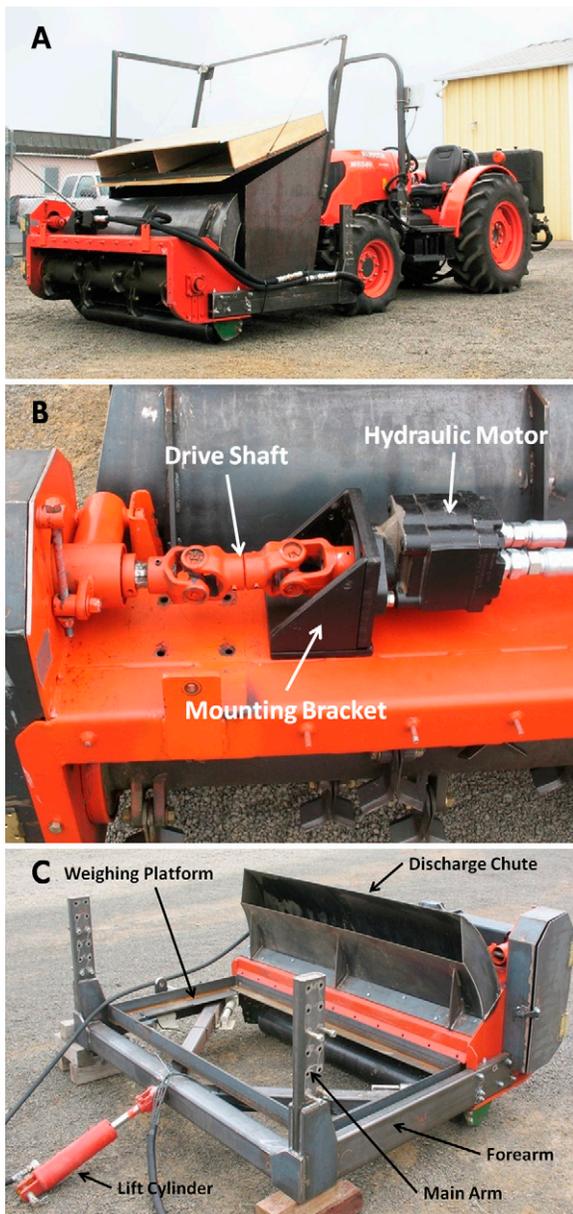


Fig. 3. (A) Flail mower and collection box attached to front of tractor, (B) hydraulic motor with mounting bracket and double universal joint drive shaft, and (C) components of harvesting system including main arms and forearms, weighing platform, discharge chute, and lift cylinder.

fluid reservoir. Hydraulic fluid held in the 189.5-L (50-gal) fluid reservoir helps dissipate heat buildup. Given a power rating of 32.3 kW at 1620 rpm and 20% inefficiency, the hydraulic system needed a cooling performance of at least 6.5 kW to avoid overheating ($32.3 \times 0.2 = 6.5$). To estimate the performance of the cooling system, an infrared thermometer was used to measure the difference in temperature between the hydraulic pump and hydraulic reservoir when the system had been running at full power for several hours. The difference in temperature was found to be 4.6°C at an ambient air temperature of 27°C. Given this temperature drop, a specific heat capacity of 2.1 kJ kg⁻¹ °C⁻¹ for tractor hydraulic fluid, and the flow rate of 2.08 L s⁻¹ (1.77 kg s⁻¹ at 0.85 kg l⁻¹ oil density), the system was capable of dissipating heat at about 17 kJ s⁻¹ ($2.1 \times 1.77 \times 4.6 = 17.1$), or 17 kW, which is sufficient to stabilize the temperature of the hydraulic fluid.

Flail Mower

A Rears Standard SPF PAK-Flail mower was purchased from Rears Manufacturing Company (Eugene, OR) for \$5000. The mower is 1.8 m wide and cuts a 1.52-m swath. It came from the factory with a drive assembly consisting of a double universal joint driveshaft, three-groove drive pulley, three-groove driven pulley, belts, and a driveline guard. A hydraulic hose is connected from the hydraulic pump on the drive system to a hydraulic motor on the flail mower at the front of the tractor (Fig. 3A). Oil is routed from the motor through a hose to the hydraulic fluid reservoir. The hydraulic motor chosen to power the flail is a model M30A679BEA20–30 (Commercial Shearing, Inc., Youngstown, OH) that is capable of 155 kg m (1140 lb ft) of torque at a speed of 26.7 Hz (1600 rpm). The motor is fastened to an angle-type mounting bracket that is welded from steel plate (Fig. 3B). It offers a 1.9-cm-thick front surface with two 12.7-mm (0.5-in) diam. bolt holes for attaching the pump and a 1.3-cm-thick base surface with four holes for bolting to the top the flail housing. The drive shaft with double universal joints receives power from the motor and transmits it to the drive pulley. Three V-belts are trained around the three-groove drive pulley (20.5-cm diam.) and driven pulley (18-cm diam.), and tautened to rotate the flail rotor. The working output from the motor and 1:1.14 pulley ratio gave a flail rotor speed of 30 Hz (1800 rpm) as measured with a contacting hand-held tachometer.

The flail was modified by cutting a 161.3 cm long by 14 cm wide discharge opening into the rear of the flail housing and attaching a discharge chute (Fig. 3C). Constructed of 3.2-mm-thick steel sheet, the discharge chute is curved backward to deflect the blown forage into a collection box. The front of the chute measures 147.3 cm by 17.8 cm. Bending is achieved by roll bending with a rolling mill to a radius of curvature of 43.2 cm. For the 64.1 cm by 160.0 cm back section, the upper half is formed by passing the metal half way through the rolling mill whereas the opposite lower half is left flat. The lower half of the chute forms a partial housing for enclosing the flail rotor. Together, the lower and upper halves of the discharge chute deflect the blown material upward and backward into a collection box (described below).

Support Arm Assembly

The support arm assembly connects the flail mower to the front of the tractor and supports the collection box and weighing platform that are directly behind the flail mower (see Fig. 4). This assembly consists of two main arms and two forearms that are made from 6.35-mm (0.25-in)-thick A36 mild steel square tubing (Fig. 3C). The dimensions of the main arms are 9.2 cm long by 0.8 cm wide by 1.6 cm high (23 by 2 by 4 in) and the forearms are 182.9 cm long by 5.1 cm wide by 15 cm high (72 by 2 by 6 in). A main arm is welded at a right angle to one end of a forearm. The joint between each arm is reinforced with welded steel plate (0.2 cm [0.5 in] thick). A cross member of square tubing 120 cm long by 10 cm wide by 10 cm high (48 by 4 by 4 in) is welded between the arms. To add strength, two 90 cm long by 7.5 cm wide by 7.5 cm high (36 by 3 by 3 in) braces are welded at a 45° angle from the cross member to the two arms. The forward end of each forearm is bolted to either the lower left or lower right side of the flail housing.

A hinge device was constructed for coupling the rotatable arms to the front of the tractor (Fig. 5). The hinge consists of a

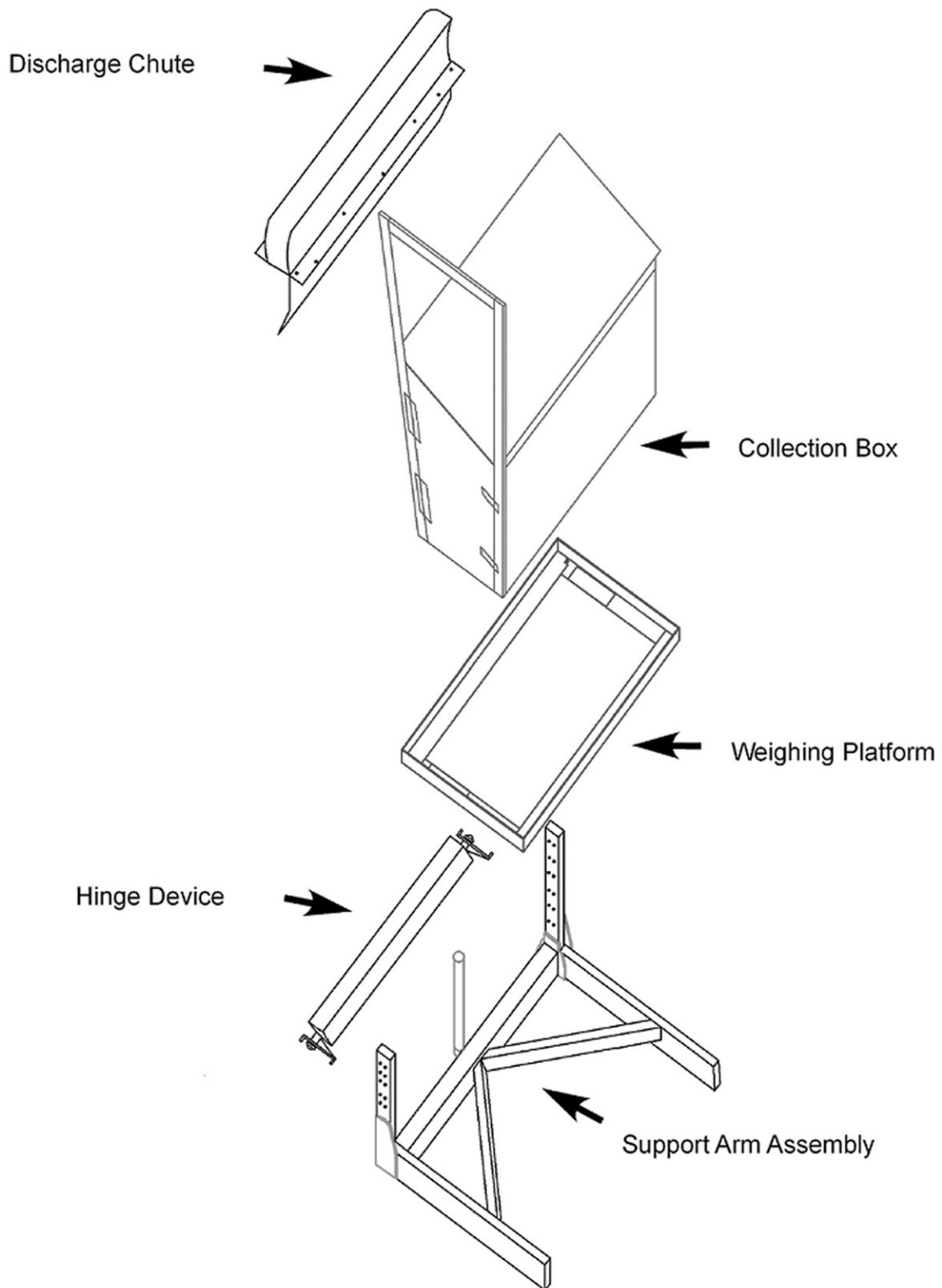


Fig. 4. Exploded view of support arm assembly with discharge chute, collection box, weighing platform, hinge device, and support arms.

housing constructed from square steel tubing that is 142 cm long by 10 cm wide by 10 cm high (56 by 4 by 4 in), a 25-cm-long steel shaft (5.1-cm diam.) extended from each end of the housing, and a hub that swings on each shaft with a mounting plate for bolting to a main arm (Fig. 5). A hub is inserted over a shaft and secured

with a lock collar. Rotation around the shaft is on a plane bearing surface that is lubricated with grease. A mounting bracket for the support arm assembly is constructed of 0.2-cm-thick steel plate and welded to the center of the housing of the hinge device. A mounting block with bolt holes is available on the tractor's frame

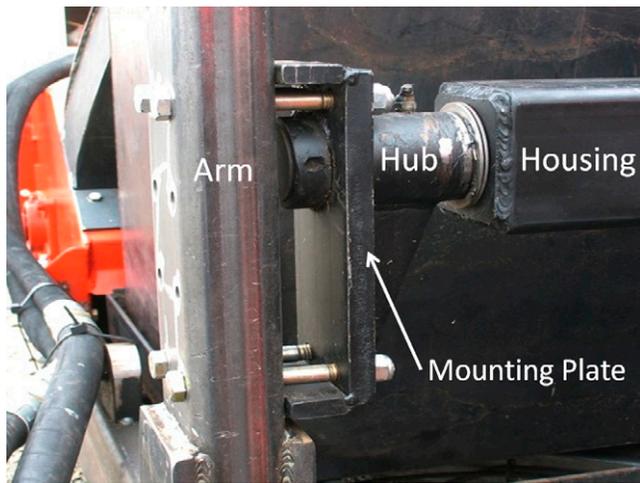


Fig. 5. Hinge with rotating hub and arm on shaft that extends from housing. View of hinge on left side of harvester.

for receiving the mounting bracket of the hinge device so that the forage harvester can be attached to the front of the tractor.

The hinge device allows the harvester system to float with uneven terrain and be hydraulically lifted from the ground. In the down position, the weight of the flail is supported by its elongated steel roller that contacts the ground. A one-way hydraulic lift cylinder is required for raising the arm assembly with attached flail (Fig. 3C). The lift cylinder is connected to a loader bracket that had been fastened to each of the two longitudinal side frames beneath the tractor. The actuating end of the cylinder is then connected to a bracket that is welded to the cross member of the arm



Fig. 6. Hand winch and pulley/cable system for raising and lowering lid over collector box.

assembly. Fluid connection is by means of hydraulic hose between the cylinder and one of the tractor's remote directional valves.

Collection Box and Weighing Platform

Cut forage is delivered upward into the discharge chute and blows into the collection box as the flail rotor turns in the counter-clockwise direction (viewed from left side of the machine). The collection box is constructed of 3.2-mm-thick sheet steel. The overall dimensions of the irregular quadrilateral-shaped collection box are 83.8 cm long by 153.7 cm wide by 109.2 cm high. Volume of the collection space within the box is approximately 1 m³. The collection box rests on a weighing platform that is constructed of two 81-cm (32.4-in) and two 158-cm (63.2-in) lengths of 6.4-mm (0.25-in)-thick steel angle iron that is 7.5 by 10 cm (3 by 4 in) (Fig. 3C and 4). The lengths are welded together to form a rectangular platform to support the collection box. The collection box is then spot welded to the weighing platform.

A wire screen lid on top of the collection box retains the finely chopped plant material while allowing blown air to escape. Blowing air is deflected away from the tractor's operator by means of a deflector, which is constructed of 127-mm (0.5-in)-thick plywood. The hinged lid and deflector are raised and lowered using a hand winch and simple 1:1 pulley/cable system (Fig. 6). A metal door occupies the right side of the collection box and is hinged on one side to allow it to pivot away from the doorway and provide access to the cut forage.

Electronic Weighing System

The collection box and weighing platform rest on four 341-kg (750-lb) capacity weigh bars (Avery Weigh-Tronix, Fairmont, MN) that are bolted to the arm assembly. The four weigh bars are connected by cables to an electronic scale indicator (Model 915A, Avery Weigh-Tronix) that is mounted near the tractor operator (Fig. 7). A Transfer Data Module (TDM, Avery Weigh-Tronix, Fairmont, MN) is available to save data to 64 Kb of nonvolatile memory. Later, these data can be downloaded to a computer through an RS-232 serial port. A second serial port is available for output to a printer. Electrical power to the weighing system is obtained from the tractor's 12-V charging system.

OPERATION AND PERFORMANCE

Accuracy of the weighing system was within the manufacturer's specification of 0.25% as determined from calibration weights of 2.29 and 15.9 kg. In 2010, the machine was successfully used on level ground to harvest switchgrass from within the 12.2-m-long plots. Because the plots were contiguous, each plot had only one side for the harvester to enter and exit. A harvesting operation required three persons: one to operate the harvester, and two to record plot weights, subsample the forage, and empty the collector box. Time to complete the harvest of each plot was about 5 min. By setting the tractor at a PTO speed of 9 Hz (540 rpm) and a ground speed of 0.18 m s⁻¹, the switchgrass was chopped into 5- to 15-cm pieces. Individual plot weights were obtained by taring the weigh scale to zero after backing the harvester out of a plot. The hinged door provided access to the interior of the collection box as needed to obtain subsamples of forage for moisture and quality analysis. We emptied the collection box at the end of each plot to avoid contaminating subsamples. The collection box had been lined with a plastic tarp to catch residue.



Fig. 7. Electronic weighing system

The residue could then be removed quickly by dragging the tarp and its contents out through the hinged door. Performance could be improved by installing a hydraulic cylinder between the flail housing and collection box as needed to raise and lower a swing arm that in turn would invert the collection box for dumping. Material cost for this feature is estimated at \$1200.

Capacity is determined by the volume of the collection box, but also the density and moisture content of the forage species being harvested. The largest individual forage sample filling the collection box consisted of 45 kg of fresh switchgrass at 70% moisture content (26.5 kg dry). The harvester's collection box would be full on 17.4-m-long plots at dry switchgrass yields of 10 Mg ha⁻¹, 11.6-m plots at 15 Mg ha⁻¹, and 8.8-m plots at 20 Mg ha⁻¹ (Table 1). For longer plots, it would be necessary to stop and empty the collection box. Many researchers may also have forage trials in their research programs as well as biomass energy crops. Though other crops were not available for testing the harvester, we expect that the collection box has the capacity to accommodate other grasses and forages with shape and size characteristics that are similar to switchgrass. The combined tractor-flail harvester is 5.6 m long, 1.8 m wide, and 2.2 m high. It weighs <3000 kg and can be easily transported on a flat bed trailer. As with all experiments, field plot layout is important for optimizing the operation of this harvester. Maneuverability of the tractor is determined largely by its wheelbase of 2.1 m (6.9 ft) and turning radius of 6.1 m (19.9 ft) with the front-mounted flail. Thus, it may be necessary to allow >8.2-m (27-ft)-wide alleys or headlands at the end of plots to allow turning. The harvester also might be limited to plots not less than its 1.8-m overall width.

The cutting height of the Rears SPF PAK-Flail mower is determined by the position of its pivoting steel roller. The normal range in cutting height is from 0 to 15 cm, but the roller's pivoting arm can be easily braced to support the roller at greater heights. We set the roller at a height of 15 cm as needed to avoid damaging the elevated growing point of switchgrass. Cutting efficiency was about 90% at this height. Adjusting the steel roller to lower cutting heights will improve efficiency. Cutting height can also be controlled by means of the hydraulic lift cylinder, but harvesting is normally conducted with the roller resting on the ground.

The rotation direction of the knives at the top of the flail rotor is forward and down. Thus, crop residue in front of the machine will

Table 1. Estimated dry biomass corresponding to different plot lengths and switchgrass yields of 1, 5, 10, 15, and 20 Mg ha⁻¹.

Plot length m	Switchgrass yield, Mg ha ⁻¹				
	1	5	10	15	20
	Estimated dry biomass, kg				
1	0.2	0.8	1.5	2.3	3.0
5	0.8	3.8	7.6	11.4	15.2
10	1.5	7.6	15.2	22.8	30.4
15	2.3	11.4	22.8	34.2	45.6
20	3.0	15.2	30.4	45.6	60.8

be projected downward, which minimizes the potential of sending debris in an upward trajectory. Based on our discussions with the flail manufacturer, a protective chain shield can be purchased and installed to the opening in front of the mower that allows forage to pass freely to the flail rotor while protecting ground personnel from objects thrown from the front of the machine. Readers are cautioned that operation of flail harvesters should be stopped if there are bystanders who are likely to be hit by ejected debris.

About 1.5 h is required to detach the harvester from the tractor, which involves disconnecting the hydraulic hoses, unbolting the support arm assembly from the tractor's mounting block, disconnecting the lift cylinder, and removing the hydraulic drive. The tractor may then be used as a source of power for other operations. An overhead hoist is needed to transfer the hydraulic drive from the tractor's three-point hitch to the ground. A floor stand could be constructed from steel angle iron or tubing to store the hydraulic drive when not mounted on the tractor.

Mechanical drawings are available from the corresponding author by request. A cost estimate for materials to construct the hydraulic drive frame, support arm assembly, weighing platform, collection box, and deflector, excluding labor, is \$2000. Addition of the flail, hydraulic pump and motor, hoses, hose couplers, fluid reservoir, fluid filter, right angle gear box, universal drive shafts, hydraulic cylinder, PTO shaft, digital weigh scale, weigh bars, and miscellaneous hardware brings the estimated cost to \$10,000. Total cost for an assembled harvester, including the tractor, is estimated at \$40,000.

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