ornl

ORNL/TM-13724

OAK RIDGE
NATIONAL
LABORATORY

LOCKHEED MARTIN

Forage Harvest and Transport Costs

Anthony Turhollow
Mark Downing
James Butler

MANAGED AND OPERATED BY
LOCKHEED MARTIN ENERGY RESEARCH CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

ORNL-27 (3-96)

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ORNL/TM-13724

FORAGE HARVEST AND TRANSPORT COSTS

Anthony Turhollow[1]
Mark Downing[1]
James Butler[2]

[1]Oak Ridge National Laboratory, Oak Ridge, TN 37831
[2]2823 Rainwater, Tifton, GA 31794

Date Published-December 1998

Prepared for the
Office of Transportation Technologies
and the
Office of Power Technologies
U.S. DEPARTMENT OF ENERGY

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6285
managed by
LOCKHEED MARTIN ENERGY RESEARCH CORPORATION
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-96PR22464

CONTENTS

Page

LIST OF FIGURES v

LIST OF TABLES vii

ABSTRACT xi

EXECUTIVE SUMMARY xiii
  COSTS xvii

INTRODUCTION 1

HAY 2
  TRANSPORTATION AND BALE SIZE 9
  IN-FIELD TRANSPORTATION 9
  TRANSPORTATION 10

SILAGE AND HAYLAGE 11
  DIRECT CUT 13
  WILTING 16
  IN-FIELD TRANSPORTATION 16

MODULES: AN ALTERNATIVE TO BALES AND LOOSE BIOMASS 22

CROP RESIDUES 24

CALCULATING COSTS 31
  SOURCES FOR MACHINERY PARAMETERS 33
  VALUE AFTER N YEARS 34
  DEPRECIATION 35
  INTEREST 35
  INSURANCE, HOUSING, AND TAXES 35
  REPAIRS AND MAINTENANCE 35
  FUEL AND OIL 36
  LABOR 36

POWER REQUIREMENTS 37

CONTENTS (continued)

Page

COSTS 41
TRUCK AND OVER-THE-ROAD TRANSPORTATION COSTS 41
TRACTOR COSTS 44
HAY 45
SILAGE COSTS 51
Direct-Cut Systems 51
Wilted Systems 58
HAY MODULE COSTS FOR DIRECT-CUT SYSTEMS 59
CROP RESIDUES 63
Bales 63
Modules 66

SUMMARY AND CONCLUSIONS 71

REFERENCES 75

APPENDIX A: MACHINERY, BALE, MODULE, AND SILAGE COSTS 77

FIGURES

Figure		Page
1	Cost of hay harvest and in-field transport versus yield for a farmer using a round baler	48
2	Effect of area (of annual use) on cost of hay harvest and in-field transport	50
3	Effect of hours of large rectangular baler operation on hay harvest and in-field transport costs	50
4	In-field harvest costs for a farmer using a pull-type forage harvester with a 3-row head at standard hours and a yield of 22 dMg/ha (10 dt/ac)	55
5	How annual harvest area affects in-field harvest costs for a farmer using a 3-row head on a pull-type forage harvester based on 22.4 dMg/ha	55
6	How hours of use affects harvest and in-field transport for a custom operator using a self-propelled forage harvester with a 6-row head based on 22.4 dMg/ha (10 dt/ac)	56
7	Effect of area on cost of hay module harvest and in-field transport (based on a pull-type forage harvester).	60
8	Effect of hours of self-propelled forage harvester operation on hay module harvest and in-field transport costs (based on one cut).	61

TABLES

Table		Page
ES1	Silage harvesting options	xiv
ES2	Machinery parameters	xvi
ES3	Areal coverage and maximum throughput for forage harvest implements	xvii
ES4	Hay, module, and silage over-the-road transportation costs for standard hours and 2000 hours of annual truck use	xviii
ES5	In-field harvest plus over-the-road transportation costs for hay bales, silage, hay modules, crop residue bales, and crop residue modules	xix
ES6	Least cost options for biomass (in-field harvest plus over-the-road transportation costs)	xx
1	Limitations on trucks	2
2	Machinery complements for hay	3
3	Mower-conditioners with specifications	4
4	Windrowers with specifications	6
5	Baler characteristics	8
6	Bale size, weight, and trailer height	10
7	Machinery complements for silage	12
8	Forage harvester specifications	15
9	Tractor size requirements for pull-type forage harvesters	16
10	High dump forage wagon characteristics	18
11	Forage harvester field efficiency as affected by dump cycle time and forage wagon capacity	20

TABLES (continued)

Table		Page
12	Forage wagon load for two different forage wagon sizes	21
13	Number of forage wagons and maximum crop yield that can be transported to field edge	22
14	Machinery complements used for hay modules	23
15	Maximum yield module builders can handle for varying numbers and types of forage harvesters	23
16	Machinery complement for crop residue harvest and transport	25
17	Upper bounds on crop residue yields	26
18	Baler characteristics harvesting crop residues	27
19	Forage harvester characteristics harvesting crop residues	29
20	Matched pairs of high dump forage wagons and their capacities	29
21	Maximum crop residue yield a matched pair of forage wagons can handle	30
22	Maximum capacity of forage harvester and wagon	31
23	Machinery parameters	32
24	Remaining value as a percentage of list price at the end of the nth year	34
25	Value of equipment as a percentage of list price at end of assumed life, based on standard hours	34
26	Power requirement parameters	38
27	Area covered and maximum yield machinery capable of handling	39
28	Hourly truck and forklift costs	42
29	The effect of annual hours of use on truck and forklift costs	42

TABLES (continued)

Table		Page
30	Transportation costs for bales, modules, and silage	43
31	Hay, module, and silage over-the-road transportation costs for standard hours and 2000 hours of annual truck use	44
32	Labor hours and energy consumption for bale, module and silage transportation	44
33	Tractor costs	45
34	Mowing, windrowing, and raking costs	45
35	Baler costs	46
36	Costs of moving bales to the field edge for standard hours	47
37	Hay harvest and in-field transport costs under varying assumption for equipment utilization, yields, and number of cuts	49
38	Hay harvest and transport costs for baseline and least-cost cases	51
39	Forage harvester costs	52
40	Costs for high dump forage wagons used for silage	53
41	In-field cost of silage harvest based on 22.4 dMg/ha (10 dt/ac)	54
42	Fuel and labor use for options 0 and 2 for silage harvest and in-field transport based on a yield of 22.4 dMg/ha (10 dt/ac)	57
43	In-field plus transport costs of silage for pull-type and self-propelled forage harvesters for two rates of annual use	58
44	Costs for forage harvesters with windrow pickup heads	60
45	Hay module harvest and in-field transport costs under varying assumption for equipment utilization, yields, and number of cuts	62
46	Hay module harvest and transport costs for baseline and least-cost cases	63

TABLES (continued)

Table		Page
47	Hourly costs for machinery used to make and move bales of crop residues	64
48	Rates and costs for machinery used to make and move bales of crop residues	65
49	In-field costs of crop residue bales	65
50	Delivered costs of crop residue bales	66
51	Cost of pick up, in-field haul, and building crop residue module (phm)	67
52	Cost of forage wagon pairs	67
53	Hourly costs by wagon size for pickup, haul, and building modules	68
54	Cost of corn residue modules using 1 module builder	69
55	Cost of small grain residue modules using 1 module builder	69
56	Maximum yield with 2 module builders	70
57	In-field and module building costs of crop residue modules as affected by yield	71
58	In-field harvest plus over-the-road transportation costs for hay bales, silage, hay modules, crop residue bales, and crop residue modules	72
59	Least cost options for biomass (in-field harvest plus over-the-road transportation costs)	74
A.1	Detailed machinery costs	78
A.2	In-field harvest costs for hay by yield, number of cuts, hours or area harvested, and type of operation	79
A.3	In-field harvest cost, diesel use and labor for a pull-type forage harvester at standard hours and a self-propelled forage harvester of 400 hours	82

ABSTRACT

An engineering-economic approach is used to calculate harvest, in-field transport, and over-the-road transport costs for hay as bales and modules, silage, and crop residues as bales and modules. Costs included are equipment depreciation; interest; fuel, lube, and oil; repairs; insurance, housing, and taxes; and labor. Field preparation, pest control, fertilizer, land, and overhead are excluded from the costs calculated. Equipment is constrained by power available, throughput or carrying capacity, and field speed.

Generally, silage is the least expensive and modules the most expensive. Custom operations are generally less expensive than farm-scale operations. Under typical conditions, costs for harvest, in-field transport, and over-the-road transport are, in \$/dMg (\$/dt):

silage (trucks in field, no forage wagons)	11-14 (10-12)
silage (trucks at field edge)	14-21 (13-19)
hay bales	19-22 (17-20)
hay modules	23-31 (21-28)
crop residue bales	18-23 (16-21)
crop residue modules	28-38 (25-34)

Under least-cost conditions, costs are, in \$/dMg (\$/dt):

silage (trucks in field, no forage wagons)	9-10 (8-9)
silage (trucks at field edge)	11-14 (10-13)
hay bales	16-19 (15-17)
hay modules	21-27 (19-25)

Least-cost conditions include high yields, a single cutting, and high rates of equipment utilization.

EXECUTIVE SUMMARY

Thin- and thick-stemmed forages are typically handled as hay and silage, respectively. In this report costs of harvest and transport for: (1) hay and crop residues as bales, (2) hay and crop residues as modules, and (3) silage are estimated.

Legal regulations affect bale size and how much, both volume and weight, a truck may carry. For our baseline case, we assume a truck may carry a load 2.59 m (8.5') wide, 3.35 m (11') high and 14.63 m (48') long, with a maximum load weight of 22,680 kg (50,000 lb).

For hay, as bales, the operations are: mowing-conditioning or windrowing, raking, baling, carrying bales to field edge, loading bales on a truck, driving the truck to the conversion facility, and unloading the bales at the conversion facility. To efficiently transport hay bales, round bales are limited to 1.80 m (5.90') diameter and 1.22 m (4') wide. Rectangular bales of 1.22 m x 1.27 m x 2.44 m (3.90' x 4.17' x 8') are an efficient size to transport. Based on round bales at 159 kg/m^3 (9.95 lb/ft^3) and rectangular bales at 188 kg/m^3 (11.72 lb/ft^3) and 12% moisture, each round bale weighs 493 kg (1086 lb) and each rectangular bale weighs 680 kg (1500 lb). For the baseline cases, trucks with 30 round bales carry 13.0 dry Mg (dMg) [14.3 dry tons (dt)]/trip and with 24 rectangular bales carry 14.4 dMg (15.8 dt)/trip.

We assume rates for mowing-conditioning and raking are independent of yield. Large round balers and large rectangular balers are constrained by their throughput capacity of 10.0 dMg/hr (11.0 dt/hr) and 20.0 dMg/hr (22.0 dt/hr), respectively, and not by the power of their tractors of 75 kW (100 hp) and 119 kW (160 hp), respectively. Bales are carried to the field edge by a 34 kW (45 hp) tractor. For large round bales both a front end loader and bale carrier are attached to the tractor, so two bales can be carried at once at a rate of 3.5 dMg/hr (3.9 dt/hr). For large rectangular bales one bale at a time is carried with a front end loader attached to the tractor at a rate of 3.0 dMg/hr (3.3 dt/hr).

To build modules from hay, one undertakes the following operations: mowing-conditioning or windrowing, raking, picking up the dried crop with a windrow pickup head on a forage harvester and blowing into a forage wagon pulled by the harvester, when the wagon is full dumping into a tractor-pulled forage wagon, the tractor taking its forage wagon to the field edge and dumping it into a module builder where modules are made. Based on making one 9.1 Mg (10 ton) module at 12% moisture [or 8.0 dMg (8.8 dt)] per hour, approximately 3 trips of a 22.7 m^3 (800 ft^3) forage wagon are required [based on dried hay at 125 dry kg/m^3 (7.8 dry lb/ft^3)]. We estimate a forage wagon can make approximately four trips per hour to the field edge. A module truck carries one module at a time.

Thick-stemmed silage crops can be handled in a direct-cut system if moisture content is below 75%, or in a wilting system if moisture content is above 75%. In a direct-cut system, the silage is chopped by a forage harvester using a row head and blown into a truck or forage wagon. In a wilting system, the silage is first cut with a mower or windrower, allowed to wilt in the field to 40 to 50% moisture, then a forage harvester with a windrow pickup head picks up the silage and blows it into a truck or forage wagon. We consider five different options for getting the silage from the forage harvester to the field edge. The five systems are summarized in Table ES1. We cost systems using pull-type and self-propelled (SP) forage harvesters. Because the silage is relatively mature at harvest, we assume it has 50% moisture content.

Table ES1. Silage harvesting options

Activity	Option				
	0	1	2	3	4
Sever using forage harvester with row head[a] (mow or windrow, wilt in field, pick up using forage harvester with windrow pickup head[b])	X	X	X	X	X
Blow into forage harvester-pulled auto steer forage wagon with roof and scale		X	X	X	
Blow into tractor-pulled forage wagon with scale					X
Blow into truck with scale, in field	X				
Detach full forage wagon from forage harvester, detach empty forage wagon from tractor, attach full forage wagon to tractor, attach empty forage wagon to forage harvester				X	
Dump forage-harvester pulled wagon into tractor-pulled wagon			X		
Dump forage wagon into truck in field		X			
Tractor takes full forage wagon to field edge			X	X	X
Dump forage wagon into truck at field edge			X	X	X
Truck travels to conversion facility	X	X	X	X	X

[a]Activity required if direct cut system is used.
[b]Activity required if wilting system is used.

We examine four options for crop residues: (1) make round or large rectangular bales, (2) use a forage harvester and make modules, (3) for small grains modify the grain combine, blow the residues into a forage wagon, move the wagon to the field edge, and make modules, and (4) for small grains haul a baler behind the combine. For corn it is necessary to mow and rake the residues before harvesting because many corn stalks are still attached to their roots after grain harvest.

An engineering-economic approach is used to calculate costs. We calculate costs for: depreciation (straight line based on purchase price minus discounted salvage value); interest; insurance, housing, and taxes (2% of initial list price per year); repairs; fuel, lube and oil; and labor. Interest is the real discount rate (6% in our base case) multiplied by the equipment's average value over its life (one half purchase price plus one half discounted salvage value). Repairs per hour are total life repair and maintenance (R&M) costs from ASAE (1995) divided by hours of life.

Fuel is diesel for all equipment and is priced at $0.211/L ($0.80/gal) for field operations and $0.304/L ($1.15/gal) for trucks (which includes road use taxes). Oil and lube costs are 15% of fuel costs. Fuel use is: L = maximum PTO (kW) * 0.252 [gal = maximum PTO (hp) * 0.04938]. Labor costs, including benefits, are $8/hr for field labor (there are 1.25 labor hours per machine hour so costs are $10/machine hour), and $15/hr for trucking.

Hourly costs and machinery parameters are listed in Table ES2. The hours listed in Table ES2 are standard hours. A more complete listing of machine parameters and costs is found in appendix Table A.1. Hours of useful life and salvage value come primarily from ASAE (1995) and are supplemented by other sources when necessary. Hours of annual use are values representative of those found in crop budgets or are reasonable for hours of use for the forage operations we examine. These hours we call standard hours. Years of life are consistent with hours of life and annual use.

Purchase price is 90% of initial list price [primary source is NAEDA (1995)]. Salvage value (as a % of initial list price) is based on ASAE (1995) formulas: tractors $68(0.920)^n$; combines, cotton pickers, SP windrowers $64(0.885)^n$; balers, forage harvesters, blowers, and SP sprayers $56(0.885)^n$; and all others $60(0.885)^n$ (where n is end of year in which salvage value is estimated). Salvage value is then discounted at 6%. The values in the power columns are either the power of the implement (tractors, forklift, and SP equipment) or the power of the tractor, SP forage harvester or windrower using the implement.

Area covered is calculated as:

ha/hr = field speed (km/hr) * implement width (m) * field efficiency (fraction)/10 or

[ac/hr = field speed (mi/hr)*implement width (ft)*field efficiency(fraction)/8.25]

Field efficiency and speed are from ASAE (1995), and equipment width is based on information in NAEDA (1995) or for row heads based on 76 cm (30") row widths. Area covered is shown in Table ES3. Also shown in Table ES3 is the maximum yield that balers and forage harvesters can handle. If the yield is higher, then the field speed must be reduced. We assume PTO power required to process the crop is [a + b * width + c * feed rate + 15 kW (20 hp)] * (1 + range), where a, b, c and range are parameters from ASAE (1995). The 15 kW (20 hp) represents the power needed for the equipment other than actual processing of the crop (e.g., air conditioning), and range represents an allowance for poor field conditions. This equation is solved for feed rate (yield) and is a conservative estimate of maximum yield. For hay, above a yield of 6.59 dMg/ha (2.94 dt/ac) for a large round baler and 10.7 dMg/ha (4.78 dt/ac) for a large rectangular baler, the balers must slow down so throughput does not exceed 10 dMg/hr (11 dt/hr) for a large round baler and 20 dMg/hr (22 dt/hr) for a large rectangular baler.

Table ES2. Machinery parameters

Implement	Power kW	Power hp	Life hr	Life years	Annual use hr	List price $	Salv. value $	Fuel L/hr	Fuel gal/hr	Repairs lifetime	Labor $/hr	Total cost $/hr
Tractor	33.6	45	12000	24	500	21000	1930	8.46	2.22	1.00	10.00	17.25
Tractor	74.6	100	12000	21.82	550	42000	4631	18.80	4.94	1.00	10.00	24.59
Tractor	119.4	160	12000	20	600	72000	9238	30.08	7.90	1.00	10.00	33.97
Tractor	156.7	210	12000	20	600	93000	11933	39.48	10.37	1.00	10.00	41.12
Front end loader	33.6	45	1000	4	250	3000	1104			0.40		3.67
Mower-conditioner	74.6	100	2500	12.5	200	10000	1303			0.80		8.89
Mower-conditioner (disk)	74.6	100	2500	12.5	200	15000	1954			1.00		14.54
Windrower-6.40m (21')	74.6	100	2500	12.5	200	8700	1134			0.70		7.39
SP windrower-4.88m (16')	74.6	100	3000	10	300	54000	10186	18.80	4.94	0.55	10.00	47.42
Rake	33.6	45	2500	12.5	200	3000	391			0.60		2.43
Rectangular baler	119.4	160	3000	5	600	65000	19761			0.80		37.52
Large round baler	74.6	100	1500	10	150	16000	2641			0.75		21.71
Forage harvester	119.4	160	2500	10	250	22000	3631			0.65		17.03
Windrow head-2.13m (7')	119.4	160	1000	10	100	3000	495			0.80		6.26
2-row head	119.4	160	2000	10	200	3600	594			0.80		3.75
3-row head	156.7	210	2000	10	200	6000	990			0.80		6.26
SP forage harvester	201.4	270	4000	10	400	116000	19146	50.76	13.33	0.50	10.00	74.05
SP forage harvester	320.8	430	4000	10	400	168000	27729	80.84	21.23	0.50	10.00	104.53
Windrow head-2.13m (7')	201.4	270	1000	10	100	3000	495			0.80		6.26
Windrow head-2.13m (7')	320.8	430	1000	10	100	3000	495			0.80		6.26
4-row head	201.4	270	2000	5	400	10000	3040			0.80		8.66
6-row head	320.8	430	2000	5	400	19000	5776			0.80		16.45
Bale carrier	33.6	45	500	2	250	500	235			0.30		0.90
Bale wagon	33.6	45	3000	10	300	3000	531			0.80		2.08
Forage wagon-scale,22.7m^3			2000	10	200	16160	2858			0.50		14.39
Forage wagon-hi dump,22.7m^3	33.6	45	2000	10	200	19200	3395			0.50		17.10
Forage wagon-scale,31.2m^3			2000	10	200	19710	3486			0.50		17.55
Forage wagon-hi dump,31.2m^3	33.6	45	2000	10	200	20500	3625			0.50		18.25
Cotton module	33.6	45	3000	7.5	400	20000	4800			0.80		12.78
Tandem truck			5000	10	500	58000	10257	17.79	4.70		15.00	38.60
Silage truck			5000	12.5	400	80000	10424	17.79	4.70		15.00	47.48
Module truck			5000	5	1000	100000	32574	17.79	4.70		15.00	43.94
Forklift	29.8	40	5000	10	500	17000	3006	7.48	1.98			9.67

Table ES3. Areal coverage and maximum throughput for forage harvest implements

Implement	Head	Power[a]		Coverage[b]		Maximum throughput[c]			
		kW	hp	ha/hr	ac/hr	dMg/hr	dt/hr	dMg/hr	dt/hr
Mower-conditioner		75	100	1.91	4.73				
Mower-conditioner (disk)		75	100	2.68	6.62				
Windrower 6.40 m(21')		75	100	3.71	9.16				
SP windrow 4.88 m(16')		75	100	3.14	7.76				
Rake 2.90 m(9.5')		34	45	2.24	5.53				
Rectangular baler		119	160	1.60	3.94	37.2	41.0	20.0	22.0
Large round baler		75	100	0.70	1.73	16.5	18.2	10.0	11.0
Forage harvester-heavy duty	Windrow head -2.13 m(7')	75	100	0.72	1.78	5.6	6.2		
Forage harvester-heavy duty	Windrow head -2.13 m(7')	119	160	0.72	1.78	11.2	12.3		
Forage harvester-heavy duty	Windrow head -2.13 m(7')	157	210	0.72	1.78	15.8	17.4		
Forage harvester-heavy duty	2-row head	119	160	0.52	1.27	13.7	15.1		
Forage harvester-heavy duty	3-row head	157	210	0.77	1.91	19.4	21.4		
SP forage harvester-201 kW (270 hp)	Windrow head -2.13 m(7')	201	270	0.84	2.08	21.4	23.6		
SP forage harvester-321 kW (430 hp)	Windrow head -2.13 m(7')	201	270	1.12	2.77	21.4	23.6		
SP forage harvester-201 kW (270 hp)	4-row head	201	270	1.20	2.97	26.2	28.9		
SP forage harvester-321 kW (430 hp)	6-row head	321	430	1.80	4.45	44.3	48.9		

[a]PTO power of tractor used or power of SP unit

[b]Not accounting for impact of rake preceding balers. A 2.9 m (9.5') wide rake puts hay into a windrow the width of the baler which increases the effective baler coverage to 1.86 ha/hr (4.61 ac/hr) for a large rectangular baler and 1.51 ha/hr (3.74 ac/hr) for a large round baler.

[c]Based on available power, except for balers which are constrained by physical throughput.

COSTS

Hourly costs at standard hours for trucks and a forklift are shown in Table ES2. Bales are put onto and taken off hay trucks using a forklift. We assume the forklift is paired with a truck, and in an 8 hour workday, each is operated 4 hours. A module truck loads and unloads modules using its tipping bed. Silage is loaded into a silage-hauling truck either by being directly blown into the truck, or from a high dump forage wagon, and we assume the silage truck dumps its load at the conversion facility. Hay, module and silage trucks make 3, 5, and 4 round trips per day, respectively. Transportation costs for standard hours and 2000 annual hours of use are in Table ES4. Baseline case costs for hauling are $6.48/dMg ($5.88/dt) for 1.80 m (5.90') diameter large round bales, $5.87/dMg (5.33/dt) for 24 large rectangular bales, $8.81/dMg ($7.99/dt) for modules, and $8.37/dMg ($7.60/dt) for 50% dry matter silage.

Table ES4. Hay, module, and silage over-the-road transportation costs for standard hours and 2000 hours of annual truck use

Type of biomass and packaging		Cost ($/dMg)		Cost ($/dt)		
	Standard hours	Standard hours	2000 hours	Standard hours	2000 hours	Percent change
Hay						
Round bales - 30/load, 1.80 m (5.90') diameter	500	6.49	5.53	5.89	5.02	15
Round bales - 30/load, 1.83 m (6.00') diameter	500	6.26	5.34	5.68	4.84	15
Rectangular bales - 24/load	500	5.87	5.01	5.33	4.54	15
Rectangular bales - 32/load	500	4.48	3.75	3.99	3.41	15
Modules	1000	8.81	7.77	7.99	7.05	12
Silage						
70% moisture	400	13.96	10.36	12.66	9.40	26
50% moisture	400	8.37	6.22	7.60	5.64	26

Costs for standard hours for farm-scale equipment and actual hours for custom operator-scale equipment, for two yield levels, are summarized in Table ES5. In general, we expect the silage type crops to have a higher yield, but costs can be compared among hay bales, silage, and hay modules for a yield of 15.7 dMg/ha (7 dt/ac). Crop residues in Table ES5 fall in a range of $18 to $23/dMg ($16 to $21/dt). The lowest cost option is silage when dumping directly into trucks in the field (option 0), $11 to $14/dMg ($10 to $12/dt). Silage option 0 minimizes the handling of biomass. If two wagons are needed and the truck is loaded at the field edge (option 2), then costs are $14 to $21/dMg ($13 to $19/dt). At equal yields, 15.7 dMg/ha (7 dt/ac), costs are similar between hay bales and silage using two wagons (option 2). The highest harvest, in-field transport, and over-the-road transport costs are for modules, ranging from $23 to $31/dMg ($21 to $28/dt) for hay and $28 to $38/dMg ($25 to $34/dt) for crop residues. In general, costs are lower for a custom operator operating 400 hours than a farmer operating at standard hours.

Table ES5. In-field harvest plus over-the-road transportation costs for hay bales, silage, hay modules, crop residue bales, and crop residue modules

Crop and equipment	Hours	Yield (dMg/ha)	Cost ($/dMg)	Yield (dMg/ha)	Cost ($/dMg)
Hay					
Round baler	Standard	9.0	21.75	15.7	20.48
Rectangular baler	400	9.0	20.60	15.7	18.85
Silage					
Pull-type, 3-row head (option 0)	Standard	15.7	13.69	22.4	12.09
SP, 6-row head (option 0)	400	15.7	12.65	22.4	11.38
Pull-type, 3-row head (option 2)	Standard	15.7	20.55	22.4	16.90
SP, 6-row head (option 2)	400	15.7	17.38	22.4	14.43
Modules					
Pull-type	Standard	9.0	30.69	15.7	28.42
SP	400	9.0	27.46	15.7	22.98
Crop residues-corn					
Round baler	Standard	6.7	22.30	10.1	19.82
Rectangular baler	400	6.7	23.09	10.1	19.36
Modules, pull-type	Standard	6.7	32.43	10.1	27.60
Modules, SP	400	6.7	32.56	10.1	28.10
Crop residues-small grains					
Round baler	Standard	2.2	20.76	3.4	18.17
Rectangular baler	400	2.2	21.97	3.4	19.30
Modules, pull-type	Standard	2.2	37.47	3.4	27.91
Modules, SP	400	2.2	37.65	3.4	28.04
Crop and equipment	Hours	Yield (dt/ac)	cost ($/dt)	Yield (dt/ac)	cost ($/dt)
Hay					
Round baler	Standard	4	19.73	7	18.58
Rectangular baler	400	4	18.69	7	17.10
Silage					
Pull-type, 3-row head (option 0)	Standard	7	12.42	10	10.97
SP, 6-row head (option 0)	400	7	11.48	10	10.32
Pull-type, 3-row head (option 2)	Standard	7	18.64	10	15.33
SP, 6-row head (option 2)	400	7	15.77	10	13.09
Modules					
Pull-type	Standard	4	27.84	7	25.78
SP	400	4	24.91	7	20.85
Crop residues-corn					
Round baler	Standard	3	20.23	4.5	17.98
Rectangular baler	400	3	20.95	4.5	17.56
modules, pull-type	Standard	3	29.42	4.5	25.04
modules, SP	400	3	29.54	4.5	25.49

Table ES5 (continued)

Crop and equipment	Hours	Yield (dMg/ha)	Cost ($/dMg)	Yield (dMg/ha)	Cost ($/dMg)
Crop residues-small grains					
Round baler	Standard	1	18.83	1.5	16.48
Rectangular baler	400	1	19.93	1.5	17.51
Modules, pull-type	Standard	1	33.99	1.5	25.32
Modules, SP	400	1	34.16	1.5	25.44

We have also calculated some least-cost scenarios, which, under the assumptions we made (e.g., interest rate, wage rate), represent as low as possible costs one might achieve (Table ES6). Equipment and labor are utilized to what might be considered a maximum. Silage (option 0) cost is as low as $9 to $10/dMg ($8 to $9/dt). If two wagons are needed (option 2) then costs increase to $11/dMg ($10/dt). Note that at high hours of operation and high yield, the gap narrows between silage options 0 and 2. Hay bales cost between $16 and $19/dMg ($15 and $17/dt) and hay modules between $21 and $27/dt ($19 to $25/dt).

Table ES6. Least cost options for biomass (in-field harvest plus over-the-road transportation costs)

Type of biomass and equipment	Yield		Description	Hours/area	Cost	
	dMg/ha	dt/ac			$/dMg	$/dt
Hay						
Round baler	15.7	7	1 cut,1.83 m(6') dia	202 ha(500 ac), 2000 hr/truck	18.82	17.07
Rectangular baler	15.7	7	1 cut, 32/truck	1000 hr/baler, 2000 hr/truck	16.06	14.57
Silage						
3-row, pull-type	22.4	10	option 0	405ha(1000 ac),2000 hr/truck	9.82	8.91
6-row, SP	22.4	10	option 0	2000hr/forage harvester,2000 hr/truck	8.76	7.95
3-row, pull-type	22.4	10	option 2	405ha(1000 ac),2000 hr/truck	14.40	13.06
6-row, SP	22.4	10	option 2	2000hr/forage harvester,2000 hr/truck	11.47	10.40
Hay modules						
Pull-type	15.7	7	1 cut	202 ha(500 ac), 2000 hr/truck	27.19	24.67
SP	15.7	7	1 cut	1000hr/forage harvester,2000 hr/truck	20.61	18.70

The generalized costs presented are based on the assumptions shown in the tables. If hours of operation and/or area harvested, and yields are changed, the costs can change significantly. At low hours of operation and low yields, costs can be considerably higher.

We have calculated harvest, in-field transport, and over-the road transport costs. We have not included land rent, overhead, fertilizer, weed control, land preparation, storage, and handling at the conversion facility costs. These excluded costs can be considerable.

What we have shown is that with good equipment utilization rates and high yields; harvest, in-field transport, and over-the road transport costs can be as low as \$9 to \$21/dMg (\$8 to \$19/dt).

INTRODUCTION

There are two types of forages: thin-stemmed (e.g., switchgrass) and thick-stemmed (e.g., sweet sorghum, energy cane). Thin-stemmed species can be handled as silage (60%–70% moisture[1]), haylage (40%–50% moisture), or hay (10%–20% moisture). Thick-stemmed species can be handled as silage or haylage. The handling systems considered for silage and haylage are the same, and, henceforth, we will call both systems silage. There are exceptions to how different species are handled. Some thick-stemmed species may be too dry at harvest to be handled as silage, and some thin-stemmed species may not be dry enough to be treated as hay.

For haying systems the basic operations are mowing or (windrowing), raking, baling, and transport. Raking or windrow turning between mowing or windrowing and bailing may or may not be needed. For silage, the system used depends upon whether the crop requires some field drying (known as wilting). If no field drying is required, then one would harvest with a forage harvester which severs the stalk, chops it, and blows it into a forage wagon or truck. The forage can then be transported to a silo for storage, or some densification operation could take place before transport from the field and storage.

The objective of this report is to develop appropriate machinery complements for hay, haylage, and silage operations as well as crop residue harvest. The appropriate machinery complement will vary by farm size and for a custom harvest operation. There are very wide ranges in the capital cost of some of the machinery options. For example, a pull-type forage harvester can cost as little as $14,000, while a self-propelled (SP) forage harvester can cost as much as $170,000, with many options in between. There is a tradeoff between capital cost of equipment and labor requirements. To effectively use the more expensive equipment either a very large farm or a custom operation is required.

Legal regulations on truck characteristics affect the choice of bale size for hay and how much can be carried by a single truck. Weight and dimension regulations for trucks are summarized in Table 1. A truck cab and load is limited to 36.29 Mg (80,000 lb). With an assumed cab and trailer weight of 13.61 Mg (30,000 lb), the load is limited to 22.68 Mg (50,000 lb). Width, height, and length are limited to 2.59 m (8.5'), 4.27 m (14') and 16.16 m (53'), respectively. We assume a trailer length of 14.63 m (48').

Parameter and cost data for equipment used for hay, silage, and crop residue harvest and transport are listed in appendix Table A1. This table contains much of the data needed for this report. How these data were obtained and derived is explained in the sections that follow. Much detailed information is presented in the report. The purpose of providing detailed information is to allow an interested reader to reproduce the calculations in the report or to perform their own calculations using different assumptions.

Costs are in 1995 dollars.

---

[1]Moisture is on a wet weight basis.

Table 1. Limitations on trucks

Weight	kg	lb
Total	36,290	80,000
Cab & trailer	13,610	30,000
Load	22,680	50,000
Dimensions	m	ft
Width	2.59	8.5
Height		
Total	4.27	14
Bed	0.91	3
Load	3.35	11
Length[a]	16.16	53

[a]Longest single trailer manufactured.

Hay

Basic hay operations are: cutting, raking, field drying to 12% moisture, baling, moving bales to the field edge, loading on a truck, and hauling to the conversion facility. There are a number of different options for packaging hay: small rectangular bales, large round bales, and large rectangular bales. We do not consider small rectangular bales as an option because compared to large round bales they have higher labor requirements with no saving in capital cost. Because of the 8.5' width limit of trucks, we only consider 4' wide round bales, which minimizes transportation costs. Large rectangular balers produce more dense bales than large round balers; plus their rectangular shape allows for more efficient transport than a round bale. Options for hay harvest and transport are summarized in Table 2.

The first operation in haying is cutting the standing crop. This is accomplished with either a mower-conditioner (the conditioner speeds crop drying) or a windrower. Windrowers are faster than mower-conditioners. Most mower-conditioners are pull-type. There presently are no new self-propelled mower-conditioners on the market, although there have been in the past and are expected to be in the future. Mower-conditioners range in cutting width from 2.21 to 4.95 m (7.25' to 16.25') and in price from $9,000 to $21,000 (Table 3). Mower-conditioners with cutting widths of 2.2 to 3.7 m (7' to 12') require 37 to 75 kW (50 to 100 hp) tractors. Windrowers can either be pull type or self propelled. Most self-propelled windrowers have header widths of 3.66 to 6.40 m (12' to 21') and cost in the range of $34,000 to $54,000. Self-propelled windrowers are available with up to a 9.15 m (30') header width. Pull types range in width from 6.4 to 15.2 m (21' to 50') and cost from $9,000 to $30,000 (Table 4).

Table 2. Machinery complements for hay

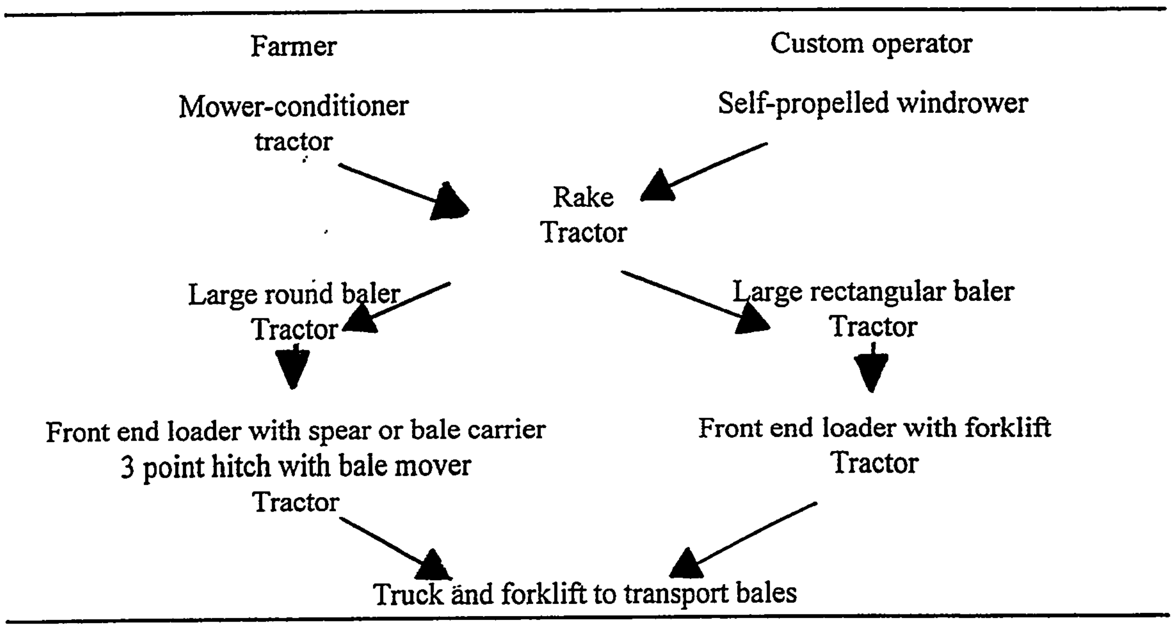

Table 3. Mower-conditioners with specifications

Manufacturer and model number	Cutting width		Weight		List price ($)	Knives (k) or discs (d)
	(m)	(ft)	(kg)	(lb)		
AGCO Hesston						
1110	2.21	7.25	1463	3225	8830	k
1120	2.82	9.25	1588	3500	9690	k
1130	2.82	9.25	1669	3680	11090	k
1150	3.66	12	2146	4730	13990	k
1160	4.27	14	2540	5600	17680	k
1170	4.88	16	2948	6500	20165	k
1320	2.80	9.17	1702	3752	13700	d
1340	3.66	12	2293	5055	17760	d
AGCO New White						
5209	2.82	9.25	1669	3680	14030	d
5212	3.58	11.75	2189	4825	17460	d
Case IH						
8320	2.21	7.25	1424	3140	9060	k
8330	2.82	9.25	1588	3500	10030	k
8340	2.82	9.25	1492	3290	11780	k
8350	3.66	12	2041	4500	14450	k
8370	4.27	14	2540	5600	18830	k
8380	4.88	16	2937	6475	20720	k
8309	2.80	9.17	1778	3920	14380	d
8312	3.66	12	2402	5295	17940	d
Ford New Holland						
472	2.21	7.25	1137	2506	9380	k
488	2.82	9.25	1364	3006	9590	k
492	2.82	9.25	1474	3250	10980	k
499	3.73	12.25	2146	4730	17250	k
116	4.95	16.25	2550	5622	18880	k
408	2.49	8.17	1461	3220	12430	d
Flail disc 412	2.97	9.75	1573	3468	12650	d
411	2.97	9.75	1679	3701	14980	d
415	3.51	11.5	1872	4127	15440	d

Table 3 (continued)

Manufacturer and model number	Cutting width		Weight		List price ($)	Knives (k) or discs (d)
	(m)	(ft)	(kg)	(lb)		
Gehl						
2175	2.82	9.25	1490	3285	11363	k
2245	3.73	12.25	2575	5678	16647	k
2275	4.34	14.25	2658	5860	17842	k
DC2340	2.77	9.08	1542	3400	13532	d
DC2360	3.15	10.33	1724	3800	15088	d
John Deere						
1217	2.21	7.25	1129	2490	10030	k
1219	2.82	9.25	1393	3070	11060	k
1600	4.27	14.00	2631	5800	20130	k
1600	4.88	16.00	2631	5800	20880	k
920	2.97	9.75	1855	4090	14800	d
930	3.51	11.50	2059	4540	17700	d
Krone Niemeyer						
AM230CV	1.98	6.5	660	1454	9650	d
AM242CV	2.39	7.83	760	1676	10590	d
AM243CV	2.39	7.83	760	1676	10150	d
AM283CV	2.79	9.17	490	1080	11930	d
AMT283CV	2.79	9.17	1402	3090	15880	d
AMT323CV	3.20	10.5	1701	3750	17280	d
MacDon						
4000	2.82	9.25	1601	3530	12140	k
5000	4.27	14	3130	6900	19040	k

Source: NAEDA (1995).

Table 4. Windrowers with specifications

Manufacturer and model	Fuel	Width (m)	Width (ft)	Weight (kg)	Weight (lb)	List price ($)	Price change ($) for 4.26 m (14') head	4.88 m (16') head	5.49 m (18') head
	Self propelled								
AGCO Hesston									
8100	Gasoline	4.88	16	2722	6000	34541		std[a]	
8200	Diesel	4.27	14	4019	8860	36691	std	600	
8400	Diesel	4.27	14	5012	11050	49154	std	800	
Case IH									
8820	Gasoline	4.88	16	4132	9110	38790	std		
8830	Diesel	4.27	14	4112	9065	43800	std	500	
8840	Diesel	4.88	16	4926	10860			std	
Ford New Holland									
2450	Diesel	3.66	12	4806	10595	46560	1000[b]	2000	
2550	Diesel	4.27	14	4967	10950	52750	std	1000	1500
John Deere									
3430	Diesel	4.27	14	3877	8547	44280	std	1500	
3830	Diesel	4.88	16	4673	10301	53900		std	
MacDon									
9000	Gasoline	6.40	21	4246	9360	32832			
9000	Gasoline	7.62	25	4373	9640	34474			
9000	Gasoline	9.15	30	4513	9950	36115			
	Pull type								
MacDon									
3000		6.40	21	3968	8748	3100			
3000		7.62	25	4409	9720	3400			
3000		9.15	30	4850	10692	3750			
3000		10.98	36	5511	12150	4500			
3000(duplex)		15.24	50	8818	19440	8724			

[a]Standard head.
[b]3.66 m (12') head standard.
Source: NAEDA (1995).

Depending on drying conditions and the biomass, it may be necessary to use a rake or windrow turner to allow the bottom of a windrow to dry sufficiently. A rake or windrow turner costs about $4,000 and requires a 30 to 45 kW (40 to 60 hp) tractor.

Large round balers range in price from $9,000 to $20,000 with maximum bale diameters ranging from 0.91 to 1.91 m (3' to 6.25') and bale widths from 1.17 to 1.83 m (3.83' to 6') (Table 5). Truck bed width is limited to 2.59 m (8.5') and height is limited to 4.27 m (14'). Assuming a truck bed height of 0.91 m (3'), stacked hay is limited to a height of 3.35 m (11'). Because of highway transportation restrictions, we only consider balers with bale widths of 1.22 m (4') and bale diameters of 1.80 m (5.90') (Table 5).

The derivation of these sizes is explained in more detail under the section on transport. There are four manufacturers of large round balers meeting these specifications. List prices range from $14,400 to $17,700.

Power requirements are listed for balers in brochures, but in talking with people in the industry, they indicate that a larger tractor size is advised, although there is disagreement of the exact size. For example, a Ford New Holland Model 650 large round baler [bale diameter of 0.92 to 1.78 m (3' to 5.83') and bale width of 1.18 m (3.88')] lists a minimum PTO requirement of 49 kW (65 hp). We use a tractor with a PTO output of 75 kW (100 hp).

Large round balers meeting the 1.22 m (4') width specification can make bales of up to 680 kg (1500 lb) at a diameter of 1.83 m (6'). If we assume a typical bale is 75% of maximum weight and a constant density, then a 1.83 m (6') diameter bale would weigh 510 kg (1125 lb), a 1.80 m (5.90') diameter bale would weigh 493 kg (1087 lb), and a 1.63 m (5.33') diameter bale would weigh 403 kg (889 lb).

At present there is only one large rectangular bale maker, AGCO Hesston. Model 4900 makes bales 1.18 m (3.88') high, 1.27 m (4.17') wide and 2.44 m (8') long, with a maximum weight of 907 kg (2000 lb). Again we assume an actual weight of 75% of maximum or 680 kg (1500 lb). List price is $65,000 (Table 5). We use a tractor with a PTO output of 119 kW (160 hp).

Balers are also limited by physical throughput. Implement & Tractor (1995) lists a baler capacity of 27.2+ Mg/hr (30+ tons/hr) for the AGCO Hesston Model 4900, but for the most round balers does not list a capacity. Hunt (1983) lists large round baler capacity of 5 to 13 Mg/hr (6 to 14 tons/hr). It is unclear whether these capacities are for continuous operation (i.e. 100% field efficiency) and the upper end of the range is probably for heavier bales than we assume. To take these factors into account we assume a 10.0 dry Mg (dMg)/hr [11.0 dry ton (dt)/hr] capacity for a large round baler and a 20.0 dMg/hr (22.0 dt/hr) capacity for a large rectangular baler, based on an hour period in which the baler operates at its assumed field efficiency (65% for a large round baler and 80% for a large rectangular baler).

Table 5. Baler characteristics

Manufacturer and model number	Maximum bale size				Maximum bale weight		Pickup width		List price	Baler weight	
	Width (m)	Diameter (m)	Width (ft)	Diameter (ft)	(kg)	(lb)	(m)	(ft)	($)	(kg)	(lb)
AGCO Hesston											
4900	[a]	[a]	[a]	[a]	907	2000	2.477	8.125	64950	8437	18600
555T	1.18	1.91	3.875	6.25	726	1600	1.473	4.833	1656	2486	5480
555S	1.18	1.91	3.875	6.25	726	1600	1.473	4.833	14430	2177	4800
Case IH											
8455	1.18	1.91	3.875	6.25	756	1666	1.473	4.833	15030	2218	4890
Ford New Holland											
650[b]	1.18	1.83	3.875	6	680	1500	1.340	4.396	17670	263	580
John Deere											
435	1.17	1.83	3.833	6	680	1500	1.166	3.825	17250	1889	4165

[a]Rectangular bale 1.22 m x 1.27 m x 2.19 m (3.90' x 4.17' x 8').
[b]Optional 1.74 m (5.71') wide pickup available for $800.

TRANSPORTATION AND BALE SIZE

We need to select optimum bale sizes given baler specifications and transport restrictions. We assume that bales are transported on standard flat-bed trailers 14.63 m (48') long, 2.59 m (8.5') wide, and a with bed height of 0.91 m (3'). The total height of the bed plus stacked hay must be less than or equal to 4.27 m (14'). Thus the hay may be stacked up to 3.35 m (11') high.

For large round bales stacked two high, the maximum bale diameter possible to still meet the 3.35 m (11') height limitations is 1.80 m (5.90'). A 1.80 m (5.90') diameter bale weighs 493 kg (1087 lb). On the 14.63 m (48') long trailer bed, two rows of eight bales on the bottom plus two rows of seven bales on the top allows for 30 bales or a total of 14.79 Mg (16.30 tons). If the bales are reduced in diameter to 1.63 m (5.33'), then the bottom rows can contain nine bales and the top rows eight bales weighing 403 kg (889 lb), for a total of 34 bales weighing 13.71 Mg (15.11 tons). For a 7% decrease in load, four (13%) more bales must be handled. Reducing diameter to accommodate more bales is not a viable option.

If the height of the trailer bed could be lowered by 0.051 m (0.167') to only 0.856 m (2.80'), then 1.83 m (6') diameter bales can be stacked two high, allowing for 30–510 kg (1125 lb) bales weighing a total of 15.31 Mg (16.88 tons) to be transported. Unless the bales could be made more dense, 15.31 Mg (16.88 tons) is the maximum weight of large round bales that can be carried on a 14.63 m (48') long trailer. By using a trailer with a lower bed, payload can be increased by about 3.5% versus a standard trailer.

For large rectangular bales, on a standard trailer, 24–680 kg (1500 lb) bales (four long by two wide by two high) can be carried for a total of 6.33 Mg (18 tons). If the height of the center 9.75 m (32') of the trailer is reduced to 0.724 m (2.38'), allowing 2.43 m (8') in width for standard wheels at the ends of the trailer, then 32 bales weighing a total of 21.77 Mg (24 tons) can be carried. If the height of the whole trailer is reduced to 0.724 m (2.38'), then 36 bales weighing 24.49 Mg (27 tons) can be hauled. However, 36 bales would exceed the allowed load weight of 22.7 Mg (25 tons).

The weight of hay hauled as a function of bale type, size, and trailer height are summarized in Table 6.

On a standard trailer, 10% more weight can be carried with large rectangular bales than large round bales. If the trailer can be modified to a lower height to accommodate three high stacking of large rectangular bales (32 bales), or two rows of 1.83 m (6') diameter large round bales, then 42% more weight can be carried with rectangular bales than round bales.

IN-FIELD TRANSPORTATION

Bales may be carried to the field edge on tractors or wagons attached to tractors, by pickup truck, or by flatbed truck. Assuming that the average haul distance from the field to the edge of the field where the bales are temporarily stored is 0.6 km (0.375 mi) for a round trip distance of 1.2 km (0.75 mi) and that the tractor travels at 8 km/hr (5 mi/hr), then the average travel time is 9 minutes. At this relatively short haul distance, transporting bales on tractors is probably as efficient as loading, moving, and unloading

Table 6. Bale size, weight, and trailer height

Bale type	Diameter		Trailer type	Trailer height		Weight of bale		Number of bales carried	Total weight carried	
	m	ft		m	ft	kg	lb		Mg	tons
Round	1.80	5.90	Standard	0.91	3.0	493	1086	30	14.79	16.30
Round	1.63	5.33	Standard	0.91	3.0	403	889	34	13.70	15.11
Round	1.83	6.00	Low	0.86	2.8	510	1125	30	15.30	16.88
Rectangular[a]	-	-	Standard	0.91	3.0	680	1500	24	16.32	18.00
Rectangular[a]	-	-	Low in Middle	0.91/ 0.72 4	3.0	680	1500	32	21.76	24.00

[a]Rectangular bale 1.22 m x 1.27 m x 2.19 m (3.90' x 4.17' x 8').

bales onto wagons or trucks. We assume hay bales are moved to the field edge with 34 kW (45 hp) tractors.

For large round bales two are carried at a time, one bale is moved on a spear attached to the front end loader and the other is carried on a bale mover mounted on the tractor's three-point hitch. Allowing 15 minutes per round trip (9 minutes travel time plus 6 minutes to load, unload, and down time), then 8 bales are hauled to the field edge per hour. An estimate of four trips per hour is close to number of trips per hour in Rider et al (1993) (p.242), although the parameter values used to arrive at the number of trips per hour are different. For 1.80 m (5.90') diameter bales of 493 kg (1087 lb) each at 88% dry matter, 3.5 dMg (3.87 dry tons) per hour are moved. For 1.83 m (6') diameter bales of 510 kg (1125 lb) each at 88% dry matter, 3.6 dMg (4.0 dry tons) per hour are moved.

For large rectangular bales a single 680 kg (1500 lb) bale is carried on a forklift attached to the front end loader. Allowing 12 minutes per round trip (9 minutes travel time and 3 minutes unload and downtime), then at 88% dry matter 3.0 dMg (3.3 dry tons) are hauled to the field edge per hour.

TRANSPORTATION

Hay is moved from the edge of the field to the conversion facility on a truck with a 14.6 m (48') tandem trailer. Bales are loaded and unloaded with forklifts. Data for 1992 list a tandem truck price of $46,000 with repair costs of $2.30/hr and fuel consumption of 17.8 L/hr (4.7 gal/hr) (Fuller et al 1992). The price listed is the net cost. To allow for inflation and dealer discounting of the truck, we adjust the list price of the tandem truck to $58,000 and increase repair costs 10% to $2.53/hr in 1995 dollars.

For the forklift we assume a 30 kW (40 hp) engine with a list price of $17,000, and repair costs of twice those of a 34 kW (45 hp) tractor, $3.50/hr. The $17,000 list price is based on list prices for 30 kW (40 hp) skid loaders listed in *Guides 2000* (NAEDA 1995). Weight is approximately 2 Mg (2.2 tons). Diesel fuel is used and consumption is based on the same ASAE methodology used for tractors and self-propelled equipment.

Critical to costing transport is the number of trips a truck can make in a day. Assuming an average loading or unloading time of 1.33 minutes per bale, and an hour for round trip travel from the conversion facility to the field edge and back [a typical trip is 40 km (24 miles) each way], and 1/3 hour for miscellaneous activities; then for 24, 30 and 32 bales; a round trip takes 2.40, 2.67, and 2.76 hours respectively, and 3.33, 3.00, and 2.90 round trips can be made in an eight hour day. We assume for hay that a truck makes 3 round trips per day.

Truck and forklift use can be done in a number of ways. A truck and forklift always travel together, and the truck driver also operates the forklift. Dedicated forklifts are at the loading area at the field edge and at the unloading area at the conversion facility. In this latter case, if there are dedicated forklift operators, then the truck driver is idle while the truck is being loaded and unloaded, unless the truck cab is detached and then attached to another truck that is ready to leave either the loading or unloading area. We assume a truck and forklift travel together.

SILAGE AND HAYLAGE

Generally thick-stemmed crops such as energy cane, napiergrass, and forage or sweet sorghum have to be handled and stored as high moisture feedstocks (40–70% moisture). It is unlikely that these crops will field dry to below 20% moisture. In arid climates, such as the southwest, thick-stemmed crops might dry to 20% moisture and be handled as hay.

Two methods are available for handling high moisture crops: (1) a direct cut system and (2) a wilting (cut, wilting in the fields, and pick up) system. If moisture content of the crop at harvest is below 75%, the direct cut system can be used, otherwise it is necessary to reduce the crop's moisture content by letting it wilt in the field between 2 hours and 2 days. Wilting reduces the moisture content to 40 to 50%. In general it is preferable to use the direct cut-system because less operations are involved and handling losses are less. Options for silage harvest are summarized in Table 7 and are discussed in more depth in the sections that follow. Four options for direct-cut silage are considered. All use a forage harvester to cut the crop. In option 0 the crop is then blown directly into a truck in the field. In option 1 the crop is blown into a wagon pulled by the forage harvester, then dumped into a truck in the field. In option 2 the crop is blown into a wagon pulled by the forage harvester, then dumped into a tractor-pulled forage wagon, and then dumped into a truck at the field edge. In option 3 the crop is blown into a wagon pulled by the forage harvester and unhitched when full and replaced by an empty wagon. The full wagon is then hitched to a tractor and hauled to the field edge and dumped into a truck. In option 4 the crop is blown into a wagon pulled by a tractor, which takes the filled wagon to the field edge where the wagon is dumped into a truck. We cost options 0, 1, and 2 for direct-cut systems.

Table 7. Machinery complements for silage

Farmer					
Direct cut					Wilting[a]
Option 0 Blow directly into truck in field	Option 1 Blow into wagon pulled by forage harvester, dump into truck in field	Option 2 Blow into wagon pulled by forage harvester, dump into tractor-hauled wagon, dump into truck at field edge	Option 3 Blow into wagon, detach wagon, attach to tractor, dump into truck at field edge	Option 4 Blow into wagon pulled by tractor, take to field edge, dump into truck at field edge	
Forage harvester with 2-or 3-row head tractor	Forage harvester with 2- or 3-row head auto-steer high dump (HD) forage wagon with roof and scale tractor			Forage harvester with 2- or 3-row head	Mower-conditioner or windrower tractor
					Forage harvester with windrow pickup head HD forage wagon with roof and scale tractor
		HD forage wagon without roof tractor	Tractor	Forage wagon with scale tractor	HD forage wagon without roof tractor
Truck filled in field and then travels to conversion facility		Truck filled at field edge and then travels to conversion facility			

Table 7 (continued)

<table>
<tr><td colspan="6">Custom operator</td></tr>
<tr><td colspan="5">Direct cut</td><td>Wilting[a]</td></tr>
<tr><td>Option 0

Blow directly in truck in field</td><td>Option 1

Blow directly into wagon pulled by forage harvester, dump into truck in field</td><td>Option 2

Blow into wagon pulled by forage harvester, dump into tractor-hauled wagon, dump into truck at field edge</td><td>Option 3

Blow into wagon, detach wagon, attach to tractor, dump into truck at field edge</td><td>Option 4

Blow into wagon pulled by tractor, take to field edge, dump into truck at field edge</td><td></td></tr>
<tr><td rowspan="3">SP forage harvester with 4-, 5-, or 6-row head</td><td colspan="3" rowspan="2">SP harvester with 4-, 5-, or 6-row head
HD forage wagon with roof and scale</td><td rowspan="2">SP harvester with 4-, 5-, or 6-row head</td><td>SP windrower</td></tr>
<tr><td>SP forage harvester with windrow pickup head
HD forage wagon with roof and scale</td></tr>
<tr><td></td><td>HD forage wagon without roof
tractor</td><td>Tractor</td><td>Forage wagon with scale
tractor</td><td>HD forage wagon without roof
tractor</td></tr>
<tr><td colspan="2">Truck filled in and then travels to conversion facility</td><td colspan="4">Truck filled at filed edge and then travels to conversion facility</td></tr>
</table>

[a]Assumed to follow option 2 under direct cut for handling once picked up by the forage harvester. Option 0 would exclude all forage wagons and option 1 would not use the forage wagon without the roof.

DIRECT CUT

The direct-cut system requires a forage harvester to blow the cut material into a forage wagon or truck. The length of the chopped material can be controlled by changing the knife configuration on the forage harvester. Forage harvesters can either be tractor pulled (pull type) operating off the tractor's power takeoff (PTO) or self propelled. One advantage of a self-propelled over a pull-type forage harvester is that cutting takes place in front of the machine, not behind. We assume a small farmer doing his own harvesting would use a pull-type forage harvester while a very large farmer or custom operator would use a self-propelled forage harvester. This decision is based upon costs.

Pull-type forage harvesters range in price from $14,000 (least cost 2 row) to $29,000 (highest cost 3 row), while self-propelled forage harvesters, including a head, range from $126,000 (least cost 4 row) to $187,000 (highest cost 6 row) (Table 8). If a farmer did not have a large enough tractor to pull a 3-row pull-type harvester, such as a 157 kW (210 hp) tractor with a capital cost of about $93,000, then the farmer might want to consider the least cost self-propelled option ($116,000).

From Ford New Holland (1995) we have data on tractor size requirements for pull-type forage harvesters (Table 9). The exact size tractor a farmer will use depends upon field conditions, crop quantity, and number of rows being cut, as well as what size tractors the farmer has available. While a custom operator can more easily optimize tractor size for a pull-type harvester, we assume that custom harvesters will use self-propelled models.

Table 8. Forage harvester specifications

Manufacturer and model	Power (kW)	Power (hp)	Windrow size (m)	Windrow size (ft)	Rows on heads	Weight (kg)	Weight (lb)	List price no head ($)	Windrow head ($)	1 row head ($)	2 row head ($)	3 row head ($)	
	Pull type												
AGCO Hesston													
7170			2.13	7	2, 3	2807	6189	22440	3000		3400	5600	
Case IH													
8750			2.13	7	2, 3	2458	5418	25110	3000		3400	5600	
Ford New Holland													
718			1.68	5.5	1, 2	1310	2889	12140	1900	2300	3800		
790			1.68	5.5	1, 2	1707	3763	15120	1900	2300	3800		
900			2.03	6.67	2, 3	2297	5065	19150	3000		3800	6400	
Gehl													
865			1.83, 2.13	6, 7	1, 2	1815	4001	13528	1500, 2600	1500	3400		
1065			1.83, 2.13	6, 7	2, 3	2153	4747	17940	1500, 2600		3400	5600	
1265			1.83, 2.13	6, 7	2, 3	2510	5533	23634	1500, 2600		34000	5600	
John Deere													
3950			1.68, 2.13	5.5, 7	2, 3	NA	NA	17380	2400, 3600		3600	6000	
3970			1.68, 2.13	5.5, 7	2, 3	NA	NA	22020	2400, 3600		3600	6000	
	Self propelled												
										3 row head ($)	4 row head ($)	5 row head ($)	6 row head ($)
Ford New Holland													
1915	201	270	2.13	7	3, 4	7076	15600	116640			9000		12000
2115	242	325	2.13	7	4, 6	7507	16550	138870			9000		12000
John Deere													
6610	201	270	2.13	7	3, 4	NA	NA	118310	3000	7500	11000		
6710	246	330	2.13	7	3, 4, 5, 6	NA	NA	137620	3000	7500	11000	14500	19000
6810	280	375	2.13	7	6	NA	NA	155440	3000				19000
6910	321	430	2.13	7	6	NA	NA	167830	3000				19000

Source: NAEDA (1995). NA= not available.

Table 9. Tractor size requirements for pull-type forage harvesters

Ford New Holland Model Number	PTO Size				Weight	
	Minimum		Maximum			
	kW	hp	kW	hp	lb	kg
718	45	60	67	90	2889	1310
790	60	80	97	130	2889	1310
900	101	135	142	190	5065	2297

Source: Ford New Holland (1995).

WILTING

For the wilting system, the forage would be cut with a mower or windrower. Mower-conditioners and windrowers were previously listed in tables 3 and 4. All mower-conditioners are pull type, and all windrowers are self propelled except for one MacDon model. Self-propelled windrowers cost between $33,000 and $54,000, with less expensive ones being gasoline powered. Most have cutting widths ranging from 3.66 to 5.49 m (12' to 18'), with the less expensive ones being various versions of the gasoline-powered MacDon model 9000 which has a cutting width from 6.40 to 9.15 m (21' to 30'). The MacDon model is also sold by Ford New Holland and John Deere. Only MacDon makes a pull-type windrower (also sold by Ford New Holland and John Deere), with costs ranging from $8,700 to $19,400. Mower-conditioners have cutting widths from 2.21 to 4.95 m (7.25' to 16.25') and range in cost from $9,000 to $21,000.

After the forage has wilted to 40 to 50% moisture, a forage harvester with a windrow pickup head is used to pick up the crop, and then the crop is blown into a wagon or truck as in the direct-cut system.

IN-FIELD TRANSPORTATION

Silage can be transported by trucks or wagons, or a combination of trucks and wagons. The silage or haylage systems under consideration handle large volumes and weights. Fresh-cut silage is 416 kg/m^3 (26 lb/ft^3) (Rider et al 1993). Assuming fresh-cut silage is at 70% moisture, then density is 125 dry kg/m^3 (7.8 dry lb/ft^3). The thick-stemmed energy crops considered for handling as silage or haylage will be more mature at harvest than typical corn silage, so we assume energy crops are 50% moisture and have a density of 250 kg/m^3 (15.6 lb/ft^3). Based on 22.4 dMg/ha (10 dt/ac), at 70% field efficiency a 2-row pull-type forage harvester handles 93 m^3 (3300 ft^3) or 23.1 Mg (25.5 tons) per hour and a 6-row self-propelled forage harvester handles 320 m^3 (11,400 ft^3) or 80.8 Mg (89.1 tons) of biomass per hour.

Silage can be blown directly into trucks, if the field conditions (wetness and slope) allow this, or as is more typically done into a wagon hauled behind the forage harvester.

It is also possible to blow the silage into a wagon hauled by a tractor alongside a forage harvester.

Blowing directly into a truck appears to be the least cost method, by minimizing the amount of equipment required, the number of operations, and maximizing active forage harvesting time. To reach the legal load weight limit, which minimizes transportation costs, the truck transporting the biomass to the conversion facility requires a 14.6 m (48') long, 3.5 m (11.5') tall, and 2.6 m (8.5') wide; or 11.3 m (37') long, 4.3 m (14') tall, and 2.6 m (8.5') wide truck trailer. Disadvantages of this system are: the truck has to constantly keep up with the forage harvester, not all terrain in the field may be suitable for the truck, the 4.3 m (14') tall truck is too high for forage harvesters to blow into, losses are higher blowing into a truck without a roof as opposed to a forage wagon with a roof, and the exact weight of the biomass blown into the truck is unknown, making it possible to go over the legal weight limit. The forage blower can probably be modified to deal with the 4.3 (14') truck height and a roof designed for a truck trailer to minimize losses during blowing of silage into the truck. Either enough leeway would have to be left so the truck does not go over the weight limit or the truck would need a scale.

Options 1, 2, and 3 use high dump forage wagons pulled behind the forage harvester. Even though dumping time is a relatively short 1 to 2.5 minutes, because of the large volumes of biomass handled, high capacity wagons are desired. We assume that a forage harvester-pulled forage wagon has a scale. Implement & Tractor *Red Book* (1995) lists three manufacturers of high-dump forage wagons: McConnel Manufacturing Co., Miller-St. Nazianz Inc., and Richardton Manufacturing Co. (Table 10). Once filled the forage wagon would dump into a truck or another forage wagon. There are two types of forage wagon running gear, auto steer and tandem. Tandem with one axle, is unsuitable for pull-type forage harvesters because part of the wagon's weight is borne by the forage harvester whose weight is not large enough, so the forage harvester may be tipped off the ground and the blown silage may miss the wagon. Tandem is suitable for self-propelled forage harvesters and provides greater maneuverability. Auto-steer wagons are slightly less expensive. Wagons with roofs have capacities up to 31.2 m^3 (1100 ft^3) and wagons without roofs up to 25.5 m^3 (900 ft^3). Given that the truck transporting the silage to the conversion facility can transport a 22.7 Mg (25 ton) [91 m^3 (3200 ft^3)] load, then three wagon loads of 30.3 m^3 (1068 ft^3) or 7.56 Mg (8.33 tons) each [based on 250 kg/m^3 (15.6 lb/ft^3) are required to fill the truck]. A wagon similar in size to a 31.2 m^3 (1100 ft^3) wagon is needed. Alternatively, four loads from a 22.7 m^3 (800 ft^3) wagon could be used. Wagons of 22.7 m^3 (800 ft^3) are available; four loads of which would weigh 22.64 Mg (24.64 ton), which is just below the legal weight limit. Standard dumping height for a high dump forage wagon is about 3.4 m (11'). If the truck trailer is 4.3 m (14') high, then an extra high dumping wagon is needed.

The Miller Pro Model 8015, list price of $15,114, has a capacity of 31.2 m^3 (1100 ft^3) and 10.9 Mg (12 tons), a dumping clearance of 3.32 m (10.9'), and a dumping cycle of less than one minute. This dumping clearance limits a 14.6 m (48') trailer to a capacity of 85.3 m^3 (3010 ft^3) or 21.3 Mg (23.5 tons) or 93.9% of legal weight limit. A similar Richardton Model 750 has optional risers available that can provide and extra 0.15 m (0.5') of clearance for $600 on auto-steer versions. We assume that risers such as for the Richardton Model 750 could be used on the Miller Pro Model 8015. The additional 0.1 m (0.5') allows the trailer to be sized such that the legal weight limit can be reached.

Table 10. High dump forage wagon characteristics

Model	Units	McConnel	Miller Pro		Richardton			
		126[a]	4012	8015	750	770	960F	975
Capacity with roof	m^3	27.3	22.7	31.2	28.3	29.8	-	-
	ft^3	963	800	1100	1000	1050	-	-
Capacity without roof	m^3		13.5	18.1	21.3	22.7	19.8	25.5
	ft^3		475	640	750	800	700	900
Dumping capacity	Mg		8.16	10.89	13.61	13.61	9.07	13.61
	tons		9	12	15	15	15	15
Dumping clearance	m		3.32	3.32	3.35[b]	2.89-4.57[c,d]	2.54-4.27[c,e]	2.59-4.62[c]
	ft		10.9	10.9	11.0[b]	9.5-15.0[c,d]	8.3-14.0[c,e]	8.5-15.2[c]
Dump cycle	min		1	1	2	2.5	2.5	2.5[f]
List price (FOB)	$		11,560	15,114	17,195(as)[g] 19,785(t)[h]	18,700 (as)	14,760 (t)[i]	19,095 (t)

[a]Only information we have is on capacity with roof.
[b]Risers available to provide additional 0.152 m (0.5 ft) of clearance, $600 on auto steer and $423 on tandem.
[c]Listed in specifications as dumping height.
[d]Depends on tire height.
[e]May be up to 0.304 m (1 ft) higher, varies slightly depending on tire height.
[f]Not listed but assumed to be 2.5 minutes.
[g](as) = auto steer.
[h](t) = tandem.
[i]Scale available for $3495.
Sources: Implement & Tractor (1995), Miller-St. Nazianz (1995), Richardton (1995).

Another model that meets these specifications is the Richardton Model 770, list price $18,700, volume capacity of 29.8 m^3 (1050 ft^3), weight capacity of 13.6 Mg (15 tons), maximum dumping height of 4.6 m (15'), and dump time of 2.5 minutes. A scale is not listed in the literature we have for the Model 770, but for another, slightly smaller model (Model 960F), a factory installed scale is available for $3495. We assume that it is possible to have a Model 770 with a scale for a list price of $22,200.

We also assume that the Miller Pro Model 8015 with risers and a scale is available for $19,210.

The second alternative (option 2) is that silage from the wagon hauled behind the forage harvester is dumped into another high dump forage wagon pulled by a tractor. This tractor-pulled forage wagon is then driven to the edge of the field where a truck is waiting to be filled and the wagon dumps into the truck. The tractor-pulled wagon would not have a roof. The largest high dump wagons without a roof we know of are the Richardton Model 975 (tandem) with 25.5 m^3 (900 ft^3), list price $19,095, and the Richardton Model 770 with 22.7 m^3 (800 ft^3) of volume capacity. Both can dump over 4.3 m (14') high, but have dump times of 2.5 minutes.

In option 2, it is possible to haul a smaller and less expensive wagon behind the forage harvester. If dumping from one forage wagon to another, a 4.3 m (14') high dumping clearance is not required, but the standard 3.4 m (11') dumping clearance is adequate. The Miller Pro Model 4012, capacity of 22.7 m^3 (800 ft^3) and 8.2 Mg (9 tons), dump cycle of one minute, and a list price of $11,560; or the Richardton Model 750, capacity of 28.3 m^3 (1000 ft^3) and 13.6 Mg (15 tons), dump cycle of two minutes, and a list price of $17,195 for an auto steer version, are examples. Neither is priced with a scale, which we assume would cost $3495. The disadvantage of using these wagons is that their dumping height limits the height of a truck one can dump into, if one sometimes uses higher than 3.14 m (11') trailers.

In addition to the Richardton Model 770 with its 22.7 m^3 (800 ft^3) capacity, we will consider a wagon with a capacity of 31.2 m^3 (1100 ft^3) without a roof and assume it has a list price of $20,000.

For option 3, when the forage harvester-pulled wagon is full, it is replaced by a empty wagon. This requires unhitching the full wagon, hitching the full wagon to a tractor, unhitching an empty wagon from a tractor, and hitching the empty wagon to the forage harvester. For a forage harvester with a 2-row head this would be acceptable from a time perspective, but for a self-propelled harvester with a 6-row head this would result in too much down time for the expensive forage harvester and reduce field efficiency to unacceptably low levels. A self-propelled forage harvester operating at 70% field efficiency with a 6-row head requires 14 wagon loads per hour with a 22.7 m^3 (800 ft^3) wagons. We consider this option no further.

For options 1 and 2, where silage is blown into a forage wagon pulled behind the forage harvester, what is the most efficient configurations of types of wagons to use with regard to volume capacity and dump cycle time? The ultimate measure of efficiency is cost, but to start with we first calculate field efficiency of the forage harvester.

Field efficiency for the forage harvester is the amount of time it is performing productive work, that is, harvesting biomass. ASAE (1995) lists a range of 55 to 85% for forage harvesters. We assume that 85% is indicative of a forage harvester that never has to stop to unload a forage wagon. The decrease in field efficiency depends on the number of times a forage wagon must be dumped and the dump cycle time. We define field efficiency (FE) as:

FE = 0.85 - number of loads * dump time (min)/(60 min/hr)

Where: $\text{number of loads} = \dfrac{\text{yield * area covered @ 100\% FE * FE}}{\text{capacity of a wagon load}}$

Solving these two equations simultaneously

$$FE = \frac{0.85}{[1+(\text{yield} * \text{area covered @ 100\% FE} * \text{dump time})/(\text{capacity of a wagon load} * 60)]}$$

Field efficiency for 22.7 m^3 (800 ft^3) and 30.3 m^3 (1068 ft^3) wagons with dump cycle times of 1 and 2.5 minutes are reported in Table 11. Using 70% field efficiency as a target, for the Base case yield of 22.4 dMg/ha (10 dt/ac) at 50% moisture, wagon size and dumping cycle time do not matter for a 2-row head, but do matter for larger than 2-row heads. For the 6-row head, only the 30.3 m^3 (1068 ft^3) wagon with a dump cycle time of 1 minute allows field efficiency to be near 70%, at 67.7%. To get to a field efficiency of 70%, down time for the forage harvester would have to be reduced by 3%, so the starting efficiency would be 88% instead of 85%, which is possible.

Table 11. Forage harvester field efficiency as affected by dump cycle time and forage wagon capacity

	Dump cycle time (min)			
	1		2.5	
	Forage wagon capacity (m^3)			
	22.7	30.3	22.7	30.3
	Forage wagon capacity (ft^3)			
	800	1068	800	1068
Head	Forage harvester field efficiency[a]			
2 row	0.775	0.792	0.684	0.719
3 row	0.742	0.766	0.623	0.668
4 row	0.693	0.727	0.543	0.597
6 row	0.634	0.677	0.459	0.519

[a]Assuming field efficiency of 0.85 without forage wagon dumping and a yield of 22.4 dMg/ha (10 dt/ac) at 50% moisture.

To determine the number of forage wagons required for option 2, we make the following assumptions:

a round trip travel time, forage harvester to truck and back of 9 minutes (same as for tractors moving bales and same assumptions),

a dumping time of 1 minute for the wagon attached to the forage harvester and 2.5 minutes for the wagon that goes from the forage harvester to the truck [(Miller-St. Nazianz (1995) and Richardton (1995) literature state 1 to 2.5 minutes or less)], and 3 minutes of slack time per round trip.

Total round trip time is 15.5 minutes; 9 minutes for travel, 1 minute to be dumped into by the forage harvester hauled wagon, 2.5 minute to dump into a truck, and 3 minutes of slack time. Thus each wagon makes 3.87 round trips per hour. A 22.7 m^3 (800 ft^3) wagon carrying 5.66 Mg (6.24 tons) or 2.83 dMg (3.12 dt) has a capacity of 21.9 Mg (24.2 tons) or 11.0 dMg/hr (12.1 dt/hr). A 31.2 m^3 (1100 ft^3) wagon carrying 7.56 Mg (8.33 tons) or 3.78 dMg (4.17 dt) has a capacity of 29.3 Mg (32.3 tons) or 14.6 dMg/hr (16.1 dt/hr) (Table 12). The 31.2 m^3 (1100 ft^3) wagon is limited in its load by the 30.3 m^3 (1068 ft^3) load size needed so that three wagon loads fill the truck to its legal limit.

Table 12. Forage wagon load for two different forage wagon sizes

Per trip		Per hour	
Size (m^3)	Load (dMg)	Size (m^3)	Load (dMg)
22.7	2.83	87.8	10.96
30.3	3.78	117.2	14.63
Size (ft^3)	Load (dt)	Size (ft^3)	Load (dt)
800	3.12	3097	12.08
1068	4.17	4134	16.12

The number of forage wagons required to transport silage from the field to the field edge depends on crop yield and moisture content, the forage crop head used and its associated rate of operation (ha/hr or ac/hr), and the hourly capacity of each wagon. Four different row heads are considered (2 row, 3 row, 4 row, and 6 row). Based on the two wagon sizes and their capacities (Table 12), we calculate the required number of forage wagons based on dry matter yields (Table 13).

Based on 22.4 dMg/ha (10 dt/ac), for 22.7 m^3 (800 ft^3) wagons, a 2-row head requires 2 wagons, a 3-row head requires 2 wagons, a 4-row head requires 3 wagons [note that the 4 row head on a 201 kW (270 hp) forage harvester is limited to 21.7 Mg/ha (9.7 dt/ac) by its power], and a 6-row head requires 4 wagons. For the larger capacity wagons, 31.2 m^3 (1100 ft^3) wagons, the 2-row head requires only 1 wagon, the 3-row head still requires 2 wagons, while the 4- and 6-row heads require 1 less wagon, 2 and 3, respectively.

Table 13. Number of forage wagons and maximum crop yield that can be transported to field edge

	Area covered		Number of 22.7 m^3 (800 ft^3) wagons					Number of 30.3 m^3 (1068 ft^3) wagons				
Head	100% FE	Actual FE	1	2	3	4	5	1	2	3	4	5
	ha/hr		Maximum yield (dMg/ha)									
2 row	0.74	0.52	21.3	42.5	63.8	85.1	106.3	28.4	56.8	85.2	113.5	141.9
3 row	1.10	0.77	14.2	28.4	42.5	56.7	70.9	18.9	37.8	56.8	75.7	94.6
4 row	1.72	1.20	9.1	18.2	27.3	36.5	45.6	12.2	24.3	36.5	48.7	60.8
6 row	2.58	1.80	6.1	12.2	18.2	24.3	30.4	8.1	16.2	24.3	32.4	40.6
	ac/hr		Maximum yield (dt/ac)									
2 row	1.82	1.27	9.5	19.0	28.5	38.0	47.4	12.7	25.3	38.0	50.7	63.3
3 row	2.73	1.91	6.3	12.7	19.0	25.3	31.6	8.4	16.9	25.3	33.8	42.2
4 row	4.24	2.97	4.1	8.1	12.2	16.3	20.3	5.4	10.9	16.3	21.7	27.1
6 row	6.36	4.45	2.7	5.4	8.1	10.8	13.6	3.6	7.2	10.9	14.5	18.1

MODULES: AN ALTERNATIVE TO BALES AND LOOSE BIOMASS

In cotton production, a module builder is used to form approximately rectangular blocks of cotton lint and seed. These modules are approximately 9.75 m (32') long, 2.21 m (7.5') wide at the base (modules are tapered), and 2.4 m (8') tall, and contain about 15 bales of lint plus cottonseed. The module builder compresses the cotton. A mechanically tipping wagon can be used to fill the module builder.

To use a module builder for a hay crop one would undertake the following series of operations: mowing-conditioning or windrowing, field drying, picking up with a windrow head on a forage harvester and blowing into a wagon, unloading the wagon into the module builder, when the module is built unloading it from the module builder, and using a specialized truck to transport the module to the conversion facility. Small tractors, 34 kW (45 hp) are required to pull the wagons and to provide power to the module builder. Machinery requirements for making modules are described in Table 14.

Modules make the biomass more dense than if it is loose. Modules of biomass are 9.1 Mg (10 tons). A module builder can build one module in an hour. An hour is enough time to build the module, put a tarp on the module, and move the module builder.

A 22.7 m^3 (800 ft^3) forage wagon has a nominal load limit of 2.83 dMg (3.12 dt) at 12% moisture. However, a module is 7.98 dMg (8.8 dt), so three wagon loads of 2.66 dMg (2.93 dt) each makes a module. For a tractor-pulled forage harvester system, once a yield of 8.15 dMg/ha (3.64 dt/ac) is reached, a second module builder is required (or the flow of hay through the system is limited by slowing down the forage harvester). At 16.29 dMg/ha (7.27 dt/ac) a third module builder would be needed. However, we assume that the maximum hay yield on a single cutting is 15.7 dMg/ha (7 dt/ac). For a single self-propelled forage harvester at a yield of 6.99 dMg/ha (3.12 dt/ac) a second module builder is needed, and at 14.0 dMg/ha (6.24 dt/ac) a third module builder is needed. We model using three self-propelled forage harvesters with a single self-propelled windrower. Thus the yield increments at which module builders are added for three self-propelled forage harvesters are small relative to those for a single forage harvester (Table 15).

Table 14. Machinery complements used for hay modules

Hay
Mower-conditioner or windrower
Tractor
or
Self-propelled windrower
↓
Self-propelled forage harvester
with windrow pickup
or
Pull-type forage harvester
with windrow pickup
Tractor
↓
Wagons and tractors
↓
Module builder and tractor
↓
Truck to transport module

Table 15. Maximum yield module builders can handle for varying numbers and types of forage harvesters

Number of module builders	Number and type of forage harvester							
	1 pull-type	1 SP	2 SP	3 SP	1 pull-type	1 SP	2 SP	3 SP
	dMg/ha				dt/ac			
1	4.00	3.44	1.72	1.15	3.63	3.12	1.56	1.04
2	8.00	6.88	3.44	2.29	7.26	6.24	3.12	2.08
3		10.32	5.16	3.44		9.36	4.68	3.12
4			6.88	4.59			6.24	4.16
5			8.60	5.73			7.80	5.20
6				6.88				6.24
7				8.02				7.28

If a 30.3 m^3 (1100 ft^3) forage wagon without a roof exists, it could be utilized to be dumped into by the forage harvester-pulled wagon (which would have a roof) and it in turn would dump into the module builder. Two loads would equal a 7.78 dMg (8.58 dt) module which is 97.5% of the maximum module size. Thus transportation costs would be 2.6% higher. We model the use of 22.7 m^3 (800 ft^3) wagons.

CROP RESIDUES

Crop residues are usually left in the field as part of a conservation or reduced tillage practice. In 1993 over 26% of cropland used a tillage system which leaves, after planting, 15%-30% of crop residue from the previous crop as cover. Another 35% of cropland used no-till, ridge-till, or mulch till. These systems leave, after planting, at least 30% residue cover (USDA/ERS 1994). However, there are opportunities to harvest crop residues as an energy source.

Currently, grain and oilseed harvesting equipment is not designed with the purpose of harvesting both the grain or oilseed and the rest of the plant. The harvester stores the grain or oilseed in a bin and the rest of the plant is returned to the field. With harvest of small grains one can control the height at which the small grain is cut. If a residue harvest is desired and one is not limited by the amount of residue that is required to be left in the field, one would cut as low as possible, about 8 cm (3"). We examine four options for crop residues: (1) use haying equipment to make bales, (2) use a forage harvester and make modules, (3) modify a grain combine and make modules, and (4) for small grains haul a baler behind the combine.

There are two options available for harvesting residues that are lying in the field. One is to rake (if necessary), bale, move the bales to the side of the field, and then transport the bales to the conversion facility. Two is to rake (if necessary), pick-up with a windrow pickup head on a forage harvester and blow the residue into a wagon or truck, and then transport the loose material to a conversion facility, or make the residue into a module using a cotton module builder and then transport the module to the conversion facility[2]. The machinery complements have already been discussed in the sections on hay, silage and haylage, and modules.

As a general rule when biomass is harvested as hay there is enough biomass in the windrow that a raking operation is not necessary to accumulate enough biomass for a baler or forage harvester with a windrow pickup head, but it may be necessary to use a rake to turn over the hay so that it may properly dry. With corn residues it is necessary to accumulate biomass into a windrow with a raking operation so that the pickup equipment can operate efficiently. For small grains, raking is not necessary as the residue from small grains can be put into windrows by the combine. Rakes are relatively inexpensive, costing about $4000. They range in width from about 2.6 to 4.0 m (8.5' to 13.2'), and require a relatively small tractor, 30 to 45 kW (40 to 60 hp) PTO.

There would be two advantages if harvest machinery could be modified so that as the grain or oilseed is harvested, the rest of the plant is collected in a wagon or truck running beside the harvester. The biomass would not touch the ground and accumulate soil particles and fewer machinery operations would be required (i.e., no raking, no pick up). A possible disadvantage would be that biomass is in a loose form. To overcome this disadvantage a cotton module builder could be used to create a more dense module out of

---

[2]In the past a stover pickup head was available, designed specifically to pick up stover after grain harvest (Rider et at 1993). Presumably if enough demand was present this head would be available again.

the loose biomass. A critical point about any crop residue recovery operation is that it cannot take too much time away from the harvest of the primary grain or oilseed crop.

Machinery requirements for crop residues are summarized in Table 16.

Table 16. Machinery complement for crop residue harvest and transport

<table>
<tr><th>Bales</th><th>Loose biomass</th><th>Module</th><th>Modified grain combine</th></tr>
<tr><td colspan="3">Rotary mower and tractor (for corn)</td><td rowspan="3">Utilizes combine harvesting grain</td></tr>
<tr><td colspan="3">Rake and tractor (for corn)</td></tr>
<tr><td>Baler and tractor</td><td>Forage harvester with windrow pickup and tractor</td><td></td></tr>
<tr><td>Tractor to move bales
or
bale wagon and tractor</td><td rowspan="4">Wagon and tractor
or
truck</td><td>Wagon and tractor</td><td>Wagon and tractor</td></tr>
<tr><td rowspan="3">Truck with forklift</td><td>Module builder and tractor</td><td>Module builder and tractor</td></tr>
<tr><td>Truck</td><td>Truck</td></tr>
<tr><td></td><td></td></tr>
</table>

We have generically discussed crop residues. Different crops will require somewhat different systems depending on crop characteristics and residue yields. The range of expected crop residue yields is shown in Table 17. We assume maximum residue recovery is 67%. Not all residues are physically recoverable and in many fields need to be left for erosion control. The yields shown in Table 17 are *upper limits*, but can be used to design the machinery complements to be used for residue recovery. Total residue yield is calculated using recent average state grain yields and crop residue factors (ratio of crop residue to grain crop) from Heid (1984). We assume that baled crop residues have the same dry matter bale density as hay, 140 dry kg/m^3 (8.75 dry lb/ft^3) for large round bales and 159 dry kg/m^3 (9.95 dry lb/ft^3) for large rectangular bales, and that loose crop residues have the same dry matter density as silage 125 dry kg/m^3 (7.8 dry lb/ft^3).

Table 17. Upper bounds on crop residue yields

Crop	Residue yield at 67% recovery	
	Range	Average
	(dMg/ha)	
Corn	3.9 - 9.4	6.6
Sorghum	1.5 - 3.7	2.4
Winter wheat	2.0 - 7.1	2.7
Spring wheat	1.6 - 5.4	2.1
Barley	1.8 - 5.4	2.5
Oats	1.3 - 3.4	1.8
	dt/ac	
Corn	1.7 - 4.2	3.0
Sorghum	0.7 - 1.7	1.1
Winter wheat	0.9 - 3.2	1.2
Spring wheat	0.7 - 2.4	0.9
Barley	0.8 - 2.4	1.1
Oats	0.6 - 1.5	0.8

Note from Table 17 that corn has a considerably higher average residue yield, 6.6 dMg/ha (3.0 dt/ac) than the small grains (winter wheat, spring wheat, barley and oats) and sorghum, 1.8 to 2.7 dMg/ha (0.8 to 1.2 dt/ac). (Hereafter we will combine sorghum with small grains and refer to them as small grains. Yields and residue recovery systems are similar for these crops.)

Corn is harvested for grain with a combine. The stalks are usually still attached to the ground and first require a rotary mower to sever them. Then raking is performed to gather the stalks into a windrow. We assume they are gathered from a 3.66 m (12') wide area into a 1.22 m (4') wide windrow.

For small grains the amount of residue remaining can be controlled by the height at which the grain is cut. We assume that the residue exiting out the rear of the combine is not spread out over the width of the combine head, but is left in a 1.22 m (4') wide area. Combine heads vary from 3.66 m (12') to 9.15 m (30'). Typical small-grain combine heads range from 6.10 m to 7.62 m (20' to 25'). We assume that the residue from a 6.10 m (20') width is accumulated in a 1.22 m (4') wide area. The mowing and raking operation required for corn residues are not needed for small grains residues.

The first systems we consider use balers to pick up residues. The balers can be either large round balers (option 1) or large rectangular balers (option 2). Corn residues are accumulated into an area covering one-third of the field and small grains into an area covering one-fifth of the field in windrows. Based on baler width, field speed, field efficiency, and the area residues are concentrated in, for large round balers, bale residues are collected from 1.52 ha/hr (3.74 ac/hr) and 3.19 ha/hr (7.88 ac/hr) for corn and small grain residues, respectively. For large rectangular balers, residues are collected from 1.87 ha/hr (4.61 ac/hr) and 3.93 ha/hr (9.70 ac/hr) for corn and small grain residues, respectively. While the balers effectively cover a large area in an hour, they are limited by their physical throughput capacity of 10 dMg/hr (11 dt/hr) for a large round baler and 20 dMg/ha (22 dt/hr) for a large rectangular baler. Using these areas covered and baler throughput, then once crop residue yield reaches 6.58 dMg/ha (2.94 dt/ac) for corn and 3.13 dMg/ha (1.40 dt/ac) for small grains, economies of scale for large round balers are exploited Once crop residue yield reaches 10.70 dMg/ha (4.78 dt/ac) for corn and 5.08 dMg/ha (2.27 dt/ac) for small grains, economies of scale for large rectangular balers are exploited. These baler characteristics are summarized in Table 18.

Table 18. Baler characteristics harvesting crop residues

Baler	Area covered	Maximum throughput	Maximum yield
	ha/hr	dMg/hr	dMg/ha
Corn			
Rectangular	1.87	19.96	10.70
Round	1.52	9.98	6.58
Small grains			
Rectangular	3.93	19.96	5.08
Round	3.19	9.98	3.13
	ac/hr	dt/hr	dt/ac
Corn			
Rectangular	4.61	22.00	4.78
Round	3.74	11.00	2.94
Small grains			
Rectangular	9.70	22.00	2.27
Round	7.88	11.00	1.40

[a]Assuming corn residue concentrated from a 3.66 m (12') width and small grain residues from a 6.10 m (7') into 1.22 m (4') wide windrow.

The next systems considered use windrow pickup head on forage harvesters, forage wagons, and module builders to pick up and package crop residues. The forage harvesters may be either pulled by a tractor (option 3 and 4) or self-propelled (option 5). Either type of forage harvester uses a 2.13 m (7') wide windrow pickup. While we assume that the raking operation concentrates corn residues or the small grain harvester concentrates the small grain residues into 1.22 m (4') wide windrows, for the windrow pickup head they would simply need to be concentrated within the 2.13 m (7') wide pickup area. For option 3 we assume that a heavy-duty (hd) pull-type forage harvester with a 119 kW (160 hp) tractor is used, as is used for silage harvesting. This unit can pick up yields up to 11.2 dMg/hr (12.3 dt/hr), based on 70% field efficiency. At relatively low crop residue yields, it is feasible to use a medium-duty (md) forage harvester with a 75 kW (100 hp) tractor (option 4). It has the power to pick up yields up to 5.6 dMg/hr (6.2 dt/hr), based on 70% field efficiency. Whether one wants to use a heavy- or medium-duty forage harvester depends upon the range of expected crop residue yields. For the self-propelled forage harvester a "small" model, 201 kW (270 hp), provides adequate power and can collect up to 21.4 dMg/hr (23.6 dt/hr), based on 70% field efficiency (option 5).

The pull-type forage harvester can pick up corn residues from 1.24 ha/hr (3.05 ac/hr) and small grain residues from 2.06 ha/hr (5.09 ac/hr). The self-propelled forage harvester has a slightly faster field speed and picks up corn residues from 1.44 ha/hr (3.56 ac/hr) and small grain residues from 2.40 ha/hr (5.94 ac/hr). The 119 kW (160 hp) tractor with a pull-type forage harvester has enough power to process corn residue yields up to 9.04 dMg/ha (4.04 dt/ac) and small grain residues with yields up to 5.42 dMg/ha (2.42 dt/ac). The 119 kW (160 hp) tractor provides adequate power for all small grain residue yields and all except the highest corn residue yields of 9.4 dMg/ha (4.2 dt/ac). In many instances a 74 kW (100 hp) tractor would provide adequate power. The self-propelled forage harvester is capable of picking up corn residues up to 8.89 dMg/ha (3.97 dt/ac), which cover nearly all expected crop residue yields. Forage harvester characteristics are summarized in Table 19.

The crop residues picked up by the forage harvester are blown into a forage wagon or truck. We assume that a high dump forage wagon with a roof is pulled behind the forage harvester. When this wagon is full, it dumps into a high dump forage wagon without a roof (but with the same volume capacity as the wagon pulled by the forage harvester). The tractor then takes the forage wagon to a module builder at the field edge. These matched pairs of high dump forage wagons range in capacity from 15.6 m^3 (550 ft^3) to 22.7 m^3 (800 ft^3). We also hypothesize the existence of a 31.2 m^3 (1100 ft^3) wagon without a roof to allow a matched pair at this size (Table 20). Based on the same assumptions as forage wagon travel time used in the section on silage (9 minutes round trip travel time, 3 minutes of slack time, plus dumping time), a wagon is capable of making about four trips per hour to the module builder. The choice of forage wagons depends on trip length, expected yield of crop residues, and type of forage harvester (Table 21).

Taking the minimum of forage harvester capacity (maximum yield) (Table 19) and wagon capacity (maximum yield) (Table 21), gives maximum capacity of the forage harvester/wagon portion of the system (Table 22).

Table 19. Forage harvester characteristics harvesting crop residues

Crop and forage harvester type	Power	Area covered	Maximum yield
	kW	ha/hr	dMg/hr
Corn			
Heavy-duty pull-type	119	0.98	11.42
Medium-duty pull-type	75	0.98	5.75
Self-propelled	201	1.14	18.70
Small grains			
Heavy-duty pull-type	119	2.06	5.42
Medium-duty pull-type	75	2.06	2.73
Self-propelled	201	2.41	8.88
	hp	ac/hr	dt/hr
Corn			
Heavy-duty pull-type	160	2.42	5.10
Medium-duty pull-type	100	2.42	2.57
Self-propelled	270	2.82	8.35
Small grains			
Heavy-duty pull-type	160	5.09	2.42
Medium-duty pull-type	100	5.09	1.22
Self-propelled	270	5.94	3.97

Table 20. Matched pairs of high dump forage wagons and their capacities

Size m^3 (ft^3)/ manufacturer & model		List price delivered	Total cost	Load per wagon		Dump cycle	Loads per hour	Maximum hourly load	
		$	$/hr	dMg	dt	min		dMg/hr	dt/hr
15.6[a]	550[b]								
Richardton 1200[c]		9555	8.51			1			
Richardton 700[d]		11955	10.65			2			
Total		21510	19.15	1.95	2.15		4.00	7.78	8.58
18.1	640								
Richardton 1400		10385	9.25			1			
Miller 8015		15614	13.90			1			
Total			23.15	2.26	2.50		4.29	9.70	10.70
21.3	750								
Richardton 700		11955	10.65			2			
Richardton 750		17695	15.76			2			
Total			26.40	2.65	2.93		3.75	9.95	10.97

Table 20 (continued)

Size m^3 (ft^3)/ manufacturer & model		List price delivered	Total cost	Load per wagon		Dump cycle	Loads per wagon	Maximum hourly load	
		$	$/hr	dMg	dt	min		dMg/hr	dt/hr
22.7	800								
Miller 4012		12060	10.74			1			
Richardton 770		19200	17.10			2.5			
Total			27.84	2.83	3.12		3.87	10.96	12.08
31.2	1100								
Miller 8015		15614	13.90			1			
Hypothetical		20500	18.25			2.5			
Total			32.16	3.89	4.29		3.87	15.07	16.61

[a]Wagon size (m^3).
[b]Wagon size (ft^3).
[c]First wagon with roof.
[d]Second wagon without roof.

Table 21. Maximum crop residue yield a matched pair of forage wagons can handle

Wagon volume	Load per wagon	Dump cycle	Loads	Maximum hourly load	Corn		Small grains	
					Pull type	Self propelled	Pull type	Self propelled
m^3	dMg	Min	Per hour	dMg/hr	Maximum yield (dMg/ha)			
15.6	1.95	3	4.00	7.78	7.95	6.81	3.78	3.24
18.1	2.26	2	4.29	9.70	9.91	8.49	4.71	4.03
21.3	2.65	4	3.75	9.95	10.16	8.71	4.83	4.14
22.7	2.83	3.5	3.87	10.96	11.19	9.59	5.31	4.56
31.2	3.89	3.5	3.87	15.07	15.38	13.19	7.31	6.26
ft^3	dt			dt/hr	Maximum yield (dt/ac)			
550	2.15	3	4.00	8.58	3.55	3.04	1.69	1.44
640	2.50	2	4.29	10.70	4.42	3.79	2.10	1.80
750	2.93	4	3.75	10.97	4.54	3.89	2.15	1.85
800	3.12	3.5	3.87	12.08	4.99	4.28	2.37	2.03
1100	4.29	3.5	3.87	16.61	6.87	5.89	3.26	2.80

Table 22. Maximum capacity of forage harvester and wagon

Crop and forage harvester type	Wagon volume (m^3)				
	15.6	18.1	21.3	22.7	31.2
	dMg/ha				
Corn					
Heavy-duty pull-type	7.95	9.91	10.16	11.19	11.42
Medium-duty pull-type	5.75	5.75	5.75	5.75	5.75
Self-propelled	6.81	8.49	8.71	9.59	13.19
Small grains					
Heavy-duty pull-type	3.78	4.71	4.83	5.31	5.42
Medium-duty pull-type	2.73	2.73	2.73	2.73	2.73
Self-propelled	3.24	4.03	4.14	4.56	6.26
	Wagon volume (ft^3)				
	550	640	750	800	1100
	dt/ac				
Corn					
Heavy-duty pull-type	3.55	4.42	4.54	4.99	5.10
Medium-duty pull-type	2.57	2.57	2.57	2.57	2.57
Self-propelled	3.04	3.79	3.89	4.28	5.89
Small grains					
Heavy-duty pull-type	1.69	2.10	2.15	2.37	2.42
Medium-duty pull-type	1.22	1.22	1.22	1.22	1.22
Self-propelled	1.44	1.80	1.85	2.03	2.80

CALCULATING COSTS

Costs can be broken into the following categories:

- depreciation (or capital replacement)
- interest
- insurance, housing, and taxes
- repair
- fuel, lube, and oil
- labor

In calculating costs we need to make assumptions regarding useful life (in hours of use or years), salvage value, discount rate, initial price, field efficiency, and repair costs. One method we use to calculate costs is to use "standard hours" of equipment use in a year [annual use (hr) in Table 23]. Standard hours represent typical hours of equipment use in a year. We also make calculations using actual hours of equipment use, which result in different costs.

Table 23. Machinery parameters

Implement	Power kW	Power hp	Life hr	Life years	Annual use hr	List price $	Salv. value $	Fuel L/hr	Fuel gal/hr	Repairs lifetime	Labor $/hr	Total cost $/hr
Tractor	33.6	45	12000	24	500	21000	1930	8.46	2.22	1.00	10.00	17.25
Tractor	74.6	100	12000	21.82	550	42000	4631	18.80	4.94	1.00	10.00	24.59
Tractor	119.4	160	12000	20	600	72000	9238	30.08	7.90	1.00	10.00	33.97
Tractor	156.7	210	12000	20	600	93000	11933	39.48	10.37	1.00	10.00	41.12
Front end loader	33.6	45	1000	4	250	3000	1104			0.40		3.67
Mower-conditioner	74.6	100	2500	12.5	200	10000	1303			0.80		8.89
Mower-conditioner (disk)	74.6	100	2500	12.5	200	15000	1954			1.00		14.54
Windrower-6.40m (21')	74.6	100	2500	12.5	200	8700	1134			0.70		7.39
SP windrower-4.88m (16')	74.6	100	3000	10	300	54000	10186	18.80	4.94	0.55	10.00	47.42
Rake	33.6	45	2500	12.5	200	3000	391			0.60		2.43
Rectangular baler	119.4	160	3000	5	600	65000	19761			0.80		37.52
Large round baler	74.6	100	1500	10	150	16000	2641			0.75		21.71
Forage harvester	119.4	160	2500	10	250	22000	3631			0.65		17.03
Windrow head-2.13m (7')	119.4	160	1000	10	100	3000	495			0.80		6.26
2-row head	119.4	160	2000	10	200	3600	594			0.80		3.75
3-row head	156.7	210	2000	10	200	6000	990			0.80		6.26
SP forage harvester	201.4	270	4000	10	400	116000	19146	50.76	13.33	0.50	10.00	74.05
SP forage harvester	320.8	430	4000	10	400	168000	27729	80.84	21.23	0.50	10.00	104.53
Windrow head-2.13m (7')	201.4	270	1000	10	100	3000	495			0.80		6.26
Windrow head-2.13m (7')	320.8	430	1000	10	100	3000	495			0.80		6.26
4-row head	201.4	270	2000	5	400	10000	3040			0.80		8.66
6-row head	320.8	430	2000	5	400	19000	5776			0.80		16.45
Bale carrier	33.6	45	500	2	250	500	235			0.30		0.90
Bale wagon	33.6	45	3000	10	300	3000	531			0.80		2.08
Forage wagon-scale,22.7m^3			2000	10	200	16160	2858			0.50		14.39
Forage wagon-hi dump,22.7m^3	33.6	45	2000	10	200	19200	3395			0.50		17.10
Forage wagon-scale,31.2m^3			2000	10	200	19710	3486			0.50		17.55
Forage wagon-hi dump,31.2m^3	33.6	45	2000	10	200	20500	3625			0.50		18.25
Cotton module	33.6	45	3000	7.5	400	20000	4800			0.80		12.78
Tandem truck			5000	10	500	58000	10257	17.79	4.70		15.00	38.60
Silage truck			5000	12.5	400	80000	10424	17.79	4.70		15.00	47.48
Module truck			5000	5	1000	100000	32574	17.79	4.70		15.00	43.94
Forklift	29.8	40	5000	10	500	17000	3006	7.48	1.98			9.67

SOURCES FOR MACHINERY PARAMETERS

Machinery parameters are shown in Table 23. An expanded version of Table 23 is appendix Table A1. Table 23 lists all machinery used for biomass harvest and transport. The smallest 33.5 kW (45 hp) tractor is used for moving bales, hauling wagons, raking, and powering a cotton module. The 74.6 kW (100 hp) tractor provides adequate power for most tractor pulled equipment, with the exception of the rectangular baler and forage harvester. The rectangular baler and forage harvester with a 2-row or windrow pickup head require a 119.4 kW (160 hp) tractor. A forage harvester with a 3-row head requires a 156.7 kW (210 hp) tractor.

Most values for hours of life and repair parameters [lifetime repairs (list)] are from ASAE (1995). ASAE does not have values for the front end loader, windrower, forage harvester heads, bale carrier, cotton module, forklift, and trucks. For the cotton module we assume the values are the same as for a large rectangular baler. For the windrower, we assume it has the same lifetime repairs (list) as the self-propelled windrower plus 0.15 (the same differential as between a forage harvester and a self-propelled forage harvester). For forage harvester heads, repairs values are assumed to be the same as for a mower-conditioner.

For other parameters, information from Johnson (1991) is used as a starting point. Johnson lists lifetime for a self-propelled forage chopper of 1600 hours, row head of 800 hours, and windrow head of 400 hours; and lifetime repairs for all at 60% of list price. ASAE (1995) lists lifetime for a self-propelled forage harvester of 4000 hours. We assume the ASAE lifetime for the self-propelled forage harvester and the lifetime of row heads to be one-half (2000 hours) for row heads and one-quarter (1000 hours) for the windrow head. Lifetime repairs for the heads are equal to that of the self-propelled forage harvester, 80% of list price.

Johnson (1991) lists a front end loader life of 1000 hours and lifetime repairs of 40% of list price. We use these values. For a bale carrier Johnson (1991) lists a life of 300 hours and lifetime repairs of 30% of list. We assume the bale carrier will last one season of standard hours of a 33.6 kW (45 hp) tractor, 500 hours, and adjust lifetime repair costs to 50% of list price so the average $1 hour repair cost is the same as Johnson (1991).

For the forklift repairs are assumed to be two times those of a 33.6 kW (45 hp) tractor and lifetime is assumed to be 5000 hours.

For trucks, lifetime and repair costs are based on data in Fuller et al (1992) and adjusted for each truck according to its relative list price.

List prices for tractors, front end loaders, mower-conditioners, windrowers, forage harvesters, and forage harvester heads are based on typical values from NAEDA (1995). List prices for the rake, bale carrier, and bale wagon are based on values in Johnson (1991). Forage wagon list prices are based on data from Miller-St. Nazianz (1995) and Richardton (1995). Cotton module list price is from personal communication to Jim Butler from Bill Dykes, CEO of Peerless Manufacturing Co. (a cotton module builder) (15 September 1995). The list price of a forklift is based on a comparably sized skid loader in NAEDA (1995).

VALUE AFTER N YEARS

The ASAE (1995) has formulas to determine the values of farm equipment after n years. The value as a percent of initial list price is in Table 24. In cost calculations for standard hours, we assume that equipment is used for a certain number of years, based on assumed hours of life divided by standard hours. When hours of annual use differ from standard hours, years of life is adjusted accordingly based on the assumption that hours of life are fixed. Salvage value as a percent of list price for equipment used to harvest forage is listed in Table 25.

Table 24. Remaining value as a percentage of list price at the end of the nth year

Equipment	Remaining value (% of list price)
Tractors	$68(0.920)^n$
Combines, cotton pickers, SP windrowers	$64(0.885)^n$
Balers, forage harvesters, blowers, and SP sprayers	$56(0.885)^n$
All others	$60(0.885)^n$

Source: ASAE (1995)

Table 25. Value of equipment as a percentage of list price at end of assumed life, based on standard hours

Equipment	Assumed years of life	Remaining value as % of list price at end of assumed life		
		Nominal	Discounted at	
			6%	10%
Tractors	24	9.2	2.3	0.9
	21.8	11.0	3.1	1.4
	20	12.8	4.0	1.9
Self-propelled windrowers	10	18.9	10.5	7.3
	5	34.7	26.0	21.6
Balers, forage harvesters	10	16.5	9.2	6.4
	5	30.4	22.7	18.9
All others	12.5	13.0	6.3	4.0
	10	17.7	9.9	6.8
	5	32.6	24.3	20.2
	4	36.8	29.2	25.1
	2	47.0	41.8	28.8

The remaining value, also known as salvage value when calculated for the end of its useful life, is used to determine depreciation and interest costs.

DEPRECIATION

Depreciation on a straight-line basis is: depreciation/hour = (purchase price - discounted salvage value)/(hours of life), where purchase price is assumed to be 90% of list price. We believe that hours of use rather than some assumed years of use not based on hours of use is a more accurate representation of the useful life of equipment.

Suppose a farmer or custom operator uses the equipment the number of assumed hours of life (Table 23) in only half the number of years of assumed life (Table 23). Depreciation per hour of life is relatively insensitive to the number of years of life, if hours of life is constant. Depreciation is 4 to 7% lower if the assumed hours of life are used in only half the time. (Depreciation is lower because the discounted salvage value is higher). Although we calculate depreciation on a straight line basis, new equipment loses 25 to 40% of its market value (based on list price) in its first year. Even if selling price is 90% of list price new equipment loses 15 to 30% of its value in the first year. Because we assume the equipment will be used until the end of its useful life, straight line depreciation serves our purpose.

INTEREST

We calculate interest using a real interest rate of 6% (or in nominal terms about 9%). The average amount of interest paid in any given year is:

interest = [(purchase price - discounted salvage value)/2]*interest rate

Interest represents the opportunity cost of the money invested in the equipment. Note that interest for a given period of time is approximately fixed regardless of equipment use rates. So if equipment is used more, then the rate per hour or hectare (acre) decreases. We say it is approximately fixed because the discounted salvage value changes with years of life. If the useful life is used up in half the number of years assumed (Table 23), then interest per hour is 4 to 7% higher.

INSURANCE, HOUSING, AND TAXES

Insurance, housing, and taxes are 2% of list price.

REPAIRS AND MAINTENANCE

Total lifetime undiscounted repair costs are listed in Tables 23 and appendix Table A.1. We do not discount repair costs, so repair costs are overestimated. We have simply taken lifetime undiscounted repair costs (ASAE 1995) and divided by number of hours of life to get repairs cost per hour. For example, for a rake, in Table 23, lifetime repairs are 0.60 (of list price). List price ($3000) * lifetime repairs (0.60) / hours of life (2500) = $0.72/hr (as in appendix Table A.1).

FUEL AND OIL

From ASAE D497.2MAR94 typical diesel fuel consumption is modeled as:

$$L/kWh = 2.64X + 3.91 - 0.203\,(738X + 173)^{0.5}$$

or

$$gal/hp\text{-}hr = 0.52X + 0.77 - 0.04(738X + 173)^{0.5}$$

where X is the ratio of PTO required for an operation versus maximum available PTO power. To get total fuel use:

$$L/hr = \text{maximum PTO power (kW)} * X * [2.64X + 3.91 - 0.203(738X+173)^{0.5}]$$

or

$$gal/hr = \text{maximum PTO power (hp)} * X * [0.52X + 0.77 - 0.04(738X + 173)^{0.5}]$$

Following Walsh (1994), we assume X = 0.5, then the equations simplify to:

L = maximum PTO power (kW) * 0.252

or gal = maximum PTO power (hp) * 0.04938.

These coefficients are in close agreement with average annual fuel consumption for tractors as determined by ASAE EP496.2 MAR94:

L = maximum PTO power (kw) * 0.222

or gal = maximum PTO power (hp) * 0.0438.

We use the first set of coefficients as in Walsh (1994). We assume the fuel consumption coefficients apply to self-propelled equipment and forklifts.

Oil and lube costs are 15% of fuel costs.

Diesel cost for off-road use (i.e. farm equipment) is assumed to be $0.211/L ($0.80/gallon) and for trucks is $0.304/L ($1.15/gallon). The difference is road use taxes.

LABOR

For field labor, we assume the number of labor hours is 1.25 times the number of machine hours. This allows for time spent transporting and setting up machinery. Labor is charged at $8/hour, including benefits, for agricultural operations (or $10/hr of actual equipment operation) and $15/hour for trucking, including benefits.

Per unit area costs

Per ha (per ac) costs are determined by dividing hourly costs by the area covered by an implement in an hour. For SI units:

ha/hr = field speed (km/hr) * 1000 m/km * implement width (m) * field efficiency (fraction)/(10,000 m^2/ha)

or ha/hr = field speed (km/hr) * implement width (m) * field efficiency (fraction)/10

and similarly for English units:

ac/hr = field speed (mi/hr) * 5280 ft/mi * implement width (ft) * field efficiency (fraction)/ 43560 ft^2/ac

or ac/hr = field speed (mi/hr) * implement width (ft) * field efficiency (fraction) / 8.25.

If a rake or windrower precedes a baler and makes a windrow smaller than the baler's pick up width, then the operating width of the baler is the width of the rake or windrow. For baling operations, except for small grain residues, we assume a rake precedes the baler and that the width of the baler for purposes of costing the baler on a per ha (acre) basis is the width of the rake. For a baler used for small grain residues, the combine is assumed to have a 6.10 m (20')-wide head which leaves a windrow the width of the baler's pickup head. Note that in the case of a baler, the area it can cover in an hour is constrained by its throughput capacity, 10 dMg/hr (11 dt/hr) for a large round baler and 20 dMg/ha (22 dt/hr) for a large rectangular baler.

POWER REQUIREMENTS

The power required for the various implements used in forage production vary greatly. A formula for computing power requirements is:

total power = drawbar power/(traction efficiency * 0.96) + PTO power + hydraulic power + electrical power (ASAE 1995).

The factor 0.96 represents the typical mechanical efficiency of the transmission and power train. For forage harvesting equipment PTO power is by far the largest component of power requirements. PTO power required is computed as:

PTO power = a + b * width + c * feed rate,

where width is the operational width of the equipment and feed rate is the quantity of biomass processed by the equipment. Values of a, b, and c (Table 26) with assumed equipment widths, field speeds, and yields are used to calculate PTO power requirements. Under the ASAE system we are using, note that PTO power requirements for mower-conditioners, windrowers, and rakes depend only on implement width (i.e., a = c = 0). Balers and forage harvesters depend on the constant a, which is relatively small, and the feed rate of biomass. For balers the feed rate is a wet weight and for forage harvesters the feed rate is a dry rate, assuming a 9 mm (0.35") length of cut. A footnote to the table from which the coefficients are taken from [ASAE (1995), p. 339 Table 1] says that if length of cut at a specific throughput is reduced by 50%, then power use [as determined from the feed rate] increases by 25%. We assume that the converse is true. If length of cut is doubled to 18 mm (0.70"), then power use decreases by 20%. This change in power requirements is not trivial at the relatively high throughput rates we assume of up to 15.7 dMg/ha (7.0 dt/ac) for hay and 22.4 dMg/ha (10.0 dt/ac) for silage crops.

Adequate power requirements are of concern primarily for the pull-type forage harvesters. For mower-conditioners, windrowers, and rakes; power requirements are calculated to be relatively small. A 75 kW (100 hp) tractor provides adequate power for mower-conditioners, windrowers, and large round balers. A 34 kW (45 hp) tractor provides adequate power for a rake and for transporting bales and wagons in the field; and also for operating a module builder. For the large rectangular baler the 119 kW (160 hp) tractor provides adequate power. ASAE provides a range on the calculated power requirements. We add 15 kW (20 hp) for all other power requirements besides PTO power and then multiply by (1 + range), to get power requirements: power = [a + b*width + c*feed rate (average speed) + 15 kW(20 hp)]*(1 + range). This value is based on typical speed. Based on the machine's power we can solve for feed rate per hour.

Divide feed rate per hour by coverage at 100% field efficiency (FE) to get maximum yield in Table 27. If the yield is any higher than this maximum yield calculated, then the machine must slow down so that it does not exceed its maximum feed rate. For those implements whose power requirements depend only on implement width; windrowers, mower-conditioners, and rakes (c=0); field speed has no effect. Only baler and forage harvester power requirements are affected by field speed.

For the large round balers, a 75 kW (100 hp) tractor is adequate for yields up to 15.7 dMg/ha (7 dt/ac), assuming 12% moisture at baling and typical speed of 8.1 km/hr (5.0 mi/hr). Even at typical field speed and adding 15 kW (20 hp) for other power demand and then adding 50% which is the maximum end of the range of required power, 59 kW (79 hp) is adequate. Only at maximum speed and at the top of the range would 75 kW (100 hp) be inadequate.

For the large rectangular baler, the story is the same as for the large round baler. The 119 kW (160 hp) tractor chosen as the power source is adequate except in the case of operating at maximum baler speed, even when allowing 15 kW (20 hp) for power needs other than PTO, and taking the maximum value in the range.

Table 26. Power requirement parameters

	a	b	c	a	b	c	Range
Implement	kW	kW/m	kWh/Mg	hp	hp/ft	hp-hr/ton	%
Mower-conditioner (cutterbar)	0	4.5	0	0	1.8	0	30
Mower-conditioner (disk)	0	8.0	0	0	3.3	0	30
Windrower/swather (small grain)	0	1.3	0	0	0.5	0	40
Rake side delivery	0	0.4	0	0	0.2	0	50
Rake (rotary)	0	2.0	0	0	0.8	0	40
Baler-large rectangular	4.0	0	1.3	5.4	0	1.6	35
Baler-large round with variable chamber	4.0	0	1.1	5.4	0	1.3	50
Forage harvester (direct cut)	6.0	0	5.7	8.0	0	6.9	40
Forage harvester (wilted alfalfa)	6.0	0	4.0	8.0	0	4.9	40
Forage harvester (corn silage)	6.0	0	3.3	8.0	0	4.0	40
Forage wagon	0	0	0.3	0	0	0.3	40

Source: ASAE (1995), ASAE D497, Table 1.

Table 27. Area covered and maximum yield machinery capable of handling[a]

Implement		Power	a	b	c	Range	Field efficiency	Width	Speed	Coverage - 100% FE	Coverage - actual FE	Maximum yield
		kW	kW	kW/m	kW/Mg	%	%	m	km/hr	ha/hr	ha/hr	dry Mg/ha
Mower-conditioner		74.6	0	4.5	0	30	80	2.97	8.05	2.39	1.91	
Mower-conditioner (disk)		74.6	0	8	0	30	80	2.97	11.27	3.35	2.68	
Windrower		74.6	0	1.3	0	40	80	6.40	7.25	4.64	3.71	
SP windrower		74.6	0	1.3	0	40	80	4.88	8.05	3.93	3.14	
Rake		33.6	0	0.4	0	50	80	2.90	9.66	2.80	2.24	
Rectangular baler		119.4	4	0	1.3	35	80	2.48	8.05	1.99	1.60	24 (26.5)
Large round baler		74.6	4	0	1.1	50	65	1.34	8.05	1.08	0.70	24 (26.7)
Forage harvester	Windrow head	156.7	6	0	4	40	70	2.13	4.83	1.03	0.72	21.9
Forage harvester	2-row head	119.4	6	0	3.3	40	70	1.52	4.83	0.74	0.52	26.6
Forage harvester	3-row head	156.7	6	0	3.3	40	70	2.29	4.83	1.10	0.77	25.1
SP forage harvester	Windrow head	201.4	6	0	4	40	70	2.13	5.64	1.20	0.84	25.4
SP forage harvester	Windrow head	320.8	6	0	4	40	70	2.13	5.64	1.20	0.84	43.0
SP forage harvester	4-row head	201.4	6	0	3.3	40	70	3.05	5.64	1.72	1.20	21.8
SP forage harvester	6-row head	320.8	6	0	3.3	40	70	4.57	5.64	2.58	1.80	24.6
		hp	hp	hp/ft	hp/ton	%	%	ft	mi/hr	ac/hr	ac/hr	dt/ac
Mower-conditioner		100	0	1.8	0	30	80	9.75	5	5.91	4.73	
Mower-conditioner (disk)		100	0	3.3	0	30	80	9.75	7	8.27	6.62	
Windrower		100	0	0.5	0	40	80	21	4.5	11.45	9.16	
SP windrower		100	0	0.5	0	40	80	16	5	9.70	7.76	
Rake		45	0	0.2	0	50	80	9.5	6	6.91	5.53	
Rectangular baler		160	5.4	0	1.6	35	80	8.125	5	4.92	3.94	10.6 (11.8)
Large round baler		100	5.4	0	1.3	50	65	4.396	5	2.66	1.73	10.6 (11.9)
Forage harvester	Windrow head	210	8	0	4.9	40	70	7	3	2.55	1.78	9.8
Forage harvester	2-row head	160	8	0	4	40	70	5	3	1.82	1.27	11.9
Forage harvester	3-row head	210	8	0	4	40	70	7.5	3	2.73	1.91	11.2
SP forage harvester	Windrow head	270	8	0	4.9	40	70	7	3.5	2.97	2.08	11.3
SP forage harvester	Windrow head	430	8	0	4.9	40	70	7	3.5	2.97	2.08	19.2
SP forage harvester	4-row head	270	8	0	4	40	70	10	3.5	4.24	2.97	9.7
SP forage harvester	6-row head	430	8	0	4	40	70	15	3.5	6.36	4.45	11.0

[a]For balers power calculation done on a wet weight. Numbers in ( )under maximum yield are wet weight yield. Hay dry yield based on 12% moisture content.

For forage harvesters, ASAE (1995) lists three sets of power coefficients; one for corn silage, another for wilted alfalfa, and the third for direct cut [hay]. We use the corn silage coefficients for thick-stemmed species (e.g. sorghum, energy cane) and the wilted alfalfa coefficients for thick- or thin-stemmed species that have been mowed or windrowed, left to field dry, and then picked up with a windrow pickup head.

Dry matter yield is critical to the choice of forage harvesters and tractor size, or self-propelled forage harvester power size. Also critical is the length of the cut. For thick-stemmed species we assume the rows are 0.76 m (2.5') in width. First we discuss pull-type forage harvesters.

Assume that the thick-stemmed species harvested using forage harvesters are high yielding. At a yield of 15.7 dMg/ha (7.0 dt/ac), a 119 kW (160 hp) tractor provides adequate power for operating a windrow pickup (if the crop had to be partly field dried) by wilting, a 2-row head, or a 3-row head at typical field speed of 4.8 km/hr (3.0 mi/hr). Only at maximum speed and at the maximum end of the range of power requirements would a 119 kW (160 hp) tractor be inadequate. As a goal we are expecting 22.4 dMg/ha (10 dt/ac). At this yield a 119 kW (160 hp) tractor is adequate only for a 2-row head, not a windrow pickup or 3-row head. At 22.4 dMg/ha (10 dt/ac) a 149 to 159 kW (200 to 210 hp) tractor would be sufficient, unless operating the forage harvester at maximum speed. This larger sized tractor has the maximum power pull-type forage harvesters are designed to handle. In all cases, we would recommend the heavy duty pull-type forage harvester, with list prices of between $19,000 and $25,000 without any head, plus an additional $3600 for a 2-row head or $6000 for a 3-row head. A 149 to 157 kW (200 to 210 hp) tractor has a list price of about $90,000 to $95,000, so the total cost for the tractor plus forage harvester would be about $120,000. This is only slightly less than the list price of a 201 kW (270 hp) self-propelled forage harvester with a 4-row head, which is about $130,000. So a question to ask is, does the farmer already have a 149 to 157 kW (200 to 210 hp) tractor or, if he does not already own one, could he use it for other field operations, or should the farmer have a custom operator perform the harvest? What we assume is that the primary forage harvest operation is a direct cut of corn silage-type material with a heavy-duty pull-type forage harvester using a 2-row head and a 119 kW (160 hp) tractor. If the farmer needs to harvest a wilted crop, then field speed is reduced to 3.2 km/hr (2.0 mi/hr) so that the 119 kW (160 hp) tractor provides adequate power. For a 3-row head the farmer would use a 149 to 157 kW (200 to 210 hp) tractor.

Self-propelled forage harvesters are designed to handle large quantities of biomass. Their power ranges from 201 to 321 kW (270 to 430 hp). At typical field speed, a 22.4 dMg/ha (10 dt/ac) yield, and for a windrow pickup or a 4-row head, the "smallest" self-propelled forage harvester, 201 kW (270 hp) has adequate power, even at the maximum range of power requirements. However, if one wished to harvest 5 or 6 rows then a more powerful engine is needed. We assume that a custom operator operating in the high yield environment we are considering will have a 321 kW (430 hp) self-propelled forage harvester, with a 6-row head and a 2.13 m (7') windrow pickup head. At typical field speed this size unit provides adequate power. Such a unit with the windrow pickup head and a 6-row head has a list price of $190,000. If a custom operator uses a windrow pickup head much, then a 201 kW (270 hp) unit would be less costly.

COSTS

TRUCK AND OVER-THE-ROAD TRANSPORTATION COSTS

Fuller et al (1992) list the price of a tandem truck at $46,000, annual use of 500 hours, a lifetime of 5000 hours (and thus a lifetime of 10 years), repair costs of $2.30/hr, and diesel use of 17.8 L/hr (4.7 gallons/hr). The price of the truck listed is a net cost, so any dealer discounting is included. To adjust for inflation between 1992 and 1995 and for dealer discounting we assume a 1995 list price of $58,000 and, to adjust for inflation, repair costs of $2.53/hr. A tandem truck [14.6 m (48') trailer] is used to haul hay. Trucks hauling hay make three round trips in an eight hour day and because of loading and unloading time, are assumed to operate only four out of those eight hours (see p. 11 for assumptions regarding number of round trips per day).

Forklifts are needed to move bales on and off the trailers. For simplicity we pair a forklift with a truck and assume it operates the four hours the truck is not operating. (There may be less costly truck-forklift configurations.) A 30 kW (40 hp) forklift is used with a list price of $17,000 [based on the list price of a comparably powered skid loader in NAEDA (1995)], an assumed lifetime of 5000 hours, and the same annual use as the tandem truck, 500 hours. Fuel use of 7.48 L/hr (1.98 gallons/hr) is based on the forklifts' power and the methodology described in the section on fuel and oil.

Tandem truck cost excluding labor is $23.60/hr and including $15/hr for labor is $38.60/hr. Forklift cost excluding labor is $9.67/hr and including labor at the truck driver rate is $24.67/hr. For an eight-hour day the combined cost of the tandem truck plus forklift, for four hours each, is $253.

A silage truck is assumed to have a list price of $80,000, a lifetime of 5000 hours, and operates 400 hr/year. The 400 operating hr/year is based on a custom silage operation working 400 hr/year and the trucks that haul silage are used in a just-in-time manner (i.e. they haul silage when silage is being harvested) with no off site (from the conversion facility) storage. Fuel use is the same as for the tandem truck.

Repair costs are proportional to relative list prices of the silage and tandem truck, $3.49/hr ($80,000/$58,000*$2.53/hr). A silage truck operates eight hours in an eight hour working day and makes four round trips in a working day. Total cost including labor is $47.48/hr or $380/eight-hour working day.

Module trucks are specially designed to pick up modules off the ground, transport them, and then put them back on the ground. List price is assumed to be $100,000, lifetime is 5000 hours, and annual hours of operation is 1000 hours. We assume 1000 hours of annual use because of the trucks expense (the more expensive the more one wants to use it) and that modules can be moved any time after they are made. Fuel use is the same as for tandem trucks. Repair costs are proportional to relative list prices of the module and tandem truck, $4.36/hr ($100,000/$58,000*$2.53/hr). A module truck operates eight hours/working day and makes five round trips/day. Total cost including labor is $43.94/hr or $352/eight-hour working day.

Table 28 summarizes hourly truck and forklift costs. Table 29 shows the impact of annual hours of use. Biomass transportation costs based on how much the trucks can carry are calculated in Table 30. Based on standard hours, hay transport costs range from

$4.40 to $6.49/dMg ($3.99 to $5.89/dt), module transport costs $8.81/dMg ($7.99/dt), and silage transport costs $8.37/dMg ($7.60/dt) for 50% moisture content and $13.96/dMg ($12.66/dt) for 70% moisture content. For our baseline cases we use $6.49/dMg ($5.89/dt) for 1.80 m (5.90') diameter large round bales, $5.87/dMg ($5.33/dt) for 24 large rectangular bales, $8.81/dMg ($7.99/dt) for modules, and $8.37/dMg ($7.60/dt) for 50% moisture content silage. Table 31 compares transport costs for standard hours versus 2000 hours. If the trucks and forklifts used for transportation are utilized 2000 hours instead of standard hours annually, then transport costs decrease 12 to 26%, with transport costs for large rectangular bales as low as $3.75/dMg ($3.41/dt) and silage $6.22/dMg ($5.64/dt).

Labor hours and energy consumption for bale, module and silage transportation are shown in Table 32.

Table 28. Hourly truck and forklift costs

	Life		Annual use	List price	Total cost
	Hr	Years	hr	$	$/hr
Tandem truck	5000	10	500	58000	38.60
Silage truck	5000	12.5	400	80000	47.48
Module truck	5000	5	1000	100000	43.94
Forklift	5000	10	500	17000	24.67

Table 29. The effect of annual hours of use on truck and forklift costs (including labor at $15/hr)

Vehicle	Annual hours of use					
	200	300	400	600	1000	2000
	$/hr					
Tandem truck	47.22	42.71	40.25	37.38	34.40	31.39
Silage truck	57.08	50.87	47.48	43.50	39.40	35.25
Module truck	66.04	58.28	54.04	49.08	43.94	38.76
Forklift	27.20	25.88	25.16	24.31	23.44	22.56

Table 30. Transportation costs for bales, modules, and silage

Type of biomass	Number of bales	Diameter		Weight/bale		Weight/trip		Dry fraction	Weight/trip		Cost incl fork-lift	Trips/ day	Cost/ trip	cost	
		m	ft	kg	lb	Mg	Tons		dMg	dt	$/8 hr-day		$	$/dMg	$/dt
Round bales	30	1.80	5.90	493	1086	14.8	16.3	0.88	13.0	14.3	253	3	84	6.49	5.89
Round bales	30	1.83	6.00	510	1125	15.3	16.9	0.88	13.5	14.9	253	3	84	6.26	5.68
Rectangular bales	24			680	1500	16.3	18.0	0.88	14.4	15.8	253	3	84	5.87	5.33
Rectangular bales	32			680	1500	21.8	24.0	0.88	19.2	21.1	253	3	84	4.40	3.99
Modules						9.1	10.0	0.88	8.0	8.8	352	5	70	8.81	7.99
		Capacity		Density											
		m³	ft³	kg/m³	lb/ft³										
Silage - 70% moisture		54	1923	416	26	22.7	25.0	0.3	6.8	7.5	380	4	95	13.96	12.66
Silage - 50% moisture		91	3205	250	15.6	22.7	25.0	0.5	11.3	12.5	380	4	95	8.37	7.60

Table 31. Hay, module, and silage over-the-road transportation costs for standard hours and 2000 hours of annual truck use

Type of biomass and packaging	Standard hours	Cost ($/dMg)		Cost ($/dt)		% change
		Standard hours	2000 hours	Standard hours	2000 hours	
Hay						
Round bales - 30/load, 1.80 m (5.90') diameter	500	6.49	5.53	5.89	5.02	15
Round bales - 30/load, 1.83 m (6.00') diameter	500	6.26	5.34	5.68	4.84	15
Rectangular bales - 24/load	500	5.87	5.01	5.33	4.54	15
Rectangular bales - 32/load	500	4.40	3.75	3.99	3.41	15
Modules	1000	8.81	7.77	7.99	7.05	12
Silage						
70% moisture	400	13.96	10.36	12.66	9.40	26
50% moisture	400	8.37	6.22	7.60	5.64	26

Table 32. Labor hours and energy consumption for bale, module and silage transportation

Type of biomass	Labor		Fuel	
	hr/dMg	hr/dt	L/dMg	gal/dt
Round bales - 30 1.80 m (5.90') diameter	0.21	0.19	2.59	0.62
Round bales - 30 1.83 m (6.00') diameter	0.20	0.18	2.50	0.60
Rectangular bales - 24	0.19	0.17	2.34	0.56
Rectangular bales - 32	0.14	0.13	1.76	0.42
Modules	0.20	0.18	3.57	0.85
Silage - 70% moisture	0.29	0.27	5.23	1.25
Silage - 50% moisture	0.18	0.16	3.14	0.75

TRACTOR COSTS

Four tractor sizes are costed (including labor cost) (Table 33). Tractors are used with all field equipment except those that are self propelled, some forage wagons, and heads on self-propelled equipment.

Table 33. Tractor costs

Implement	Power		Life		Annual use	List price	Total cost
	kW	hp	hr	years	hr	$	$/hr
Tractor 33.6 kW(45 hp)	34	45	12000	24	500	21000	17.25
Tractor 74.6 kW(100 hp)	75	100	12000	21.8	550	42000	24.59
Tractor 119.4 kW(160 hp)	119	160	12000	20	600	72000	33.97
Tractor 156.7 kW(210 hp)	157	210	12000	20	600	93000	41.12

HAY

We calculate costs for four ways of cutting hay: (1) a 2.97 m (9.75') wide mower-conditioner, (2) a 2.97 m (9.75') wide disk-type mower-conditioner, (3) a 6.40 m (21') wide windrower, and (4) a 4.88 m (16') wide self-propelled windrower (Table 34). Because of its wide head, the 6.40 m (21') wide windrower is the least cost option. We assume a farmer will use a mower-conditioner and a custom operator will use a self-propelled windrower because of its convenience.

Table 34. Mowing, windrowing, and raking costs

Implement	Power		Life		Annual use	List price	Total cost	Area covered		Total cost	
	kW	hp	hr	years	hr	$	$/hr	ha/hr	ac/hr	$/ha	$/ac
Mower-conditioner	75	100	2500	12.5	200	10000	8.89	1.91	4.73	4.65	1.88
Tractor 74.6 kW(100 hp)	75	100	12000	21.8	550	42000	24.59			12.85	5.20
Total						52000	33.48			17.50	7.08
Mower-conditioner(disk)	75	100	2500	12.5	200	15000	14.54	2.68	6.62	5.43	2.20
Tractor 74.6 kW(100 hp)	75	100	12000	21.8	550	42000	24.59			9.18	3.72
Total						57000	39.13			14.60	5.91
Windrower 6.40 m(21')	75	100	2500	12.5	200	8700	7.39	3.71	9.16	1.99	0.81
Tractor 74.6 kW(100 hp)	75	100	12000	21.8	550	42000	24.59			6.63	2.68
Total						50700	31.98			8.62	3.49
Self-propelled windrower 4.88 m(16')	75	100	3000	10	300	54000	47.42	3.14	7.76	15.10	6.11
Rake 2.90 m(9.5')	34	45	2500	12.5	200	3667	2.97	2.24	5.53	1.33	0.54
Tractor 33.6 kW(45 hp)	34	45	12000	24	500	21000	17.25			7.71	3.12
Total						24667	20.22			9.03	3.66

For hay we assume raking is done part way through field drying the hay to aid in the drying process. Raking is relatively inexpensive, costing $8.79/ha ($3.56/ac) (Table 34).

Two hay balers, a 1.22 m (4') wider round baler which makes 493 kg (1087 lb) bales and a large rectangular baler which makes 680 kg (1500 lb) bales, are costed (Table 35). Because it covers a greater area per unit time, the rectangular baler is less expensive than the round baler per unit area. We have assumed that the rectangular baler operates 600 hours because it is used by a custom operator and the round baler only 150 hours. If both balers operate 300 hours then the cost of a round baler decreases from $21.71 to $17.94/hr [$35.74 to $29.96/ha ($14.47 to $12.13/ac)]. The cost of the rectangular baler increases from $36.44 to $44.10/hr [$22.85 to $27.65/ha ($9.25 to $11.20/ac)]. Even at equal hours the round baler plus tractor (at standard hours) is about $16/ha ($6.50/ac) more expensive to operate. However the initial price of a rectangular baler is four times that of the large round baler.

Table 35. Baler costs

	Power		Life		Annual use	List price	Total cost	Area covered		Total cost	
Implement	kW	hp	hr	years	hr	$	$/hr	ha/hr	ac/hr	$/ha	$/ac
Rectangular baler	119	160	3000	5	600	65000	36.44	1.59	3.94	22.85	9.25
Tractor 119.4 kW(160 hp)	119	160	12000	20	600	72000	33.97			21.30	8.62
Total						137000	70.41			44.15	17.87
Large round baler	75	100	1500	10	150	17200	25.06	0.70	1.73	35.74	14.47
Tractor 74.6 kW(100 hp)	75	100	12000	21.8	550	42000	24.59			35.08	14.20
Total						59200	49.65			70.82	28.67

We have assumed a capacity limitation for a large round baler of 10.0 Mg/hr (11 tons/hr) and for a large rectangular baler of 20.0 Mg/hr (22 tons/hr). At 88% dry matter content and coverage of 0.70 ha/hr (1.73 ac/hr) for a large round baler and 1.59 ha/hr (3.94 ac/hr) for a large rectangular baler, once yield reaches 12.5 dMg/ha (5.60 dt/ac) for a large round baler and 11.0 dMg/ha (4.91 dt/ac) for a large rectangular baler, cost per unit of biomass will decrease no further. The baler will slow down so that throughput does not exceed capacity.

A small 34 kW (45 hp) tractor is used to move bales from the field to its edge. Using a bale carrier mounted on its 3-point hitch and a spike on its front end loader a tractor can carry two large round bales, moving 3.51 dMg/hr (3.87 dt/hr). Using a forklift with its front end loader, a tractor can carry one large rectangular bale at a time, moving 2.99 dMg/hr (3.30 dt/hr). Unlike mowing/windrowing, raking, and baling; bale moving costs are independent of yield. Based on standard hours, for large round bales cost is $21.82/hr, or $6.22/dMg ($5.64/dt); and for large rectangular bales cost is $20.92/hr, or $6.99/dMg ($6.34/dt) (Table 36). Because a custom operator is likely to be producing the large rectangular bales, the tractor moving the bales may be operating closer to 1000 hours than 500 hours. In this case the cost of moving large rectangular bales decreases to $19.48/hr, or $6.51/dMg ($5.90/dt).

Table 36. Costs of moving bales to the field edge for standard hours

	Power		Life		Annual use	List price	Total cost
Implement	kW	hp	hr	years	hr	$	$/hr
Front end loader	34	45	1000	4	250	3000	3.67
Tractor 33.6 kW(45 hp)	34	45	12000	24	500	21000	17.25
Total						24000	20.92
Front end loader	34	45	1000	4	250	3000	3.67
Bale carrier	34	45	500	2	250	500	0.90
Tractor 33.6 kW(45 hp)	34	45	12000	24	500	21000	17.25
Total						24500	21.82

Twine costs are assumed to be $1.10/dMg ($1.00/dt).

Based on one cut of 9.0 dMg/ha (4.0 dt/ac), hay crop costs are summarized in Table 37. The yield of 9.0 dMg/ha (4.0 dt/ac) for a single cut hay crop seems like a yield a farmer could reasonably attain at the present time with switchgrass. For the farmer using a round baler, costs are estimated for three cases: equipment used for standard hours, all equipment is used only for hay on 40 ha (100 acres), and all equipment is used only for hay on 202 ha (500 acres). For the custom operator using a large rectangular baler, costs are shown for using two rectangular balers 600 hours each and the self-propelled windrower 712 hours.

In-field costs (hay harvest and moving bales to the field edge) are affected by hay yield, number of cuttings, assumptions on equipment utilization, and type of equipment (Table 37, figs. 1, 2, and 3). The effects of yield and machinery utilization on harvest and in-field transport costs for a farmer using a round baler and all other equipment at standard hours, actual hours on 81 ha (200 acres), and actual hours on 162 ha (400 acres) are shown in Fig. 1. Note that standard hours represents all equipment being utilized for a fair number of hours per year, while for 81 ha (200 acres) the number of hours of utilization is less and thus costs are higher. Fig. 2 shows how hours of equipment utilization (which is directly proportional to area of annual use) affects costs for a round baler. Fig. 3 is similar to Fig. 2, except it is for a rectangular baler. Figs. 1, 2, and 3 indicate the importance of both effective machinery utilization and yield on costs. From Table 37, using a large round baler on 202 ha (500 ac) of hay, in-field costs range from

$13 to $20/dMg ($12 to $18/dt)). For one cut hay yielding 9.0 dMg/ha (4 dt/ac) costs are $15/dMg ($14/dt). Adding in transportation costs from the field to conversion facility, delivered harvest and transport costs of round bales range from $20 to $26/dMg ($18 to $24/dt).

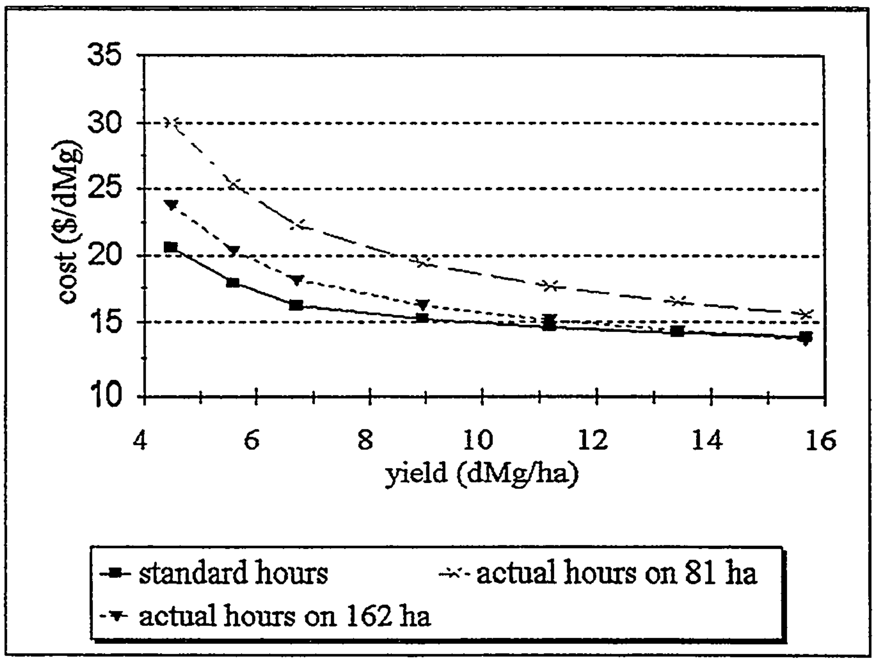

Fig 1. Cost of hay harvest and in-field transport versus yield for a farmer using a round baler.

In-field costs for the rectangular baler used 400 hours are similar to costs for using a large round baler on 202 ha (500 ac), being slightly lower at yields of 9.0 and 15.7 dMg/ha (4 and 7 dt/ac). The utilization of the large rectangular baler is much higher, 400 hours versus 267 hours for a large round baler used on 202 ha (500 ac) at a yield 9.0 dMg/ha (4 dt/ac) for one cut. The savings in using a large rectangular baler comes from transportation costs, between $0.38 and $2.09/dMg ($0.35 and $1.90/dt) and because the large round baler equipment complement is assumed to be used on a smaller area (and therefore less hours of use) each year.

Table 37. Hay harvest and in-field transport costs under varying assumption for equipment utilization, yields, and number of cuts

Type of baler and hours of equipment use	Yield (dMg/ha)					
	1 cut			2 cuts		
	5.6	9.0	15.7	9.0	15.7	22.4
Round baler	$/dMg					
Standard hours	17.90	15.26	13.99	20.54	16.10	14.66
Forage equipment only for biomass hay (actual hours), tractors at standard hours						
40 ha	24.04	18.86	15.72	23.72	17.69	15.58
202 ha	18.21	15.11	13.34	19.87	15.24	13.61
All equipment used only on biomass hay						
40 ha	35.34	35.63	19.20	32.66	22.46	18.67
202 ha	19.32	15.62	13.48	20.01	15.55	13.82
Rectangular baler - 400 hours	18.95	14.73	12.97	21.88	15.70	14.05
	Yield (dt/ac)					
	1 cut			2 cuts		
	2.5	4	7	4	7	10
Round baler	$/DT					
Standard hours	16.24	13.84	12.69	18.64	14.61	13.30
Forage equipment only for biomass hay (actual hours), tractors at standard hours						
100 ac	21.81	17.11	14.26	21.52	16.05	14.13
500 ac	16.52	13.71	12.10	18.03	13.83	12.35
All equipment used only on biomass hay, tractors at standard hours						
100 ac	32.06	23.25	17.42	29.63	20.39	16.94
500 ac	17.53	14.17	12.23	18.15	14.11	12.54
Rectangular baler - 400 hours	17.19	13.36	11.77	19.85	14.24	12.75

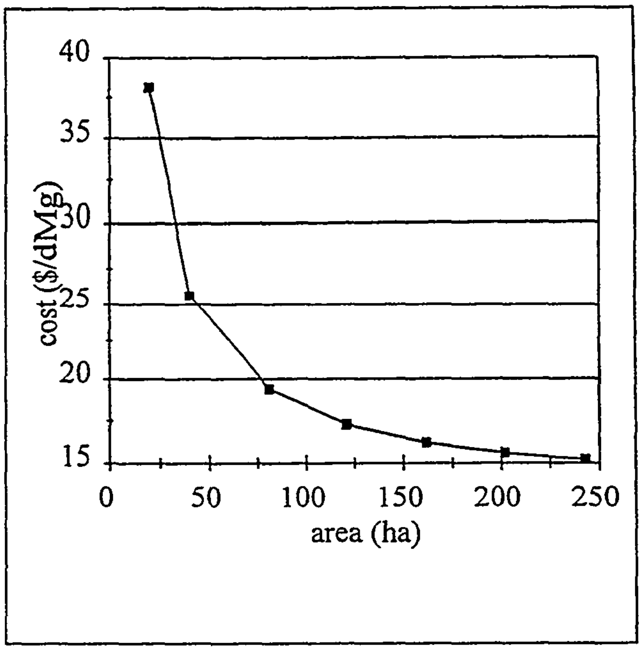

Fig 2. Effect of area (of annual use) on cost of hay harvest and in-field transport [based on a large round baler, a yield of 9.0 dMg/ha (4 dt/ac), 1 cut, and actual hours of equipment use on biomass hay crop only].

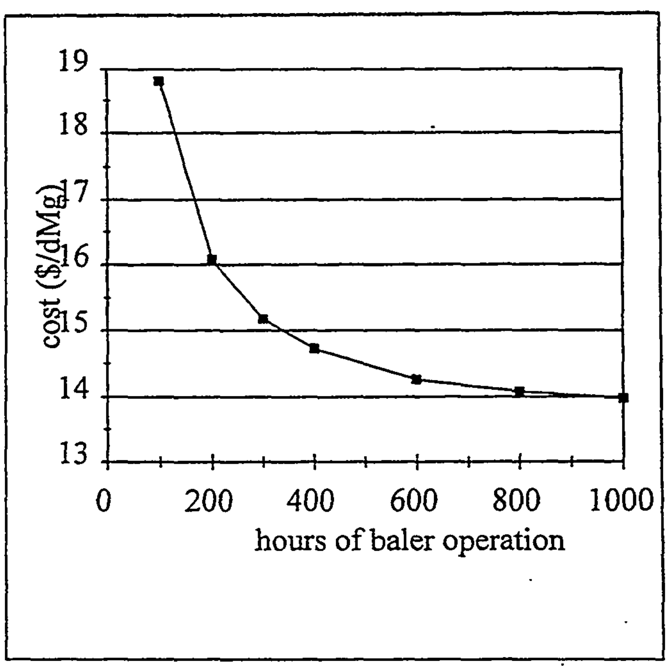

Fig 3. Effect of hours of large rectangular baler operation on hay harvest and in-field transport costs [based on a yield of 9.0 dMg/ha (4 dt/ac) and 1 cut].

One can add the costs of harvest and in-field transport (Table 37) to over-the-road transport costs (tables 30 and 31) and get what we will refer to as "delivered" costs (Table 38). However, note that these costs do not include land, management, overhead, establishment, weed control, and fertilizer costs. For our baseline cases we calculate costs for: (1) a farmer using a large round baler with all equipment utilized at standard hours, one cut on a yield of 9.0 dMg/ha (4 dt/ac), and 1.80 m (5.90') diameter bales carried 30 at a time on a truck utilized for standard (500) hours and (2) a custom operator using two large rectangular balers for 400 hours each annually, one cut on a yield of 9.0 Mg/ha (4 dt/ac), and 24 bales carried at a time on a truck utilized for standard (500) hours. We also calculate two least-cost cases: 3) a farmer using a large round baler on 202 ha (500 ac) with forage equipment costs based on actual hours of utilization and tractors at standard hours, one cut on a yield of 15.7 dMg/ha (7 dt/ac), and 1.83 m (6') diameter bales transported 30 at a time on a truck utilized for 2000 hours a year; and (4) a custom operator using two large rectangular balers for 1000 hours each annually, one cut on a yield of 15.7 dMg/ha (7 dt/ac), and 32 bales carried at a time on a truck utilized for 2000 hours annually (Table 38). If the equipment in (3) is utilized on 405 ha (1000 ac) then costs are reduced an additional \$0.72/dMg (\$0.65/dt).

Harvest and in-field costs for various hay yields and equipment utilization rates are in appendix Table A.2.

Table 38. Hay harvest and transport costs for baseline and least-cost cases

Case description	Yield	Harvest	Transport	Total	Yield	Harvest	Transport	Total
	dMg/ha	\$/dMg			dt/ac	\$/dt		
Baseline cases								
1) Farmer, large round baler, 1.80m (5.90') bales, standard hours	9.0	15.26	6.49	21.75	4	13.84	5.89	19.73
2) Custom operator, large rectangular baler (400 hr), 24 bales/truck (500 hr)	9.0	14.73	5.87	20.60	4	13.36	5.33	18.69
Least cost cases								
3) Farmer, large round baler on 202 ha (500 ac), 1.83m (6.00') bales	15.7	13.48	5.34	18.82	7	12.23	4.84	17.07
4) Custom operator, large rectangular baler(1000hr), 32 bales/truck(2000hr)	15.7	12.31	3.75	16.06	7	11.17	3.41	14.58

SILAGE COSTS

Direct-Cut Systems

The first machines used for direct-cut silage systems are pull-type or self-propelled forage harvesters. We calculate costs for two pull-type systems: a forage harvester with a

2-row head powered by a 119 kW (160 hp) tractor and a forage harvester with a 3-row head powered by a 157 kW (210 hp) tractor (Table 39). These are heavy-duty pull-type forage harvesters (abbreviated as forage harvester-hd). We also calculate costs for two self-propelled forage harvesters: a 201 kW (270 hp) model with a 4-row head and a 321 kW (430 hp) model with a 6-row head (Table 39). All four configurations are capable of handling 22.4 dMg/ha (10 dt/ac) yields except the 201 kW (270 hp) self-propelled model, which is limited to 21.8 dMg/ha (9.7 dt/ac) or a slower field speed by its available power at the assumed cut length of 9 mm (0.35"). At a longer cut length the 201 kW (270 hp) self-propelled model could handle 22.4 dMg/ha (10 dt/ac). Based on average field speeds from ASAE (1995), the coverage of the forage harvesters is controlled by the head size and the assumed 76 cm (30") row width. Forage harvesters are expensive to operate, costing between $55 and $121/hr and $67 to $106/ha ($27 to $43/ac) (including labor).

Table 39. Forage harvester costs

	Power		Life		Annual use	List price	Total cost	Area covered		Total cost	
Implement	kW	hp	hr	years	hr	$	$/hr	ha/hr	ac/hr	$/ha	$/ac
Forage harvester-hd	119	160	2500	10	250	22000	17.03			33.05	13.38
2-row head	119	160	2000	10	200	3600	3.75	0.52	1.27	7.29	2.95
Tractor 119.4 kW(160 hp)	119	160	12000	20	600	72000	33.97			65.93	26.69
Total						97600	54.76			106.27	43.02
Forage harvester-hd	157	210	2500	10	250	22000	17.03			22.04	8.92
3-row head	157	210	2000	10	200	6000	6.26	0.77	1.91	8.09	3.28
Tractor 156.7 kW(210 hp)	157	210	12000	20	600	93000	41.12			53.20	21.54
Total						121000	64.40			83.33	33.74
Self-propelled forage harvester-201 kW (270 hp)	201	270	4000	10	400	116000	74.05			61.59	24.93
4-row head	201	270	2000	5	400	10000	8.66	1.20	2.97	7.20	2.92
Total						126000	82.70			68.79	27.85
Self-propelled forage harvester-321 kW (430 hp)	321	430	4000	10	400	168000	104.53			93.18	37.72
6-row head	321	430	2000	5	400	19000	16.45	1.80	4.45	9.12	3.69
Total						187000	120.98			67.08	27.16

High dump forage wagons are used in all options except when the silage is blown directly into trucks (option 0). If the wagon is pulled behind a forage harvester, it is assumed to have both a roof and scale. If silage is blown directly into the wagon from the forage harvester, the wagon is assumed to have a scale, but no roof. If silage is dumped from the harvester-pulled wagon into a tractor-pulled wagon, the tractor-pulled wagon has no scale and no roof. High volume wagons, 22.7 and 31.2 m^3 (800 and 1100 ft^3), cost between $14.39 and $18.25/hr (Table 40). If they are hauled by a 34 kW (45 hp) tractor, the tractor costs an additional $17.25/hr (including labor).

Table 40. Costs for high dump forage wagons used for silage

Wagon characteristics	Size		Life		Annual use	List price	Total cost
	m^3	ft^3	hr	years	hr	$	$/hr
Scale, 22.7 m^3 (800ft^3), 1 min dump	22.7	800	2000	10	200	16160	14.39
High dump, 22.7 m^3 (800 ft^3), 2.5min dump	22.7	800	2000	10	200	19200	17.10
Scale, 31.2 m^3 (1100 ft^3), 1 min dump	30.3	1068	2000	10	200	19710	17.55
High dump, 31.2m^3(1100 ft^3), 2.5min dump	30.3	1068	2000	10	200	20500	18.25

In-field costs of silage harvest vary widely depending on the method by which the silage is harvested (options 0, 1 or 2) and the machinery complement used (Table 41, Fig. 4). Blowing silage directly into trucks in the field (option 0) is the lowest cost method, around $3/dMg ($2.75/dt) for a self-propelled forage harvester with a 4- or 6-row head [based on a yield of 22.4 dMg/ha (10 dt/ac) and operating the forage harvester 400 hours annually]. Pulling a forage wagon behind the forage harvester and then dumping the wagon into a truck in the field (option 1) increases the cost $0.50 to $1.50/dMg ($0.45 to $1.35/dt) over option 0 (directly blowing into a truck). Adding a tractor-pulled forage wagon and dumping into a truck at the field edge (option 2) adds between about $3 and $6/dMg ($3 to $6/dt) to cost (over option 1). As general rule, using a 3-row head instead of a 2-row head on a pull-type forage harvester is less expensive, with the break even point at between 20 and 60 ha (50 to 150 ac), costing all equipment at actual hours of use (and not standard hours). Costs for self-propelled forage harvesters using 4- and 6-row heads differ little. If the yield decreases from 22.4 to 15.7 dMg/ha (10 to 7 dt/ac), then costs increase in proportion to the yield decrease (i.e., they increase by 43%).

Hours of use (area harvested) affect the cost of harvest and in-field transport. Figures 5 and 6 show the effect for a pull-type forage harvester with a 3-row head and a self-propelled forage harvester with a 6-row head. In Fig. 6 for option 2, two 22.7 m^3 (800 ft^3) forage wagons are used. If two 31.2 m^3 (1100 ft^3) wagons are used costs would be about $1/dMg ($1/dt) lower.

Table 41. In-field cost of silage harvest based on 22.4 dMg/ha (10 dt/ac)[a]

Option number, system description, and forage wagon size, and dump time	Type of forage harvester			
	Pull type		Self propelled	
	Size of row head			
	2[b]	3[b]	4[c]	6[c]
	$/dMg			
0 directly to truck in field	4.74	3.72	3.07	2.99
1 forage wagon to truck in field				
22.7 m^3 (800 ft^3), 1 min	5.99	4.55	3.65	3.64
31.2 m^3 (1100 ft^3)[d], 1 min	6.26	4.73	3.74	3.48
22.7 m^3 (800 ft^3), 2.5 min	6.37	5.29	4.76	5.12
31.2 m^3 (1100 ft^3)[d], 2.5 min	6.32	5.00	4.38	4.56
2 forage wagon to forage wagon to truck at field edge				
22.7 m^3 (800 ft^3)	11.94	8.52	7.40	7.20
31.2 m^3 (1100 ft^3)[d,e]	9.34	8.53	6.30	6.05
	$/dt			
0 directly to truck in field	4.30	3.37	2.78	2.72
1 forage wagon to truck in field				
22.7 m^3 (800 ft^3), 1 min	5.43	4.13	3.31	3.31
31.2 m^3 (1100 ft^3)[d], 1 min	5.68	4.29	3.39	3.16
22.7 m^3 (800 ft^3), 2.5 min	5.78	4.80	4.31	4.64
31.2 m^3 (1100 ft^3)[d], 2.5 min	5.74	4.54	3.97	4.14
2 forage wagon to forage wagon to truck at field edge				
22.7 m^3 (800 ft^3)	10.83	7.73	6.71	6.53
31.2 m^3 (1100 ft^3)[d,e]	8.47	8.01	5.72	5.49

[a]See Table 7 for an explanation of the options.
[b]Farmer, based on standard hours.
[c]Custom operator, based on self-propelled forage harvester operating 400 hr/year.
[d]Actual capacity of wagon used is 30.3 m^3 (1068 ft^3).
[e]Assumes a hypothetical 31.2 m^3 (1100 ft^3) wagon with no roof exists.

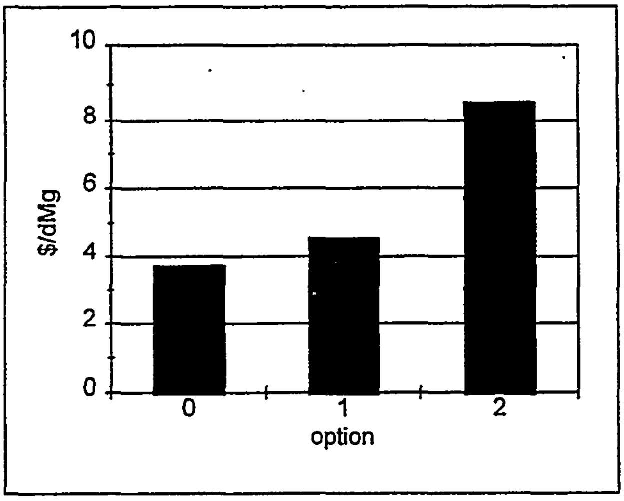

Fig. 4. In-field harvest costs for a farmer using a pull-type forage harvester with a 3-row head at standard hours and a yield of 22 dMg/ha (10 dt/ac). [Option 1 uses a 22.7 m^3 (800 ft^3) wagon with a 1 minute dump cycle and option 2 uses a pair of 22.7 m^3 (800 ft^3) wagons.]

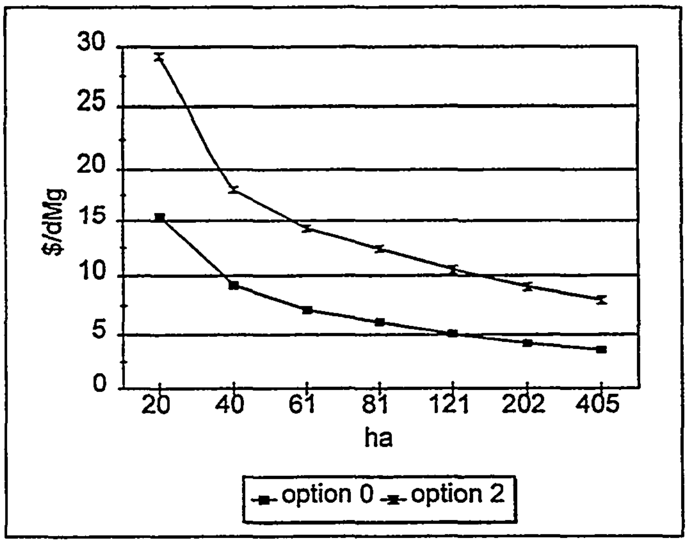

Fig. 5. How annual harvest area affects in-field harvest costs for a farmer using a 3-row head on a pull-type forage harvester based on 22.4 dMg/ha (10 dt/ac).

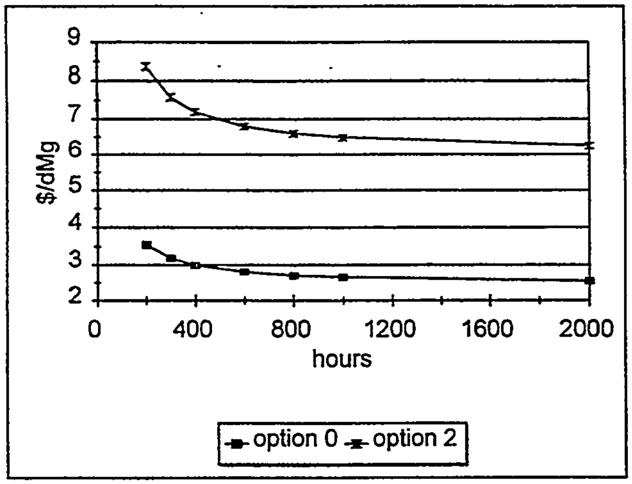

Fig. 6. How hours of use affect harvest and in-field transport for a custom operator using a self-propelled forage harvester with a 6-row head based on 22.4 dMg/ha (10 dt/ac). [Option 2 uses 22.7 m^3 (800 ft^3) wagons.]

Fuel and labor use are similar for options 0 and 1. This is because the only difference is the addition of a forage harvester-pulled forage wagon and, as we model it, only field efficiency is affected. Fuel use in options 0 and 1 range between 1.9 and 3.0 L/dMg (0.45 and 0.73 gal/dt) and labor use between 0.03 and 0.11 hr/dMg (0.03 and 0.10 hr/dt).

Fuel and labor use are higher for option 2 because of the additional tractor activity hauling the silage to the field edge. For option 0 fuel use ranges for 1.9 to 2.6 L/dMg (0.45 to 0.62 gal/dt) and for option 2 from 2.6 to 4.0 L/dMg (0.62 to 0.97 gal/dt). For option 0 labor use ranges from 0.03 to 0.11 hr/dMg (0.03 to 0.10 hr/dt) and for option 2 from 0.13 to 0.32 hr/dMg (0.12 to 0.29 hr/dt) (Table 42).

Costs, fuel, and labor use for options 0, 1, and 2 are in appendix Table A3.

One can add the costs of harvest and in-field transport (Table 41) to over-the road transport costs (Table 31) and get "delivered" costs (Table 43). However, note that these costs do not include land, management, overhead, establishment, weed control, and fertilizer costs. For a farmer, we calculate costs using a pull-type forage harvester with 3-row head, based on standard hours of equipment use and actual hours of use on 405 ha (1000 ac) for: (1) blowing directly into a truck in the field (option 0), (2) blowing into a 22.7 m^3 (800 ft^3) forage wagon with a 1 minute dump cycle pulled behind the forage harvester, dumping into a truck in the field (option 1), and (3) blowing into a 22.7 m^3 (800 ft^3) forage wagon with a 1 minute dump cycle pulled behind the forage harvester, dumping into a tractor-pulled 22.7 m^3 (800 ft^3) forage wagon with a 2.5 minute dump cycle, which then travels to the field edge and dumps into a truck (option 2). For a custom operator using a self-propelled forage harvester with a 6-row head, based on forage harvester use for 400 and 2000 hours annually and truck use for 2000 hours annually, we calculate costs for: (4) blowing directly into a truck in the field (option 0), (5) blowing into a 31.2 m^3 (1100 ft^3) forage wagon with a 1 minute dump cycle pulled behind the forage harvester, dumping into a truck in the field (option 1), and (6) blowing into a 31.2 m^3 (1100 ft^3) forage wagon with a 1 minute dump cycle pulled behind the forage harvester, then dumping into a 31.2 m^3 (1100 ft^3) tractor-pulled forage wagon with a 2.5 minute dump cycle, which then travels to the field edge and dumps into a truck (option 2). The 405 ha (1000 ac)/2000 hours of use represent least cost scenarios. Yield is 22.4 dMg (10 dt/ac) (Table 43).

Table 42. Fuel and labor use for options 0 and 2 for silage harvest and in-field transport based on a yield of 22.4 dMg/ha (10 dt/ac)

Option number, system description, and wagon size	Diesel L/dMg	Labor hr/dMg	Diesel gal/dt	Labor hr/dt
0 directly to truck in field				
2-row head	2.59	0.11	0.62	0.10
3-row head	2.27	0.07	0.54	0.07
4-row head	1.87	0.05	0.45	0.04
6-row head	1.99	0.03	0.48	0.03
2 wagon to wagon to truck at field edge				
2-row head				
22.7 m^3 (800 ft^3)	4.05	0.32	0.97	0.29
31.2 m^3 (1100 ft^3)	3.32	0.22	0.80	0.20
3-row head				
22.7 m^3 (800 ft^3)	3.24	0.22	0.78	0.20
31.2 m^3 (1100 ft^3)	3.24	0.22	0.78	0.20
4-row head				
22.7 m^3 (800 ft^3)	2.91	0.19	0.70	0.17
31.2 m^3 (1100 ft^3)	2.57	0.14	0.62	0.13
6-row head				
22.7 m^3 (800 ft^3)	3.11	0.17	0.75	0.15
31.2 m^3 (1100 ft^3)	2.70	0.13	0.65	0.12

Table 43. In-field plus transport costs of silage for pull-type and self-propelled forage harvesters for two rates of annual use [yield of 22.4 dry Mg/ha (10 dt/ac)]

Option number	Forage wagons used	Harvest		Truck		Total	
		Hours or area of use					
		Standard	405 ha	Standard[a]	2000 hr	Standard	405 ha/ 2000 hr
Farmer using pull-type forage harvester with a 3-row head							
		$/dMg					
0	None	3.72	3.60			12.09	9.82
1	1 22.7 m³ (800 ft³), 1 min[b]	4.55	4.29	8.37	6.22	12.92	10.51
2	2 22.7 m³ (800 ft³)[c]	8.52	8.18			16.89	14.40
		400 hr	**2000 hr**	**Standard**	**2000 hr**	**400 hr**	**2000 hr**
Custom operator using self-propelled forage harvester with 6-row head							
0	None	2.99	2.55			11.36	8.77
1	1 31.2 m³ (1100 ft³), 1 min	3.48	2.97	8.37	6.22	11.85	9.19
2	2 31.2 m³ (1100 ft³)[c]	6.05	5.25			14.42	11.47
		$/dt					
Farmer using pull-type forage harvester with a 3-row head							
0	None	3.37	3.27			10.97	8.91
1	1 22.7 m³ (800 ft³), 1 min[b]	4.13	3.89	7.60	5.64	11.73	9.53
2	2 22.7 m³ (800 ft³)[c]	7.73	7.42			15.33	13.06
Custom operator using self-propelled forage harvester with 6-row head							
0	None	2.72	2.31			10.32	7.95
1	1 31.2 m³ (1100 ft³), 1 min	3.16	2.70	7.60	5.64	10.76	8.34
2	2 31.2 m³ (1100 ft³)[c]	5.49	4.76			13.09	10.40

[a]Standard hours of silage truck is 400 hours.
[b]Time (1 minute) is dump cycle time.
[c]Use 1 wagon with a 1 minute dump cycle and 1 wagon with a 2.5 minute dump cycle.

Wilted Systems

In wilted systems, before a forage harvester is used, the biomass must be severed, either by a mower-conditioner or a windrower. Costs for this operation were shown in Table 34 in the section on hay costs. Following the severing operation, forage harvesters employ windrow pickup heads instead of row heads. Using a windrow pickup head requires more power than using a row head. The pull-type forage harvester uses a 157 kW (210 hp) tractor and has the power to pick up up to 21.9 dMg/ha (9.8 dt/ac) with a 2.13 (7') wide head. The 201 kW (270 hp) self-propelled forage harvester has the power to pick up 22.4 dMg/ha with a 2.13 m (7') wide head, but is limited to 19.0 dMg/ha (8.5 dt/ac) with a 2.84 m (9.33') wide head (or it must slow its speed). If wilted silage with a yield above 19.0 dMg/ha (8.5 dt/ac) needs to be picked up, one could go to a slightly more powerful 242 to 246 kW (325 to 330 hp) unit that has a list price of around $137,000 without any heads or about $21,000 more than the 201 kW (270 hp) unit. This larger unit would cost $12/hr more to operate than the 201 kW (270 hp) unit. A 321 kW (430 hp) self-propelled forage harvester has adequate power to pick up 22.4 dMg/ha (10 dt/ac).

Costs for forage harvesters with windrow pickup heads are shown in Table 44. For a farmer using pull-type equipment [a mower-conditioner with a 75 kW (100 hp) tractor and then a window head 2.1 m (7') wide on a heavy-duty forage harvester with a 22.7 m^3 (800 ft^3) forage wagon (1 minute dump time) powered by a 119 kW (160 hp) tractor, that dumps into a truck in the field (as in option 1 for direct cut systems), with a yield of 22.4 dMg/ha (10 dt/ac), and based on standard hours, harvest cost is $5.18/dMg ($4.70/dt). This compares to $4.55/dMg ($4.13/dt) for a 3-row head in option 1 for direct cut systems (Table 43). For a custom operator using a self-propelled windrower and a self-propelled forage harvester 201 kW (270 hp) with a window head 2.1 m (7') wide and towing a 22.7 m^3 (800 ft^3) forage wagon (1 minute dump time) based on the forage harvester operating 400 hours, harvest costs are $5.76/dMg ($5.22/dt). If three sets of forage harvesters are used with one self-propelled windrower, then costs are $5.53/dMg ($5.01/dt). This compares to $3.48/dMg ($3.16/dt) for a 6-row head in option 1 for direct cut systems (Table 43). For pull-type equipment at standard hours, the wilting system adds about $0.50/dMg ($0.50/dt) over the direct-cut system. For self-propelled equipment at 400 hours of forage harvester operation, the wilting system adds about $2/dMg ($2/dt) over the direct cut system.

HAY MODULE COSTS FOR DIRECT-CUT SYSTEMS

In-field costs (hay harvest, moving loose biomass to the field edge, and making modules) are affected by hay yield, number of cuttings, assumptions on equipment utilization, and type of equipment (Table 45, figs. 7 and 8). Unless otherwise stated all machinery complements use 22.7 m^3 (800 ft^3) forage wagons. Using a pull-type forage harvester on 202 ha (500 ac), in-field costs range from $19 to $36/dMg ($18 to $33/dt). For one cut yielding 9.0 dMg/ha (4 dt/ac) costs are $23/dMg ($20/dt). Adding in transportation costs from the field to conversion facility, delivered harvest and transport costs of modules range from $28 to $45/dMg ($26 to $41/dt).

In-field costs for the self-propelled forage harvester complement are lower than for using a pull-type forage harvester on 202 ha (500 ac), but are only slightly lower in the two-cut situation or at lower yields. Delivered costs range from $23/dMg ($21/dt) to $43/dMg ($39/dt).

Table 44. Costs for forage harvesters with windrow pickup heads

Implement	Power kW	Power hp	Life hr	Life years	Annual use hr	List price $	Total cost $/hr	Area covered ha/hr	Area covered ac/hr	Total cost $/ha	Total cost $/ac
Forage harvester-hd	157	210	2500	10	250	22000	17.03			23.61	9.56
Windrow head-2.13 m(7')	157	210	1000	10	100	3000	6.26	0.72	1.78	8.67	3.51
Tractor 157 kW(210 hp)	157	210	12000	20	600	93000	41.12			57.00	23.08
Total						118000	64.40			89.28	36.15
Self-propelled forage Harvester 201 kW(270 hp)	201	270	4000	10.00	400	116000	74.05			87.98	35.62
Windrow head-2.13 m(7')	201	270	1000	10	100	3000	6.26	0.84	2.08	7.43	3.01
Total						119000	80.30			95.41	38.63
Self-propelled forage Harvester 321 kW(430 hp)	321	430	4000	10	400	168000	104.53			93.18	37.72
Windrow head-2.13 m(7')	201	270	1000	10	100	4000	8.34	1.12	2.77	7.44	3.01
Total						172000	112.87			100.62	40.74

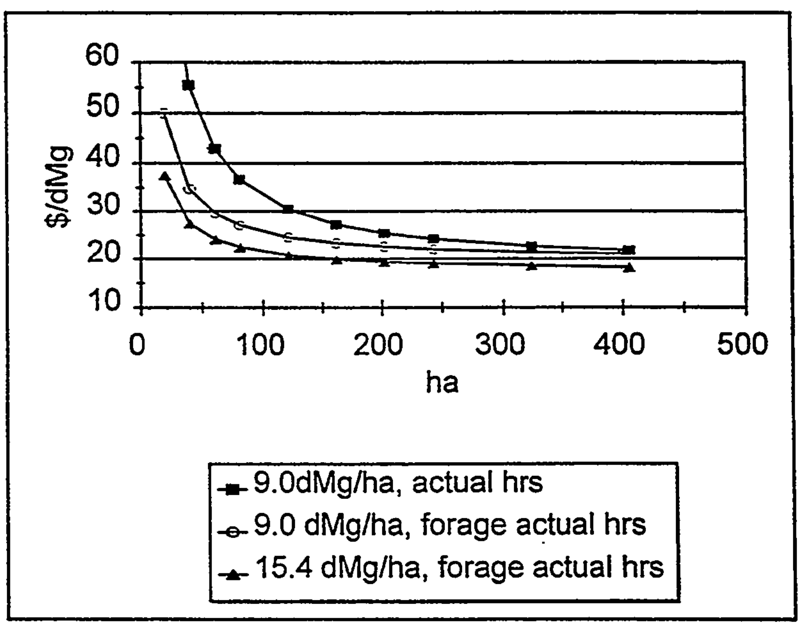

Fig. 7. Effect of area on cost of hay module harvest and in-field transport (based on a pull-type forage harvester).

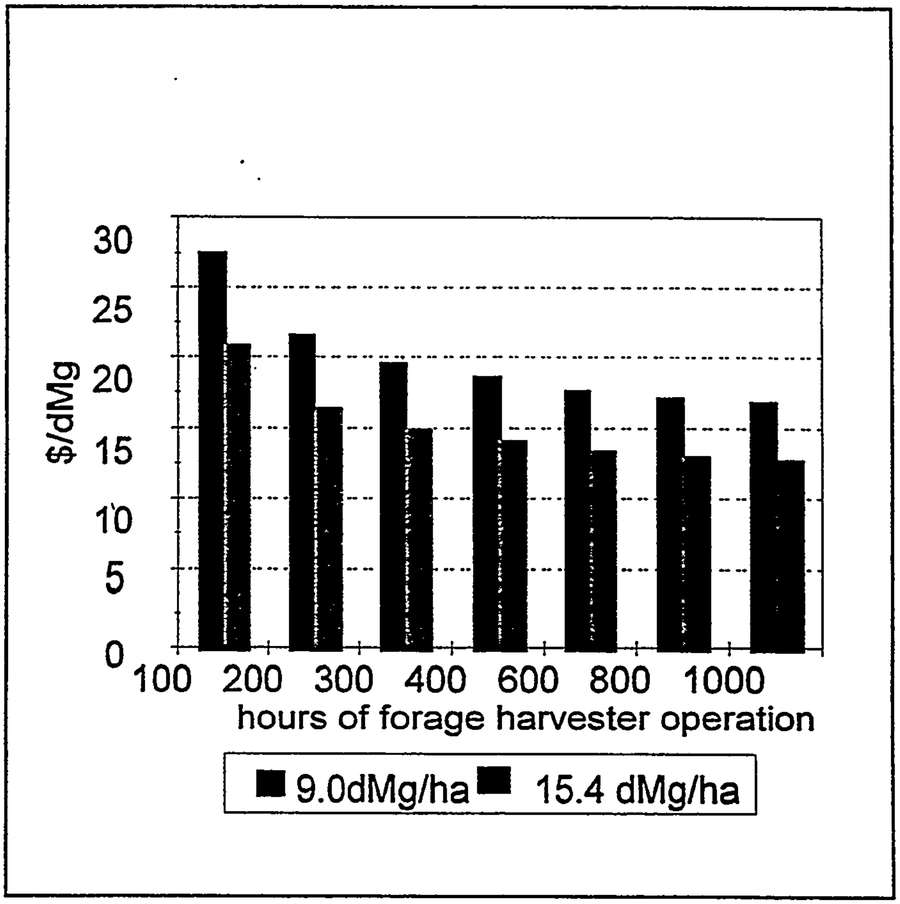

Fig. 8. Effect of hours of self-propelled forage harvester operation on hay module harvest and in-field transport costs (based on one cut).

For our baseline cases we calculate costs for: (1) a farmer using a pull-type forage harvester with all equipment utilized at standard hours, one cut on a yield of 9.0 dMg/ha (4 dt/ac), and a module truck utilized for standard (1000) hours and (2) a custom operator using three self-propelled forage harvesters for 400 hours each annually, one cut on a yield of 9.0 Mg/ha (4 dt/ac), and a module truck utilized for standard (1000) hours. We also calculate two least-cost cases: (3) a farmer using a pull-type forage harvester on 202 ha (500 ac) with forage equipment costs based on actual hours of utilization and tractors at standard hours, one cut on a yield of 15.7 dMg/ha, and a module truck utilized for 2000 hours a year; and (4) a custom operator using three self-propelled forage harvesters for 1000 hours each annually and one self-propelled windrower, one cut on a yield of 15.7 dMg/ha (7 dt/ac), and a module truck utilized for 2000 hours annually (Table 46). If the equipment in 3) is utilized on 405 ha (1000 ac) then costs are reduced an additional $0.72/dMg ($0.65/dt).

Harvest and in-field costs for modules for various hay yields and equipment utilization rates are in appendix Table A.2.

Table 45. Hay module harvest and in-field transport costs under varying assumption for equipment utilization, yields, and number of cuts

Type of forage harvester and area/hours of equipment use	Yield (dMg/ha)					
	1 cut			2 cuts		
	5.6	9.0	15.7	9.0	15.7	22.4
Pull-type	$/dMg					
Standard hours	29.54	21.88	19.61	36.93	23.05	20.51
Forage equipment only on biomass hay, tractors at standard hours						
40 ha	46.18	34.73	27.52	45.25	29.21	25.30
202 ha	30.21	22.58	19.42	35.26	22.27	19.62
All equipment used only on biomass hay						
40 ha	75.61	55.56	40.50	62.28	40.33	33.86
202 ha	34.35	25.46	20.93	36.49	23.14	20.17
Self-propelled - 400 hours	28.26	18.65	14.18	34.03	21.92	17.10
	Yield (dt/ac)					
	1 cut			2 cuts		
	2.5	4	7	4	7	10
Pull-type	$/dt					
Standard hours	26.80	19.85	17.79	33.50	20.91	18.61
Forage equipment only on biomass hay, tractors at standard hours						
100 ac	41.89	31.51	24.97	41.05	26.50	22.95
500 ac	27.41	20.48	17.62	31.99	20.20	17.80
All equipment used only on biomass hay						
100 ac	68.59	50.40	36.74	56.50	36.59	30.72
500 ac	31.16	23.10	18.99	33.10	20.99	18.30
Self-propelled - 400 hours	25.64	16.92	12.86	30.87	19.89	15.51

Table 46. Hay module harvest and transport costs for baseline and least-cost cases

Case description	Yield	Harvest	Transport	Total	Yield	Harvest	Transport	Total
	dMg/ha	$/dMg			dt/ac	$/dt		
Baseline cases								
1) Farmer, pull-type forage harvester, standard hours	9.0	21.88	8.81	30.69	4	19.85	7.99	27.84
2) Custom operator, self-propelled forage harvester (400 hr), module truck (1000 hr)	9.0	18.65	8.81	27.46	4	16.92	7.99	24.91
Least cost cases								
3) Farmer, pull-type forage harvester on 202 ha (500 ac), module truck (2000 hr)	15.7	19.42	7.77	27.19	7	17.62	7.05	24.67
4) Custom operator, self-propelled forage harvester (1000hr), module truck (2000 hr)	15.7	12.84	7.77	20.61	7	11.65	7.05	18.70

CROP RESIDUES

Bales

Hourly costs and machinery used for mowing, with a rotary mower-conditioner (mower conditioner-disk), raking, baling, and moving bales are shown in Table 47. Recall that mowing and raking are required for corn residues, but not small grain residues. Equipment coverage rates and costs for corn residues (mowing, raking, baling, moving bales to field edge, and twine costs) and small grain residues (baling, moving bales to field edge, and twine costs) are summarized in Table 48.

To get total in-field costs per unit weight for corn (Table 49), sum mowing, raking, and baling costs per unit area (Table 48) and divide by yield; and add moving and twine costs (Table 48). To get total in-field costs per unit weight for small grains (Table 49), take baling costs per unit area (Table 48) and divide by yield; and add moving and twine costs (Table 48). Note that moving and twine costs are constant per unit weight. In Table 49 costs vary by yield, but once yield reaches the point where baler capacity is reached for small grains, for round balers 3.13 dMg/ha (1.40 dt/ac) and for rectangular balers 5.08 dMg/ha (2.27 dt/ac), costs decrease no more with increased yield. For corn residues, costs decrease some after baler capacity is reached, 6.58 dMg/ha (2.94 dt/ac) for round balers and 10.70 dMg/ha (4.78 dt/ac) for rectangular balers, because per unit costs of mowing and raking till decrease with yield. Delivered costs of bales of crop residues are shown in Table 50. The costs in Table 50 are the costs in Table 49 plus transportation costs of $6.48/dMg ($5.88/dt) for round bales and $5.87 dMg ($5.33/dt) for rectangular bales. At lower yields round bales cost less and at higher yields rectangular bales cost less. At equal yields, bales of small grains cost less than bales of corn residues, but average corn residue yields are higher than small grain resides (Table 17). At average corn residue yields of 6.6 dMg/ha (3.0 dt/ac) and small grain residue yields of about 2.5 dMg/ha (1.1 dt/ac), harvest and transport costs are in the range of $20 to $22/dMg ($18 to $20/dt) for either bale or residue type.

Table 47. Hourly costs for machinery used to make and move bales of crop residues

	Round	Rectangular
	$/hr	$/hr
Mowing		
Mower-conditioner(disk)	14.54	14.54
Tractor 74.6 kW(100 hp)	24.59	24.59
Total mowing	39.13	39.13
Raking		
Rake 2.90 m(9.5')	2.97	2.97
Tractor 33.6 kW(45 hp)	17.25	17.25
Total raking	20.22	20.22
Baling		
Large round baler	25.06	
Tractor 74.6 kW(100 hp)	24.59	
Rectangular baler		36.44
Tractor 119.4 kW(160 hp)		33.97
Total baling	49.65	70.41
Moving		
Bale carrier	0.90	
Front end loader	3.67	3.67
Tractor 33.6 kW(45 hp)	17.25	17.25
Total moving	21.82	20.92

Table 48. Rates and costs for machinery used to make and move bales of crop residues

		Round	Rectangular		Round	Rectangular
Corn						
Mowing	ha/hr	2.68	2.68	ac/hr	6.62	6.62
Raking	ha/hr	2.24	2.24	ac/hr	5.53	5.53
Baling	ha/hr	1.52	1.87	ac/hr	3.74	4.61
Mowing	$/ha	14.60	14.60	$/ac	5.91	5.91
Raking	$/ha	9.03	9.03	$/ac	3.66	3.66
Baling	$/ha	32.76	37.75	$/ac	13.27	15.29
Mowing, raking, baling	$/ha	56.40	61.38	$/ac	22.84	24.86
Corn and small grains						
Moving	dMg/hr	3.51	2.99	dt/hr	3.87	3.30
Moving	$/dMg	6.22	6.99	$/dt	5.64	6.34
Moving, twine	$/dMg	7.32	8.09	$/dt	6.64	7.34
Corn						
Mowing, raking, baling	$/ha	56.40	61.38	$/ac	22.84	24.86
Moving, twine	$/dMg	7.32	8.09	$/dt	6.64	7.34
Small grains						
Baling	ha/hr	3.19	3.93	ac/hr	7.88	9.70
Baling	$/ha	15.56	17.93	$/ac	6.30	7.26
Moving, twine	$/dMg	7.32	8.09	$/dt	6.64	7.34

Table 49. In-field costs of crop residue bales

Yield	Round	Rectangular	Yield	Round	Rectangular
dMg/ha	$/dMg		dt/ac	$/dt	
Corn					
1.12	57.67	62.90	0.50	52.32	57.05
2.24	32.50	35.49	1.00	29.48	32.20
3.36	24.10	26.36	1.50	21.87	23.91
4.48	19.91	21.79	2.00	18.06	19.77
6.58	15.89	17.41	2.94	14.41	15.80
6.72	15.81	17.22	3.00	14.34	15.62
8.96	14.93	14.94	4.00	13.55	13.55
10.70	14.50	13.83	4.78	13.16	12.54
Small grains					
1.12	21.21	24.10	0.50	19.24	21.86
2.24	14.27	16.09	1.00	12.94	14.60
3.13	12.30	13.82	1.40	11.15	12.54
3.36	12.30	13.43	1.50	11.15	12.18
4.48	12.30	12.09	2.00	11.15	10.97
5.08	12.30	11.62	2.27	11.15	10.54
6.72	12.30	11.62	3.00	11.15	10.54

Table 50. Delivered costs of crop residue bales

Yield	Round	Rectangular	Yield	Round	Rectangular
dMg/ha	$/dMg		dt/ac	$/dt	
			Corn		
1.12	64.16	68.77	0.50	58.20	62.38
2.24	38.98	41.36	1.00	35.36	37.52
3.36	30.59	32.23	1.50	27.75	29.24
4.48	26.40	27.66	2.00	23.94	25.09
6.58	22.37	23.28	2.94	20.30	21.12
6.72	22.30	23.10	3.00	20.23	20.95
8.96	21.42	20.81	4.00	19.43	18.88
10.70	20.99	19.70	4.78	19.04	17.87
			Small grains		
1.12	27.70	29.97	0.50	25.13	27.19
2.24	20.75	21.97	1.00	18.83	19.93
3.13	18.78	19.69	1.40	17.04	17.87
3.36	18.78	19.30	1.50	17.04	17.51
4.48	18.78	17.96	2.00	17.04	16.30
5.08	18.78	17.49	2.27	17.04	15.87
6.72	18.78	17.49	3.00	17.04	15.87
8.96	18.78	17.49	4.00	17.04	15.87

Modules

To build modules from crop residues requires the same machinery for mowing and, for corn residues, raking (Table 47). To make a module, the residues must be picked up using a forage harvester with a windrow head and pulling a forage wagon, transported to the module builder at the field edge using a forage wagon, and made into a module. Recall that a module builder requires a 34 kW (45 hp) tractor for power. For picking up residues, we cost three options (based on standard hours): (1) a pull-type heavy duty forage harvester (forage harvester-hd) with a 2.13 m (7') wide windrow pickup head powered by a 119 kw (160 hp) tractor, (2) a pull-type heavy duty forage harvester (forest harvester-hd) with a 2.13 m (7') wide windrow pickup head powered by a 75 kw (100 hp) tractor, and (3) a 201 kw (270 hp) self-propelled forage harvester with a 2.13 m (7') wide windrow pickup head (Table 51). For each option five different pairs of wagon sizes are costed (Table 52). The range in cost from the smallest sized wagon pair [15.6 m^3 (550 ft^3)] to the largest sized wagon pair [31.2 m^3(1100 ft^3)] is from $19.15 to $32.16/hr. Hourly costs for pick up, moving from the forage harvester to the module builder, and building the module (phm); which is all the in-field costs for small grain residues, but excludes the mowing and raking costs for corn residues; are shown in Table 53. Mowing and raking costs for corn residues are $23.63/ha ($9.57/ac). These costs are for one module builder. Each additional module builder and tractor costs $30.03/hr.

Table 51. Cost of pick up, in-field haul, and building crop residue module (phm)

Equipment	List price ($)	Option 3	Option 4	Option 5
		Total cost ($/hr)		
Forage harvester-heavy duty (hd)	22000	17.03		
Windrow head-2.13 m(7'	3000	6.26		
Tractor-119kw(160hp)	72000	33.97		
Forage harvester-medium duty (md)	17800		13.78	
Windrow head-2.13 m(7')	3000		6.26	
Tractor-75kw(100hp)	42000		24.59	
Self-propelled forage harvester-201 kW(270 hp)	116000			74.05
Windrow head-2.13 m(7')	3000			6.26
2 forage wagon-15.6 m^3 (550 ft^3)	21510	19.15	19.15	19.15
Tractor-34kw(45hp)	21000	17.25	17.25	17.25
Module builder	20000	12.78	12.78	12.78
Tractor-34kw(45hp)	21000	17.25	17.25	17.25
Total phm[15.6 m^3(550 ft^3)]		123.69	111.06	146.73
Corn				
Coverage	ha/hr	0.98	0.98	1.14
Total phm[15.6 m^3(550 ft^3)]	$/ha	126.31	113.41	128.44
Coverage	ac/hr	2.42	2.42	2.82
Total phm[15.6 m^3(550 ft^3)]	$/ac	51.15	45.93	52.01
Small grains				
Coverage	ha/hr	2.06	2.06	2.41
Total phm[15.6 m^3(550 ft^3)]	$/ha	60.00	53.87	61.01
Coverage	ac/hr	5.09	5.09	5.94
Total phm[15.6 m^3(550 ft^3)]	$/ac	24.30	21.82	24.71

Table 52. Cost of forage wagon pairs

Wagon volume		Total cost
m^3	ft^3	$/hr
15.6	550	19.15
18.1	640	23.15
21.3	750	26.40
22.7	800	27.84
31.2	1100	32.16

Table 53. Hourly costs by wagon size for pickup, haul, and building modules (phm)

Wagon volume		Option 3	Option 4	Option 5
m^3	ft^3	$/hr		
15.6	550	123.69	111.06	146.73
18.1	640	127.69	115.06	150.73
21.3	750	130.94	118.31	153.98
22.7	800	132.38	119.74	155.42
31.2	1100	136.70	124.07	159.74

Three things constrain throughput in the harvesting and handling systems: (1) the power available for the forage harvester, (2) the capacity of the wagons hauling residues to the module builder, and (3) the capacity of the module builder(s) [8.0 dMg/hr (8.8 dt/hr) per module builder]. Option 4 is always limited by the power available to pick up the residues (with the windrow head); thus there is never an advantage to using any but the smallest wagons under our assumptions. If yields for corn residues are below 5.7 dMg/ha (2.6 dt/ac) and small grain residues are below 2.7 dMg/ha (1.2 dt/ac), then option 4 is the least cost option. With one module builder options 3 and 5 are limited by wagon size for 15.6 m^3 (550 ft^3) wagons, and the capacity of the module builder for larger wagons. Maximum yields and minimum costs for a single module builder are in tables 54 and 55. If yield is greater than maximum yield listed in tables 54 and 55, a capacity constraint has been reached and cost can go no lower. If a second module builder is used, then options 3 and 5 can probably handle any crop residue yield (Table 56). Option 3 is only limited by power with two module builders and 31.2 m^3 (1100 ft^3) wagons, while option 5, with two module builders, is never limited by power. The self-propelled method (option 5) is slightly more expensive than the heavy-duty forage harvester (option 3), but by less than $2.50/ha ($1/ac).

Table 54. Cost of corn residue modules using 1 module builder

Wagon volume	Option 3	Option 4	Option 5	Wagon volume	Option 3	Option 4	Option 5
m^3	$/ha			m^3	$/ac		
15.6	149.95	137.05	152.07	550	60.72	55.50	61.58
18.1	154.03	141.13	155.57	640	62.37	57.15	63.00
21.3	157.35	144.45	158.41	750	63.72	58.49	64.15
22.7	158.81	145.91	159.67	800	64.31	59.09	64.66
31.2	163.23	150.33	163.45	1100	66.10	60.88	66.19
	Maximum yield (dMg/ha)				**Maximum yield (dt/ac)**		
15.6	7.9	5.7	6.8	550	3.5	2.6	3.0
18.1	8.2	5.7	7.0	640	3.6	2.6	3.1
21.3	8.2	5.7	7.0	750	3.6	2.6	3.1
22.7	8.2	5.7	7.0	800	3.6	2.6	3.1
31.2	8.2	5.7	7.0	1100	3.6	2.6	3.1
	Minimum cost ($/dMg)				**Minimum cost ($/dt)**		
15.6	18.86	23.85	22.32	550	17.11	21.63	20.25
18.1	18.89	24.56	22.26	640	17.14	22.28	20.20
21.3	19.30	25.13	22.67	750	17.51	22.80	20.57
22.7	19.48	25.39	22.85	800	17.67	23.03	20.73
31.2	20.02	26.16	23.39	1100	18.16	23.73	21.22

Table 55. Cost of small grain residue modules using 1 module builder

Wagon volume	Option 3	Option 4	Option 5	Wagon volume	Option 3	Option 4	Option 5
m^3	$/ha			ft^3	$/ac		
15.6	60.00	53.87	61.01	550	24.30	21.82	24.71
18.1	61.94	55.81	62.67	640	25.08	22.60	25.38
21.3	63.52	57.39	64.02	750	25.72	23.24	25.93
22.7	64.21	58.08	64.62	800	26.00	23.52	26.17
31.2	66.31	60.18	66.41	1100	26.85	24.37	26.89
	Maximum yield (dMg/ha)				**Maximum yield (dt/ac)**		
15.6	3.8	2.7	3.2	550	1.7	1.2	1.4
18.1	3.9	2.7	3.3	640	1.7	1.2	1.5
21.3	3.9	2.7	3.3	750	1.7	1.2	1.5
22.7	3.9	2.7	3.3	800	1.7	1.2	1.5
31.2	3.9	2.7	3.3	1100	1.7	1.2	1.5
	Minimum cost ($/dMg)				**Minimum cost ($/dt)**		
15.6	15.89	19.73	18.85	550	14.42	17.90	17.10
18.1	15.99	20.44	18.88	640	14.51	18.55	17.13
21.3	16.40	21.02	19.29	750	14.88	19.07	17.50
17.5	16.58	21.28	19.47	800	15.04	19.30	17.66
31.2	17.12	22.05	20.01	1100	15.53	20.00	18.15

Table 56. Maximum yield with 2 module builders

Wagon volume	Option 3	Option 4	Option 5	Wagon volume	Option 3	Option 4	Option 5
m^3	dMg/ha			ft^3	dt/ac		
Corn							
15.6	7.9	5.7	6.8	550	3.5	2.6	3.0
18.1	9.9	5.7	8.5	640	4.4	2.6	3.8
21.3	10.2	5.7	8.7	750	4.5	2.6	3.9
22.7	11.2	5.7	9.6	800	5.0	2.6	4.3
31.2	11.4	5.7	13.2	1100	5.1	2.6	5.9
Small grains							
	dMg/ha				dt/ac		
15.6	3.8	2.7	3.2	550	1.7	1.2	1.4
18.1	4.7	2.7	4.0	640	2.1	1.2	1.8
21.3	4.8	2.7	4.1	750	2.2	1.2	1.8
22.7	5.3	2.7	4.6	800	2.4	1.2	2.0
31.2	5.4	2.7	6.3	1100	2.4	1.2	2.8

Using one module builder, costs up to and including the module builder, are about \$23/dMg (\$21/dt) for corn residues for 6.7 dMg/ha (3.0 dt/ac) and \$24 to \$28/dt (\$22 to \$25/dt) for small grain residues for 2.2 dMg/ha (1.0 dt/ac). If corn residue yield increases to 10.1 dMg/ha (4.5 dt/ac), then for option 3 costs decrease to \$19/dMg (\$17/dt). If small grain yield increases to 3.4 dMg/ha (1.5 dt/ac), then costs decrease to \$19 to \$20/dMg (\$17 to \$18/dt) (Table 57). The use of a second module builder decreases costs over the use of a single module builder when, for corn residues, yield reaches 10 dMg/ha (4.5 dt/ac) for option 3 and 9.4 dMg/ha (4.2 dt/ac) for option 5, and for small grains, yield reaches 4.5 dMg/ha (2.0 dt/ac) for option 3 and 3.8 dMg/ha (1.7 dt/ac) for option 5. So delivered costs for crop residue modules range from \$28 to \$33/dMg (\$25/dt to \$30/dt). At yields below 6.7 dMg/ha (3.0 dt/ac) for corn and 2.2 dMg/ha (1.0 dt/ac) for small grains, costs will be higher than this range.

Table 57. In-field and module building costs of crop residue modules as affected by yield

Yield	Option 3	Option 4	Option 5	Yield	Option 3	Option 4	Option 5
dMg/ha	$/dMg			dt/ac	$/dt		
			Corn				
1.12	137.51	122.35	138.88	0.5	124.75	111.00	126.00
2.24	68.76	61.18	69.44	1.0	62.37	55.50	63.00
3.36	45.84	40.78	46.29	1.5	41.58	37.00	42.00
4.48	34.38	30.59	34.72	2.0	31.19	27.75	31.50
5.60	27.50	24.47	27.78	2.5	24.95	22.20	25.20
6.72	22.92	23.84	23.15	3.0	20.79	21.63	21.00
7.84	19.64	23.84	22.26	3.5	17.82	21.63	20.20
8.96	18.89	23.84	22.26	4.0	17.14	21.63	20.20
10.08	18.89	23.84	22.26	4.5	17.14	21.63	20.20
			Small grains				
1.12	55.30	48.09	55.95	0.5	50.16	43.63	50.76
2.24	27.65	24.05	27.97	1.0	25.08	21.82	25.38
3.36	18.43	19.73	18.88	1.5	16.72	17.90	17.13
4.48	15.99	19.73	18.88	2.0	14.51	17.90	17.13
5.60	15.99	19.73	18.88	2.5	14.51	17.90	17.13
6.72	15.99	19.73	18.88	3.0	14.51	17.90	17.13

SUMMARY AND CONCLUSIONS

We have made an engineering-economic analysis of hay bale, silage, hay module, and crop residue bale and module harvest; in-field transport; and over-the-road transport costs. Costs accounted for are: depreciation; interest; repair; fuel, lube, and oil; insurance, housing, and taxes; and labor. For farm-scale equipment we calculate costs based both on standard (i.e., typical) and actual hours of equipment use and for custom operator-scale equipment on actual hours of use.

Costs for standard hours for farm-scale equipment and actual hours for custom operator-scale equipment, for two yield levels, are summarized in Table 58. In general, we expect the silage type crops to have a higher yield, but costs can be compared among hay bales, silage, and hay modules for a yield of 15.7 dMg/ha (7 dt/ac). Crop residue bales in Table 58 fall in a range of $18 to $23/dMg ($16 to $21/dt). The lowest cost option is silage when dumping directly into trucks in the field (option 0), $11 to $14/dMg ($10 to $12/dt). Silage option 0 minimizes the handling of biomass. If two wagons are needed and the truck is loaded at the field edge (option 2), then costs are $14 to $21/dMg ($13 to $19/dt). At equal yields, 15.7 dMg/ha (7 dt/ac), costs are similar between hay bales and silage using two wagons (option 2). The highest harvest, in-field transport, and over-the-road transport costs are for modules, ranging from $23 to $31/dMg ($21 to $28/dt) for hay and $28 to $38/dMg ($25 to $34/dt) for crop residues. In general, costs are lower for a custom operator at 400 hours than a farmer at standard hours.

Table 58. In-field harvest plus over-the-road transportation costs for hay bales, silage, hay modules, crop residue bales, and crop residue modules

Crop and equipment	Hours	Yield (dMg/ha)	Cost ($/dMg)	Yield (dMg/ha)	Cost ($/dMg)
Hay					
Round baler	Standard	9.0	21.75	15.7	20.48
Rectangular baler	400	9.0	20.60	15.7	18.85
Silage					
Pull-type, 3-row head (option 0)	Standard	15.7	13.69	22.4	12.09
Self-propelled, 6-row head (option 0)	400	15.7	12.65	22.4	11.38
Pull-type, 3-row head (option 2)	Standard	15.7	20.55	22.4	16.90
Self-propelled, 6-row head (option 2)	400	15.7	17.38	22.4	14.43
Modules					
Pull-type	Standard	9.0	30.69	15.7	28.42
Self-propelled	400	9.0	27.46	15.7	22.98
Crop residues-corn					
Round baler	Standard	6.7	22.30	10.1	19.82
Rectangular baler	400	6.7	23.09	10.1	19.36
Modules, pull-type	Standard	6.7	32.43	10.1	27.60
Modules, self-propelled	400	6.7	32.56	10.1	28.10
Crop residues-small grains					
Round baler	Standard	2.2	20.76	3.4	18.17
Rectangular baler	400	2.2	21.97	3.4	19.30
Modules, pull-type	Standard	2.2	37.47	3.4	27.91
Modules, self-propelled	400	2.2	37.65	3.4	28.04

Table 58 (continued)

Crop and equipment	Hours	Yield (dt/ac)	Cost ($/dt)	Yield (dt/ac)	Cost ($/dt)
Hay					
Round baler	Standard	4	19.73	7	18.58
Rectangular baler	400	4	18.69	7	17.10
Silage					
Pull-type, 3-row head (option 0)	Standard	7	12.42	10	10.97
Self-propelled, 6-row head (option 0)	400	7	11.48	10	10.32
Pull-type, 3-row head (option 2)	Standard	7	18.64	10	15.33
Self-propelled, 6-row head (option 2)	400	7	15.77	10	13.09
Modules					
Pull-type	Standard	4	27.84	7	25.78
Self-propelled	400	4	24.91	7	20.85
Crop residues-corn					
Round baler	Standard	3	20.23	4.5	17.98
Rectangular baler	400	3	20.95	4.5	17.56
Modules, pull-type	Standard	3	29.42	4.5	25.04
Modules, self-propelled	400	3	29.54	4.5	25.49
Crop residues-small grains					
Round baler	Standard	1	18.83	1.5	16.48
Rectangular baler	400	1	19.93	1.5	17.51
Modules, pull-type	Standard	1	33.99	1.5	25.32
Modules, self-propelled	400	1	34.16	1.5	25.44

We have also calculated some least-cost scenarios, which, under the assumptions we make (e.g. interest rate, wage rates), represent costs as low as one might achieve (Table 59). Equipment and labor are utilized to what might be considered a maximum. Silage (option 0) cost is as low as $9 to $10/dMg ($8 to $9/dt). If two wagons are needed (option 2) then costs increase to $11/dMg ($10/dt). Note that at high hours of operation and high yield, the gap narrows between silage options 0 and 2. Hay bales cost between $16 and $19/dMg ($15 and $17/dt) and hay modules between $21 and $27/dt ($19 to $25/dt).

The generalized costs presented are based on the assumptions shown in the tables. If hours of operation, area harvested, and/or yields are changed, costs can change significantly. At low hours of operation and low yields, costs can be considerably higher.

We have calculated harvest, in-field transport, and over-the road transport costs. We have not included land rent, overhead, fertilizer, weed control, land preparation, storage, and handling at the conversion facility costs. These excluded costs can be considerable. What we have shown is that with good equipment utilization rates and high yields; harvest, in-field transport, and over-the road transport costs can be as low as $9 to $21/dMg ($8 to $19/dt).

Table 59. Least cost options for biomass (in-field harvest plus over-the-road transportation costs)

Type of biomass and equipment	Yield		Description	Hours and area of use	Cost	
	dMg/ha	dt/ac			$/dMg	$/dt
Hay						
Round baler	15.7	7	1 cut,1.83 m (6') diameter	202 ha(500 ac), 2000 hr/truck	18.82	17.07
Rectangular baler	15.7	7	1 cut, 32 bales/truck	1000 hr/baler, 2000 hr/truck	16.06	14.57
Silage						
3-row, pull-type	22.4	10	option 0	405 ha(1000 ac), 2000 hr/truck	9.82	8.91
6-row, self-propelled	22.4	10	option 0	2000 hr/forage harvester, 2000 hr/truck	8.76	7.95
3-row, pull-type	22.4	10	option 2	405 ha(1000 ac), 2000 hr/truck	14.40	13.06
6-row, self-propelled	22.4	10	option 2	2000 hr/forage harvester, 2000 hr/truck	11.47	10.40
Hay modules						
Pull-type	15.7	7	1 cut	202 ha(500 ac), 2000 hr/truck	27.19	24.67
Self-propelled	15.7	7	1 cut	1000 hr/forage harvester, 2000 hr/truck	20.61	18.70

REFERENCES

ASAE. 1995. ASAE standards 1995, 42nd ed. American Society of Agricultural Engineers, St. Joseph, MI.

Fuller, E., B. Lazarus, L. Carrigan, and G. Green. 1992. Minnesota farm machinery economic cost estimates for 1992. AG-FO-2308C. Minnesota Extension Service, University of Minnesota, St. Paul, MN.

Heid, Walter G., Jr. 1984. Turning Great Plains crop residues and other products into energy. Agricultural Economic Report Number 523. United States Department of Agriculture, Economic Research Service, Washington, D.C.

Hunt, D. 1983. Farm power and machinery management, 8th ed. Iowa State University Press, Ames, IA.

Implement & Tractor. 1995. Red Book 1995, 79th ed. Argus Agronomics, Clarksdale, MS.

Johnson, L. 1991. Guide to farm planning. Agricultural Extension Service, University of Tennessee, Knoxville, TN.

Miller-St. Nazianz. 1995. Miller Pro hydraulic dump boxes, promotional literature. Miller-St. Nazianz, Inc., St. Nazianz, WI.

NAEDA. 1995. Guides 2000: Official guide north central region. North American Equipment Dealers Association, St. Louis, MO.

New Holland. 1995. New Holland pull-type forage harvesters: 718 790 900, promotional literature. New Holland North America, Inc.

Richardton. 1995. High dump forage wagon promotional literature. Richardton Manufacturing Co., Richardton, ND.

Rider, A., A. Barr and A. Pauli. 1993. Hay and forage harvesting, 4th ed. Deere & Company Service Publications, Moline, IL.

USDA/ERS. 1994. Agricultural resources and economic indicators. Agricultural Handbook Number 705. United States Department of Agriculture, Economic Research Service, Washington, D.C.

Walsh, M. 1994. Costs of producing switchgrass as a dedicated energy crop. Working Report from Bioenergy Feedstock Development Program, Oak Ridge National Laboratory, Oak Ridge, TN.

APPENDIX A

MACHINERY, BALE, MODULE, AND SILAGE COSTS

In Table A.1 the following abbreviations are used:
Mow cond = mower-conditioner
Windrower-21 = a 6.40 m (21') wide pull-type windrower
SP windrow-16 = a 4.88 m (16') wide self-propelled windrower
Windrow head-7 = a 2.13 m (7') wide windrow head
SP forage harv = a self-propelled forage harvester
For wag-s,800 = a 22.7 m^3 (800 ft^3) forage wagon with a scale
For wag-hi,800 = a 22.7 m^3 (800 ft^3) high dump forage wagon
For wag-s,1100 = a 31.2 m^3 (1100 ft^3) forage wagon with a scale
For wag-hi,1100 = a 31.2 m^3 (1100 ft^3) high dump forage wagon
dsv = discounted salvage value
iht = insurance, housing, and taxes

Table A.1. Detailed machinery costs

Implement	Power kW	Power hp	Life hr	Life years	Annual use hr	List price $	Price paid $	Salvage value $	dsv $	Depreciation $/hr	Interest $/hr	Fuel liters/hr	Fuel gal/hr	Fuel, lube, oil $/hr	Repairs[a] lifetime	repairs $/hr	iht $/hr	labor $/hr	total cost $/hr
Tractor	33.6	45	12000	24	500	21000	18900	1930	477	1.54	1.16	8.46	2.22	2.04	1.00	1.75	0.76	10.00	17.25
Tractor	74.6	100	12000	21.82	550	42000	37800	4631	1299	3.04	2.13	18.80	4.94	4.54	1.00	3.50	1.37	10.00	24.59
Tractor	119.4	160	12000	20	600	72000	64800	9238	2881	5.16	3.38	30.08	7.90	7.27	1.00	6.00	2.16	10.00	33.97
Tractor	156.7	210	12000	20	600	93000	83700	11933	3721	6.66	4.37	39.48	10.37	9.54	1.00	7.75	2.79	10.00	41.12
Front end loader	33.6	45	1000	4	250	3000	2700	1104	875	1.83	0.43				0.40	1.20	0.22		3.67
Mow cond	74.6	100	2500	12.5	200	10000	9000	1303	629	3.35	1.44				0.80	3.20	0.90		8.89
Mow cond-disk	74.6	100	2500	12.5	200	15000	13500	1954	943	5.02	2.17				1.00	6.00	1.35		14.54
Windrower-21	74.6	100	2500	12.5	200	8700	7830	1134	547	2.91	1.26				0.70	2.44	0.78		7.39
SP windrow-16	74.6	100	3000	10	300	54000	48600	10186	5688	14.30	5.43	18.80	4.94	4.54	0.55	9.90	3.24	10.00	47.42
Rake	33.6	45	2500	12.5	200	3000	2700	391	189	1.00	0.43				0.60	0.72	0.27		2.43
Rectangularbaler	119.4	160	3000	5	600	65000	58500	19761	14767	14.58	3.66				0.80	17.33	1.95		37.52
Large roundbaler	74.6	100	1500	10	150	16000	14400	2641	1475	8.62	3.17				0.75	8.00	1.92		21.71
Forage harvester	119.4	160	2500	10	250	22000	19800	3631	2028	7.11	2.62				0.65	5.72	1.58		17.03
Windrow head-7	119.4	160	1000	10	100	3000	2700	495	276	2.42	0.89				0.80	2.40	0.54		6.26
2-row head	119.4	160	2000	10	200	3600	3240	594	332	1.45	0.54				0.80	1.44	0.32		3.75
3-row head	156.7	210	2000	10	200	6000	5400	990	553	2.42	0.89				0.80	2.40	0.54		6.26
SP forage harv	201.4	270	4000	10	400	116000	104400	19146	10691	23.43	8.63	50.76	13.33	12.27	0.50	14.50	5.22	10.00	74.05
SP forage harv	320.8	430	4000	10	400	168000	151200	27729	15484	33.93	12.50	80.84	21.23	19.53	0.50	21.00	7.56	10.00	104.53
Windrow head-7	201.4	270	1000	10	100	3000	2700	495	276	2.42	0.89				0.80	2.40	0.54		6.26
Windrow head-7	320.8	430	1000	10	100	3000	2700	495	276	2.42	0.89				0.80	2.40	0.54		6.26
4-row head	201.4	270	2000	5	400	10000	9000	3040	2272	3.36	0.85				0.80	4.00	0.45		8.66
6-row head	320.8	430	2000	5	400	19000	17100	5776	4316	6.39	1.61				0.80	7.60	0.86		16.45
Bale carrier	33.6	45	500	2	250	500	450	235	209	0.48	0.08				0.30	0.30	0.04		0.90
Bale wagon	33.6	45	3000	10	300	3000	2700	531	296	0.80	0.30				0.80	0.80	0.18		2.08
For wag-s,800			2000	10	200	16160	14544	2858	1596	6.47	2.42				0.50	4.04	1.45		14.39
For wag-hi,800	33.6	45	2000	10	200	19200	17280	3395	1896	7.69	2.88				0.50	4.80	1.73		17.10
For wag-s,1100			2000	10	200	19710	17739	3486	1946	7.90	2.95				0.50	4.93	1.77		17.55
For wag-hi,1100	33.6	45	2000	10	200	20500	18450	3625	2024	8.21	3.07				0.50	5.13	1.85		18.25
Cotton module	33.6	45	3000	7.5	400	20000	18000	4800	3101	4.97	1.58				0.80	5.33	0.90		12.78
Tandem truck			5000	10	500	58000	52200	10257	5727	9.29	3.48	17.79	4.70	6.22		2.53	2.09	15.00	38.60
Silage truck			5000	12.5	400	80000	72000	10424	5032	13.39	5.78	17.79	4.70	6.22		3.49	3.60	15.00	47.48
Module truck			5000	5	1000	100000	90000	32574	24341	13.13	3.43	17.79	4.70	6.22		4.36	1.80	15.00	43.94
Forklift	29.8	40	5000	10	500	17000	15300	3006	1679	2.72	1.02	7.48	1.98	1.82		3.50	0.61		9.67

[a]Fraction of list price.

Table A.2. In-field harvest costs for hay by yield, number of cuts, hours or area harvested, and type of operation

	Cost ($/dMg)					Cost ($/dt)			
Yield = 5.6 dMg/ha					Yield = 2.5 dt/ac				
	Hay		Modules			Hay		Modules	
	1 cut	2 cut	1 cut	2 cut		1 cut	2 cut	1 cut	2 cut
Farmer - standard hours									
	17.91	28.49	29.54	59.08		16.24	25.85	26.80	53.59
Farmer - forage actual hours, tractors standard hours									
ha					acres				
20	31.33	40.98	66.12	92.34	50	28.42	37.18	59.98	83.77
40	24.04	33.69	46.17	72.40	100	21.81	30.57	41.89	65.68
61	21.61	31.27	39.52	65.75	150	19.61	28.36	35.85	59.64
81	20.40	30.05	36.20	62.42	200	18.51	27.26	32.84	56.63
121	19.18	28.84	32.87	59.10	300	17.40	26.16	29.82	53.61
162	18.58	28.23	31.21	57.44	400	16.85	25.61	28.31	52.11
202	18.21	27.86	30.21	56.42	500	16.52	25.27	27.41	51.19
243	17.97	27.41	29.55	55.48	600	16.30	24.87	26.81	50.33
Farmer - actual hours									
ha					acres				
20	55.36	64.12	127.19	151.22	50	50.22	58.17	115.39	137.19
40	35.34	44.10	75.61	99.65	100	32.06	40.00	68.59	90.40
61	28.66	37.42	58.42	82.45	150	26.00	33.95	53.00	74.80
81	25.33	34.09	49.82	73.86	200	22.98	30.92	45.20	67.00
121	21.99	30.75	41.23	65.26	300	19.95	27.90	37.40	59.20
162	20.32	29.08	36.93	60.96	400	18.44	26.38	33.50	55.30
202	19.32	28.08	34.35	58.38	500	17.53	25.47	31.16	52.96
243	18.65	27.41	32.63	56.66	600	16.92	24.87	29.60	51.41
Custom operator-hay									
hours					hours				
200	21.13	34.50	32.77	57.55	200	19.17	31.29	29.72	52.21
300	19.77	31.94	29.76	53.36	300	17.93	28.98	27.00	48.41
400	18.95	30.40	28.26	51.26	400	17.19	27.58	25.64	46.51
600	18.31	29.03	26.76	49.17	600	16.61	26.34	24.27	44.60
Yield = 9.0 dMg/ha					Yield = 4 dt/ac				
	Hay		Modules			Hay		Modules	
	1 cut	2 cut	1 cut	2 cut		1 cut	2 cut	1 cut	2 cut
Farmer - standard hours									
	15.26	20.55	21.88	36.92		13.84	18.64	19.85	33.50
Farmer - forage actual hours, tractors standard hours									
ha					acres				
20	23.42	28.28	49.94	57.71	50	21.24	25.65	45.30	52.36
40	18.86	23.72	34.73	45.25	100	17.11	21.52	31.51	41.05
61	17.35	22.21	29.67	41.09	150	15.74	20.14	26.91	37.28
81	16.59	21.45	27.13	39.01	200	15.05	19.46	24.61	35.39
121	15.83	20.69	24.60	36.94	300	14.36	18.77	22.31	33.51
162	15.45	20.23	23.33	35.90	400	14.01	18.35	21.17	32.57
202	15.11	19.87	22.57	35.27	500	13.71	18.03	20.48	31.99
243	14.87	19.59	22.06	34.67	600	13.49	17.77	20.02	31.46
Farmer - actual hours									
ha					acres				
20	38.14	42.53	93.17	94.51	50	34.60	38.58	84.53	85.74
40	25.62	30.02	55.56	62.28	100	23.25	27.23	50.40	56.50xx

Table A.2 (continued)

	Cost ($/dMg)					Cost ($/dt)		
61	21.45	25.85	43.02	51.53	150	19.46	23.45	39.03	46.75
81	19.37	23.76	36.75	46.16	200	17.57	21.56	33.34	41.88
121	17.28	21.68	30.48	40.79	300	15.68	19.67	27.65	37.00
162	16.24	20.63	27.35	38.10	400	14.73	18.72	24.81	34.57
202	15.61	20.01	25.47	36.49	500	14.17	18.15	23.10	33.10
243	15.20	19.59	24.21	35.41	600	13.79	17.77	21.96	32.13
Custom operator-hay									
Hours					Hours				
200	16.09	24.61	21.63	38.27	200	14.59	22.32	19.62	34.72
300	15.18	22.67	19.64	35.44	300	13.77	20.57	17.82	32.15
400	14.72	21.88	18.65	34.03	400	13.36	19.85	16.92	30.87
600	14.27	20.97	17.66	32.61	600	12.94	19.02	16.02	29.58
Yield = 12.3 dMg/ha					Yield = 5.5 dt/ac				
	Hay		Modules			Hay		Modules	
	1 cut	2 cut	1 cut	2 cut		1 cut	2 cut	1 cut	2 cut
Farmer - standard hours									
	14.45	17.60	20.07	29.34		13.11	15.97	18.21	26.62
Farmer - forage actual hours, tractors standard hours									
ha					acres				
20	20.18	23.09	43.63	48.24	50	18.30	20.94	39.58	43.76
40	16.86	19.78	30.73	37.18	100	15.30	17.94	27.88	33.73
61	15.76	18.67	26.43	33.49	150	14.30	16.94	23.97	30.39
81	15.21	18.12	24.28	31.65	200	13.80	16.44	22.02	28.71
121	14.66	17.52	22.13	29.81	300	13.30	15.90	20.07	27.04
162	14.24	17.09	21.05	28.89	400	12.92	15.50	19.10	26.21
202	13.98	16.82	20.41	28.33	500	12.68	15.26	18.51	25.71
243	13.81	16.90	19.98	27.97	600	12.53	15.33	18.12	25.37
Farmer - actual hours									
ha					acres				
20	30.64	33.26	78.68	78.69	50	27.79	30.17	71.37	71.39
40	21.54	24.16	47.55	51.33	100	19.54	21.92	43.14	46.57
61	18.50	21.13	37.18	42.21	150	16.79	19.16	33.72	38.29
81	16.99	19.61	31.99	37.65	200	15.41	17.79	29.02	34.16
121	15.47	18.09	26.80	33.09	300	14.03	16.41	24.31	30.02
162	14.71	17.33	24.21	30.81	400	13.35	15.72	21.96	27.95
202	14.26	16.88	22.65	29.44	500	12.93	15.31	20.55	26.71
243	13.95	16.90	21.61	28.53	600	12.66	15.33	19.61	25.88
Custom operator-hay									
Hours					hours				
200	14.40	19.87	19.17	28.90	200	13.06	18.03	17.39	26.22
300	13.64	18.63	17.43	26.69	300	12.37	16.90	15.81	24.21
400	13.33	18.01	16.55	25.58	400	12.09	16.34	15.02	23.21
600	12.92	17.30	15.68	24.48	600	11.73	15.70	14.22	22.21
Yield = 15.7 dMg/ha					Yield = 7 dt/ac				
	Hay		Modules			Hay		Modules	
	1 cut	2 cut	1 cut	2 cut		1 cut	2 cut	1 cut	2 cut
Farmer - standard hours									
	13.99	16.11	19.61	23.05		12.69	14.61	17.79	20.91
Farmer - forage actual hours, tractors standard hours									
ha					Acres				
20	18.32	20.29	37.67	37.90	50	16.62	18.41	34.17	34.38
40	15.72	17.69	27.53	29.21	100	14.26	16.05	24.97	26.50
61	14.85	16.83	24.15	26.32	150	13.47	15.26	21.91	23.87
81	14.42	16.39	22.46	24.87	200	13.08	14.87	20.38	22.56

Table A.2 (continued)									
	Cost ($/dMg)					Cost ($/dt)			
121	13.89	15.81	20.77	23.42	300	12.60	14.34	18.84	21.25
162	13.55	15.46	19.93	22.70	400	12.29	14.03	18.08	20.59
202	13.34	15.55	19.42	22.26	500	12.10	14.11	17.62	20.20
243	13.50	15.31	19.08	21.97	600	12.25	13.89	17.31	19.93
Farmer - actual hours									
ha					acres				
20	26.35	28.12	64.95	61.83	50	23.90	25.51	58.92	56.09
40	19.20	20.97	40.49	40.33	100	17.42	19.02	36.74	36.59
61	16.82	18.59	32.34	33.17	150	15.25	16.86	29.34	30.09
81	15.62	17.39	28.27	29.58	200	14.17	15.78	25.64	26.84
121	14.43	16.20	24.19	26.00	300	13.09	14.70	21.95	23.59
162	13.84	15.61	22.15	24.21	400	12.55	14.16	20.10	21.96
202	13.48	15.55	20.93	23.13	500	12.23	14.11	18.99	20.99
243	13.54	15.31	20.11	22.42	600	12.29	13.89	18.25	20.34
Custom operator-hay									
Hours					Hours				
200	14.05	17.16	16.41	24.89	200	12.75	15.57	14.89	22.58
300	13.29	16.19	14.92	22.92	300	12.06	14.68	13.54	20.79
400	12.98	15.70	14.18	21.93	400	11.77	14.24	12.86	19.89
600	12.57	15.21	13.43	20.94	600	11.41	13.80	12.19	19.00
Yield = 22.4 dMg/ha					Yield = 10 dt/ac				
	Hay		Modules			Hay		Modules	
	1 cut	2 cut	1 cut	2 cut		1 cut	2 cut	1 cut	2 cut
Farmer - standard hours									
	13.48	14.66	19.10	20.52		12.23	13.30	17.33	18.61
Farmer - forage actual hours, tractors standard hours									
ha					Acres				
20	16.28	17.40	31.11	32.40	50	14.77	15.78	28.22	29.39
40	14.46	15.58	24.01	25.30	100	13.12	14.13	21.78	22.95
61	13.86	14.97	21.65	22.93	150	12.57	13.58	19.64	20.81
81	13.50	14.57	20.46	21.75	200	12.24	13.22	18.56	19.73
121	13.02	14.09	19.28	20.57	300	11.81	12.78	17.49	18.66
162	13.09	14.17	18.69	19.98	400	11.88	12.85	16.95	18.12
202	12.88	13.87	18.33	19.62	500	11.68	12.58	16.63	17.80
243	12.67	13.66	18.08	19.38	600	11.49	12.39	16.40	17.58
Farmer - actual hours									
ha					Acres				
20	21.63	22.63	49.85	50.99	50	19.63	20.53	45.22	46.25
40	16.63	17.62	32.73	33.87	100	15.09	15.99	29.69	30.72
61	14.96	15.95	27.03	28.16	150	13.57	14.47	24.52	25.55
81	14.13	15.12	24.17	25.31	200	12.82	13.72	21.93	22.96
121	13.29	14.28	21.32	22.45	300	12.06	12.96	19.34	20.37
162	13.19	14.18	19.89	21.03	400	11.97	12.87	18.05	19.08
202	12.88	13.87	19.04	20.17	500	11.68	12.58	17.27	18.30
243	12.67	13.66	18.47	19.60	600	11.49	12.39	16.75	17.78
Custom operator-hay									
Hours					Hours				
200	13.67	15.36	15.27	19.54	200	12.40	13.94	13.85	17.73
300	12.90	14.49	13.87	17.91	300	11.71	13.15	12.58	16.25
400	12.59	14.06	13.17	17.09	400	11.43	12.75	11.95	15.51
600	12.19	13.62	12.47	16.27	600	11.06	12.36	11.31	14.76

Table A.3. In-field harvest cost, diesel use and labor for a pull-type forage harvester (2- or 3-row head) at standard hours and a self-propelled forage harvester (4- or 6-row) of 400 hours

Option number and system description, head size, forage wagon size and dump time	Cost $/dMg	Diesel L/dMg	Labor hr/dMg	Cost $/dt	Diesel gal/dt	Labor hr/dt
0 directly to trucks in field						
2 row	4.74	2.59	0.11	4.3	0.62	0.1
3 row	3.72	2.27	0.07	3.37	0.54	0.07
4 row	3.07	1.87	0.05	2.88	0.45	0.04
6 row	2.99	1.99	0.03	2.72	0.48	0.03
1 wagon to truck in field						
2 row						
22.7 m^3 (800ft^3), 1 min.	5.99	2.59	0.11	5.43	0.62	0.1
31.2 m^3 (1100ft^3), 1 min.	6.26	2.59	0.11	5.68	0.62	0.1
22.7 m^3 (800ft^3), 2.5 min.	6.37	2.65	0.11	5.78	0.64	0.1
31.2 m^3 (1100ft^3),2.5 min.	6.32	2.59	0.11	5.74	0.62	0.1
3 row						
22.7 m^3 (800ft^3), 1 min.	4.55	2.27	0.07	4.13	0.54	0.07
31.2 m^3 (1100ft^3), 1 min.	4.73	2.27	0.07	4.29	0.54	0.07
22.7 m^3 (800ft^3), 2.5 min.	5.29	2.55	0.08	4.8	0.61	0.07
31.2 m^3 (1100ft^3),2.5 min.	5	2.38	0.08	4.54	0.57	0.07
4 row						
22.7 m^3 (800ft^3), 1 min.	3.65	1.94	0.05	3.31	0.46	0.04
31.2 m^3 (1100ft^3), 1 min.	3.74	1.93	0.05	3.39	0.46	0.04
22.7 m^3 (800ft^3),2.5 min.	4.76	2.46	0.06	4.31	0.59	0.06
31.2 m^3 (1100ft^3),2.5 min.	4.38	2.24	0.06	3.97	0.54	0.05
6 row						
22.7 m^3 (800ft^3), 1 min.	3.64	2.19	0.03	3.31	0.53	0.03
31.2 m^3 (1100ft^3), 1 min.	3.48	2.05	0.03	3.16	0.49	0.03
22.7 m^3 (800ft^3), 2.5 min.	5.12	3.03	0.05	4.64	0.73	0.04
31.2 m^3 (1100ft^3),2.5 min.	4.56	2.68	0.04	4.14	0.64	0.04

Table A.3 (continued)

Option number and system description, head size, forage wagon size and dump time	Cost $/dMg	Diesel L/dMg	Labor hr/dMg	Cost $/dt	Diesel gal/dt	Labor hr/dt
2 wagon to wagon to truck at field edge						
2 row						
22.7 m^3 (800ft^3)	11.94	4.05	0.32	10.83	0.97	0.29
31.2 m^3 (1100ft^3)	9.34	3.32	0.22	8.47	0.8	0.2
3 row						
22.7 m^3 (800ft^3)	8.52	3.24	0.22	7.73	0.78	0.2
31.2 m^3 (1100ft^3)	8.83	3.24	0.22	8.01	0.78	0.2
4 row						
22.7 m^3 (800ft^3)	7.4	2.91	0.19	6.71	0.7	0.17
31.2 m^3 (1100ft^3)	6.3	2.57	0.14	5.72	0.62	0.13
6 row						
22.7 m^3 (800ft^3)	7.2	3.11	0.17	6.53	0.75	0.15
31.2 m^3 (1100ft^3)	6.05	2.7	0.13	5.49	0.65	0.12

INTERNAL DISTRIBUTION

1. G. E. Courville
2. T. R. Curlee
3-27. M. E. Downing
28. S. G. Hildebrand
29. C. I. Moser
30. R. B. Shelton
31. A. F. Turhollow
32. Central Research Library
33. Document Reference Section
34. ESD Library
35. Laboratory Records Dept.
36. Laboratory Records, ORNL-RC

EXTERNAL DISTRIBUTION

37. Lilia A. Abron, President, PEER Consultants, P.C., 1460 Gulf Blvd. 11th Floor, Clearwater, Florida 34630

38. J. Butler, 2823 Rainwater, Tifton, Georgia 31794

39. Thomas E. Drabek, Professor, Department of Sociology, University of Denver, Denver, Colorado 80208-0209

40. P. Richard Rittelmann, FAIA, Executive Vice President, Burt Hill Kosar Rittelmann Associates, 400 Morgan Center, Butler, Pennsylvania 16001-5977

41. Susan F. Tierney, The Economic Resource Group, Inc. One Mifflin Place, Cambridge, Massachusetts 02138

42. C. Michael Walton, Ernest H. Cockrell Centennial Chair in Engineering and Chairman, Department of Civil Engineering, University of Texas at Austin, Austin, Texas 78712-1076

43-44. Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831