ENERGY USE FOR FIELD OPERATIONS, CROP DRYING, AND SWINE HOUSING ON UNIVERSITY FARMS

H. M. Hanna, J. D. Harmon, D. D. Schweitzer

ABSTRACT. *Energy is an input to agricultural production. Knowing typical values can help farmers to evaluate management options. Diesel, propane, and electrical energy used on the farm during selected field operations, crop drying, and in swine housing were measured on Iowa State University research and demonstration farms. Baseline values were measured and tractor operation management styles were compared.*

Strategies for saving fuel were confirmed in 43 of 48 tractor operation comparisons. Comparisons of tillage depth, gear/engine speed, travel speed, and use of front-wheel-assist averaged 28%, 25%, 17%, and 13% more energy used than the fuel-saving alternative. Single-drive wheels used 8% more energy than duals, but results were mixed when comparing different tire inflation pressures.

Energy used in high-temperature drying in bins ranged from 4.67 to 7.70 MJ kg^{-1} (2010 to 3310 Btu lb^{-1}). Most of the energy was from propane (96%). Propane use averaged 0.0027 L kg^{-1} (0.018 gal bu^{-1}) per percentage point of moisture removed.

Minimum ventilation fans had the highest duty cycle in a curtain-sided swine finishing barn. Electrical use was greater in tunnel-ventilated than curtain-sided barns (29.0 vs. 20.9 kWh pig space^{-1} yr^{-1}) and propane use was greater in wean-to-finish than finish-only operations (10.6 L vs. 2.5 L pig space^{-1} yr^{-1}, 2.8 gal vs. 0.67 gal pig space^{-1} yr^{-1}).

Keywords. *Energy efficiency, Fuel consumption, Grain drying, Machinery management, Tractor, Ventilation.*

U.S. farmers spent $16.5 B for gasoline, fuels, and oils and $8.3 B for utilities in 2012 according to the USDA Agricultural Census (USDA, 2014). Purchase of diesel fuel, liquid propane (LP), and natural gas are included in gasoline, fuels, and oils. Electricity, telephone charges, internet fees, and purchased water are included in utilities costs. Iowa spent more than $1 B including $867 million on gasoline, fuels, and oils (primarily diesel fuel and LP) and $329 million on utilities (primarily electricity).

University Extension staff estimate energy consumption (Hanna, 2001). Estimates are frequently based on either old or very limited data. McLaughlin et al. (2008) measured fuel use of 21.6, 13.9, and 7.3 L ha^{-1} (2.31, 1.49, and 0.78 gal acre^{-1}) for moldboard plowing, chisel plowing, and disking (tandem disk harrow) in southwestern Ontario. Tillage depth and travel speeds were 187 mm (7.4 in.) and 5.6 km h^{-1} (3.5 mi h^{-1}) for moldboard plowing, 169 mm (6.7 in.) and 6.6 km h^{-1} (4.1 mi h^{-1}) for chisel plowing, and 59 mm (2.3 in.) and 6.5 km h^{-1} (4.0 mi h^{-1}) for disking, within ranges normally used in the region.

Because of a lack of current fuel consumption data for field operations, most machinery and crop production budgets developed by Extension staff and others use values estimated from ASABE standards (*ASABE Standards,* 2014a, 2014b). Estimates are based on fuel consumption models for tractors from OECD tractor tests (Grisso et al., 2008) and estimation of drawbar and rotary-powered load forces from implement geometry, soil conditions, travel speed, and tillage depth.

Energy use for grain drying is also estimated from old or very limited public data. Morey et al. (1978) drying corn from 22.3% moisture content (m.c.) to 15.8% m.c. with 100°C (212°F) air used 5.71 MJ of energy per kg of water removed (2461 Btu lb^{-1}) using a small automatic batch dryer (10.6 m^3; 300 bu). Treatments also included use of high-temperature drying to intermediate moisture contents (e.g., 18% and 21%) followed by natural-air drying. Higher energy efficiencies were associated with treatments to intermediate moisture contents in the high-temperature dryer. Wilcke and Bern (1986) dried corn with unheated ambient-air during two seasons. Corn dried from 24.7% to 13.0% m.c. used 3.02 MJ kg^{-1} (1300 Btu lb^{-1}) energy per water removed. Corn dried the second year from a lower initial moisture content, 19.7% to 14.3% used 4.10 MJ kg^{-1} (1760 Btu lb^{-1}). Limited

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field observations such as these, along with modeling estimates, have been used by Extension staff to estimate crop drying energy consumption (Morey and Cloud, 1980). Wilcke and Bern (1985) estimated propane energy consumption in a high-temperature dryer to range from 0.0015 to 0.0037 L kg^{-1} (0.01 to 0.025 gal bu^{-1}) per percentage point of moisture removal and electrical consumption to range from 0.00028 to 0.0012 kWh kg^{-1} (0.007 to 0.03 kWh bu^{-1}) per percentage point of moisture removal. Electrical consumption in a natural-air dryer was estimated to range from 0.011 to 0.017 kWh kg^{-1} pt^{-1} (0.28 to 0.42 kWh bu^{-1} pt^{-1}) for drying corn from 20% m.c. and 0.012 to 0.028 kWh kg^{-1} pt^{-1} (0.31 to 0.71 kWh bu^{-1} pt^{-1}) for drying corn from 24% m.c.

In order for swine producers to gauge energy consumption and the need for energy conservation measures, benchmarks for energy usage are needed. Energy benchmarks for swine production are not widely available. This is due to the wide variation in production facilities and the fact that energy usage is often aggregated within whole farm usage. Harmon et al. (1998) metered an individual barn and found that a hybrid ventilated finishing building (22 to 114 kg) that utilized fans for cold weather ventilation and sidewall ventilation curtains for warm weather ventilation used 10.9 kWh pig space^{-1} yr^{-1} of electricity and 2.3 L of propane pig space^{-1} yr^{-1} (0.6 gal pig space^{-1} yr^{-1}). Other studies have reported utility cost in terms of cost per pig marketed without separating electricity from heating fuel. Navia et al. (2007) found that finishing pigs required an average utility cost of Canadian $1.70 per pig marketed with a range of $1.30 to $2.10. Predicala and Navia (2008) reported the same average with a broader range of $1.20 to $2.60 pig^{-1} marketed. Likewise, Finbin (2014) reports that 58 wean-finish (6 to 122 kg) farms reporting in Minnesota in 2012 and 2013 reported utilities cost of $0.64 pig^{-1} marketed with fuel and oil reported to be $1.25 pig^{-1} marketed. These numbers illustrate that there are inconsistencies in how energy usage is reported and partitioned and highlight the need to find a more uniform, descriptive way of reporting the data.

Measurement of on-farm energy use is needed to either validate older measurements or establish new benchmarks using more current technology. Comparison of energy management techniques on local research and demonstration farms helps farmers to evaluate and adopt improved energy management strategies.

OBJECTIVE

Measure baseline energy use values for field operations, corn drying, and swine housing on university research and demonstration farms and compare management techniques where possible.

METHODS AND MATERIALS

Iowa State University has research and demonstration farms located throughout the state. Larger farms have 200 acres or more of cropland. Individual farms reflect local differences in soil and climate (fig. 1). Although a large portion of the cropland is used for smaller scale research plots, larger tracts of ‘bulk’ acres are frequently tilled and seeded on smaller ISU farm locations near the central Agricultural Engineering and Agronomy Research Farm, the Northwest (Allee) Research Farm, and on the Ag 450 Teaching Farm near Ames. On-site grain dryers are used at the Northeast, Southwest (Armstrong), and Ag 450 farms. Livestock operations on outlying farms are limited due to distance from campus, but a swine feeding operation is present on the Ag 450 teaching farm near Ames.

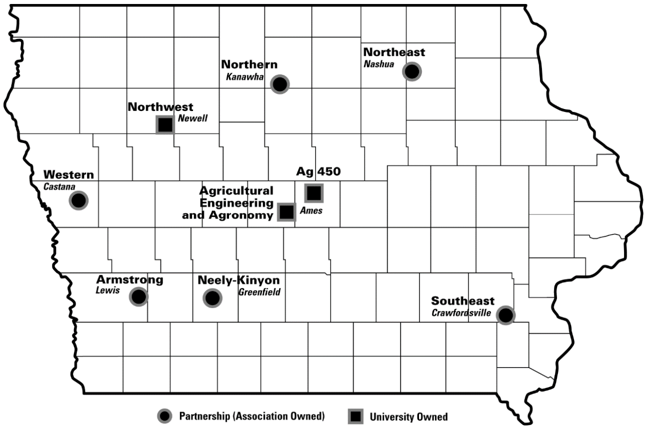

Figure 1. Iowa State University research and demonstration farm locations.

FIELD OPERATIONS

Each farm participating in the tractor study selected a tractor for fuel measurement that was commonly used for field operations. Selected tractor models are shown in table 1. A gravimetric fuel measurement system was used to avoid potential back-pressure problems in return fuel lines on diesel engines from flow meters. A 49 L (13 gal) auxiliary fuel tank was mounted atop a 100 kg (220 lb) load cell on each tractor. Each load cell was calibrated with a known mass after initial installation, and periodically afterwards if measurements appeared incorrect. Mass on the load cell was displayed in the tractor cab. Plumbing was added for diesel fuel to be supplied and returned from the engine via either the main or auxiliary fuel tank, depending on the setting for a single flow control valve. Net mass of fuel consumed (supply – return) was measured by recording the difference in auxiliary tank weight before and after an operation in the field.

Although field work on the research farms is frequently done on small plot areas, it was desired to measure fuel consumption of 2.3 kg (5 lb) or more during single observations

Table 1. Tractors[a] used for fuel measurements by location.

Farm Location	Tractor (kW / hp)
Agricultural Engineering Agronomy	John Deere 7730 (114 / 153)
Northeast	John Deere 7430[b] (105 / 141) and 6170R[c] (107 / 143)
Northern	John Deere 7410 (79 / 106)
Northwest	John Deere 2955 (64 / 86)
Southeast	John Deere 7430 (105 / 141)
Southwest	John Deere 7420 (87 / 117)
Western	John Deere 6420 (70 / 94)

[a] Brand names are used for convenience of the reader and do not imply endorsement or critique by the authors.

[b] Used during 2013.

[c] Used after 2013.

as the load cell measured fuel in 0.045 kg (0.1 lb) increments. Multiple replications of measurements were made in most treatment comparisons as land area and timing of trials allowed. Small plots or farm scheduling tended to limit replications. Limited replications reduced the ability to measure statistical significance beyond overall trends in data in some cases. Field area covered by each observation was calculated from implement width and field distance traveled (either measured manually or with on-board electronics when available on the tractor). Fuel consumption was then calculated as L ha^{-1} (gal $acre^{-1}$).

Field length for tractor use on research farms was commonly 90 m (300 ft) or less, reducing field efficiency compared to neighboring commercial farms. Exceptions were the Agricultural Engineering Agronomy and Northwest Research Farms with longer field lengths more typical of commercial farms. Individual treatments within a day's time at a single location were compared statistically. Different locations, operators, tractors, and soil moisture content at the time of each treatment comparison limit aggregation of data, however trials were also summarized to report the effect of individual fuel saving strategies and to show the range of fuel use observed for a specific field operation (e.g., planting) at various locations and times.

CROP DRYING

Grain drying energy consumption was measured at the Ag 450, Southwest (Armstrong), and Northeast Farms. Bin dryers are used to accommodate crop size and harvest rate on the farms. Dryers ranged from less than 5 to over 20 years old. Harvest of research plots frequently slows harvest rate compared to commercial farms. Propane consumed for drying was measured by four 910-kg (2000-lb) load cells underneath the feet of propane tanks recording weight. The load cell system on each tank was calibrated after initial installation and checked periodically by comparison with propane supplier delivery amounts. A data logging system recorded tank weight every 30 min during drying. Electrical energy was measured for drying fans and mixing augers. Energy use was calculated from measurements of electric current every 30 min during grain drying and measurement of electrical power factor twice (with full bins) during the first drying season in electrical circuits supplying fan and stirring equipment energy.

At the Ag 450 and Northeast Farms, grain is dried as a 'batch-in-bin' system with a vertical stirring auger mixing the entire grain mass while a fan blows heated air up through grain from the plenum. At the Ag 450 Farm, harvesting from larger land areas filled the bins within a day. At the Northeast Farm, bins were filled during plot harvest. Bin fill was completed within 3 to 6 days resulting in shallower layer drying during earlier stages of the batch. During fall 2013 at the Ag 450 and Northeast Farms, three batches of drying were accomplished, two batches in one bin and a single batch in a second bin at both locations. Fall 2014 drying was similar except that at the Ag 450 Farm only a single batch was dried in each drying bin.

The drying bin at the Southwest Farm has a bottom sweep auger that transfers grain dried by plenum air to a center vertical auger. The vertical auger lifts grain either back to the top of the bin grain mass where it is distributed (recirculating batch mode) or lifts and transfers dried grain completely out of the bin into an adjacent storage bin (continuous flow mode). Because heated air moves in the opposite direction of grain flow, this is termed a counter-flow dryer, and was operated in both 'continuous flow' mode with dried grain immediately leaving the dryer and 'recirculating batch' mode with dried grain being recirculated to the top of the grain mass inside the bin. Drying temperatures of 60°C and 82°C (140°F and 180°F) were used with each mode during fall 2013. During fall 2014, 'continuous flow' drying was done at 60°C (140°F) and 'recirculating batch' drying was done at 82°C (180°F). Full bin capacity is 1040 m^3 (9000 bu). To accommodate plot harvest rate, total grain available, and to observe drying in a shallower layer, the bin was filled between about 220 to 450 m^3 (1900 to 3900 bu) during both recirculating-batch and continuous-flow drying modes. After high-temperature drying measurements and at the end of harvest, the bin was filled with corn to be dried with natural air (fan only). After fall 2013 harvest, samples from multiple grain probes in late winter showed the drying front had progressed about 2.1 m (7 ft) during late fall drying before grain in the bin was removed. Weather conditions following fall 2014 harvest allowed natural-air drying to be completed by late November. Because of prior inactivity, the high-temperature drying system at the Southwest Farm was refurbished before measurements started in fall 2013. Bin and fan specifications are shown in table 2.

Beginning moisture content was determined by measuring individual loads with a moisture meter used by local farm staff. Measurements by the farm meter were compared twice annually with a commercial elevator meter or if a problem was suspected. Separate water and corn dry matter weights were associated with each incoming load and were calculated from wet basis moisture content. Corn dry matter and water weights added to the bin from each incoming load were summed to determine beginning water and also to calculate initial wet basis moisture content for each group of corn dried. If time was available, farm staff at the Ag 450 and Northeast Farms measured daily intermediate moisture contents during drying from multiple samples taken in the top layer of corn in the bin. Ending moisture content was measured in the same manner at Ag 450 and Northeast Farms. Corn dry matter was assumed to be conserved during drying and final wet basis moisture content was used to calculate the weight of water remaining after drying. At the Armstrong Farm, ending moisture content was measured from the exit moisture sensor on the drying system for 1770-L (50-bu) corn increments being transferred during five-minute periods and then calculating total water and corn dry matter for all corn transferred during a drying period.

Table 2. Bin capacity and fan power.

		Capacity		Bin Diameter		Fan Power	
Location	Bin	(m^3)	(bu)	(m)	(ft)	(kW)	(hp)
Ag 450	West	342	9700	9.1	30	5.6	7.5
Ag 450	East	324	9200	8.2	27	7.5	10
Northeast	East	310	8800	8.5	28	9.3	12.5
Northeast	West	419	11,875	9.1	30	11.2	15
Southwest		317	9000	9.1	30	19.4[a]	26[a]

[a] Two 9.7 kW (13 hp) fans.

Measurement of the exit sensor was compared twice annually with a commercial elevator meter. Water removed during drying was the difference between beginning and ending water weight for each group of corn dried.

Energy required to remove water from the grain was the sum of propane used for the dryer burner and electrical energy for drying fans and the stirring and recirculating augers. Total energy consumed was divided by the amount of water removed to provide a measure of energy use for drying in MJ kg^{-1} (Btu lb^{-1}) of water removed.

SWINE HOUSING

Two approaches were used in obtaining energy usage data with swine production. In one approach a swine finishing facility was instrumented to collect detailed information on fan energy usage, including duty cycles, and heating energy usage. The second approach focused on more global data by seeking monthly energy data from production units.

The detailed monitoring occurred at the Iowa State University Ag 450 farm. This farm is managed by students in a management class and includes a swine finishing facility. This barn has four rooms [12.2 × 18.3 m (40 × 60 ft)]. Each has a capacity of 300 pigs. The rooms have three fan stages and utilize sidewall ventilation curtains for warm weather. The first stage includes two Aerotech Classic AT10SP fans (U.S. Global Resources, Seattle, Wash.) with 124 W (1/6 hp) electric motors, rated airflow of 30 m^3 min^{-1} (1060 cfm) and rated efficiency of 0.16 m^3 min^{-1} W^{-1} (5.5 cfm W^{-1}) at a static pressure difference of 25 Pa (0.1 in. water). The exact fan models for the second and third fan stages could not be confirmed because all markings had been worn away from the fans. The building owner stated that the second and third stage fans were each 249 W (1/3 hp), 61 cm (24 in.) Hired Hand Funnel Flow fans (Bremen, Ala.) with rated airflow of 178 m^3 min^{-1} (6280 cfm) and rated efficiency of 0.46 m^3 min^{-1} W^{-1} (16.1 cfm W^{-1}) at a static pressure of 25 Pa (0.1 in. water). This resulted in a nominal maximum mechanical ventilation capacity of 416 m^3 min^{-1} (14,680 cfm) or 1.4 m^3 min^{-1} pig^{-1} (49 cfm pig^{-1}). An air furnace was mounted on the exterior of each room to heat air brought from the ambient surroundings.

Monitoring equipment was installed on the ISU Ag 450 swine finishing unit to gather information on electrical and propane usage. Electrical data was collected and processed for two of the Ag 450 finishing rooms for the period of 10 December 2012 through 17 December 2014. Amperage for each 30-s period was recorded and averaged for each fan. In order to translate amperage into energy usage, the typical farm voltage (220 v) and amperage were multiplied by the power factor for each fan. Power factor was measured for each fan model using a Fluke Power Logger (Fluke 1735, Everett, Wash). For the stage 1 fans, a power factor of 0.97 was measured. For stages 2 and 3 the power factor was measured as 0.935. These were different than what was originally estimated (0.92 and 0.70). This was used to establish duty cycles and fan energy usage on each fan stage. In September, 2013 propane meters were added to all four rooms. Pulse counts were produced for each cubic foot of propane used on a 15-min basis to obtain information on when the heater was operating.

The second approach involved locating entities willing to share energy usage information. One cooperator represented a swine production company that shared data for five different 2400-head, tunnel ventilated, wean-to-finish facilities. Another source was an electrical utility within Iowa which shared data from seven different farms. In addition, one swine producer provided five years of data from two of his swine finisher buildings. These were summarized and categorized by building type to produce ranges of expected usage.

RESULTS AND DISCUSSION

FIELD OPERATIONS

Fuel use measurements during selected field operations and treatment comparisons are shown in tables 3-12. Farm staff were encouraged, when possible, to compare different treatments. These treatments included using different transmission gear and engine speed settings at the same travel speed, different travel speeds, different tillage depths, different tire inflation pressures (a lower inflation pressure as specified by the tire or tractor manufacturer for wheel load, and an over-inflated condition), operation with and without front-wheel-assist engaged, or operation with single or dual tires. The ASABE standards, S496.3 and S497.7, were also used to calculate expected fuel use.

Although different fields, tractors, and operators preclude direct comparison, summaries of the comparisons in tables 13 and 14 indicate the percentage of fuel that was saved with a specific strategy and the range of fuel consumption observed for individual field operations, respectively. A summary of observed differences in the various treatment comparisons is shown in table 13. Farm managers and agricultural economists frequently want to know a single estimate of fuel used per hectare (acre) for each field operation to incorporate into crop input budget estimates. Average, least, and greatest fuel used by field operations for treatments observed are shown in table 14. Tables 13 and 14 give guidance on values, but also demonstrate limitations and the importance of operator management.

Limited replications (often three or four) generally precluded the ability to detect statistically significant differences. Failing to shift up to a higher gear and reduce engine speed (tables 3-5) caused an average 25% more fuel use and was demonstrated in 18 of 19 comparisons. Increasing travel speed required an average of 17% more fuel and was demonstrated in 9 of 11 comparisons (tables 6 and 7). When tillage depth was increased, fuel use increased in all five comparisons by an average of 28% (table 8).

Slightly more fuel was used in three of five comparisons between correctly and overinflated tires (table 9), but results varied. Average fuel difference including all five comparisons was slightly negative (-1%). One comparison was statistically significant. Not using front-wheel-assist consumed an average of 13% more fuel in six comparisons (table 10, three statistically significant).

Treatments comparing field operations with and without the use of dual rear-drive wheels were done at the Northwest Research Farm (tables 11 and 12). In both cases, an average of 8% additional fuel was used with only single-tire wheels,

Table 3. Observed and empirical fuel use at the Northeast Iowa Research Farm with gear/engine rpm.

Operation	No. of Replications	Treatment Gear/Engine (rpm)	Fuel Use Observed (L ha^{-1})	Fuel Use Observed (gal acre^{-1})	Fuel Use Empirical (L ha^{-1})	Fuel Use Empirical (gal acre^{-1})
2013						
Field cultivation, 8 km h^{-1} (5 mi h^{-1})	3	C1/2080	7.5	0.80	4.7	0.50
	3	C2/1710	6.2	0.66	4.1	0.43
LSD $_{\alpha=0.05}$, P = 0.007[a]			0.5	0.05		
Strip till, 8.4 km h^{-1} (5.2 mi h^{-1})	3	C1/2170	19.6	2.10	11.0	1.18
	3	C2/1710	13.0	1.39	9.6	1.03
LSD $_{\alpha=0.05}$, P = 0.12[a]			NS[b]	NS[b]		
Stalk chopping, 8.0 km h^{-1} (5.0 mi h^{-1})	3	C1/2060	8.9	0.95	5.6	0.59
	3	C2/1710	6.0	0.64	5.0	0.53
LSD $_{\alpha=0.05}$, P = 0.002[a]			0.6	0.06		
2014						
Field cultivation, 8.0 km h^{-1} (5.0 mi h^{-1})	3	C1/2080	5.6	0.60	4.6	0.49
	3	C2/1720	3.8	0.41	4.0	0.43
LSD $_{\alpha=0.05}$, P = 0.15[a]			NS[b]	NS[b]		
Subsoiling, 5.9 km h^{-1} (3.7 mi h^{-1})	3	B1/2100	11.9	1.27	13.9	1.49
	3	B3/1500	10.0	1.07	12.0	1.28
LSD $_{\alpha=0.05}$, P = 0.10[a]			NS[b]	NS[b]		
2015						
Field cultivation, 8.0 km h^{-1} (5.0 mi h^{-1})	3	C1/2100	7.0	0.74	4.7	0.50
	3	C2/1800	6.5	0.69	4.2	0.45
LSD $_{\alpha=0.05}$, P = 0.07[a]			NS[b]	NS[b]		

[a] Least significant difference between treatments at a 95% confidence level; probability of no significant difference between treatments.

[b] No significant difference at the 95% confidence level.

although neither was statistically significant. Additional comparisons from these tables at the Northwest Farms were used as appropriate for gear/engine speed, travel speed, and depth treatments in summary tables 13 and 14.

Table 4. Observed and empirical fuel use at the Southwest Iowa Research Farm, with gear/engine rpm.

Operation	No. of Replications	Treatment Gear/Engine (rpm)	Fuel Use Observed (L ha^{-1})	Fuel Use Observed (gal acre^{-1})	Fuel Use Empirical (L ha^{-1})	Fuel Use Empirical (gal acre^{-1})
2013						
Moldboard plowing, 7.2 km h^{-1} (4.5 mi h^{-1})	1	B2/2250	45.3	4.84	20.2	2.90
	3	B3/2000	42.7	4.57	18.5	2.70
	4	B4/1700	34.3	3.67	16.6	2.46
LSD $_{\alpha=0.05}$, P = 0.88[a]			NS[b]	NS[b]		
Disking, 7.4 km h^{-1} (4.6 mi h^{-1})	4	B3/2200	3.2	0.34	6.0	0.64
	4	C1/2000	3.6	0.39	5.7	0.60
LSD $_{\alpha=0.05}$, P = 0.31[a]			NS[b]	NS[b]		
Planting, 6.4 km h^{-1} (4.0 mi h^{-1})	4	B2/2225	4.3	0.46	4.4	0.47
	5	B3/1850	3.6	0.39	3.9	0.42
	4	B4/1500	3.4	0.37	3.4	0.37
LSD $_{\alpha=0.05}$, P = 0.13[a]			NS[b]	NS[b]		
2014						
Moldboard plowing, 6.9 km h^{-1} (4.3 mi h^{-1})	3	B2/2250	35.2	3.76	29.0	3.10
	4	B3/2000	32.8	3.51	27.1	2.89
	3	B4/1700	26.7	2.86	24.7	2.64
LSD $_{\alpha=0.05}$, P = 0.01[a]			4.6	0.49		
Planting, 6.4 km h^{-1} (4.0 mi h^{-1})	4	B2/2200	4.0	0.43	3.4	0.36
	4	B3/1900	3.5	0.38	3.0	0.32
	4	B4/1520	3.6	0.39	2.6	0.28
LSD $_{\alpha=0.05}$, P = 0.77[a]			NS[b]	NS[b]		
2015						
Moldboard plowing, 7.2 km h^{-1} (4.5 mi h^{-1})	4	B3/2000	28.1	3.00	27.0	2.89
	3	B4/1700	26.2	2.80	24.7	2.64
LSD $_{\alpha=0.05}$, P = 0.19[a]			NS[b]	NS[b]		
Planting, 6.8 km h^{-1} (4.2 mi h^{-1})	4	B3/1950	4.6	0.49	3.0	0.32
	4	B4/1600	3.6	0.39	2.6	0.28
LSD $_{\alpha=0.05}$, P = 0.56[a]			NS[b]	NS[b]		

[a] Least significant difference between treatments at a 95% confidence level; probability of no significant difference between treatments.

[b] No significant difference at the 95% confidence level.

Table 5. Observed and empirical fuel use at the Northern, Southeastern, and Western Iowa Research Farms, with gear/engine rpm.

Operation	No. of Replications	Treatment Gear/Engine (rpm)	Fuel Use Observed		Fuel Use Empirical	
			(L ha^{-1})	(gal acre^{-1})	(L ha^{-1})	(gal acre^{-1})
Northern						
Field cultivation, 10.1 km h^{-1} (6.3 mi h^{-1})	2	C2/2170	4.1	0.43	3.8	0.40
	1	C4/1480	2.8	0.30	3.0	0.32
Southeastern						
Chisel plow, 7.4 km h^{-1} (4.6 mi h^{-1})	6	B2/2200	11.6	1.24	10.8	1.16
	6	C1/2000	10.3	1.10	9.9	1.06
LSD $_{\alpha=0.05}$, P = 0.04[a]			1.3	0.13		
Western						
Planting (2014), 8.3 km h^{-1} (5.2 mi h^{-1})	8	B4/2150	5.4	0.57	3.6	0.39
	8	C2/1900	4.6	0.50	3.3	0.35
LSD $_{\alpha=0.05}$, P = 0.0001[a]			0.3	0.03		
Planting (2015), 8.3 km h^{-1} (5.2 mi h^{-1})	8	B4/2150	5.4	0.58	3.6	0.39
	8	C2/1900	4.7	0.50	3.3	0.35
LSD $_{\alpha=0.05}$, P = 0.0002[a]			0.3	0.03		
Grain drill, 8.3 km h^{-1} (5.2 mi h^{-1})	8	B4/2150	5.2	0.56	4.4	0.48
	8	C2/1900	3.7	0.39	4.1	0.44
LSD $_{\alpha=0.05}$, P = 0.0001[a]			0.4	0.04		

[a] Least significant difference between treatments at a 95% confidence level; probability of no significant difference between treatments.

Table 6. Observed and empirical fuel use during chisel plowing with different travel speeds.

Location	No. of Replications	Treatment, Travel Speed		Fuel Use Observed		Fuel Use Empirical	
		(km h^{-1})	(mi h^{-1})	(L ha^{-1})	(gal acre^{-1})	(L ha^{-1})	(gal acre^{-1})
Southeast (chisel)	3	6.0	3.8	10.5	1.12	11.5	1.27
	3	7.2	4.5	13.0	1.39	10.4	1.21
LSD $_{\alpha=0.05}$, P = 0.37[a]				NS[b]	NS[b]		
Northern (chisel)	3	7.4	4.6	8.5	0.91	12.1	1.29
	3	8.2	5.1	6.5	0.69	11.8	1.27
	3	8.9	5.5	10.3	1.10	11.7	1.25
LSD $_{\alpha=0.05}$, P = 0.49[a]				NS[b]	NS[b]		
Southwest (chisel)	1	4.8	3.0	9.9	1.06	11.5	1.23
	1	6.9	4.3	9.1	0.98	10.4	1.12
	1	7.6	4.7	8.8	0.94	10.3	1.10

[a] Least significant difference between treatments at a 95% confidence level; probability of no significant difference between treatments.

[b] No significant difference at the 95% confidence level.

Table 7. Observed and empirical fuel use during disking at the Southwest Farm, field cultivating and disking at the Northwest Farm, and rotary mowing and hauling corn at the Western Farm with different travel speeds.

Operation	No. of Replications	Treatment, Travel Speed		Fuel Use Observed		Fuel Use Empirical	
		km h^{-1}	mi h^{-1}	L ha^{-1}	gal acre^{-1}	L ha^{-1}	gal acre^{-1}
Disking (Southwest)	4	7.2	4.5	2.4	0.26	6.5	0.69
	4	8.0	5.0	2.8	0.30	6.4	0.69
LSD $_{\alpha=0.05}$, P = 0.69[a]				NS[b]	NS[b]		
Disking (Northwest)	3	6.8	4.2	5.5	0.58	5.8	0.62
	3	7.6	4.7	5.3	0.56	5.6	0.60
	3	8.0	5.0	7.9	0.84	6.0	0.64
	3	8.5	5.3	5.9	0.63	5.9	0.64
LSD $_{\alpha=0.05}$, P = 0.001[a]				0.8	0.08		
Disking (Northwest)	3	6.1	3.8	8.2	0.88	5.8	0.62
	3	6.9	4.3	9.1	0.97	6.1	0.65
LSD $_{\alpha=0.05}$, P = 0.06[a]				NS[b]	NS[b]		
Disking (Northwest)	3	7.1	4.4	6.2	0.66	4.7	0.50
	3	8.2	5.1	7.0	0.75	4.9	0.52
LSD $_{\alpha=0.05}$, P = 0.22[a]				NS[b]	NS[b]		
Field cultivating	6	7.2	4.5	5.2	0.55	3.8	0.40
	6	8.4	5.2	5.4	0.58	4.0	0.43
LSD $_{\alpha=0.05}$, P = 0.62[a]				NS[b]	NS[b]		
Mowing hay	4	7.2	4.5	5.9	0.63	4.7	0.50
	4	8.5	5.3	6.8	0.73	4.4	0.47
LSD $_{\alpha=0.05}$, P = 0.0003[a]				0.2	0.02		
Hauling corn[c]	4	27	17	0.4	0.17	0.3	0.12
	4	32	20	0.5	0.21	0.3	0.13
LSD $_{\alpha=0.05}$, P = 0.0001[a]				0.01	0.002		

[a] Least significant difference between treatments at a 95% confidence level; probability of no significant difference between treatments.

[b] No significant difference at the 95% confidence level.

[c] Fuel use, L km^{-1} or gal mi^{-1}.

Table 8. Observed and empirical fuel use with tillage depth during disking at the Southwest Iowa Research Farm (2013 and 2014) and field cultivating and disking at the Northwest Farm (2015).

Operation	No. of Replications	Treatment, Disking Depth		Fuel Use Observed		Fuel Use Empirical	
		(cm)	(in)	(L ha^{-1})	(gal acre^{-1})	(L ha^{-1})	(gal acre^{-1})
2013							
Disking, 7.4 km h^{-1} (4.6 mi h^{-1})	4	8	3	3.3	0.35	5.0	0.53
	4	13	5	3.6	0.38	6.6	0.71
LSD $_{\alpha=0.05}$, P = 0.56[a]				NS[b]	NS[b]		
2014							
Disking, 7.6 km h^{-1} (4.7 mi h^{-1})	4	10	4	2.1	0.23	5.5	0.59
	4	15	6	3.0	0.32	7.4	0.79
LSD $_{\alpha=0.05}$, P = 0.43[a]				NS[b]	NS[b]		
2015							
Field cultivation, 7.9 km h^{-1} (4.9 mi h^{-1})	6	8	3	4.7	0.50	3.4	0.36
	6	11	4.5	5.9	0.63	4.4	0.47
LSD $_{\alpha=0.05}$, P = 0.05[a]				1.2	0.13		
Disking, 7.1 km h^{-1} (4.4 mi h^{-1})	6	10	4	6.6	0.71	4.8	0.51
	6	14	5.5	8.6	0.92	5.9	0.64
LSD $_{\alpha=0.05}$, P = 0.0002[a]				0.6	0.06		

[a] Least significant difference between treatments at a 95% confidence level; probability of no significant difference between treatments.

[b] No significant difference at the 95% confidence level.

Fuel-saving strategies were generally well demonstrated for shifting up and throttling back with reduced drawbar loads, reducing tillage depth, and engaging front-wheel-drive. Fuel savings were also demonstrated at lower travel speeds, although savings were not as great as transmission and depth, and results were mixed as lower engine speed and good torque characteristics in some instances compensated for small increases in draft load. Fuel savings were demonstrated in two comparisons of single versus dual drive tires. Fuel savings observed were marginal (often within the range of measurement accuracy) and least apparent when comparing tire inflation. Overall, 43 of 48 treatment comparisons showed expected trends in fuel savings and 23 of the comparisons were statistically significant.

Empirical fuel use values calculated using procedures from ASABE standards were generally greater than observed values for travel speed, tillage depth, and tire inflation comparisons, but lower than observed values for gear/engine speed, front-wheel-assist, and dual versus single tire comparisons (table 13). Variations between observed and estimated values may be due to in-field factors such as turns on short plot rows or inherent variability in applying ASABE estimation techniques. Grisso et al. (2008) reported that ASABE standard S497.7 often over-predicted fuel use unless adjusted for individual tractor test data.

Fuel used by various field operations had a wide range of treatment mean values (table 14). This suggests better estimates for crop input budgets may be made if additional

Table 9. Observed and empirical fuel use with tire inflation at the Ag Engineering Agronomy Farm during 2013, and the Northern and Southwest Iowa Research Farms during 2014.

Location/Operation	No. of Replications	Treatment, Tire Pressure		Fuel Use Observed		Fuel Use Empirical	
		Rear/Front (kP)	Rear/Front (psi)	(L ha^{-1})	(gal acre^{-1})	(L ha^{-1})	(gal acre^{-1})
Ag Engineering Agronomy Farm							
Chisel plowing[a], 7.7 km h^{-1} (4.8 mi h^{-1})	3	69/138	10/20	14.9	1.59	12.0	1.29
	3	138/207	20/30	15.1	1.61	12.0	1.29
LSD $_{\alpha=0.05}$, P = 0.59[b]				NS[c]	NS[c]		
Chisel plowing[d], 7.7 km h^{-1} (4.8 mi h^{-1})	3	69/138	10/20	13.2	1.41	12.0	1.29
	3	138/207	20/30	13.4	1.43	12.0	1.29
LSD $_{\alpha=0.05}$, P = 0.04[b]				0.2	0.02		
Northern Farm							
Chisel plowing[d], 5.8 km h^{-1} (3.6 mi h^{-1})	3	97/235	14/34	10.2	1.09	13.1	1.40
	4	138/235	20/34	10.5	1.12	13.1	1.40
LSD $_{\alpha=0.05}$, P = 0.98[b]				NS[c]	NS[c]		
Southwest Farm							
Chisel plowing[d], 5.8 km h^{-1} (3.6 mi h^{-1})	3	69/221	10/32	11.3	1.21	11.9	1.28
	3	138/221	20/32	10.8	1.16	11.9	1.28
LSD $_{\alpha=0.05}$, P = 0.43[b]				NS[c]	NS[c]		
Disking, 7.6 km h^{-1} (4.7 mi h^{-1})	4	69/221	10/32	2.7	0.29	6.5	0.69
	4	97/221	14/32	2.5	0.27	6.5	0.69
LSD $_{\alpha=0.05}$, P = 0.84[b]				NS[c]	NS[c]		

[a] Summer, after small grain harvest.

[b] Least significant difference between treatments at a 95% confidence level; probability of no significant difference between treatments.

[c] No significant difference at the 95% confidence level.

[d] Fall, after grain harvest.

Table 10. Observed and empirical fuel use at the Western Iowa Research Farm, with and without mechanical front wheel drive.

Operation	No. of Replications	MFD[a]	Fuel Use Observed (L ha^{-1})	Fuel Use Observed (gal acre^{-1})	Fuel Use Empirical (L ha^{-1})	Fuel Use Empirical (gal acre^{-1})
Planting (2014), 8.3 km h^{-1} (5.2 mi h^{-1})	8	Disengaged	5.2	0.55	3.5	0.37
	8	Engaged	4.8	0.52	3.4	0.36
LSD $_{\alpha=0.05}$, P = 0.01[b]			0.3	0.03		
Planting (2015), 8.3 km h^{-1} (5.2 mi h^{-1})	8	Disengaged	5.2	0.56	3.5	0.37
	8	Engaged	4.8	0.52	3.4	0.36
LSD $_{\alpha=0.05}$, P = 0.01[b]			0.3	0.03		
Grain drill, 8.3 km h^{-1} (5.2 mi h^{-1})	8	Disengaged	4.5	0.49	4.3	0.46
	8	Engaged	4.3	0.46	4.2	0.45
LSD $_{\alpha=0.05}$, P = 0.23[b]			NS[c]	NS[c]		
Hauling bales[d], 8.0 km h^{-1} (5.0 mi h^{-1})	4	Disengaged	0.8	0.33	0.9[e]	0.38[e]
	4	Engaged	0.7	0.29	0.8[e]	0.33[e]
LSD $_{\alpha=0.05}$, P = 0.01[b]			0.1	0.02		
Rotary mowing, 6.9 km h^{-1} (4.3 mi h^{-1})	4	Disengaged	7.3	0.78	4.6	0.49
	4	Engaged	5.5	0.59	4.6	0.49
LSD $_{\alpha=0.05}$, P = 0.03[b]	4		1.4	0.15		
Spread manure, 6.9 km h^{-1} (4.3 mi h^{-1})	4	Disengaged	5.6	0.60	4.1	0.44
	4	Engaged	4.9	0.52	4.1	0.44
LSD $_{\alpha=0.05}$, P = 0.02[b]			0.5	0.06		

[a] Mechanical front wheel drive.

[b] Least significant difference between treatments at a 95% confidence level; probability of no significant difference between treatments.

[c] No significant difference at the 95% confidence level.

[d] Fuel use, L km^{-1} or gal mi^{-1}.

[e] Draft used for roller packer.

Table 11. Observed and empirical fuel use at the Northwest Research Farm in 2014 during field cultivation using dual wheels, varying depth, and travel speed.

Operation	No. of Replications	Treatment Wheels	Travel Speed (km h^{-1})	Travel Speed (mi h^{-1})	Depth (cm)	Depth (in.)	Fuel Use Observed (L ha^{-1})	Fuel Use Observed (gal acre^{-1})	Fuel Use Empirical (L ha^{-1})	Fuel Use Empirical (gal acre^{-1})
Field cultivation	6	Dual	7.7	4.8	13	5	7.8	0.83	4.9	0.52
	6	Dual	7.7	4.8	13[a]	5[a]	6.7	0.71	4.9	0.52
	5	Dual	8.2	5.1	13	5	6.2	0.66	4.8	0.52
	5	Single	8.2	5.1	13	5	6.9	0.74	4.8	0.52
	6	Dual	7.7	4.8	8	3	5.9	0.63	3.6	0.38
LSD $_{\alpha=0.05}$, P = 0.05[b]							1.4	0.15		

[a] Loose soil in second pass; other field cultivation operations were secondary tillage, but first pass on firm ground.

[b] Least significant difference between treatments at a 95% confidence level; probability of no significant difference between treatments.

Table 12. Observed and empirical fuel use at the Northwest Research Farm in 2014 during planting using dual wheels, varying gear/throttle operation, and travel speed.

Operation	No. of Replications	Treatment Wheels	Gear/Engine (rpm)	Travel Speed (km h^{-1})	Travel Speed (mi h^{-1})	Fuel Use Observed (L ha^{-1})	Fuel Use Observed (gal acre^{-1})	Fuel Use Empirical (L ha^{-1})	Fuel Use Empirical (gal acre^{-1})
Planting	5	Dual	5/2100	8.0	5.0	2.3	0.24	2.1	0.23
	4	Dual	5/2400	9.3	5.8	2.3	0.24	2.2	0.23
	4	Single	5/2100	8.0	5.0	2.4	0.25	2.1	0.23
	4	Dual	6/1675	9.7	6.0	1.8	0.19	1.7	0.18
	5[a]	Single	6/1675	9.7	6.0	1.8	0.19	1.7	0.18
	4[a]	Single	6/1900	11.3	7.0	1.8	0.20	1.7	0.18
	4	Single	6/1675	10.0	6.2	1.8	0.20	1.7	0.18
LSD $_{\alpha=0.05}$, P = 0.001[b]						0.3	0.03		

[a] Soil previously field cultivated at 8 cm (3 in.) depth; other treatments were previously field cultivated at 13 cm (5 in.) depth.

[b] Least significant difference between treatments at a 95% confidence level; probability of no significant difference between treatments.

fuel saving strategies are known and employed by tractor operators. Comparing tillage fuel consumption values with those reported by McLaughlin et al. (2008), fuel use was greater for moldboard plowing, and at most sites lower for chisel plowing and disking.

CROP DRYING

Conditions and energy used during crop drying are shown in tables 15-18. Several factors involved in the drying process limit the ability to make direct comparisons between locations, individual bins at the locations, and even drying batches in the same bin. Factors that affect drying include different incoming corn moisture, different corn moisture at the end of drying, different ambient air conditions during drying, and different loading rates resulting in different depths of corn that fans had to push air through. Although direct comparisons are not possible, relative measurements can be useful to assess what may have affected energy consumption during drying.

Energy used to remove water from grain ranged from 4.67 to 7.70 MJ kg^{-1} (2010 to 3310 Btu lb^{-1}). Morey et al. (1978) reported that 5.7 MJ kg^{-1} was required when corn was dried from 22% m.c. Most energy used was from propane (96% average) rather than electricity in these high-temperature drying systems. Energy consumption averaged 0.0027 L pt^{-1} kg^{-1} (0.018 gal pt^{-1} bu^{-1}) for propane and 0.00087 kWh

Table 13. Number of treatment comparisons showing expected trend and statistical significance, percentage difference in observed fuel use, and average difference of ASABE predicted values from observed values.

Treatment Comparison	No. of Comparisons Total	Trend[a]	Statistical Significance[b]	Percentage Difference of Observed Fuel Use Average (%)	Greatest (%)	Least (%)	Average Percentage Difference of ASABE Predicted Value (%)
Gear/engine speed	19	18	8	25.2	51	-12	-11
Travel speed	11	9	6	16.7	59	-21	3
Tillage depth	5	5	3	27.6	41	7	25
Tire inflation	5	3	1	-1.4	2	-8	31
Front wheel assist	6	6	5	13.4	31	5	-17
Dual vs. Single tires	2	2	0	7.9	12	4	-17

[a] Expected trend observed.

[b] Statistically significant at the 95% confidence level.

Table 14. Observed fuel use on university farms by field operation.

Operation	No. of Means[a]	Average (L ha^{-1})	Average (gal acre^{-1})	Least[b] (L ha^{-1})	Least[b] (gal acre^{-1})	Greatest[c] (L ha^{-1})	Greatest[c] (gal acre^{-1})
Chisel plow	18	11.0	1.18	6.5	0.69	15.1	1.61
Plant	20	4.0	0.43	1.8	0.19	5.4	0.58
Field cultivate	18	5.9	0.63	2.8	0.30	7.8	0.83
Disk	18	4.9	0.52	2.1	0.23	9.1	0.97
Moldboard plow	8	33.9	3.63	26.2	2.80	45.3	4.84
Grain drill	4	4.4	0.47	3.7	0.39	5.2	0.56
Rotary mower	4	6.4	0.68	5.5	0.59	7.3	0.78
Subsoiler	2	10.9	1.17	10.0	1.07	11.9	1.27
Strip till	2	16.3	1.75	13.0	1.39	19.6	2.10
Stalk chopper	2	7.5	0.80	6.0	0.64	8.9	0.95
Spread manure	2	1.3	0.56	1.2	0.52	1.4	0.60
Move bales[d]	2	0.7	0.31	0.7	0.29	0.8	0.33
Haul corn[d]	2	0.4	0.19	0.4	0.17	0.5	0.21

[a] Number of treatment means used to calculate average.

[b] Least treatment mean for field operation.

[c] Greatest treatment mean for field operation.

[d] Fuel use L km^{-1} or gal mi^{-1}.

Table 15. Conditions during corn in-bin drying at Iowa State University farms during fall 2013.

Location	Drying Principle	Corn Dried (Mg)	Corn Dried (Wet bu)[a]	Drying Air Temperature (°C)	Drying Air Temperature (°F)	Date Beginning	Date Ending	Outside Air Temperature[b] (°C)	Outside Air Temperature[b] (°F)
Ag 450 west	Stirred batch	232.4	9150	43	110	24-Oct	28-Oct	4.5	40.1
Ag 450 west	Stirred batch	228.6	9000	43	110	3-Nov	12-Nov	3.3	38.0
Ag 450 east	Stirred batch	182.9	7200	43	110	4-Nov	12-Nov	3.0	37.4
Northeast east	Stirred batch	172.5	6790	54	130	15-Oct	24-Oct	2.6	36.7
Northeast east	Stirred batch	182.6	7190	54	130	29-Oct	8-Nov	5.7	42.2
Northeast west	Stirred batch	202.7	7980	54	130	6-Nov	13-Nov	0.2	32.3
Southwest	Counterflow batch[c]	61.7	2430	82	180	21-Oct	21-Oct	6.4	43.6
Southwest	Counterflow batch[c]	62.7	2470	60	140	22-Oct	22-Oct	5.5	41.9
Southwest	Continuous flow[d]	55.6	2190	60	140	24-Oct	24-Oct	4.9	40.9
Southwest	Continuous flow[d]	48.3	1900	82	180	25-Oct	25-Oct	7.0	44.6

[a] 56 lb units or wet ‘bushels.’

[b] Average air temperature during drying period.

[c] Counterflow recirculating batch.

[d] Counterflow continuous flow

$\text{pt}^{-1}\ \text{kg}^{-1}$ ($0.022\ \text{kWh pt}^{-1}\ \text{bu}^{-1}$) across all high-temperature drying tests (tables 16 and 18). These values are near the mid-point of the ranges estimated by Wilcke and Bern (1985). Electrical energy used for natural-air drying in 2014 was slightly below the range estimated by Wilcke and Bern (1985). Energy consumption for high-capacity commercial dryers using natural gas is often estimated at lower levels although reported measurements are scarce.

Because propane energy use predominates during high-temperature drying, a useful measure for dryer operators in the United States is the amount of propane used per thousand bushels of corn dried. Results from the high-temperature drying tests (fig. 2) show a strong relationship ($R^2 = 0.92$) between propane use and initial corn moisture content, with each additional moisture point requiring approximately 16.2 gal (61 L) propane per thousand bushels (i.e., 56,000 lb incoming corn).

Energy use was more highly correlated with ambient air temperature ($R^2 = 0.32$), than with drying air temperature, initial and final moisture content, and bushels dried (all $R^2 < 0.2$). Energy use per mass of water removed versus average outside air temperature during drying is shown by individual drying batches for each of the three drying locations in figure 3. Greater ambient air temperature as air is pre-heated would be expected to improve drying efficiency unless relative humidity also correspondingly increases. Energy use values at or below about $5.8\ \text{MJ kg}^{-1}$ ($2500\ \text{Btu lb}^{-1}$) generally occurred when ambient air temperatures were 10°C (50°F) or greater, or with the drying system at the Southwest Farm. Energy use seemed to decrease with higher air temperature more

Table 16. Energy used for corn in-bin drying at Iowa State University farms during fall 2013.

		Corn Dried		Moisture Content (%)		Energy per Water Removed		Propane Use		Electricity Use	
Location	Drying Principle	(Mg)	(Wet bu)[a]	Beginning	Ending	(MJ kg^{-1})	(Btu lb^{-1})	(L pt^{-1} kg^{-1})	(gal pt^{-1} bu^{-1})	(kWh pt^{-1} kg^{-1})	(kWh pt^{-1} bu^{-1})
Ag 450 west	Stirred batch	232.4	9150	17.1	13.4	6.58	2830	0.0028	0.019	0.00071	0.018
Ag 450 west	Stirred batch	228.6	9000	19.0	14.8	7.56	3250	0.0033	0.022	0.00154	0.039
Ag 450 east	Stirred batch	182.9	7200	18.0	14.2	7.70	3310	0.0033	0.022	0.00205	0.052
Northeast east	Stirred batch	172.5	6790	23.6	15.0	6.51	2800	0.0028	0.019	0.00094	0.024
Northeast east	Stirred batch	182.6	7190	23.5	14.8	5.77	2480	0.0025	0.017	0.00083	0.021
Northeast west	Stirred batch	202.7	7980	25.4	14.8	6.77	2910	0.0030	0.020	0.00071	0.018
Southwest	Counterflow batch[b]	61.7	2430	20.2	14.5	5.81	2500	0.0027	0.018	0.00047	0.012
Southwest	Counterflow batch[b]	62.7	2470	18.6	14.8	5.70	2450	0.0025	0.017	0.00059	0.015
Southwest	Continuous flow[c]	55.6	2190	18.9	14.6	4.67	2010	0.0022	0.015	0.00051	0.013
Southwest	Continuous flow[c]	48.3	1900	17.2	14.4	5.91	2540	0.0028	0.019	0.00079	0.020

[a] 56 lb units or wet 'bushels.'

[b] Counterflow recirculating batch.

[c] Counterflow continuous flow.

Table 17. Conditions during corn in-bin drying at Iowa State University farms during fall 2014.

		Corn Dried		Drying Air Temperature		Date		Outside Air Temperature[b]	
Location	Drying Principle	(Mg)	(Wet bu)[a]	(°C)	(°F)	Beginning	Ending	(°C)	(°F)
Ag 450 west	Stirred batch	208.6	8210	49	120	7-Oct	18-Oct	10.9	51.7
Ag 450 east	Stirred batch	202.9	7986	49	120	9-Oct	18-Oct	10.5	51.0
Northeast east	Stirred batch	149.5	5884	54	130	19-Oct	23-Oct	9.7	49.5
Northeast east	Stirred batch	143.1	5634	54	130	27-Oct	31-Oct	5.9	42.7
Northeast west	Stirred batch	200.3	7886	54	130	2-Nov	5-Nov	6.9	44.5
Southwest	Continuous flow[c]	50.5	1990	60	140	11-Oct	11-Oct	6.3	43.4
Southwest	Counterflow batch[d]	98.6	3883	82	180	15-Oct	15-Oct	10.4	50.8
Southwest	Natural air	190.5	7500			4-Nov	10-Nov	6.9	44.5

[a] 56 lb units or wet 'bushels'.

[b] Average air temperature during drying period.

[c] Counterflow continuous flow.

[d] Counterflow recirculating batch.

Table 18. Energy used for corn in-bin drying at Iowa State University farms during fall 2014.

		Corn Dried		Moisture Content (%)		Energy per Water Removed		Propane Use		Electricity Use	
Location	Drying Principle	(Mg)	(Wet bu)[a]	Beginning	Ending	(MJ kg^{-1})	(Btu lb^{-1})	(L pt^{-1} kg^{-1})	(gal pt^{-1} bu^{-1})	(kWh pt^{-1} kg^{-1})	(kWh pt^{-1} bu^{-1})
Ag 450 west	Stirred batch	208.6	8210	24.1	14.0	5.23	2250	0.0023	0.015	0.00067	0.017
Ag 450 east	Stirred batch	202.9	7986	23.4	13.0	5.36	2310	0.0022	0.015	0.00127	0.032
Northeast east	Stirred batch	149.5	5884	24.4	15.2	5.75	2470	0.0026	0.017	0.00075	0.019
Northeast east	Stirred batch	143.1	5634	22.3	14.5	6.69	2880	0.0029	0.020	0.00089	0.023
Northeast west	Stirred batch	200.3	7886	20.5	14.7	6.88	2960	0.0030	0.020	0.00081	0.021
Southwest	Continuous flow[b]	50.5	1990	21.4	14.9	6.42	2760	0.0028	0.019	0.00077	0.020
Southwest	Counterflow batch[c]	98.6	3883	19.9	14.7	6.01	2590	0.0026	0.018	0.00057	0.015
Southwest	Natural air	190.5	7500	16.5	15.2	3.24	1390	0	0	0.01037	0.263

[a] 56 lb units or wet 'bushels'.

[b] Counterflow continuous flow.

[c] Counterflow recirculating batch.

at the Ag 450 Farm, somewhat at the Northeast Farm, but the impact was not apparent at the Southwest Farm.

At the Ag 450 Farm bins were filled quickly, within about a day. As a strategy to reduce overall energy consumption, the burner was usually turned off at about 16% m.c. and fan-only energy was used to cool grain and remove the last 1 to 1.5 percentage points of moisture. This resulted in higher kWh pt^{-1} bu^{-1} values for electrical use than estimated by Wilcke and Bern (1985) in some cases, but avoided propane consumption during the final drying stage. Some commercial dryers also use unheated air to finish drying.

At the Northeast Farm, it took three to six days to completely fill each bin during plot harvest. Corn was initially dried in a shallower layer, allowing the fan to not work against as much static air pressure. In this layer drying technique, additional corn was added as drying progressed. In 2013, initial corn moisture content was higher at the Northeast Farm.

At the Southwest Farm, incoming grain moisture content was generally drier than the other two locations. Corn depth during drying was held to only about 1.2 m (4 ft) during most recirculating-batch- and continuous-flow modes [except last recirculating-batch mode in 2014 was about 2.1 m (7 ft)]. Recirculating-batch- or continuous-flow drying was completed in one day during daylight hours for these shallow-layer dryings. Airflow was in a counterflow mode with wet grain meeting high-temperature air near the bin floor rather than the whole mass of grain inside the bin drying as one as with stirred batches. This type of counterflow bin dryer is more commonly used in a continuous-flow mode.

SWINE HOUSING

Table 19 provides the overall data summary for electrical usage. Data were collected continuously, including periods that pigs were not present in the building. Production facili-

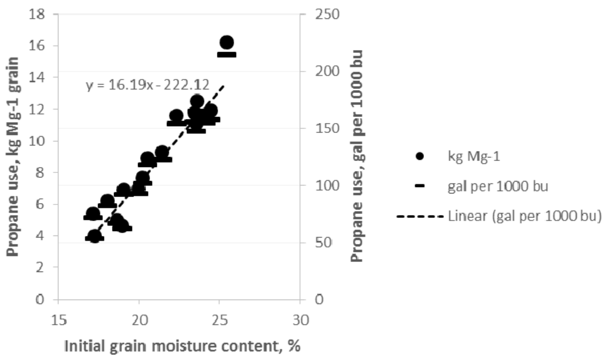

Figure 2. Propane use per 1000 bu vs. initial corn moisture content.

ties normally have a period between pig groups when no animals are present in order to facilitate sanitation. This time period ranges from a few days to a week or more; no adjustment was made for these periods. Calculations for energy per pig space was based on the nominal room size.

Table 19. Electrical energy used for fan ventilation for 300 head rooms within a curtain-sided finisher, ISU Ag 450 farm collected December 2012 to December 2104.

	East Room			West Room		
	Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3
Duty cycle	93.0%	15.8%	0.4%	97.2%	11.5%	0.54%
Avg. amps	1.55	2.12	2.36	1.55	2.45	1.66
kWh yr^{-1} [a]	2689	603	18	2824	510	15
kWh yr^{-1} pig space^{-1}	9.0	2.0	0.06	9.4	1.7	0.05
% of total kwh	81%	18%	1%	84%	15%	0.5%
Total fan	11.0 kWh yr^{-1} pig space^{-1}			11.2 kWh yr^{-1} pig space^{-1}		

[a] kWh yr^{-1} is calculated assuming 220 V and the measured power factor for each fan, 0.97 for stage 1 and 0.935 for stages 2 and 3.

In table 19, duty cycle refers to the percentage of hours monitored which any particular fan stage was operating. In the Ag 450 facility the minimum ventilation fans typically operated even when the sidewall ventilation curtain was open. Therefore, in this situation the only time stage 1 fans did not operate was between groups of pigs when the building stood empty or during a malfunction. Stage 2 operated less than 20% while stage 3 operated less than one percent of the time. The low percentage for stage three may have been, in part, due to fan malfunctions. The total consumption per year for each fan was divided by the animal capacity of each room to obtain energy usage per pig-space by fan stage. This illustrates that energy efficiency rating in selection of minimum ventilation fans, which are generally the smallest and least efficient fans in a system, should be an important consideration because of the high duty cycle and high percentage of the energy expelled on the first fan stage. System duty cycles for fan stages will vary by management decisions, fan selection, and building configuration. For instance, in a tunnel ventilation system minimum ventilation fans would play a lessor role in the overall energy usage because of the larger number of high capacity fans for summer weather. It should be noted that stage 3 in the west room required less amperage than the stage 3 fan in the east room. This could be because a replacement motor may have been installed on one of the fans or some other malfunction. Overall, the rooms tended to have similar electrical consumption for fan ventilation, 11.0 and 11.2 kWh yr^{-1} pig space^{-1}.

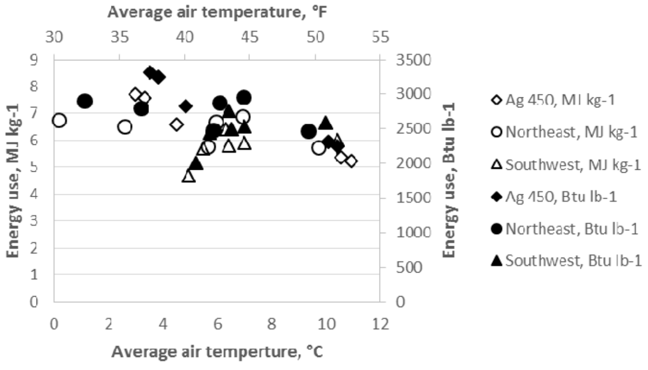

Figure 3. Drying energy used per pound of water removed vs. average ambient air temperature during drying.

Propane usage was measured in each of the four finishing rooms. However, the heater malfunctions were frequent and the farm staff opened doors between rooms to heat the room without a functioning heater. The building as a whole, between 23 September 2013 and 1 June 2015, used a total of 40,818 L (10,783 gal) of propane. This is equivalent to 17 L of propane pig space^{-1} yr^{-1} (4.5 gal pig-space^{-1} yr^{-1}). The usage in this finishing facility was higher than most farmers raising pigs in a wean-to-finish use as a goal which is typically 7.6 L propane pig space^{-1} yr^{-1} (2 gal pig space^{-1} yr^{-1}; Mike Brumm, University of Nebraska, personal communication, 2014). This was likely due to the leaky nature of the building and relatively poor management of ventilation curtains.

Data received from outside sources was compiled and is presented in table 20. As expected, electrical cost was greater for all tunnel-ventilated barns (average of 29.0 kWh pig space^{-1} yr^{-1}) versus hybrid barns that use mechanical ventilation for cold weather and transition to natural ventilation sidewall curtains during warmer weather (average of 20.9 kWh pig space^{-1} yr^{-1}), independent of animal size. It was also expected that those farms which have wean-to-finish facilities starting with 6 kg (13 lb) pigs have much higher propane usage (10.6 L or 2.8 gal pig-space^{-1} yr^{-1}) than do those that are purely finishing pigs, which start pigs at 20 to 30 kg (44 to 66 lb) (2.5 L or 0.67 gal pig space^{-1} yr^{-1}). It should also be noted that the values vary considerably within each type of building as well as between building types. Several factors could contribute to this variation. The time of year in which the buildings are stocked can influence the energy usage. Small pigs placed in winter will increase the propane usage while having large pigs in August may add to the electrical usage due to increased need for cooling. Management such as controller settlings, maintenance and building leakage can all impact these figures as well.

The ISU Ag 450 farm averaged 11.1 kWh pig space^{-1} yr^{-1} for finishing while the survey data for hybrid finishing buildings averaged 22.6 kWh pig space^{-1} yr^{-1}. Likewise the ISU Ag 450 farm averaged 17 L propane pig space^{-1} (4.5 gal pig space^{-1} yr^{-1}) while the survey data for hybrid finishing buildings averaged 2.5 L propane pig space^{-1} yr^{-1} (0.67 gal pig space^{-1} yr^{-1}). This illustrates the wide variations that can occur in energy usage due to system design, building construction, weather conditions, incoming pig size, and operational management. While it is difficult to draw a defensible conclusion

Table 20. Propane and electrical usage on various swine finishing farms.

Description	Electrical Usage yr^{-1} (kWh pig space^{-1})	Electrical Usage yr^{-1} (Years of Data)	Propane Usage yr^{-1} (L pig space^{-1})	Propane Usage yr^{-1} (gal pig space^{-1})	Propane Usage yr^{-1} (Years of Data)
Hybrid- fans with side-wall ventilation curtains, Finishing					
2-1000 head	22.3	3.0	2.5	0.67	5.0
1-2400 head	19.0	1.0			
1-1200 head	22.1	1.0			
2-1000 head	26.8	1.0			
Average	*22.6*		*2.5*	*0.67*	
Tunnel ventilation, Finishing					
2-1200 head	30.7	1.0			
2-1200 head	26.5	1.0			
Average	*28.6*				
Hybrid-fans with side-wall ventilation curtains, wean-to-finish					
1-2400 head	14.3	1.0			
Tunnel ventilation with electric brooders, wean-to-finish					
2-2400 head	24.3	1.0			
Tunnel ventilation with gas brooders, wean-to-finish					
2-1200 head	27.9	2.9	11.7	3.1	0.7
2-1200 head	31.6	2.9	12.5	3.3	0.8
2-1200 head	35.1	1.6	9.5	2.5	1.0
2-1200 head	28.6	2.4	10.6	2.8	0.9
2-1200 head	27.5	0.8	8.3	2.2	1.0
Average	*30.1*		*10.6*	*2.8*	

as to the cause of differences, these may illustrate philosophical management differences in controller setup. The ISU Ag 450 farm management team wanted to use ventilation curtains starting at colder ambient temperatures than is typical. While this may have saved electricity, it tended to use more propane. At times it was observed that ventilation curtains were open while heaters were operating. This may not explain the differences, but indicates that possible variability which can occur.

CONCLUSIONS

Within the range of conditions measured on university farms, the data support the following conclusions.

Fuel saving using different techniques was demonstrated during field operations in 43 of 48 treatment comparisons (23 statistically significant). Fuel-saving strategies were generally well demonstrated for reducing tillage depth, shifting up, and throttling back during reduced drawbar loads, and making use of front-wheel-drive (average increased fuel use of 28%, 25%, and 13%, respectively, if fuel saving strategy was not used). Fuel savings were also demonstrated at lower travel speeds (fuel use increased an average of 17% at higher speeds) but results were more mixed as engine speed and torque characteristics matched to loads. Fuel use increased 8% when single tires were used rather than duals in two comparisons. Fuel-saving results were marginal (often within the range of measurement accuracy) and least apparent when comparing tire inflation. Fuel use values calculated using procedures from ASABE standards were generally greater than observed values for tillage depth, travel speed, and tire inflation comparisons, but lower than observed values for gear/engine speed, front-wheel-assist, and dual vs. single tire comparisons.

Energy used per mass of water removed during high-temperature drying ranged from 4.67 to 7.70 MJ kg^{-1} (2010 to 3310 Btu lb^{-1}). Propane use accounted for 96% of energy consumption during high-temperature drying and averaged 0.0027 L kg^{-1} (0.018 gal bu^{-1}) per percentage point of moisture removed. Conditions such as initial corn moisture content and average ambient air temperature during each drying treatment differed. Drying during periods with greater ambient air temperature tended to use less energy, as did the drying system on the Southwest Research Farm.

Minimum ventilation fans had the highest duty cycle (>93%) and the highest energy consumption of all the fan stages in a hybrid, sidewall curtain ventilated finishing barn indicating that selection of energy efficient stage 1 fans is an important consideration. Approximately 11 kWh pig space^{-1} yr^{-1} was used for fan ventilation in this facility. Tunnel ventilated barns tend to use more electricity than do hybrid curtain-sided barns (29.0 vs. 20.9 kWh pig space^{-1} yr^{-1}). Wean-to-finish barns tended to use more propane than do finishing barns (10.6 L vs. 2.5 L pig space^{-1} yr^{-1}, 2.8 gal vs. 0.67 gal pig space^{-1} yr^{-1}). Management, maintenance, and controller settings tend to cause variation in energy usage.

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