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Evaluating Center Pivot Distribution Uniformity from Catch Can Tests

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Abstract. *Center pivot irrigation is an important irrigation method in Missouri. However, only about half of the pivots in MO are the "typical", full-circle seven-span pivots. The other half are either partial circles and/or have shorter or longer span lengths. Both items significantly impact the economics of pivot irrigation; however, while the percent of circle being irrigated affects unit area costs it does not affect uniformity.*

System evaluations were performed on 60 center pivots in MO. End guns irrigated an average of 16.8% of the area irrigated with pivots. The application rate under the end gun was, on average, 0.83 of the span, but in many instances was more (as much as double).

An alternative procedure for describing uniformity was compared to the standard method. Since the catch can spacing was only 3 m (10 feet) it was reasoned that the adjacent down- and up-stream catch affected the crop around any particular catch can. As normally calculated, the state average CU was 79.6%; using the 3-can averaging method (CU_{adj}) uniformity values increased to 83.8%. The CU value was only improved 1 % by excluding the end gun catches in the calculations.

Keywords. Center pivots, distribution uniformity, system evaluations, Missouri

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Introduction

Center pivot irrigation accounts for approximately 40% of the 0.5 to 0.6 million irrigated hectares (1.3 to 1.5 million acres) within the state of Missouri (USDA/NASS, 2004). There are an estimated 4,000 center pivots in Missouri. By crop type, pivot is the irrigation method for 80% of the irrigated corn, 40% of irrigated soybeans, 60% of irrigated cotton, 90% of irrigated potatoes, and 20% of the irrigated sorghum.

There are four main regions of irrigation in Missouri. The largest one is the Southeast Missouri (SEMO) region, often referred to as the *Bootheel*; the nine counties that make up SEMO have 80% of the state's irrigation. The other regions are near Mexico, MO (CentMO), Lamar, MO (SWMO), and Mound City, MO (NWMO). While SEMO has significant areas of both flood and pivot irrigation, the other three regions are predominantly pivot-irrigated. Table 1 shows irrigated pivot acreage in the four major irrigated areas of Missouri (Henggeler, 2000).

Table 1. Center pivot irrigation by regions in Missouri

Region	SEMO	CentMO	SWMO	NWMO
Total Irrigated Area (hectares [acres])	461,350 (1,140,000)	13,000 (32,000)	18200 (45,000)	18200 (45,000)
% Irrigated Land that is Pivot Irrigated	42.0%	88.7	73.0	100.0%
% of Pivots that are Fixed	30.6%	63.7%	68.8%	100.0%
% of Pivots that are Towable	11.4%	25.0%	4.2%	0.0%

a) Evaluating Center Pivot Performance

Poor distribution in center pivots can lead to leaching of agricultural chemicals into the groundwater, especially in light of the fact that many Missouri pivots are located on sandy soils, which are porous and have small water-holding capacities. In addition, pivots are frequently used on highly fertilized crops, like potatoes and corn.

Farmers whose pivot was shown to have serious distribution issues could re-nozzle their problem pivot. An incentive to re-nozzling was that in most instances inlet pressure could be reduced in the re-nozzling process, thus saving the farmer money. Fuel prices rose dramatically in 2004, which in turn increased the level of interest by farmers to re-nozzle. Federal EQIP program funds were also available in many counties in Missouri for cost-sharing the pivot re-nozzling expense at rates shown in Table 2.

Table 2. Re-Nozzling cost-sharing incentives per unit length of lateral

Item	Cost
Just nozzles	\$5.91/m (\$1.80/ft)
Nozzles & drops	\$9.68/m (\$2.95/ft)
Nozzles, drops, & pressure regulators.	\$13.22/m (\$4.03/ft)

Proper irrigation uniformity on center pivots is important since it has both economic and environmental implications. Harrison and Perry (2007) separated pivot Christiansen Uniformity (CU) values as *excellent*: > 90%, *good*: 85 to 90%, *fair*: 80 to 85%, and *poor*: < 80%. Furthermore, the USDA-NRCS established that chemigation should only be used on pivots having CU values >85% (USDA/NRCS, 2003).

ASABE Standard S436.1 (ASABE, 2007) calls for double rows of catch cans and distances between cans being no greater than 3 m for sprays and 5 m for impacts, based on the work of Ring and Heerman (1978). In practice, placing, retrieving, and measuring double rows of collectors for the pivot lengths common in Missouri is impractical. In their manual on irrigation system evaluation Merriam and Keller (1978) call for a single row of cans spaced no more than 9 m (30 ft) apart, but preferably at 4.6 to 6 m (15 to 20 ft).

New Pivot Testing Protocols. ASABE Standard S436.1 (ASABE, 2007) recommends that the test be done with the end gun either on or off, depending on how the pivot sprinkler package was designed. The standard and NRCS Code 442 (USDA/NRCS, 2003) appear to downplay end gun results, even though improvements to overall system performance can often be done at a small cost with simple modification to the endgun. Indeed, end guns are problematic to pivot testing for a variety of reasons. Depending on the location of the end tower, the end gun may be in the on or off mode not corresponding to package design. Also, the rotating action of the end gun creates distribution problems that single rows of catch cans might miss, especially when the pivot speed is set to a high rate.

When end guns are on at locations where watering of roadways take place, it suggests to passing travelers that water is not being appropriately used (even when relatively insignificant amounts of water are involved) and, in some states, is illegal. In these cases the whole irrigation industry can be affected. With industry recognizing the fact that (1) end guns can be controversial, (2) their normal distribution often times is non-stellar, (3) they irrigate a relatively small portion of the field, and (4) in arid climates they have large amounts of evaporation and drift loss, there may be a desire by all to perform evaluations ignoring the end gun data. However, including data on the end gun can alert users on the need to make adjustments.

The catch from individual cans is used to calculate hydraulic uniformity indices of the pivot. However, root extension and capillary movement of soil moisture can expand, to some degree, the area influenced by any given wetted point. If catch cans are not too far apart then it is reasonable that neighboring up- and down-stream catch amounts will have bearing on the portion of the crop that a can is assumed to influence. Several authors (e.g., Lia and Kawano [1996]; Mecham [2001]; Dukes et al. [2006]; and Vis et al. [2007]) have compared areal soil moisture distribution to sprinkler discharge uniformity. The soil moisture distribution is generally

better than the sprinkler distribution. Seginer (1979) used harmonic analysis to obtain the effective uniformity coefficients stemming from root systems which explained why hydraulic uniformity falls short of areal uniformity.

Uniformity tests on trickle irrigation systems already use the concept of catch averaging to provide a better description of actual system uniformity (Merriam and Keller, 1978).

In light of this, a three-can method can be used to describe an adjusted uniformity (CU_{adj}) that better reflects the impact of uniformity on a crop. Such a procedure would smooth out any anomalies of either very low or very high catches in the hydraulic data set and more closely relate to final soil moisture profiles after amelioration actions have taken place. Additionally, this procedure would be able to mitigate some of the problems associated with having just a single row of catch collectors, rather than the Standard's recommended two rows. The up- and down-stream catch amounts can be averaged evenly with the center can, or can be weighted such that the center catch is relegated more influence than up- and down-stream catches.

Aerial images of farm fields are readily available from websites like Google Earth (Google, Inc., Mountain View, CA)¹ or aerial flybys. Observing an image of the farm may help identify uniformity problems since the radial nature of the area covered by sprinklers with uniformity problems shows up as rings, not to be confused with problems stemming from other factors. Figure 1 shows a Google Earth view of a Missouri pivot exhibiting uniformity problems, in this case at the transition from lateral to end gun areas.



Figure 1. Aerial view from Google Earth showing a SEMO pivot exhibiting distribution problems.

¹ Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the University of Missouri or the U.S. Department of Agriculture.

b) Configuration of Pivots in Missouri

Pivot Investment Costs. A “typical” center pivot might be described as being ≈400 m (≈1300 ft) long and irrigating a full circle. If economic estimates for pivot irrigation are based on this typical configuration, then deviations from length (either shorter or longer) as well as deviations from a full 360° sweep can cause significant changes to pivot economics. Thus, there was a need to obtain a snapshot of how an “average” Missouri pivot is configured and determine corresponding economic factors. Resources, such as Scherer (2005) and Burt et al. (2000) indicate that the per-acre cost of center pivots is \$667-\$1,312/ha (\$270 -\$400/acre). However, using these broad, generic cost estimates may lead to poor investment analysis for pivots configured in non-traditional ways.

Making Pivot Irrigation More Profitable. Pertinent information, some of which is often overlooked, can be readily gathered during pivot tests that will afford basis to provide sound agronomic and economic suggestions for owners. Data on pivot age and information from the hour totalizer gage (on pivot or power unit) can be used to determine if over- or under-irrigation is occurring relative to regional requirements. Information on operating pressure can be used to develop re-nozzling recommendations. Pooling information on application efficiency can help provide overviews on efficiency by categories (e.g., type of nozzle, drops versus non-drops, etc.).

Increasing an irrigator’s financial situation is generally thought of as an economic impact. However, financial well being of the irrigator can become an environmental issue since “strapped” farmers may forego investments in adapting conservation BMPs such as correcting poor uniformities, using border strips, etc. This phenomenon of decreasing the amount of degradation of natural resources as economic situations rise is recognized as the Environmental Kuznets Curve (Richmond and Zencey, 2007). Thus, as pivot-testing takes place individuals can improve their bottom line from pivot-specific recommendations, and collectively pivot irrigation becomes more profitable as it capitalizes on the generalized information gathered from regional testing programs.

This purpose of this paper is to discuss two issues involving pivot irrigation in Missouri:

- The results from pivot distribution uniformity tests conducted in Missouri, including the use of new testing protocols that might enhance the information derived from these tests.
- Configuration of the “typical” pivot in Missouri from using aerial reconnaissance.

Methods and Materials

a) Pivot Evaluations in Missouri

In 2003-2006 a pivot-testing program was conducted in Missouri. The testing program was developed by the University of Missouri and funded by the Missouri Department of Natural Resources using water quality education funds from the 319 Nonpoint Source Management program. The testing program was initiated to gather information on distribution uniformity of Missouri’s pivots.

The pivots were evaluated by placing a single line of catch cans at generally 3-m (10-ft) intervals, out from the pivot point. The first can was placed at 30 m (100 ft) and then 3 m (10 ft) from the preceding one thereafter. Since the can's number is readily tied back to its distance from the pivot point, there was no need to separately measure distance to towers, thus speeding up the testing process. When time allowed, three or four rows of cans were placed in the area wetted by the end gun.

A single row of cans was used during the testing program instead of the Standard's recommendation of two lines since the size of some of the fields coupled with the small distance between cans (3 m [10 ft]) meant large numbers of cans were already employed with just a single row (Figure 2). Transporting and installing 200 to 300 catch cans plus stakes, especially when a crop was present, offered enough of a logistics problem without doubling number of cans. Many farmers did not wish to start up their pivots prior to the crop needing irrigation for the first time since their bills included monthly stand-by charges. Thus, in most cases fields had crops on them when the tests were done. Catch cans had a rim diameter of 9.2 cm and were 15 cm in height. Readings were taken within two hours after the pivot passed over them.



Figure 2. Technicians hold the large number of catch cans (telescoped into each other) that were used to run a single row of catch cans.

The pivot system was allowed to irrigate across the line of cans, after which technicians measured the amount of water collected in each can. Values from all cans were recorded in ml, rounded to the closest 5 ml, and later converted to depth. The wetted distance was determined by the last can with an appreciable amount of water. CU calculations were made using only cans within the wetted diameter. If a crop was present, bamboo stakes were used to elevate the cans above the canopy. Often times the situation on the ground dictated where/when the test was done. Thus, in rare cases tests were done under situations deviating from standard protocols and those tests were so noted.

Other collected data included pivot speed setting and travel distance of the last tower during a fixed time, the portion of the circle irrigated, the current hours of operation of the pivot and

engine, and the pressure readings at the beginning and end of the pivot. System flowrate during the test was measured using a strap-on, transit time ultrasonic flowmeter, Sono-Tek ST-30 (Engineering Measurements Company, Longmont, CO). The distance to each tower and to the end gun was calculated by noting its position relative to the nearest catch can on the data collection form.

Following the test, satellite images of the tested field were collected and weather data at the time of the test were obtained from the nearest University of Missouri weather station (AgEBB, 2009) to record wind speed and calculate vapor pressure deficit during the test.

Various indices of uniformity and efficiency were calculated from the dataset. System uniformities were broken down and reported as to the whole wetted area, the area beneath only the lateral span, and the area wetted only by the end gun. Average depths by lateral quartile were also calculated and reported. The amount of land irrigated by the end gun was reported in hectares (acres) and as a percent of the total. An end gun to span precipitation ratio was calculated. Economic information regarding re-nozzling (based on inlet pressure & annual hours of operation) was reported.

New Pivot Testing Protocols. The Coefficient of Uniformity (CU) values for the tested pivots were calculated using the standard procedure of Merriam and Keller (1978). However, uniformity values were also calculated by using a 3-can method (Equation 1), assigning equal weight for all three catches. Figure 3 shows an example of using the 3-can method. The ratio of the end gun to lateral span precipitation rates (EG-LS_{ratio}) was also calculated. Values less than 1.0 indicated the average end gun precipitation rate was smaller than the average precipitation rate of the lateral span.

$$C_{3-can} = \frac{C_u + C + C_d}{3} \quad \text{Eq. 1}$$

Where:

C_{3-can} = modified catch amount for can, C, equal weight per catch (in or mm)

C = catch amount at position (in or mm)

C_u = catch amount upstream of C (in or mm)

C_d = catch amount downstream of C (in or mm)

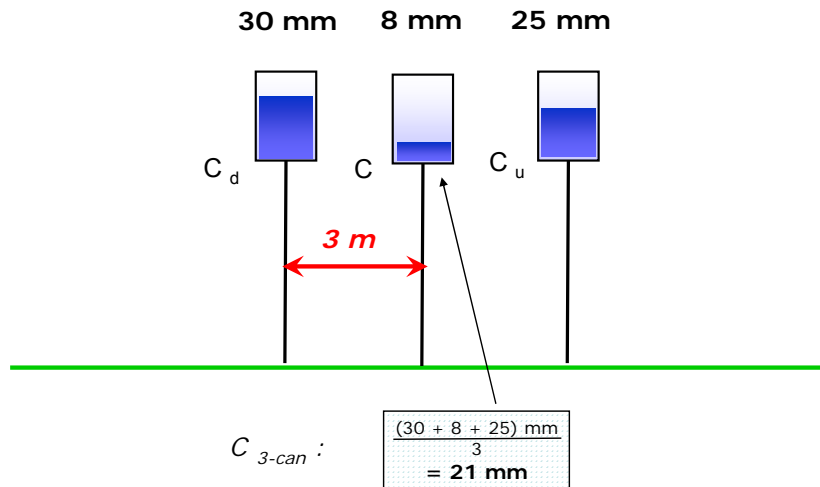


Figure 3. Demonstration of 3-can calculation method.

b) Configuration of Pivots in Missouri

Aerial views from Google Earth at 15,244 m (50,000 feet) above surface level were constructed and analyzed for eight of the counties of the Bootheel. The number of pivots in each county was counted, and their length and the portion of a full 360° circle made were recorded. Area for these pivots was calculated. Also, the initial investment cost and per-hectare (per-acre) investment cost were determined by assuming a pivot pad cost of \$9,000 and a lateral span cost of \$93 per m (\$28 per foot). These values resulted in a typical 400-m (1320-foot) pivot costing \$46,200, close to the reported figure of \$48,000 for such a pivot in SEMO (Reinbott, 2009). The calculated per-acre cost for all the pivots found in the aerial views were rank sorted to determine the average cost per quartile (both by total acres and total numbers). The Farm and Irrigation Report conducted by the National Agricultural Statistics Service (USDA-NASS, 2004) was used to estimate operating pressures for Missouri pivots.

Results and Discussion

a) Pivot Evaluations in Missouri

Table 3 shows the average, high, and low CU and CU_{adj} values for both the single can calibration method and the 3-can calibration method. A second form of CU_{adj} was calculated that weighted up- and down-stream values at half the weight of the actual can, but the results were very similar to the case where all three cans have equal weight, so, the results were not reported.

Table 3. Average, High, and Low Christiansen Uniformity Values, Missouri, 2003-2006.

Number Tested	60	
	CU	CU _{adj}
Average Uniformity	79.6%	83.8%
High Uniformity	91.8%	95.4%
Low Uniformity	48.6%	61.3%

Thirty-seven percent of the tested center pivots in Missouri had a CU value of either *excellent* (>90%) or *good* (85-90%); this amount increases to 52% for CU_{adj}. Table 4 shows the distribution of results.

Table 4. – Percentage of Pivots in Selected Christiansen’s Uniformity Ranges, Missouri, 2000-2003.

CU Score	Rating	Missouri Results	
		CU	CU _{adj}
		----- % in that category -----	
Excellent	> 90%	8	21
Good	85 - 90 %	29	31
Fair	80 - 85 %	22	22
Poor	75 - 80 %	14	14
	70 - 75 %	12	7
	65 - 70 %	3	3
	< 65 %	12	2

The average CU value decreased by only 1.2 % (80.8 versus 79.6%) by leaving out the end gun results. The average percentage of irrigated land covered by the end gun was 16.8 %. The net flow rate on an areal basis was 1.2 l/s/ha (8.0 GPM/acre).

New Pivot Testing Protocols. The 3-can method of calculating uniformity increased the values of CU an additional 4%. The weighting methodology appeared to increase CU more on pivots with low uniformity. The values for the EG-LS_{ratio} ranged from 0.5 to 2.0. Unevenness in water amounts between the span and the end gun can often be easily improved by properly sizing the end gun orifice.

One of the recommendations of S436.1 is that in the locations where the depth caught was “10% higher or lower than the arithmetic average depth (they) should be investigated to determine the cause of variation.” The average number of caught values in a test was 106. We evaluated our database and found out that if we used the 10% variation amount as a guide then

on average of 61 of these 106 locations would need to be reexamined, which is unrealistic. A value of 30% variation from the mean seems more appropriate, in which case only 18 locations would need to be examined. Figure 5 shows the number of locations requiring re-examination based on percent variation trigger used.

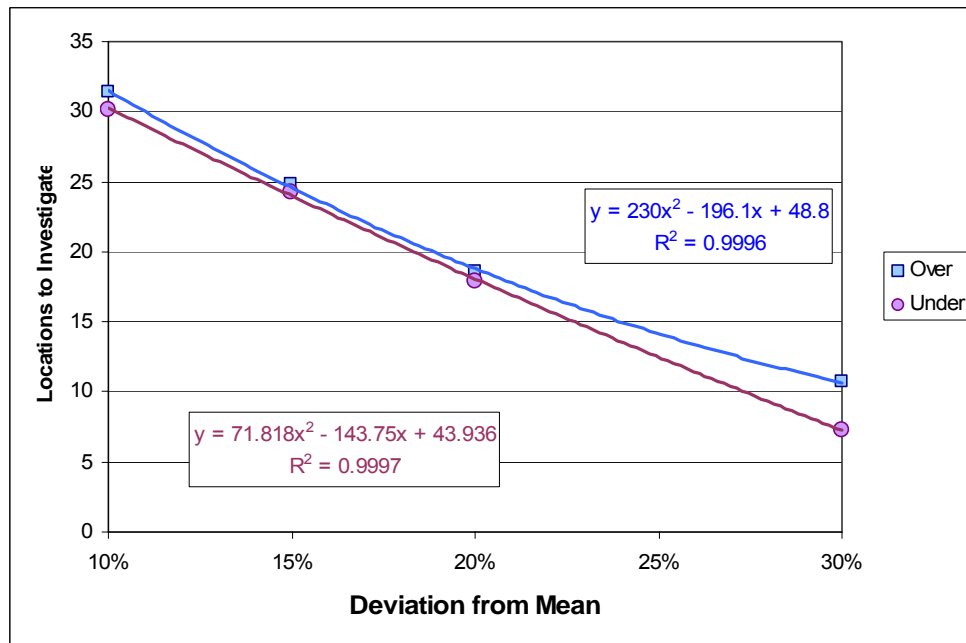


Figure 5. The number of locations that would be required to be investigated based on the value used as the variation trigger. Note that the both the deviations above and below the threshold are shown. Thus, for a threshold of 15% about 50 locations require investigating.

b) Make-up of Missouri Pivots

Operating Pressure. Figure 6 shows the breakdown of Missouri pivots by amount of inlet pressure (USDA/NASS, 2004). Nine percent of pivots in Missouri are high-pressure pivots with inlet pressures > 413 kPa (60 PSI). Re-nozzling could provide significant savings for this group, especially if diesel or propane is the fuel source. The local NRCS reported that over 200 pivots have been re-nozzled in the SEMO area under the EQIP program. The average inlet pressure from the tested pivots was 267 kPa (38.7 psi).

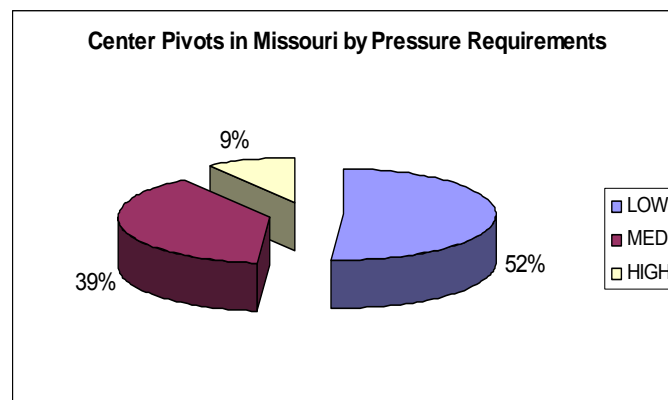


Figure 6. Breakdown of Missouri pivots by inlet pressure requirements.

Table 5 shows the breakeven pressure reductions needed to pay back the investment of re-nozzling with and without EQIP funds (Table 2) for electric, diesel, and propane systems. Analysis of investment cost was based on 400 m (1300 ft) of re-nozzling, 8% interest, and 7 year return. Analysis of energy cost was based on 46 hectares (135 acres), 250 mm (10 inches) applied annually, and fuel costs of \$0.13/kWh, \$0.61/l (\$2.30/gal), and \$0.48/l (\$1.80/gal) for electric, diesel, and propane, respectively.

Table 5. Breakeven Pressure Reduction Needed with and without EQIP Funds

Item	Annualized Investment Cost	w/ EQIP \$			w/out EQIP \$		
		Electric	Diesel	Propane	Electric	Diesel	Propane
		----- kPa -----					
Just nozzles	\$456	21	21	14	48	41	27
Nozzles & drops	\$742	41	34	21	76	62	48
Nozzles, drops, & pressure regulators	\$1,022	55	41	34	103	89	62

Pivot Length and Angles of Irrigation Swept. The aerial evidence showed that only about 48% of the pivots in southeast Missouri (SEMO) are the standard 360° pivot with a length of 400 m (1300 feet) or more. Such a pivot configuration would have a unit area cost of \$909/hectare (\$368/acre).

The average area irrigated by a center pivot in SEMO was about 40 hectares (100 acres). Wetted radii ranged from 145 to 866 m (470 to 2,840 feet). The arc irrigated ranged from 40° to 360°. Table 6 shows the average degrees swept and length of pivots based on breakdown of pivots generically classified as quarter-, half-, three-quarters-, or full-circle types.

Table 6. Average degrees swept and length of pivots in southeast Missouri based on generic quarter-, half-, three-quarters-, and full-circle types.

Item	Pivots Based on Portion of the Circle Swept			
	Quarter circle	Half circle	Three-quarter circle	Full circle
% (by number)	8%	18%	3%	71%
% (by acreage)	2%	10%	2%	86%
Average Degrees Swept	94 °	187 °	269 °	360 °
Average Length (m [ft])	355 [1166]	342 [1121]	388 [1273]	369 [1211]
Average Size (ha [acres])	10.1 [25.1]	20.4 [50.3]	34.0 [84.0]	47.4 [117.0]

Either decreasing length from the typical 400 m (1300 feet) or decreasing the arc irrigated from full circle increases the per-area cost of the center pivot from the normal \$909/ha (\$368/acre) investment cost. Per-acre costs ranged from \$437 to \$14,325/ ha (\$177 to \$5,800/ac). This greatly increases the overall cost of irrigation in Missouri since the investment cost is already 60% of total costs, under the “normal” pivot configuration. In addition, if a pivot does not make a full circle a new set of management considerations exist. The cost relative to the “normal” cost is seen in Table 7 based on quartiles ranked by per-area costs for number of pivots and for area. Since short pivots sweeping small portions of a circle will have small areas, there will be a large amount of difference in viewing quartiles, depending upon whether it is based on number

of pivots or number of hectares. A histogram showing the estimated purchase cost of pivots in SEMO is seen in Figure 7. While the mode value is the one an expected “normal” pivot would cost (i.e., > \$1000/ha), about 20% of the units would have cost three times or more then this “generic” cost.

Table 7. Average relative cost to “normal” pivot per-acre cost by quartiles based on number of pivots and acres irrigated.

Item	Pivots Based on Portion of the Circle Swept			
	1 st Quartile	2 nd Quartile	3 rd Quartile	4 th Quartile
By number of pivots	0.88	1.00	1.57	3.52
By hectares irrigated	0.94	1.01	1.02	2.63

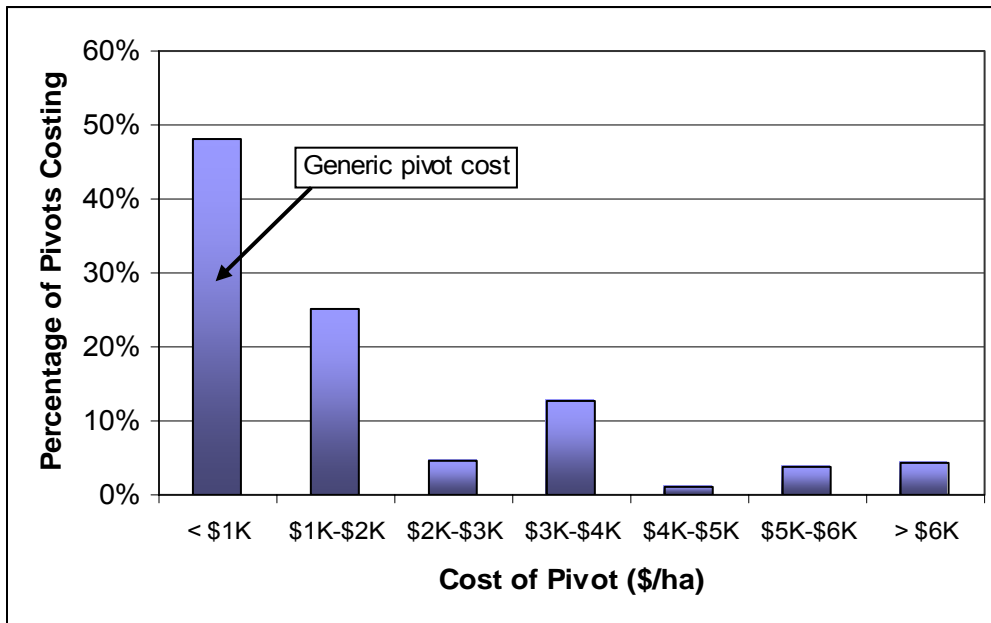


Figure 7. Histogram of unit area investment cost for pivots in SEMO.

Conclusion

In Missouri there is significant variation in pivot length and percentage of a full circle swept, leading to large differences in investment cost from the generic center pivot. While three quarters of the pivots (area basis) would have cost less than or close to the often quoted price of \$909/ha (\$368/ac), a quarter would have cost significantly more. Therefore, it is important in doing investment analysis that site-specific, rather than generic costs be used.

The average CU for the tested pivots was 78%. Using the 3-can method for calculating CU, about 4% was added to the traditional CU values. A new test is planned for 2009 to validate various uniformity calculation procedures and compare them to soil moisture and yield uniformity on corn on a sandy soil irrigated with a lateral having low uniformity.

The ASABE S436.1 standard should consider these items:

- Change the current recommendation of examining catch outliers deviating by + or – 10% of average catch to 30%.
- Suggest that aerial images of the tested field become part of the test documentation.
- While continuing to report results of the pivot as a whole, also include span and endgun results separately.
- Include Application Efficiency data.

Based on the results from the upcoming test comparing hydraulic, areal, and yield distribution it may be later suggested that a 3-can averaging protocol (under conditions of short catch intervals) also be calculated.

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References

- AgEBB. 2009. Missouri Weather Stations. Columbia, MO: Agricultural Electronic Bulletin Board. Available at: <http://agebb.missouri.edu/weather/stations/index.htm>
- ASABE Standard. 2007. S436.1: *Test Procedure for Determining the Uniformity of Water Distribution of Center Pivot and Lateral Move Irrigation Machines Equipped with Spray or Sprinkler Nozzles*. St. Joseph, Mich.: ASABE.
- Burt, C.M., A.J. Clemmens, R. Bliesner, J.L. Merriam, and L. Hardy. 2000. *Selection of Irrigation Methods for Agriculture*. Reston, VA: American Society of Civil Engineers.
- Dukes, M., M. B. Haley, and S. A. Hanks. 2006. *Sprinkler irrigation and soil moisture uniformity*. In proc: 2006 Annual International Irrigation Show. Falls Church, VA: Irrigation Association.
- Harrison, K. and C. Perry. 2007. *Evaluating and interpreting application uniformity of center pivot irrigation systems*. Circular 911. Athens, GA: University of Georgia.
- Henggeler, J. 2000. Unpublished paper: *White Paper on: Profitable Irrigation in the Humid Mid-South With Special Attention to Irrigation in Missouri*. University of Missouri Delta Center, Portageville, MO.
- Lia, J. and H. Kawano. 1996. *The areal distribution of soil moisture under sprinkler irrigation* *Agricultural Water Management*. 32(1): 29-36.

- Mecham, B. 2001. *Distribution uniformity results comparing catch-can tests and soil moisture sensor measurements in turfgrass irrigation*. In proc: 2001 Irrigation Association 2003 Conference. Falls Church, VA: Irrigation Association.
- Merriam, J.L., and J. Keller. 1978. *Irrigation System Evaluation: A Guide for Management*. 3rd ed. Published by Agricultural and Irrigation Engineering Department, Utah State University, Logan, Utah. 271 p
- Reinbott, D. 2009. *Missouri irrigation: irrigation systems*. At: <http://agebb.missouri.edu/irrigate/economics/index.htm>. Accessed 28 April, 2009.
- Richmond, A. and E. Zencey. 2007. "Environmental kuznets curve." In: *Encyclopedia of Earth*. C. J. Cleveland, ed. Washington, D.C.: Environmental Information Coalition, National Council for Science and the Environment. Available at; http://www.eoearth.org/article/Environmental_kuznets_curve. Accessed 23 April, 2009.
- Ring, L. and D.F. Heerman. 1978. Determining center-pivot sprinkler uniformities. Paper 78:2001. St. Joseph, Mich.: ASABE.
- Scherer, T. 2005. *Selecting a sprinkler irrigation system*. Bulletin AE-91. Fargo, ND: NDSU Available at: <http://www.ag.ndsu.edu/pubs/ageng/irrigate/ae91w.htm>. Accessed 30 April, 2009.
- Seginer, I. 1979. Irrigation uniformity related to horizontal extent of root zone: A Computational Study. *Irrigation Science*. (1): 89- 96.
- Tarjuelo, J.M., J. Montero, F. T. Honrubia, J. J. Ortiz and J. F. Ortega. 1999. *Analysis of uniformity of sprinkler irrigation in a semi-arid area*. *Agricultural Water Management*. 40(2-3): 315-331
- USDA/NASS. 2004. *Farm and Ranch Irrigation Survey (2003) Volume 3, Special Studies Part 1*. Washington, D.C.: USDA National Agricultural Statistics Service. At: <http://www.nass.usda.gov/census/census02/fris/fris03.htm>. Accessed 15 February 2005.
- USDA/NRCS. 2003. *Conservation Practice Standard: Irrigation System, Sprinkler*. CODE 442. Washington, D.C.: USDA Natural Resource Conservation Service.
- Vis, E., R. Kumar, and S. Mitra. 2007. *Comparison of Distribution Uniformities of Soil Moisture and Sprinkler Irrigation in Turfgrass*. Pomona, CA: California Polytechnic State University.