Agricultural Irrigation Initiative: Pivot Evaluation Best Practices

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Executive Summary

Growers using center pivot irrigation delivery systems generally schedule irrigation based on the driest ten percent of a field. While this approach meets crop water requirements for most areas, it can overwater others. The challenge of uniformly meeting crop water requirements is compounded when the amount of water applied by the center pivot’s sprinklers varies significantly. Improving the distribution uniformity (DU) of irrigation water plays a large role in both water and energy conservation. The amount of energy wasted due to non-uniformity is inversely proportional to DU. Additional energy waste occurs through excessive evaporation due to the use of inefficient spreader plates.

The Northwest Energy Efficiency Alliance (NEEA) commissioned this study as part of its Agricultural Irrigation Initiative with the goal of establishing a cost-effective approach to improving distribution uniformity that results in potential energy and water savings. While methods for measuring and characterizing irrigation distribution uniformity are well-developed and widely-used in academic research, they are rarely used in commercial farm operations. The team adapted and refined these methods to provide a prototype of a commercially-viable approach for assessing pivot performance, and to recommend specific repairs to increase pivot distribution uniformity and water application efficiency.

The team’s prototype approach for each pivot evaluated in this study involved identifying water application areas exhibiting high degrees of variance, then calculating an estimated distribution uniformity value for that pivot with the high-variability data points removed from the dataset; this value simulates the DU results attainable after the hypothetical completion of recommended pivot repairs. If a pivot in the study achieved a simulated DU of at least 90% that would require “tuning” less than about one-third of the sprinkler drops, the study team’s “pivot evaluator” (the person conducting the pivot evaluation) recommended a pivot tune-up. If the evaluator would need to tune roughly one-third or more of the drops to achieve the 90% DU goal, the evaluator recommended a full sprinkler package replacement.

The NEEA team observed that about half of the thirty-one pivots evaluated in this study would benefit from complete sprinkler package replacements. Nearly all of the remaining pivots evaluated could benefit significantly from tune-ups consisting of low-cost repairs. The tune-up approach should provide growers a better return on investment when compared with the cost of a full sprinkler package replacement. Implementation of recommended pivot repairs would help growers to save money, while maximizing crop value, in the following ways:

1 The Overview of Center Pivot Irrigation Systems report describes basic center pivot design and function; the Soil Science and the Basics of Irrigation Management report describes the relationships between soil and irrigation.
2 A component of the sprinkler package, further addressed in the body of this report.
3 Through the use of a catch-can test, defined and described in the body of this report.
4 In this exploratory study, the study team chose 90% as the target DU threshold for determining “tune vs. replace” pivot repair recommendations. Specification of a definitive DU threshold for wide-scale commercial use in pivot evaluations will require more research.
5 The findings in this report are based upon the study team’s trials of evolving methods and tools. The exploratory nature of this work mandated a departure from scientific and technical rigor. Readers should therefore view the
Improving distribution uniformity enables growers to reduce the amount of water they pump to meet minimum crop requirements across the entire field.

- Selecting the appropriate sprinkler head designs can reduce evaporative losses.
- Servicing worn parts such as leaky pipes, regulators, sprinkler heads, and worn or broken gear boxes enables the grower to irrigate more uniformly and to improve crop yield.
- Optimizing system pressure benefits the grower in multiple ways:
  - Improves yield and quality of yield
  - Reduces energy costs in cases with pressures originally too high
  - Decreases other inputs such as fertilizers, pesticides, and other chemicals

The prototype pivot evaluation process appears to be economically viable as a new service offering, the method has not undergone rigorous third-party evaluation at this point. It will require additional development to become commercially feasible on a large scale. The study team recommends an expanded experiment to complete the development of the methods and tools used in this study as a precursor to the launch of a large-scale market introduction.

Utilities could potentially accelerate the rate of market adoption of pivot evaluations by offering incentives and educational courses to growers. The study team’s working theory is that once growers see the benefits, the pivot evaluation process will soon become common operational practice. Increased adoption by growers would escalate pivot repairs and sprinkler package replacements, ultimately driving overall improvements in irrigation uniformity.

This *Pivot Evaluation Best Practices* report is one in a series of twelve reports addressing specific areas of NEEA’s Agricultural Irrigation Initiative. All twelve reports are available at [http://neea.org/reports](http://neea.org/reports).
1. Introduction

As part of its Agricultural Irrigation Initiative to reduce energy use in irrigated agriculture by twenty percent by 2020, the Northwest Energy Efficiency Alliance (NEEA) assembled a team of experts to review existing center pivot evaluation methods and to refine the systematic process for evaluating pivot performance. NEEA is an alliance funded by 140 utilities and energy efficiency organizations in Idaho, Oregon, Montana, and Washington working to accelerate the innovation and adoption of energy-efficient products, services, and practices in the Northwest.

This report summarizes the findings of the experts on NEEA’s study team and introduces a range of evaluation methods for validating pivot performance, diagnosing performance issues and defective components, and for making recommendations to growers for cost-effective improvements based on subjective assessments of measured data. This report is one in a series of twelve reports addressing specific areas of this Initiative, all of which are available at http://neea.org/reports.

The study team conducted pivot evaluations on thirty-one pivots during the 2014 growing season. The evaluation sites ranged across the Columbia River Basin from Ephrata, Washington to Hermiston, Oregon and in south-central Idaho from Grandview to Grace, as illustrated in Figure 1.6

Figure 1. Locations of Pivot Evaluation Sites

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6 The team will deliver the recommendations to the growers in winter 2014/2015.
This report details combinations of evaluation methods, including objective measurements and tests, subjective field observations, and assumptions for analyzing results that the researchers used to characterize pivot performance and to make recommendations for improvements. This study may help utilities to identify opportunities for program development that would improve irrigation efficiency and may help growers to cost-effectively improve productivity.

Unless otherwise noted, all observations and recommendations in this report are those of the study team based upon its trials of evolving methods and tools. Due to the exploratory nature of this work, readers should consider the team’s recommendations and the methods and tools described herein as works in progress rather than as fully-vetted applications ready for implementation in the field.

Given the industry-specific and scientific natures of some terms used in this report, please refer to the AgGateway AgGlossary (http://agglossary.org/wiki/index.php/main_page) for definitions.

1.1. Background
Center pivot irrigation comprises about eighty-five percent of all electricity consumed by the agriculture sector in the territory served by NEEA (Idaho, Montana, Oregon, and Washington) (NPCC 2010). Center pivots provide a critical function by uniformly applying water according to crop needs and to the growers’ objectives. Growers frequently schedule irrigation to ensure application of enough water to satisfy the crop requirements for the driest part of the field. This practice works well for uniform fields, assuming that the irrigation system applies a uniform application depth of water along the entire pivot. In situations in which irrigation system distribution is not uniform, growers often increase irrigation to meet crop demands in the under-watered areas. Doing so frequently leads to overwatering the majority of the acreage, resulting in wasted water, energy, and nutrients, and in lower crop quality and yield.

Many factors can seriously deteriorate application uniformity, and periodic maintenance of center pivots is critical for maintaining expected levels of performance. Often, however, growers overlook such maintenance in the complexity of farm operations.

1.2. Purpose of Research
NEEA commissioned this research with the goal of establishing a prototype of a cost-effective approach for evaluating and improving pivot performance that would ultimately result in energy savings. The study team demonstrated the prototype pivot evaluation process on the thirty-one pivots in this study to determine the combination of methods most acceptable to growers.
1.3. Key Figures of Merit

Methods for measuring irrigation uniformity date back to the 1940s and are explained in some detail in Appendix A. Researchers commonly use the approach of distributing an array of collection containers (called catch cans) in the field and measuring the amount of water collected in each catch can (explained in Section 2.1.5 and Section 3.5). The study team used the catch-can test\(^7\) approach for this study and analyzed the resultant data, calculating three frequently-cited figures of merit:

- Coefficient of Uniformity (CU)
- Distribution Uniformity (DU)
- Application Efficiency

CU and DU are different mathematical treatments of the same data collected in the field by performing catch-can tests, while application efficiency is a metric indicating the extent of evaporative losses. These approaches can be used for all irrigation delivery systems, both fixed and moveable, and are described in detail in this report.

1.3.1. Coefficient of Uniformity

The Coefficient of Uniformity (CU) provides an accurate description of the uniformity of as-applied water for the pivot measured; higher percentages indicate higher uniformity.

**Calculation:** The standard deviation of the water application depth measured in each catch can collection container divided by the mean, weighted by the distance from the center of the pivot to account for the different sizes of the areas covered by each sprinkler drop\(^8\) on the field – drops on the outer span of a quarter-mile pivot may irrigate thirty acres, whereas those on the inner span may irrigate only two acres.

1.3.2. Distribution Uniformity

Distribution Uniformity (DU) utilizes the same catch-can data as does CU, but it is calculated differently. DU is the average of the lowest quarter\(^9\) of the catches weighted by distance, divided by the mean catch value. Most growers use DU more frequently than CU because they can use it to determine the minimum amount of water that must be applied to adequately irrigate the low quarter of that field. Given that crop yield loss is often greater due to drought stress than to stress induced by overwatering, growers often use the common practice of scheduling irrigation according to the driest areas of the field. This practice illustrates one reason that improving distribution uniformity plays such a large role in both water and power conservation: the amount of energy wasted due to non-uniformity is inversely proportional to DU.

**Example:** A grower wants to apply one inch of water. If the DU is 80%, the grower must apply 1 inch/0.8, or 1.25 inches of water in order to get that one inch to the low quarter of the field.

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\(^7\) Also known as a precision water application test; see the *Precision Water Application Test* report for the findings from another such assessment

\(^8\) See the *Overview of Center Pivot Irrigation Systems* report for more information

\(^9\) Depths of irrigation water in the twenty-five percent (one-quarter) of catch cans with the least amounts of water; the areas of the field receiving amounts of water in this lowest twenty-five percent are called the “low quarter.”
As detailed in Section 3 (Pivot Evaluation Study Findings), the study team believes that a target DU value 90% or greater for a well-tuned pivot is prudent and realistic. If the DU is below 90%, evaluators will recommend diagnostic tests focused on identifying and correcting problems at specific locations on the pivot. Fixing a few sprinkler drops frequently leads to significant improvements in efficiency. For cases in which significant variations in uniformity are spread over a large number of drops, evaluators will likely recommend a full sprinkler package replacement.

### 1.3.3. Application Efficiency

Application efficiency refers to the percentage of water flowing through the pipe that makes it to the ground. Low application efficiencies usually result from high evaporative losses. Sprinkler manufacturers offer a range of spreader plate solutions tailored to reducing evaporative losses, improving application uniformity under each drop, and avoiding large droplets that can lead to surface compaction.

Other studies (ASABE 2012) have shown that some sprinkler designs experience as much as 45% evaporative losses, which growers can dramatically reduce by choosing the proper spreader plate design when doing a full sprinkler package replacement. Even the best spreader plates available today can result in as much as 15% in evaporative losses.
2. Pivot Evaluation Process Flow and Methods

Center pivot dealers typically use custom software to create a custom irrigation system design for each field and pivot, accurately specifying the size and location of each component in the design. The full set of components recommended in the design document they create is referred to in the industry as a sprinkler package. This varying complexity of irrigation system designs, together with the wide range of farm practices, complicates the identification of a single pivot evaluation process to satisfy all situations.

The team for this NEEA study created a preliminary menu of evaluation methods for use in pivot evaluation processes. Once these methods have been refined and the process is available as a market-ready commercial service for growers, professional “pivot evaluators”\textsuperscript{10} will be able to use analytical tools and subjective judgment to choose and apply the optimal set of evaluation methods from this menu, based on specific farm and pivot conditions as well as on the grower’s needs and preferences. The goal of this process is to balance results and cost to create maximum value for the grower.

2.1. Pivot Evaluation Process Flow

In this study, the pivot evaluators on the team followed a consistent set of process steps to perform each pivot evaluation, selecting the appropriate methods for each particular case. Figure 2 below illustrates this process,\textsuperscript{11} from initial characterization of the irrigation system through identification of recommended action steps to save water and energy. The subsections that follow describe how pivot evaluators for this study generally performed each of these steps. This process also provides a good starting point for future studies.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{pivot_evaluation_process_flow.png}
\caption{General Pivot Evaluation Process Flow}
\end{figure}

\textsuperscript{10} The terms “pivot evaluator” and “evaluator” in this report primarily denote individuals on the NEEA study team who conducted evaluations on the pivots in this study. Cases in which “pivot evaluator” refers to the professionals who will eventually provide commercial pivot evaluation services to growers are noted as such.

\textsuperscript{11} The figure shown suggests a sequential process. In practice, pivot evaluators can conduct some of these steps in parallel based on their judgment.
2.1.1. Characterize the Irrigation System
In this study, the pivot evaluators used system specifications from available documentation and grower interviews to characterize the irrigation systems of the demonstration pivots. This information helped the evaluators to establish context and to identify unique challenges on each farm. Evaluators collected the following information in order to calculate estimated energy savings:

- General layout of water delivery system
  - Presence or absence of booster pumps
  - Presence or absence of pumps with Variable Frequency Drives
  - Estimate of pumping system efficiency
  - Total dynamic head (how high the water is pumped)
- General description of pivot, including age, panel type, design flow rate
- Sprinkler brand and model
- Copy of the current sprinkler chart, if available
- Spreader plate type and reason(s) for choosing
- Sprinkler package installation year
- Pump operating pressures and determining factors in pressure selection
- Pivot maintenance plan, including frequency of sprinkler package replacement
- Current electricity rates

When executing this step, the study team evaluators sought to understand the unique problems faced by an individual grower in irrigating his/her crops. Doing so provided context and insights while building a relationship and credibility with the grower. Appendix B outlines the types of information collected in grower interviews for this study.

2.1.2. Inspect Sprinkler Components for Wear
Evaluators inspected the components and field conditions for each pivot system, and documented those that needed attention or provided insights into irrigation practices. The team inspected the following components and conditions during the 2014 season:

- Crop uniformity (either for the current season or from historical aerial photos)
- Spray pattern uniformity
- Extent of field erosion
- Depth of wheel track ruts
- Boots and fittings (for leaks)
- Rotator plates (whether or not they were sticking)
- Nozzles (whether or not they were plugged)
- Tires (checking for flats)
- Gear box operation
2.1.3. Measure Pivot Water Flow and Inlet Pressure
Evaluators used pivot water flow rate and operating pressure as inputs for estimating irrigation-related energy consumption. While these flow rate and pressure measurements are frequently displayed on the control panel, they are frequently out of calibration. For that reason, the evaluator measured flow rate using a portable ultrasonic flow meter, and measured pressure at different points along the pivot arm. Appendix A and the Instrumentation and Hardware Best Practices in Precision Agriculture report provide more information on flow meters.

2.1.4. Measure Pivot Speed
Average pivot speed plays a significant role in calculating application efficiency, as described in Section 3.9. The evaluators on the study team measured pivot speed by measuring the distance the last pivot tower\textsuperscript{12} traveled and the time it took to travel that distance.

2.1.5. Measure Distribution Uniformity with a Catch-Can Test
The catch-can test is designed to quantify the uniformity of water distribution actually delivered to the field. Academic researchers and sprinkler designers frequently use catch-can testing to characterize application uniformity. The Precision Water Application Test report describes a catch-can testing study that was also part of this Initiative.

For this pivot evaluation study, the team performed a catch-can test for each pivot evaluated. They placed collection containers (“catch cans”) at regular intervals of ten or twenty feet (three or six meters) approximately perpendicular to the direction of pivot travel, as Figure 3 illustrates. After the pivot passed over the collection containers, researchers recorded the application depth in each container (“catches”) (see Figure 4) and analyzed the data to evaluate variations in application depth along the length of the pivot.

During the catch-can test, evaluators also recorded the distance from the pivot to the outermost tower and the total wetted radius of the pivot.

\textsuperscript{12} Described in the Overview of Center Pivot Irrigation Systems report
2.1.6. Diagnose Areas Exhibiting High Variability
The evaluators used three diagnostic methods to determine the specific cause(s) of variation and to identify the exact actions required to repair individual drops. These included:

- Testing water pressure at the outlet of the nozzle to determine whether the regulators are performing to specification
- Measuring the flow rate of individual drops to determine whether the measured flow rate matches the design flow rate on the sprinkler chart
- Inspecting the sprinkler head, nozzles, and spreader plates to determine the extent of wear

When pivot evaluations become available as a service in the marketplace, evaluators will be able to conduct recommended repairs concurrently with performing the diagnostics.
2.1.7. Analyze Pivot Evaluation Results Using a Pivot Evaluation Calculator

To facilitate analysis of the pivot data and information collected through the evaluation methods outlined above, the study team created a prototype spreadsheet-based center pivot evaluation calculator with the working name PEval\textsuperscript{13} (described in detail in Section 3.6, and in greater detail in Appendix A). The reports generated by such a calculator provided pivot evaluators with a wealth of easily-interpreted information to use in advising growers on potential pivot improvements. Section 3.7 describes findings based upon experimental usage of this prototype calculator with the pivot data for this study.

For each pivot evaluation, the evaluator reviewed the analytical results from PEval, categorized the pivots based upon key values that PEval calculated for each one, and then used informed professional judgment to determine whether a pivot tune-up or a full sprinkler package replacement would be advisable.

PEval generates a report for the grower, documenting the findings and recommendations for the pivot evaluated. The reports allow pivot evaluators the analytical capabilities to:

- Quantify the uniformity or expected performance of the pivot
- Pinpoint problem areas and report the number of areas needing tuning
- Determine whether sufficient application variability exists to justify purchasing a new sprinkler package
- Run scenarios for the grower for varying levels of investment in pivot repairs
- Estimate the cost of a pivot tune-up compared to purchasing a new sprinkler package

2.2. Pivot Evaluation Methods Specific to Variable Speed Irrigation (VSI)

Variable Speed Irrigation (VSI) presents an additional complication in evaluating pivot performance. For cases in which the pivot does not accurately execute the changes in speed that are programmed into it, the application amount won’t match the intended (programmed) amount, thus introducing an entirely new dimension of errors in application rate. This problem is similar to the issues described in Section 2.1.4 for pivots that are programmed to move at a constant speed; however, pivots equipped with VSI require the development of more sophisticated methods to characterize the speed profile to accommodate their variations in speed as a function of rotation angle. These VSI evaluation methods will be the subject of future work.

\textsuperscript{13} The New South Wales Department of Primary Industries created an earlier version of this spreadsheet calculator. Troy Peters at Washington State University refined it further, and the research team for this project continues its development and expansion of functionalities. The study team created the first prototype of PEval after the collection of all 2014 field data; teams conducting future studies should use PEval in the field at the time of data collection to allow execution of evaluation, diagnostics, and repairs all in the same visit to the farm.
2.3. Pivot Evaluation Methods Specific to Variable Rate Irrigation (VRI)

The pivot evaluation methods for pivots equipped with Variable Rate Irrigation (VRI) determine whether each solenoid bank of the VRI hardware responded to the controller in a manner consistent with the controller instructions (see the Overview of Center Pivot Irrigation Systems report for more information on controllers). These VRI evaluation methods will be the subject of future work.
3. Pivot Evaluation Study Findings

The team tested a wide range of evaluation methods on the thirty-one pivots in this 2014 study, and by the end of the season reached consensus on the working prototype pivot evaluation process outlined in Section 2 of this report.

In general, the Distribution Uniformity (DU) evaluation method emerged from the study findings (as described below in Section 3.6) as the preferred method for initially assessing overall pivot performance.

The team discovered other key findings through analysis of the results from the thirty-one pivots evaluated, as explained in the following sections:

- Nearly half of the pivots evaluated exhibited sufficient variability to warrant a full sprinkler package replacement
- All remaining pivots in the study either required major repairs or could benefit from a tune-up
- Evaporative losses appear to be substantially greater than would be expected, and may be reduced through selection and use of more efficient sprinkler heads
- The potential energy savings associated with replacing worn-out sprinklers, decreasing variability by implementing sprinkler tune-ups, and by selecting more efficient sprinkler head designs appear to be substantial, but proved difficult to accurately assess this season

While the data from this study are quite preliminary, the team believes the study findings provide tangible evidence of the feasibility of achieving significant energy savings by commercializing a pivot evaluation process.

3.1. Results of Irrigation System Characterizations

The findings from this study determined that to successfully implement a pivot evaluation, the evaluator needs only a few specific pieces of information from the grower:

- Total dynamic head
- Current electricity rates
- Copy of the sprinkler chart, if available

3.1.1. Impact of Water Quality on Characterizing an Irrigation System

Water quality appears to have a significant impact on the life expectancy of regulators, nozzles, and spreader plates, although the evaluators in this study found it difficult to quantify this effect. They hypothesized that the quality of water from deep wells could be significantly better than that of water from surface canals. Although the published life expectancy of regulators is 6,000 to 10,000 hours, evaluators observed that some sprinkler packs wore out in less than 3,200 hours. This occurred at pivot sites where irrigation source water came from a surface canal with a significant amount of suspended solids and grit in the water. Conversely, pivot sites with irrigation source water from a deep well included some sprinkler packs still in good functional order after more than 20,000 hours of operation.
This high degree of variation in life spans among regulators and sprinkler packs demonstrates the criticality of periodically testing pivot performance to maintain optimal uniformity. Water that carries abrasive grit will erode nozzles, and the water flow will gradually increase. Measuring nozzle diameter on a small sample of drops can quickly determine whether nozzles are worn. If a few nozzles are worn, they all need to be replaced. In addition, nozzles have longer life spans than do spreader plates; therefore, if the spreader plates are worn or broken, the grower should replace both the spreader plates and nozzles.

3.1.2. Pressure Regulators
While the use of pressure regulators improves irrigation uniformity, the team observed wide variations in their usage for the demonstration pivots. Since lowering the pivot inlet pressure reduces energy consumption, proper specifications and mounting locations are important:

- Regulators are variously mounted on the bottom or on top of the drop. Since water pressure increases by one pound per square inch (PSI) (6.9 kilopascals) for every 2.3 feet (0.7 meters) of head, the pressure the sprinkler head experiences will be two to three PSI higher when the regulator is mounted on top of the pivot.
- Sprinkler heads are relatively tolerant to a range of pressures, as long as the pressure is consistent from drop to drop. Frequent, wide pressure fluctuations reduce the life spans of the regulators.
- Irrigation system designers often use twenty-PSI regulators when a fifteen-PSI regulator would work just as well and would require less system pressure supplied to the pivot.

Based on these observations, the study team recommends typically mounting fifteen-PSI regulators at the bottom of the drop right above the sprinkler head, unless other design factors suggest otherwise.14

3.1.3. Factors Impacting Irrigation Uniformity
The study team observed irregularities in water application that impacted irrigation uniformity for some fields. Examples included:

- Crop uniformity: On several fields, plant vigor varied in ring-shaped patterns that correlated with the application depth measured in the catch-can test. Crop vigor was negatively impacted by both local overwatering and local under-watering.
- Spray pattern uniformity: On many pivots, specific sprinkler drops exhibited clear variations in application. The team observed potentially contributing factors including rotating spreader plates that failed to rotate, plugged nozzles, and significant leaks.
- Extent of field erosion: Extensive erosion is a sign that the application rate exceeds the rate at which the soil can absorb applied water. The evaluators for this study based their recommended changes on other contextual factors, including topography, soil type, and

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14 For example, research is underway on new technologies called Low Energy Precision Application (LEPA) and Low Elevation Spray Application (LESA). LEPA and LESA work with even lower pressures, thus potentially conserving additional energy and further reducing evaporative losses.
3.2. Findings from Wear Inspections of Pivot Hardware

The study team observed multiple wear and tear issues on the pivots’ hardware:

- **Depth of wheel track ruts:** Some pivots exhibited wheel ruts sufficiently deep that they slowed pivot travel, increased wear on pivot hardware, and occasionally caused the pivots to get stuck. While the team took no specific action related to wheel track depth for this study, its impact constitutes an important consideration for future work.
- **Leaking boots or fittings:** Several pivots exhibited leaks that could be easily repaired.
- **Stuck rotator plates:** In some cases, team members observed rotating spreader plates that were not rotating and spreader plates so clogged or worn that the spray pattern had become highly irregular.
- **Plugged nozzles:** The team observed partially or fully plugged nozzles on most pivots in the study.
- **Flat tires:** Evaluators observed three flat tires on one pivot, which significantly altered the pivot speed. They decided that checking the tire pressure would be more trouble than it was worth, so they documented only that the tires were visibly deflated.
- **Two pivots needed such substantial degrees of repair that while they were still being used for irrigation, the team could not perform full evaluations on them.**

3.3. Results of Measuring Pivot Water Flow Rate and Inlet Pressure

Pivot flow rate and inlet pressure are critical inputs in calculating an estimate of energy consumption. The study team successfully measured flow rates on most of the pivots in the study using an ultrasonic flow meter. The team could not measure flow on two pivots due to extensive corrosion inside the pipes, which prevented the ultrasonic signal transmission (the only feasible measurement method for this study). Evaluators typically used the reading on the existing pressure gauge mounted to the pivot to assess pivot inlet pressure. If that reading appeared out of range, the evaluators considered it suspect.

3.4. Results of Measuring Pivot Speed

Obtaining sufficiently accurate measurements of pivot speed required the evaluators to allow the pivot to travel a minimum of 300 feet (ninety-one meters), which they did not complete in some cases. For that reason, the team did not report application efficiency on data points that appeared to be erroneous. The team recognized that developing a more accurate method to record pivot speed would improve estimates of potential energy savings.

3.5. Insights from Catch-Can Testing

The team tried two different catch-can spacings for the fields in this study. Some evaluators spaced cans on ten-foot (three-meter) centers, and others decided to space cans on twenty-foot (six-meter) centers to decrease the labor costs of the test. During analysis, the team members collectively recognized the importance of the DU results as a primary indicator of pivot uniformity, and the importance of collecting water from every sprinkler head. As a result, they agreed that the smaller catch can spacing clearly justified the additional labor. The team recommends that future researchers space catch cans at intervals less than the smallest spacing.
between drops on the pivot. The *Precision Water Application Test* report addresses the use of catch cans in detail.

More generally, pivot designers improve application uniformity by spacing sprinkler drops with significant overlap in individual sprinkler spray patterns, as shown in Figure 5. As a result, an individual catch can nearly always collects water from more than one sprinkler head. When an evaluator observes a significant variation in application depth for a particular catch can, the data pinpoints a location on the pivot that needs tuning, but it does not pinpoint the exact drop that needs repair. For that reason, the study team recommends that the evaluator use the catch-can test results to identify areas of concern, and then conduct additional diagnostic tests on the two or three drops that contributed to that catch can’s water supply, and repair only the offending sprinkler drops.

![Figure 5. Sprinkler Spray Pattern and Catch Can Placement](image)

3.6. Insights from Data Analysis, PEval Development and Reporting Results

The study team developed a data-driven method for advising growers on the point at which replacing a sprinkler package is appropriate. Appendix A details similar previous studies; in summary, they suggest that modern pressure-regulated sprinkler packages “are capable of attaining a CU value of 90 to 95 percent” (King et al. 2011).

In the sample of pivots for this study, the team determined an expected average value for CU of a well-tuned pivot of 94.6%, with a standard deviation of 0.9%, which corroborates the previous findings. King et al. also reported that “a CU value of 85% is generally considered to be the minimum value below which a system needs updating or maintenance.” Simply applying the CU values, however, assumes that the resulting action is a full sprinkler package replacement at a cost ranging between $3,500 and $5,000.\(^\text{15}\) However, when determining whether a pivot system requires maintenance, evaluators should also factor in the following considerations:

\(^{15}\) The study team solicited quotes for estimated costs for sprinkler package replacements. The team received an initial quote for $28 per drop, or about $3,500 for a typical quarter-mile pivot, including parts and labor. The study team input these numbers into PEval to calculate estimated replacement costs. The team received subsequent quotes for $40 per drop, illustrating the wide range of pricing models in the marketplace.
• Is the source of the variation localized to a few drops that can be easily repaired (tuned)?
• Is the variation evenly distributed over the entire pivot, so that replacing the entire sprinkler package would be more cost-effective?

The industry tends to focus only on the second consideration, neglecting the benefits of tune-ups. To better understand the importance of pivot tune-ups, consider the following simile:

*Imagine that a pivot is like a piano. A piano leaves the factory in near-perfect tune. However, even the process of shipping the piano to the customer knocks a piano out of tune, so every new piano should get tuned when it arrives at the customer's site and stabilizes to its new surroundings.*

*Now imagine a scenario in which no one has yet developed the skill to tune a piano outside the factory. Every piano that has left the factory is thus more or less out of tune. If the piano is too far out of tune to serve its purpose, it gets replaced. In real-world applications, every piano should be tuned when it is installed, and then periodically tuned depending on the demands on its use, rather than replacing it when it gets out of tune.*

Similarly, based on the findings in this study, every pivot would benefit from tuning, at a minimum, or in some cases from a full sprinkler package replacement. Some need only a minor tune-up and others are way out of tune. The study team knows of no market-ready process for evaluating the degree to which to tune a pivot; the absence of such a process, together with the team members’ findings in this study, drives their assumption that most installed pivots are more or less out of tune. The study team suggests that tuning enables the attainment of significantly higher values for goal metrics such as CU and DU, and makes obsolete the conventional wisdom (see Appendix A) that a CU of 85% can be considered acceptable.

The study team’s insights into the potential for achieving significant incremental improvements led to an adjustment to its original objective: Develop a data-driven method to advise a grower when to conduct targeted repairs on specific sprinkler drops that complements a method to determine when it is cost-effective to replace the entire sprinkler package. The team began referring to the process of conducting targeted repairs on specific drops as a “tune-up.”

While the study team acknowledges the usefulness of the CU metric, the team found the DU metric to be more useful in estimating energy consumption since it more accurately reflects grower irrigation behaviors (as described earlier in this report).

The study team observed a wide range of existing levels of maintenance service among the pivots in the study. Figure 6 illustrates three examples of catch can data for which the source of variation is localized to a few drops, situations in which tuning two to six drops could boost DU to 90% or higher. The team estimated a cost of $50 to tune each drop. If the growers who own these pivots were to perform inexpensive tune-ups, they could realize a rapid return on investment.
Figure 6. Examples of Pivots for which Tuning Two to Six Drops Improved DU to More than 90%

In contrast, Figure 7 illustrates examples of three pivots for which the variability is not localized, but is instead spread over the entire pivot. In these examples, merely conducting pivot tune-ups would fail to provide the desired levels of improvement.

Figure 7. Examples of Pivots for which the Source of Variability Is Distributed over the Pivot

The study team felt that nearly half of the growers in the study had deferred replacing sprinkler packages so long that they had exceeded their useful lives, with examples of three such pivots illustrated in Figure 7 above. Some growers reported that they had not replaced sprinkler packages in more than twelve years, and those pivots yielded highly erratic catch-can test results. In cases such as these, the study team recommended a full sprinkler package replacement.

The team believes that the conventional wisdom that “a CU value of 85% is generally considered [acceptable]” is outdated, and that irrigation consultants can significantly improve CU using simple statistical process control methods that are pervasive in other industries. The study team contends that systematically decreasing variability will lead to substantially higher levels for CU (and DU) than have been previously reported.
The examples shown in Figure 6 and Figure 7 illustrate cases in which the pivot evaluation results facilitated comparatively straightforward recommendations. The team recognized that some pivots exhibited less-obvious results that required professional judgment in determining recommendations. For the prototype PEval analysis in this study, the team had to choose specific threshold levels of metrics for determining whether a pivot qualified for a tune-up or a full replacement. The choice of such levels is subjective based on the opinions of the evaluator and the grower. The team clearly recognizes that the methods used in this study are preliminary and warrant external review and additional development.

Appendix A details the approach chosen by the team for this study. Simply stated, for each pivot evaluated, the team sorted the catch can data looking for areas with high degrees of variance. The evaluators filtered those data points from the dataset and recalculated the DU without them to simulate results after hypothetical completion of recommended pivot repairs. If an evaluator managed to achieve a simulated DU of at least 90% by tuning less than about one-third of the sprinkler drops, the evaluator would recommend a tune-up. If the evaluator needed to tune about one-third or more of the drops to achieve the 90% goal, the evaluator recommended a full sprinkler package replacement.

Notably, the study team’s analyses and simulations yielded clear benefits even in tuning up pivots with already-high DU values. For one pivot with a DU already exceeding the 90% goal prior to any repair actions, PEval calculations showed that addressing six areas on that pivot could improve its DU by an additional 2.6% at an estimated cost of only $300.

Evaluators can use the process described above to offer initial pivot repair-or-replace recommendations to growers. Based on the study team’s belief that growers respond well to well-organized information, an evaluator who clearly presents quantifiable data to a grower illustrating where s/he can perform cost-effective remedies to pivot problems is more likely to find the grower willing to take those actions to improve DU, increase efficiency, decrease water and energy use, and improve crop uniformity. PEval assists the evaluator in generating an organized, highly information-dense report for the grower. Appendix A provides an example.

Evaluators can use PEval to discuss growers’ options and to describe quantitatively the benefits they should expect to achieve with varying levels of investment in repairs. For example, a grower with low energy costs may be reluctant to replace a full sprinkler package costing $3,500 to $5,000, but may be much more receptive to a $500 tune-up that achieves a significant improvement in crop uniformity.

### 3.7. Pivot Evaluation Calculator Results

PEval enabled the study team to analyze statistics for the thirty-one pivots evaluated in this study and to quantify opportunities for energy and water savings. Figure 8 shows the PEval results from the data and information collected for these demonstration pivots, using the preliminary sorting methods described in the previous sections. The PEval output summary provides overviews of the conditions observed on each of the pivots evaluated, the estimated costs of recommended repairs, and estimated improvements in DU after repairs.
### Figure 8. Summary DU Statistics and Recommendations for Each Demonstration Pivot Site

<table>
<thead>
<tr>
<th>Site</th>
<th>CU Before DU Before</th>
<th>Est. CU After Fix</th>
<th>DU After Fix</th>
<th>% Savings from DU alone</th>
<th>Cost of Fix</th>
<th>Replace?</th>
<th>Comment</th>
<th>Pareto Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Package Replacement Recommended</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>60.4%</td>
<td>94%</td>
<td>53.7%</td>
<td>91%</td>
<td>38%</td>
<td>$3,500</td>
<td>Y</td>
<td>Tune 17 areas only gets DU to 80%. Recommend replace package.</td>
</tr>
<tr>
<td>2</td>
<td>79.5%</td>
<td>94%</td>
<td>69.9%</td>
<td>91%</td>
<td>21%</td>
<td>$3,500</td>
<td>Y</td>
<td>Tune of 13 locations only bumps DU to 83.5%. Broad distribution suggests new package. Long BET due to low energy</td>
</tr>
<tr>
<td>3</td>
<td>82.9%</td>
<td>94%</td>
<td>74.7%</td>
<td>91%</td>
<td>16%</td>
<td>$3,500</td>
<td>Y</td>
<td>Highly variable pivot. Tuning 17 areas only gets DU to 84.6%, need to tune 2/3 of pivot to get to 90%. Replace package.</td>
</tr>
<tr>
<td>4</td>
<td>85.7%</td>
<td>94%</td>
<td>74.3%</td>
<td>91%</td>
<td>17%</td>
<td>$2,884</td>
<td>Y</td>
<td>Full Tune-up only gets DU up to 84.3%. Recommend a full package replacement.</td>
</tr>
<tr>
<td>5</td>
<td>86.8%</td>
<td>94%</td>
<td>81.6%</td>
<td>91%</td>
<td>9%</td>
<td>$3,612</td>
<td>Y</td>
<td>Highly erratic. Tuning 13 areas only gets DU to 82.4. Replace package.</td>
</tr>
<tr>
<td>6</td>
<td>87.0%</td>
<td>94%</td>
<td>77.2%</td>
<td>91%</td>
<td>14%</td>
<td>$3,472</td>
<td>Y</td>
<td>Replace package. Need to tune half of pivot to get DU to 90% but long payback time due to low energy costs</td>
</tr>
<tr>
<td>7</td>
<td>87.3%</td>
<td>94%</td>
<td>69.3%</td>
<td>91%</td>
<td>22%</td>
<td>$2,240</td>
<td>Y</td>
<td>Poor design or worn out. Replace package. Need to tune 1/2 of pivot to get DU to 90%.</td>
</tr>
<tr>
<td>8</td>
<td>87.5%</td>
<td>94%</td>
<td>74.3%</td>
<td>91%</td>
<td>17%</td>
<td>$3,500</td>
<td>Y</td>
<td>Borderline tune-up/replacement: small pivot needs 13 areas to achieve DU 91.9%. Low energy costs make long BET.</td>
</tr>
<tr>
<td>9</td>
<td>88.1%</td>
<td>94%</td>
<td>79.7%</td>
<td>91%</td>
<td>11%</td>
<td>$1,960</td>
<td>Y</td>
<td>Tune-up only gets DU to 83.3%. Highly erratic pivot needs package replaced.</td>
</tr>
<tr>
<td>10</td>
<td>88.3%</td>
<td>94%</td>
<td>75.8%</td>
<td>91%</td>
<td>15%</td>
<td>$3,332</td>
<td>Y</td>
<td>Very non-uniform DU. Fixing a dozen locations only gets DU up to 82% (sigma 1.7) Package is 12 yrs old. Due to extreme wear, replace entire package.</td>
</tr>
<tr>
<td>11</td>
<td>88.4%</td>
<td>94%</td>
<td>75.0%</td>
<td>91%</td>
<td>16%</td>
<td>$2,716</td>
<td>Y</td>
<td>Major Tuneup of 13 areas brings DU to 88%, and need 22 areas to get to 90%. Borderline replacement. Replace outer half?</td>
</tr>
<tr>
<td>12</td>
<td>88.4%</td>
<td>94%</td>
<td>75.0%</td>
<td>91%</td>
<td>16%</td>
<td>$2,716</td>
<td>Y</td>
<td>No quick fix. Tuning a dozen drops only gets DU 85%. Replace package.</td>
</tr>
<tr>
<td>13</td>
<td>88.8%</td>
<td>94%</td>
<td>79.5%</td>
<td>91%</td>
<td>12%</td>
<td>$2,884</td>
<td>Y</td>
<td>Very broad distribution. Repairing 14 areas only gets DU up to 87%, and 21 to get DU to 90%. Low energy leads to long BET.</td>
</tr>
<tr>
<td>14</td>
<td>89.3%</td>
<td>94%</td>
<td>84.1%</td>
<td>91%</td>
<td>7%</td>
<td>$450</td>
<td>Y</td>
<td>Repair 21 drops and boost DU over 90%. Recommend replacement</td>
</tr>
<tr>
<td>15</td>
<td>89.8%</td>
<td>94%</td>
<td>83.3%</td>
<td>91%</td>
<td>8%</td>
<td>$1,050</td>
<td>Y</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mean for Rec. Repl.</th>
<th>84.6%</th>
<th>75.1%</th>
<th>15.9%</th>
<th>$2,754</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Tune-up Recommended</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>93.2%</td>
<td>95.3%</td>
<td>84.0%</td>
<td>90.7%</td>
<td>6.7%</td>
<td>$550</td>
<td>N</td>
</tr>
<tr>
<td>17</td>
<td>92.9%</td>
<td>95.5%</td>
<td>84.6%</td>
<td>90.7%</td>
<td>6.2%</td>
<td>$500</td>
<td>N</td>
</tr>
<tr>
<td>18</td>
<td>85.8%</td>
<td>92.8%</td>
<td>84.6%</td>
<td>90.3%</td>
<td>5.6%</td>
<td>$200</td>
<td>N</td>
</tr>
<tr>
<td>19</td>
<td>93.5%</td>
<td>95.3%</td>
<td>84.8%</td>
<td>90.5%</td>
<td>5.7%</td>
<td>$700</td>
<td>N</td>
</tr>
<tr>
<td>20</td>
<td>90.3%</td>
<td>93.2%</td>
<td>85.2%</td>
<td>90.0%</td>
<td>4.8%</td>
<td>$950</td>
<td>N</td>
</tr>
<tr>
<td>21</td>
<td>93.1%</td>
<td>95.5%</td>
<td>86.7%</td>
<td>90.7%</td>
<td>4.0%</td>
<td>$310</td>
<td>N</td>
</tr>
<tr>
<td>22</td>
<td>93.6%</td>
<td>94.7%</td>
<td>86.8%</td>
<td>90.3%</td>
<td>3.3%</td>
<td>$500</td>
<td>N</td>
</tr>
<tr>
<td>23</td>
<td>92.0%</td>
<td>95.0%</td>
<td>87.0%</td>
<td>90.9%</td>
<td>3.9%</td>
<td>$250</td>
<td>N</td>
</tr>
<tr>
<td>24</td>
<td>90.0%</td>
<td>94.1%</td>
<td>87.0%</td>
<td>91.1%</td>
<td>4.1%</td>
<td>$450</td>
<td>N</td>
</tr>
<tr>
<td>25</td>
<td>92.1%</td>
<td>94.2%</td>
<td>87.5%</td>
<td>90.4%</td>
<td>2.9%</td>
<td>$450</td>
<td>N</td>
</tr>
<tr>
<td>26</td>
<td>92.7%</td>
<td>94.1%</td>
<td>88.3%</td>
<td>90.0%</td>
<td>1.7%</td>
<td>$300</td>
<td>N</td>
</tr>
<tr>
<td>27</td>
<td>93.4%</td>
<td>94.3%</td>
<td>89.6%</td>
<td>91.2%</td>
<td>1.6%</td>
<td>$200</td>
<td>N</td>
</tr>
<tr>
<td>28</td>
<td>94.8%</td>
<td>96.2%</td>
<td>90.0%</td>
<td>93.6%</td>
<td>2.6%</td>
<td>$300</td>
<td>N</td>
</tr>
<tr>
<td>29</td>
<td>94.1%</td>
<td>94.8%</td>
<td>91.5%</td>
<td>92.2%</td>
<td>0.7%</td>
<td>$50</td>
<td>N</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mean for tune-ups</th>
<th>92.3%</th>
<th>94.6%</th>
<th>87.1%</th>
<th>90.9%</th>
<th>3.9%</th>
<th>$379</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Serious Defects Rendered Pivots Untestable (but still in use)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>Untestable</td>
</tr>
<tr>
<td>31</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>Untestable</td>
</tr>
</tbody>
</table>

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Based upon the methodologies described in this report, the team recommended the actions shown in Table 1 for the pivots evaluated in this study. Forty-two percent of the pivots evaluated exhibited levels of variability high enough that the team recommended a full package replacement based on the defined criteria. Thirty-nine percent of the pivots evaluated would benefit from some tuning, with an average cost of less than $400. Thirteen percent suffered from systematic errors in which one portion of the pivot deviated significantly from the rest of the pivot. And six percent (two pivots) had defects sufficiently severe that the team could not perform a catch-can test prior to repairs.

<table>
<thead>
<tr>
<th>Recommendation</th>
<th>Number of Pivots</th>
<th>% of Sample (n=31)</th>
<th>DU Energy Saved</th>
<th>Estimated Avg. Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprinkler package replacement</td>
<td>13</td>
<td>42%</td>
<td>15.9%</td>
<td>$3,500</td>
</tr>
<tr>
<td>Tune-ups of specific areas</td>
<td>12</td>
<td>39%</td>
<td>3.9%</td>
<td>$400</td>
</tr>
<tr>
<td>Apparent design problems</td>
<td>4</td>
<td>13%</td>
<td>unknown</td>
<td>unknown</td>
</tr>
<tr>
<td>Untestable, requires major repairs</td>
<td>2</td>
<td>6%</td>
<td>unknown</td>
<td>unknown</td>
</tr>
</tbody>
</table>

Note: DU Energy Saved indicates potential energy savings attributable only to improvements in DU. Additional savings are possible through other types of pivot improvements.

Completing the recommended repairs on the pivots in this study, and confirming actual attainment of the estimated energy savings associated with improved DU, constitute important next steps beyond the scope of this study.

The left-hand graph of Figure 9 shows the histogram of DUs for all actual catch-can test results from the pivots evaluated in this study, with findings remarkably similar to those of prior studies (See Appendix A). The right-hand graph illustrates the anticipated (simulated) DUs after growers perform the recommended repairs.

Figure 9. Histogram Illustrating the Magnitude of the Opportunity
3.8. Efforts to Estimate Energy Savings and Economic Benefits

The study team intended that its developing prototype of PEval also provide the abilities to calculate an estimate of the potential energy savings associated with the recommended improvements, and an estimate of the break-even time for the grower to recoup the repair costs. Incomplete datasets for about half of the fields in this study precluded the accomplishment of these objectives. The study team believes this approach has merit, but it will require more development before it can report realistic estimates with sufficient confidence to make longer-term decisions about advancing the development of the program. This section explains the general approaches used, difficulties identified, and suggestions for future studies to overcome those difficulties. Appendix A provides more detailed descriptions of methods and issues.

3.8.1. Estimating Energy Savings Due to Improved Distribution Uniformity

In brief, the team used straightforward engineering equations embedded in the PEval calculator to estimate the theoretical energy needed to pump water to the pivot. The team assumes that energy consumption is inversely proportional to DU, so this component of energy savings is equal to:

\[
\frac{\text{Theoretical Energy Consumed}}{\text{DU after Repairs}} - \frac{\text{Theoretical Energy Consumed}}{\text{DU before Repairs}}
\]

While this method appears to have merit, the small sample size of this demonstration limited the results. Based on the partial dataset available from this study, the study team believes that future research will show that the break-even time for tune-ups will be less than the break-even time for a full sprinkler package replacement because of the significantly lower price point for a typical tune-up.

3.8.2. Estimated Energy Savings Due to Decreased System Pressure

The study team observed a majority of pivots in this study operating at suboptimal inlet pressures, in many cases more than twenty PSI above their ideal pressures. Evaluators also observed a few pivots with pressures insufficient to maintain adequate flow. Only one grower in the study had a strategy for using a Variable Frequency Drive (VFD) for optimizing pressure at each of his pivots to conserve energy, basing his strategy on which pivots were operating and the elevation of the highest point in the system. Optimizing system pressure can improve water and energy conservation, reduce wear on pivot components, improve water distribution, and improve crop yield and quality, suggesting possible areas of future study.

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16 When setting pump pressure, ideally a grower would determine the pressure needed at the highest point in the system. This pressure changes as the pivot goes up or down hills. It also changes if more than one pivot is supplied by the same pump, and if the grower doesn’t have the same pivots on all the time. Assessing these conditions real-time is nearly impossible for a grower, but could easily be accomplished by a computerized system in the future.
3.8.3. Estimating Energy Savings Due to Decreased Evaporation

The study team agreed that evaporative losses can also cause significant decreases in application efficiency, which wastes water and energy. Many previous studies report wind drift and evaporative losses as high as 45% (ASABE 2012), which would be reflected in decreased application efficiency numbers. In general, the smaller the water droplet, the more evaporative losses occur, and the lower the application efficiency. The team initially hypothesized that application efficiency could be improved to at least 85% if the grower selected an optimal spreader plate design that delivers larger droplet size, but this hypothesis proved speculative and overly simplistic.

The team was able to merely begin exploration of this complex subject. Sprinkler manufacturers provided the team with useful insights into the complexity of spreader plate selection. For example, coarser sandy soils tolerate large droplet sizes well; finer silt or clay soils tend to experience surface compaction caused by the impact of the droplet on the soil’s surface with droplets that are too large, resulting in unacceptable surface runoff. The team further suggests a future collaboration with sprinkler manufacturers to identify realistic recommendations and to measure the potential energy and water savings.

3.8.4. Other Sources of Economic Benefit

The study team also believes that the greatest effect of improving DU and application efficiency is improving the uniformity of crop vigor, ultimately increasing net yield and grower profit. Collecting and analyzing data to quantify this hypothesis was beyond the scope of this study.

3.9. Findings from Pivot Evaluation Methods Specific to Variable Speed Irrigation (VSI)

The study team had initially hoped to develop a simple and accurate method to measure pivot speed using a GPS, and to correlate that speed with the speed programmed into the pivot. However, the team ultimately had time and resources to make only one abortive attempt at collecting GPS data with sufficient precision to accomplish the objective. The team placed the GPS in a plastic bag and strapped it to the last tower of the pivot. Birds shredded the bag and dropped the GPS approximately one hundred feet (thirty meters) from the wheel track. The study team would like to refine this method in the future.

The team observed many cases in this study in which pivot tires lost traction as the pivot traveled uphill or downhill, slowing the pivot significantly on uphill climbs and accelerating its speed on downhill sections. If these variations in speed could be well-characterized, pivot software could adjust the pivot speed to compensate for the measured speed variations. Alternatively, other available hardware solutions could track and compensate for pivot speed control challenges.

Incorporating this resulting pivot speed into the calculations of DU could also provide field-level calculations rather than calculations based solely on data from a single sample.
3.10. Findings from Pivot Evaluation Methods Specific to Variable Rate Irrigation (VRI)

These 2014 pivot demonstrations included pivot evaluations on four VRI pivots from two major pivot manufacturers. This evaluation process proved highly problematic and outside the scope of this study, as described below.

A pivot evaluator on the study team attempted to verify VRI functionality on the two brands of pivots. VRI pivots have solenoid valves at each drop that are controlled by a central processing unit (CPU) in the panel. The central processing unit can turn individual drops on and off to vary application depths on the field according to the irrigation prescription; the process is analogous to an inkjet printer spraying droplets on a page, in a configuration based on computer input, to create text and images. The study team considers validating proper actuation of solenoid valves an important feature and attempted to confirm its functionality by verifying that nozzles turn on and off consistent with the instructions provided by the controller.

The team experienced challenges in trying to accomplish this objective for both brands of VRI pivots. Their general observations included the following:

- The team experienced issues with every pivot that had VRI capability; whether these were one-time issues or not proved difficult to determine.
  - Two nodes on one pivot had improperly-programmed media access control (MAC) addresses, so they did not receive instructions from the panel
  - The control boxes for one pivot had improper configurations, with the solenoid controls swapped for odd and even zones
  - Birds had completely torn off the antenna communicating to the control nodes on one pivot
  - Many of the pivots did not function properly when they were turned back on at the beginning of the second season
  - Several pivots experienced decreased efficiencies due to debris plugging the solenoid valves and blocking water flows
- One pivot brand included diagnostic programs, which could be even more useful with improvements in the depth of information.
- For the pivots from one brand, the study team created two complex checkerboard grid patterns – one pattern to verify whether the pivot nozzles turned on and off when instructed, and a second pattern to attempt to set percentage application rates. However, the test pivot failed to deposit a checkerboard pattern, and the evaluators lacked sufficient engineering experience with the device to create a useful pattern that was easy to read.
- In nearly every case, growers’ confidence that the VRI pivots performed as instructed suffered due to the absence of an understandable diagnostic for verifying functionality. This lack of trust by the growers led the study team in several cases to abort the use of VRI altogether for this study.

17 The team will provide brand-specific feedback directly to each manufacturer.
The study team had difficulty connecting with the proper engineering or support resources at the manufacturers of both brands for assistance with diagnostic activities.

In summary, the study team found both VRI pivot brands equally challenging and was unable to validate the success of VRI functionality. The study team strongly recommends that both pivot manufacturers invest in developing comprehensive diagnostic procedures that can be quickly and easily executed, and that they test the diagnostic procedures with real growers in the field.

3.11. Center Pivot End Gun Evaluation Method Results

Growers commonly use end guns on pivots to increase the effective area of production. Figure 10 shows a representative end gun in use. While some pivots in this study were outfitted with end guns, the study team did not test or develop methods to evaluate end gun performance.

NEEA and the study team discourage the use of end guns for several reasons:

- End guns require high-pressure operation, typically a minimum of seventy-five pounds per square inch (PSI) (517 kilopascals), while the rest of the pivot may require only twenty to thirty PSI (138 to 207 kilopascals) – a significant waste of energy
- Distribution uniformity for areas irrigated by end guns is ordinarily quite poor, resulting in much more variability in crop performance
- Evaporative losses are high due the distance and elevation of the end gun from the applied soil; water losses to wind drift and evaporation average about 40% compared to 15% for the rest of the pivot
- Because end guns rob water from the rest of the pivot, a grower runs the risk that the pump would be unable to deliver enough water/pressure to most of the system when the end gun is on.
- End guns also tend to have high maintenance requirements

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18 See the Overview of Center Pivot Irrigation Systems report for more information on end guns.
19 The scope of this study likewise excluded testing of the few corner or swing arms on the pivots evaluated.
3.12. Resource Requirements for Conducting Pivot Evaluations

Table 2 shows the estimated time requirements for each task in a pivot evaluation.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Comments</th>
<th>Typical Labor Hours/ Field</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel time</td>
<td>Varies</td>
<td>Varies</td>
<td>Required</td>
</tr>
<tr>
<td>Grower interview</td>
<td>Varies based on grower availability</td>
<td>1 hour</td>
<td>Required</td>
</tr>
<tr>
<td>System inspection</td>
<td>Varies based on pivot condition</td>
<td>30 minutes</td>
<td>Required</td>
</tr>
<tr>
<td>Pressure and flow</td>
<td>Attach portable Doppler Flow Meter</td>
<td>30 minutes</td>
<td>Required</td>
</tr>
<tr>
<td>Measure CU / DU</td>
<td>Faster with two people; two fields per day</td>
<td>7-10 hours</td>
<td>Required</td>
</tr>
<tr>
<td>Sprinkler dry inspection</td>
<td>Verify nozzle installation</td>
<td>1.5 hours</td>
<td>Optional</td>
</tr>
<tr>
<td></td>
<td>Nozzle wear: sample inspection</td>
<td>15 minutes</td>
<td>Required</td>
</tr>
<tr>
<td>Sprinkler wet inspection</td>
<td>Verify spreader plates function</td>
<td>15 minutes</td>
<td>Required</td>
</tr>
<tr>
<td>Pressure regulator testing</td>
<td>One person measures, second person records data</td>
<td>3 minutes per drop</td>
<td>Optional</td>
</tr>
<tr>
<td>Report generation</td>
<td>Generate report, deliver to grower</td>
<td>1-2 hours</td>
<td>Required</td>
</tr>
</tbody>
</table>

The starting price for conducting a pivot evaluation is approximately $500 to $600 per pivot; future improvements in methods may decrease this cost.
4. Risks and Challenges

Recognizing the risks and challenges associated with introducing these methods of pivot evaluation and recommended repair to the commercial production agriculture industry is important; addressing them may help to mitigate possible resultant push-back. Growers’ best financial interest means they must take steps to improve performance. The study team believes that the information provided to growers using the pivot evaluation process will create the required incentive to motivate change. Overall, the anticipated improvements in water and energy conservation and in return on investment to growers from implementing the methods recommended in this report far outweigh these risks and challenges.

4.1. Risks

- **Investing in routine pivot maintenance, in contrast to the longstanding practice of improving pivot function only through replacement of complete sprinkler packages, is not yet common grower practice. At replacement costs from $3,500 to $5,000 per pivot, growers frequently defer sprinkler package purchases until the sprinkler package is well past its useful life or until they are rotating into a high-value crop. With no effective pivot evaluation process yet available, growers have great difficulty justifying this replacement expense. Performing routine maintenance and tune-ups of pivot systems has the potential to more than pay for itself, saving growers money while improving their crop yields and profitability through energy and water savings. Continuing the current practice of replacing only entire sprinkler packages costs growers unnecessary time and money.**

4.2. Challenges

- **Proposed evaluation methods need more development:** While the prototype evaluation methods described in this document are promising, they will require significant additional development before they can be standardized and deployed at a commercial scale.
- **Effective use of diagnostics:** Some of the evaluation methods conducted by evaluators, such as flow rate and DU, can identify problems without confirming the sources of the problems. When data are inconclusive, the evaluator must conduct additional diagnostic evaluation methods on the pivot to identify problem sources before making final recommendations regarding the extent of repair required to improve DU.
- **Repeatability of diagnostics evaluation method results:** While catch-can tests do collect quantifiable data that can be translated into calculations such as DU, results can vary substantially from run to run. Wind can change the distribution uniformity, and evaporative losses vary significantly from day to day due to changes in weather. While the American Society of Agricultural Engineers (ASAE)\(^\text{20}\) standards recommend methods to mitigate these challenges, the team plans to continue development of improvements to the methods defined in the standards.

\(^\text{20}\) The American Society of Agricultural Engineers (ASAE) as of 2005 adopted its new name as the current American Society of Agricultural and Biological Engineers (ASABE).
• **Recommendations require subjective judgment:** Evaluators can organize quantifiable data that can improve a grower’s ability to make informed decisions. Each grower has the opportunity to modify or ignore those recommendations based on his/her individual operational objectives. This also complicates the ability to estimate total energy savings opportunities without extensive research. Developing more objective data sources, such as PEval, would allow growers and evaluators to examine implications of recommendations together.

• **Adoption rate:** While using the pivot evaluation process offers clear and tangible benefits, its adoption rate is likely to be slow due to lack of grower awareness and channel infrastructure. Utilities can accelerate the rate of market adoption by offering incentives and educational courses to growers. The study team anticipates that increasing growers’ awareness of the benefits will render pivot evaluation, repair, and maintenance common operational practices within a few years.

• **Lack of sufficient qualified service providers:** The anticipated increase in demand for pivot evaluations dictates the development and promotion of a training course to prepare professional pivot evaluators to offer this grower service in the market. An accredited certification would help to ensure the availability of experienced and qualified practitioners and a high-quality product.

• **Implementation of recommended repair:** Realization of potential improvements in water and energy conservation and productivity for a pivot depends upon implementation of the recommended repairs; thus, utilities should tie incentives to completion of the repairs. Evaluators should follow up on growers’ progress on recommended repairs and assist where needed.
5. Lessons Learned, Next Steps, Value of Findings

5.1. Lessons Learned

- Growers often defer center pivot maintenance, leading to wasted water and energy, and have little visibility into the economic impacts of this deferred maintenance.
- The availability of trained pivot evaluators to provide market-ready pivot evaluation services to growers, and the availability of better tools for “what-if” analyses, will be necessary to help growers shift their behavior.
- Using catch-can testing to measure DU is the most useful method identified for determining pivot performance.
  - Evaluators can analyze the results to identify problems with pivots for further diagnostic evaluations and can recommend either cost-effective tune-ups or new sprinkler packages, as needed. Further, they can quantify the benefits to the grower in tangible economic terms.
  - Catch cans should be equally spaced at intervals less than the minimum sprinkler head spacing so evaluators can pinpoint any drops that need repairs.
- The study team believes that growers respond well to data that warrant action, and that they will in general complete recommended pivot improvements based on data provided them by evaluators.
  - Growers are very likely to adopt low-cost pivot tune-ups.
  - Growers are more likely to spend $3,500 to $5,000 per replacement sprinkler package if they can see the quantifiable economic benefits of doing so.
- Few pivots run at optimal pressures.
  - The majority of pivots evaluated in this study are operating at pressures more than twenty PSI above or below their ideal pressures.
  - Only one grower in the study had a strategy to use a Variable Frequency Drive (VFD) for minimizing pressure at the pivot to conserve energy.
- Mounting pressure regulators at the bottom of the drop near the sprinkler head is preferable as it decreases the required inlet pressure by five to eight PSI.
- Conditions in the field can negatively impact evaluation results, and some simple precautions improve safety and results:
  - Wind has a strong impact on evaluation method results, and some styles of spreader plates are more prone to variation than others.
  - Evaluators should not conduct pivot evaluations during fertigation or chemigation events for safety reasons.
  - Performing a DU analysis in mature corn (or in any crop with a high canopy) will generate inaccurate data because the canopy deflects a significant percentage of the sprayed pattern.
  - Growers may not want evaluators trampling delicate plants to perform evaluations for some or all of the season.
  - Some growers time sprinkler upgrades with their crop rotations, realizing that high-value crops such as potatoes are more responsive to improved DU.
• Though the time window for conducting pivot evaluations is reasonably long, doing so becomes increasingly difficult as crops mature. Water must be running, which limits the season to April to November. Evaluating fields planted in corn becomes problematic as the canopy increases from early July to harvest.

5.2. Next Steps
As additional outcomes of this research, the team identified several opportunities for future development:

• Recommending further refinement, quality control, testing, and accredited certification of the evaluation tool and practitioners
• Determining a recommended time interval between pivot evaluations
• Clarifying the criteria for deciding when to replace the entire sprinkler package as opposed to performing extensive tuning
• Improving automation of data processing
• Improving methods for characterizing pivot speed
• Improving methods for evaluating Variable Rate Irrigation hardware
• Developing tools for setting pump pressures at the farm level

NEEA will consider conducting an expanded study to complete the development of the pivot evaluation methods and PEval tools, with a large-scale commercial launch to follow. Specific steps to achieve these goals would include:

• Deliver the pivot evaluation findings and recommendations for repairs to individual growers
• Complete the recommended repairs and confirm that the anticipated improvements in DU materialize as predicted
• Continue to refine and document the pivot evaluation process, providing the best return on investment for the growers
  o Test the process of distinguishing whether nozzles, regulators, or both need replacement
  o Add evaporation rate data into the spreadsheet
  o Improve the statistical methods in the spreadsheet analysis that identify which drops need repair
  o Develop a GPS-based speed test
  o Work with VRI manufacturers to create diagnostic procedures
  o Leverage the experience of current irrigation extension agents, manufacturers, and distributors to refine the process
  o Study evaporative losses as a function of spreader plate design and use the results to improve application efficiency
  o Study the repeatability of DU analyses, and identify methods to improve repeatability
• Develop a study course to train and certify pivot evaluators to provide market-ready pivot evaluation services to growers
- Recruit candidates for pivot evaluation certification from irrigation dealers, agronomy services, and universities
- Coordinate utility incentive development to accelerate market adoption
- Develop software-based tools to manage VFD pump pressures across the farm based on real-time pressure needs
- Adapt these methods for use with linear irrigation and Low Elevation Spray Application (LESA) systems; the methods are very similar, but have subtle differences
- Conduct grower research to determine the metric of most value in repair vs. replace decisions
- Conduct longitudinal research with a larger sample of pivots than this demonstration allowed, to facilitate collection of sufficient data to determine the ideal frequency of pivot evaluations

5.3. Value of Findings
The irrigation marketplace has a real need for improving center pivot performance. However, current methodologies, procedures, and personnel skills provide insufficient information and incentives to maximize the likelihood of growers implementing improvements. NEEA and regional utilities can take a leadership role in developing a robust set of pivot maintenance procedures such as those described in this report to reduce water and energy use.

For growers, implementation of repairs recommended after a pivot evaluation conducted by a professional pivot evaluator would help them save money, while maximizing crop value, in the following ways:

- Improving yield, uniformity, and quality while reducing inputs
- Improving distribution uniformity enables growers to reduce the amount of water they pump to meet minimum crop requirements across the entire field
- Selecting better sprinkler head designs can reduce evaporative losses
- Servicing worn parts such as leaky pipes, regulators, sprinkler heads, and repairing worn or broken gear boxes enables the grower to irrigate more uniformly, saving water and improving crop yield
- Optimizing system pressure enables the grower to reduce energy costs when the pressure is originally too high; conversely, it can improve water distribution and crop yield when the pressure is originally too low
- Minimizing overwatering reduces leaching of nutrients from soil

For industry professionals such irrigation dealers and the forthcoming trained pivot evaluators, ongoing pivot maintenance procedures would open up new streams of revenue through the provision of new services as well as through increased sales of components.

For pivot manufacturers, pivot maintenance procedures would lead to increased customer satisfaction and to increased aftermarket sales of components.
6. References


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21 The American Society of Agricultural Engineers (ASAE) as of 2005 adopted its new name as the current American Society of Agricultural and Biological Engineers (ASABE).
Appendix A – Detailed Methods Used in Pivot Evaluations

The body of this report provided high-level overviews of the methods used in this study. This appendix provides more detail on the methods and methodologies used in this study. This appendix complements the content in the report body, and is not intended to stand on its own.

The study team agreed that each evaluator on the team should use his best judgment to define the process for each evaluation, allowing flexibility to match pivot evaluation methods to the specific needs of the farm being evaluated. This caused some minor difficulties in compiling the data, since not all fields had identical datasets available for analysis. The team met regularly to discuss evaluation experiences, opportunities for process improvement, and how to design the process to deliver maximum economic value to the growers. These meetings facilitated use of the team members’ collective insights to rapidly improve their individual processes throughout the demonstration.

Following are detailed descriptions of the pivot evaluation methods in this study.

Background: Origins of the Pivot Evaluation Calculator Methods
Methods for measuring irrigation uniformity date back to the 1940s. In 1942, J. E. Christiansen devised a method for analyzing catch can data to provide a figure of merit for irrigation systems. This figure of merit is called the Coefficient of Uniformity (CU) in this paper; literature addressing this subject frequently calls it Christiansen’s Uniformity (also CU) in honor of its inventor.

In 2001, the New South Wales (Australia) Department of Primary Industries used Christiansen’s methods and equations to create a spreadsheet calculator to report CU. This calculator has evolved into a web-based application (NSW/DPI 2001).

Dr. Troy Peters (one of the authors of this paper) at Washington State University (WSU) modified the spreadsheet calculator in 2010, and has posted it on WSU’s irrigation website.22 This tool calculates CU, DU, and Application Efficiency based on catch can data.

In October 2014, Robert N. Low of Western AgTech Solutions, LLC expanded the functionality of the spreadsheet calculator and named it PEval. The study team observed growers deferring sprinkler maintenance because they had no tangible evidence that the expense of pivot repair or replacement offered adequate return on investment. The NEEA study team wanted to provide irrigation consultants and dealers with a straightforward, commercially-viable tool to calculate the financial benefits of pivot repairs.

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22 The spreadsheet is available as of December 2014 in the Highlights section on the right-hand side of the http://irrigation.wsu.edu page (Title: Center Pivot Distribution Uniformity Calculator).
PEval is still in an early prototype stage of development. The authors value any and all suggestions to improve its process, calculation methods, organization, and other features. The purpose of this appendix is to familiarize the reader with the tool and to document the primary issues for future reference by the study team.

**Background: Distribution Uniformity Testing**

The study team used the distribution uniformity testing method defined by the American Society of Agricultural and Biological Engineers (ASAE/ASABE)\(^{23}\) Standards Committee (ASAE 2001), the authoritative reference on this subject. The ASABE documentation for this method states:

> The purpose of this Standard is to define a method for characterizing the uniformity of water distribution of sprinkler packages installed on center pivots and lateral move irrigation machines. This test produces data to be used in computing the coefficient of uniformity, which can assist in system design and/or selection, and can be used to quantify certain aspects of system performance in the field. The coefficient of uniformity is only one factor in evaluating total system performance. Application rates, runoff, wind, amount of water applied, pump performance, and overall system management can greatly affect the total performance of irrigation systems (ASAE 2001).

The team followed most of the specifications in the ASAE/ASABE standard, with some minor exceptions to reduce costs. For example, some evaluators performed some tests with catch cans on twenty-foot (six-meter) spacing, whereas the standard specifies a test distance of not more than the minimum drop spacing; in addition, they performed only a few tests with the recommended two rows of catch cans. In retrospect, the study team agreed that performing the tests on centers less than the minimum drop spacing would be an extremely important test criterion for pinpointing specific problems, and that doing so would be well worth the additional labor.

Numerous previous studies have used this method to analyze CU and DU. McCann and Adkins (2007) promoted on-farm evaluations to “identify uniformity problems that cannot be seen visually.” The values for CU McCann and Adkins reported closely reflect the results in this NEEA study, summarized in the histogram shown in Figure 11.

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\(^{23}\) The American Society of Agricultural Engineers (ASAE) as of 2005 adopted its new name as the current American Society of Agricultural and Biological Engineers (ASABE).
McCann and Adkins further asserted that “If the CU was above 85%, the system was performing well,” but they did not substantiate that assertion. They appear to assume that a suitable goal value for CU should be based on what currently exists in the field (see Figure 11) without considering the possibility of tuning specific areas. Looking only at the overall CUs achieved (or in the case of this NEEA study, also at DUs) eliminates the opportunity to repair variations that exist even on brand-new installations.

King, Stark, and Kincaid (2011) also conducted a study promoting the concept of CU testing, and made a compelling argument regarding the magnitude of the economic impact of improving CU. They asserted that “Center pivot and linear-move irrigation systems equipped with new pressure-regulated, low-pressure sprinkler packages are capable of attaining CU values of 90 to 95 percent.” The NEEA study team estimated that a well-tuned pivot could achieve a CU of 94.6%, substantiating the results of King, Stark, and Kincaid.

King, Stark, and Kincaid further asserted that “A CU value of 85% is generally considered to be the minimum value below which a system needs updating or maintenance” with reference to neither the source of this goal percentage nor data to support it. As explained below, the NEEA team strongly believes that tune-ups, even on newly-installed sprinkler packages, can significantly improve this goal CU.
Almasraf, Jury, and Miller (2011) also used catch-can testing to study CU on ten pivots in Michigan. Their report has many similarities to the NEEA study, including that repairing areas of excessive variation can improve CU and DU and noting the importance of spreader selection. Their report even recommends

24 that “Regular system maintenance is necessary including repair, adjustment or modification to keep the system operating efficiently. If CUs are periodically measured (at least annually), system repairs and adjustments can be scheduled when coefficients fall below the desired values. This will save operation costs and conserve water,” without reporting goals for CU or DU, or offering any specific methods. Inspection of the graphs of their catch can results in their report appendix shows that six of the pivots they tested would benefit significantly from tune-ups, and four showed sufficient variability to suggest replacing the sprinkler packages.

Method: PEval Inputs and Resulting Outputs
PEval is designed so that all inputs are inserted into cells on the Main worksheet, and are highlighted in yellow for easier navigation.

PEval provides several layers of functionality, which emerge as an evaluator provides additional inputs.

- At the most basic level, the evaluator need only input the farm and field location, the catch can spacing, the catch can diameter, and the catch can volumes; with this information, PEval will calculate CU and DU, plot the application depth for each can, and create a histogram of the catch depths. This most basic information fully characterizes the current condition of the pivot.

25 All of the CU and DU calculations in PEval occur on the Main Sheet. Adding rows or columns to the sheet will “break” the functionality of the sheet, which requires additional editing to accomplish.

- When the evaluator inputs a “Target Variation” (explained in detail later), PEval identifies which locations on the pivot exhibit more variation than the target and how many areas should be diagnosed and repaired. It also reports the simulated CU and DU after those areas are repaired.

- To estimate the cost of a pivot tune-up compared to the cost of replacing the entire sprinkler package, the evaluator needs to input the number of drops, the estimated cost per drop for tuning, and the estimated cost per drop for a sprinkler package.

26 For this study, the team estimated a cost of $50 per drop to tune each identified area, and $28 per drop for replacing the sprinkler package.

- To estimate energy savings and break-even time, the evaluator must input several additional measurements: measured inflow rate (gallons per minute supplied to the pivot), total dynamic head, estimated pumping efficiency,27 pivot inlet pressure, electricity cost in dollars per kilowatt-hour, estimated pumping hours per year,28 percentage speed setting used during the evaluation, distance to the last tower, the distance the last tower traveled over a specific elapsed time, and the total wetted radius of the pivot.

24 (Almasraf, Jury, and Miller 2011) Recommendation #3, page 22
25 All of the CU and DU calculations in PEval occur on the Main Sheet. Adding rows or columns to the sheet will “break” the functionality of the sheet, which requires additional editing to accomplish.
26 For this study, the team estimated a cost of $50 per drop to tune each identified area, and $28 per drop for replacing the sprinkler package.
27 Ideally, the evaluator would measure pump efficiency, but doing so in this study was beyond its scope. As a result, the study team estimated pump efficiency. For systems with one pump, the study team assumed 60% efficiency (meter to water). For a pump with a booster station, the study team assumed 60% efficiency for each of

NEEA - 35
PEval includes fields in the worksheets into which the evaluator can input additional useful notes, such as:

- Pivot description, sprinkler package age and description, presence or absence of end guns or swing arms, weather conditions, or other general notes specific to the pivot
- The span number of the pivot associated with each can
- Additional information for the evaluator’s or grower’s reference, not currently used in calculations includes designed inflow rate, which can be compared to the measured inflow rate, and end drop pressure to verify the delivery of sufficient pressure to all drops on the pivot
- Finally, the evaluator can document his/her recommended changes for consideration by the grower

**Method: Using Target Variation to Identify Areas to Tune**

As described in Section 3.6, the study team had to choose specific threshold levels to determine whether a pivot qualified for a tune-up or for a full replacement package. To help the team accomplish this goal, PEval reports the number of standard deviations (or sigma) away from the mean volume of water measured in each catch can (found on the Main sheet). This method simply stratifies the amount of variance for each can to facilitate data sorting. The team used Excel’s conditional formatting feature to stratify the variation graphically in addition to the numeric value reported.

When the evaluator inputs a “Target Variation” goal, PEval compares the variation for each catch can with the target; if the variation for that can exceeds the target, Excel highlights the cell in red and labels it “Repair” (found on the Main sheet). PEval counts the number of cells labeled for “repair” at that Target Variation value, and reports it in the appropriate cell. The evaluator can change the value input into Target Variation to simulate varying scenarios, resulting in different numbers of drops recommended for repair.

This method proved quite useful, albeit somewhat cumbersome and subject to a significant degree of subjective judgment by the evaluator processing the data. The PEval developers should create an improved approach before PEval is deployed in a commercial setting.

Setting the value for the Target Variation is a subjective process, open for future debate and requiring further development. For this study, the evaluator started the analysis with the Target Variation set at 1.5 sigmas, and then checked to see whether the simulated DU met or exceeded 90 percent. A simulated DU exceeding 90% indicated that repairing fewer areas would still allow achievement of a minimum simulated DU of at least 90%, in which case the evaluator increased the Target Variation. A simulated DU of less than the 90% goal indicated that more areas needed repairs, so the evaluator increased the Target Variation. Using this process, the two pumps, for a net efficiency of 36 percent. The team recommends expanding the evaluation in future studies, and measuring pump efficiency using existing methods.

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28 This study used an estimate of 2,100 pumping hours per year.
29 “Repair” is simply shorthand for areas on the pivot flagged for further diagnostic testing and repairs
30 The 90% target for DU is arbitrary and is subject to further discussion.
evaluator iteratively identified the number of drops required to tune the pivot to achieve the DU goal of 90 percent.

If the resulting number of drops recommended for repairs to achieve the 90% goal exceeded about one-third of those on the pivot, the evaluator deemed the variation great enough to warrant a replacement package.

In addition to its cumbersome and subjective limitations as explained above, the study team members identified one significant technical flaw with the approach, which they discovered after completion of much of the analysis for this year’s data. PEval currently identifies areas to repair based only on the standard deviation from the mean, without regard to their locations on the pivot; in essence, PEval currently weights inner drops that irrigate a small area equally with outer drops that cover a large acreage. To maximize growers’ rates of return for repairs, PEval’s developers should modify its formulas to weight the sorting algorithm to account for the effect of location on the pivot.

Figure 12 shows a sample Grower Report generated by PEval.

- The graph on the left shows all of the catch can data from the catch-can test results
- The graph on the right shows the simulated pivot performance after the recommended tune-ups
- The column shown on the entire right-hand edge of the report illustrates the areas of variation; the areas recommended for repair are highlighted in red
- The evaluator’s recommendations are listed at the bottom of the report
Figure 12. Sample PEval Report
Final Analysis and Decisions Rest with the Grower
Many of the twelve pivots that the evaluators identified for tune-ups in this study would be relatively easy to tune to achieve the 90% goal. The sample PEval Grower Report shown in Figure 12 offers the grower one obvious scenario (in the middle of the report marked by the red bracket): tune two areas and improve the DU from 84.6% to 90.5% with a break-even time of much less than one year.

Not all recommendations are so clear-cut; many require subjective judgment and grower participation in the decision. For example, demonstration pivot number 20 (noted with a blue arrow in Figure 8/ Summary DU Statistics and Recommendations) exhibited sufficient variation to necessitate tuning eighteen areas to achieve a DU of 90 percent. Further analysis of this dataset shows that tuning only seven areas would achieve a DU of 89.1%, and that tuning only four areas would yield a DU of 88.9 percent. The marginal return on investment in this case is so small that the grower may choose to tune only four areas. In this example, the drops in the first fifty cans (or inner 500 feet) (152 meters) had application depths about 20% higher than those for the rest of the pivot; since the area for these drops is small, the impact on DU is small. This constitutes a minor design problem that a minor tune-up itself could not easily fix. The evaluator would share these observations and options with the grower; based on personal preference, the grower could select the level of investment appropriate to his/her operation and budget.

This example shows application efficiency exceeding 100%, suggesting the application of more water than the amount pumped through the pivot, which is impossible. The evaluator identified the cause as a too-short measurement of the distance to calculate pivot speed (in this case, only one hundred feet, or thirty meters). Future studies can easily avoid errors such as this by measuring a longer distance (and longer elapsed time), at least 300 feet (ninety-one meters). Because this error clearly drove an unrealistic application efficiency percentage, the evaluation team did not attempt to calculate efficiency gains associated with potential reductions in evaporative losses for this pivot.

Prior to PEval, growers had no data-driven method to identify the cost-effective point at which to replace a sprinkler package. With a PEval Grower Report, the grower has tangible information to facilitate making informed financial decisions about maintaining the performance of their pivot.

Method: Operating Pressures and Flow Rates
This set of tests determines whether the flow rate of the pivot at pressure is consistent with the design specifications listed on the manufacturer’s sprinkler chart. If the pivot flow rate is not consistent, the evaluator can use these tests to uncover clues behind the causes of the inconsistencies.

Pivot flow rates significantly below the designed flow rates may indicate nozzle or regulator plugging. Flow rates significantly higher than the designed flow rates may indicate nozzle and regulator wear, or excessive leaks.
The operating pressure should be sufficient to overcome friction losses, account for the pivot elevation gain at the highest point in the field, and still have pressure that is about five PSI greater than the regulator pressure rating. A typical pivot experiences friction losses that result in a reduction of about ten PSI from the center of the pivot to the outer drop. Excessive pressure at the pivot point indicates opportunities for energy savings, either by altering the pumping pressure through the use of a Variable Frequency Drive (VFD) or by trimming (maching) the pump impeller.

The evaluators used the GE Panametrics AT868 flow meter for all testing in this study, and used UTXDR Ultrasonic Flow 2MHz Transducers for two- to eight-inch (five- to twenty-centimeter) pipes. For pivots with flow meters already installed, the evaluator recorded the flow rates on both devices and compared the results.

**Method: Diagnostic Tests**

These tests can aid in diagnosing possible cause(s) of poor DU or CU performance once the problem areas are identified by the evaluator.

*Sprinkler Dry Inspection* helps to ensure that the right nozzles are installed per the sprinkler chart and that the nozzles are not excessively worn. In some cases, the wrong nozzle may be installed on one or several drops.

While sprinklers have different designs and operating characteristics, the parts such as nozzles that are exposed to high pressure and fast-moving water wear over time, especially if the water is dirty or sandy, and eventually the nozzles become slightly larger. Larger nozzles will in turn create sprinkler flow rates higher than those for which they are designed. To evaluate nozzles for wear, evaluators measured nozzle diameters on a small sample of nozzles using a feeler gauge or the blunt end of a fractional drill bit.

*Sprinkler Wet Inspection* verifies whether the spreader plates on each sprinkler head are operating properly.

Sprinkler heads are equipped with a variety of spreader plates: some spin, some wobble. With the pivot running, evaluators inspected each drop to determine whether the plate was moving consistent with its design. Evaluators also noted drops with unusually high or low flow rates.

Most sprinkler charts report the designed flow rate for each drop in the pivot. This is customized by installing nozzles of varying diameters in each drop of the pivot, designed by custom software at the irrigation dealership. To confirm whether the flow rate of any given drop matched its designed value, the evaluator used a bucket and a stopwatch to measure flow rate. One evaluator slid a six-foot (1.8-meter) long piece of four-inch (ten-centimeter) PVC pipe over the sprinkler head, thus directing the flow into the bucket and facilitating much more accurate flow rate measurements.
Pressure Regulator Testing verifies whether the pressure regulators on sprinkler drops are functioning properly.

Each evaluator tested pressures on several sprinkler drops using a Pitot tube-style pressure gauge and a sampling plan based on their individual judgment.

While the study team considers this test quite important, performing it in the field proved problematic. The results are most accurate when the Pitot tube is placed in the stream of water just outside the nozzle, as shown in Figure 13. Doing so normally requires removing the spreader plate and replacing the spreader plate with the water flowing, which can be difficult. If the Pitot tube is small enough, it may be placed inside the nozzle; however, if it blocks flow in the nozzle, the restricted flow will yield a pressure reading higher than the actual pressure.

Pressure regulators may vary slightly from their designed operating pressures. However, measured pressures that differ significantly from the operating pressure for which the regulator is rated indicate that the pressure regulator is worn and is no longer functioning properly, or that it is plugged.

Method: Variations in Pivot Speed
This test verifies whether the measured speed of the pivot matches the speed input on the panel.

Measuring the distance the pivot travels over an elapsed time is a crucial input for calculating application efficiency. Evaluators marked the location of the pivot with a flag at the start of the DU test, and again at the end of the DU test, and recorded the time and distance that the pivot had traveled. These calculations are quite sensitive to small fluctuations in time and distance, so the team recommends allowing the pivot to travel at least 300.0 feet (91.4 meters), reporting to 0.1 foot (three-centimeter) accuracy, and measuring time to a precision of one second.
One evaluator successfully measured speed using the elapsed time for the full irrigation rotation from data found in the panel software.

In this 2014 study, evaluators measured only pivot speeds for distance divided over time (see Distribution Uniformity Testing earlier in this appendix), used to calculate application efficiency.

The study team considered methods for accurately measuring pivot speed as a function of pivot angle. While development of such methods is outside of the scope of this demonstration, the study team suggests a future method incorporating the following:

- Mount a portable GPS (permanently or temporarily) to the end of the pivot
- Turn on the “Tracks” feature
- Operate the pivot for one or more rotations
- Export the “Tracks” file to a spreadsheet
- Analyze the results and report the pivot speed as a function of angle

Incorporating this resulting pivot speed into the calculations of CU and DU would provide field-level figures of merit rather than figures of merit based only on data from a single sample.
Appendix B – Irrigation System Characterization: Grower Interviews

The study team interviewed each grower participating in this study, usually on more than one occasion during the season, with the goal of gaining a solid understanding of the grower’s constraints, farm culture, irrigation strategies, and areas with opportunities to improve operations, while at the same time building the relationship with the grower.

The team found that a current, accurate sprinkler package chart is a very valuable asset in performing pivot evaluations. Sprinkler package charts show the exact configuration of the pivot, tower location, operating pressure and flow rate specification, location of every drop, and the specified regulator pressure, nozzle size, and spreader plate style on every drop – basically every element of the pivot configuration that was custom-designed for that field and that pivot. Evaluators can use these charts to confirm that the installation matches the design. The study team found that although growers frequently did not have these charts available, they proved to be valuable aids in the analysis in those cases for which they were available.

The study team compiled a list of the questions they had asked growers, along with information that growers had volunteered to them with the hope that it would help the study team to better understand the farm and its operations. The study team observed that many of these questions point to opportunities for systematically conserving electricity and water in the future. The team recommends using these questions to seed future NEEA scanning activities and to facilitate the expansion of applications for PEval beyond pivots to all aspects of the irrigation system.

- What are common operational problems faced in irrigation?
- What are the idiosyncrasies of the farm and irrigation system that create operational problems?
- What is the general layout of the irrigation system in terms of:
  - Total Dynamic Head
  - Length of pipe, pipe diameter(s), and material of mainline
  - VFD or direct drive?
  - Filtration
  - Water source (well or surface water)
  - General water quality (such as pH, sand content, sludge)
  - Age of the key components in the system
  - Has the system undergone the addition of fields or other modifications since inception?
  - Specifications of current pump and motor (name plate information)
  - Specifications of any booster pumps (name plate information)
  - How does the grower invest in periodic maintenance – how often does s/he service the pump bowls?
  - How many pivots run off of each bank of pumps?
  - How many fields can the grower irrigate at the same time?
- What are the pump operating pressures, and the reasoning behind those pressures? How does the grower decide the pressure at which to run the VFDs?
- Does s/he have pressure and flow problems?
- Which brand of pivot and model of panel is installed on the pivot being evaluated?
• Does s/he run swing arms or end guns?
• Has s/he made any after-market improvements to the pivot? (e.g., AgSense Field Commander, Lindsay FieldNET software, Valmont Base Station)
• Sprinkler brand and model; spreader plate type and why chosen; year installed?
• How old are the regulators? (should match sprinkler chart)
• How old are the sprinkler heads? (should match sprinkler chart)
• What does the grower’s typical irrigation schedule look like (and why) and how does it change with the season or crop?
  o What is the typical crop rotation on this pivot?
  o Document the typical irrigation strategy.
  o What troubles does the grower encounter during an irrigation season?
  o How much trouble does s/he have with run-off?
  o What does s/he like and dislike about his/her irrigation?
  o What height above the crop are the drops?
  o Does the grower wrap the drops when irrigating corn?
• What areas in the field yield well or poorly, and how does the grower explain these variations?
  o Are recent aerial photos available?
  o Are last year’s yield maps available?
• What is the pivot maintenance plan, and how often are sprinkler packages replaced?
• What are the current electricity rates?
• Recognizing s/he is very busy, what methods of communication does s/he prefer?

An evaluator’s staff members must be specific in terms of when they plan to be in the field and ensure that the grower is not planning chemical application during the testing period. The evaluator should reconfirm this on the day of the visit to ensure evaluator staff safety, given that farm operational plans change on a daily basis.