Irrigation Science (2020) 38:569–575
https://doi.org/10.1007/s00271-020-00667-2

ORIGINAL PAPER

Economic feasibility of conversion to mobile drip irrigation in the Central Ogallala region

Sydney Reynolds[1] · Bridget Guerrero[1] · Bill Golden[2] · Steve Amosson[3] · Thomas Marek[3] · Jourdan M. Bell[3]

Received: 13 September 2019 / Accepted: 11 February 2020 / Published online: 2 March 2020

Abstract
As groundwater levels continue to decline in the Ogallala Aquifer, stakeholders, policymakers, and producers encourage the adoption of new irrigation technology in an effort to conserve groundwater, extend the economic life of the aquifer, and enhance profitability. One such technology currently receiving attention in the Central Ogallala region is the mobile drip irrigation (MDI) application system. This study compares MDI to low elevation spray application irrigation by evaluating the changes in variable cost per hectare to calculate the payback period for a MDI system under three levels of investment cost for grain and fiber crops representing three levels of water use while holding yield constant. Using a 3% discount rate, under the medium level of investment cost ($371 per hectare), a discounted payback period of 4.9, 9.0, and 6.3 years is required for corn, cotton, and sorghum/wheat, respectively. As the cost per hectare to convert an existing center pivot drops to $185 per hectare, the payback period also drops to 2.3, 4.2, and 3.0 years, respectively. Thus, producers growing higher water use crops are able to recover the costs of the conversion to MDI through increased water use efficiency quicker than producers growing medium and lower water use crops.

Introduction

Many rural communities overlying the Ogallala Aquifer rely heavily on irrigated agriculture, and this is undoubtedly true in the central region of the aquifer. This area is facing the challenge of maintaining agricultural production with the current rate of decline in aquifer depth. The Central Ogallala region is a key producer of several agricultural products that have been traditionally irrigated from the aquifer including corn, cotton, sorghum, and wheat. Irrigated yields from 2014 to 2018 for these crops in the Texas Panhandle have averaged 12,428 kg/ha for corn, 1222 kg/ha for cotton, 5837 kg/ha for sorghum, and 3497 kg/ha of wheat (National Agricultural Statistics Service 2019). These crops received an average price, over the same five-year period, of $0.15, $1.41, $0.14, and $0.17 per kg, respectively (Texas A&M AgriLife Extension Service 2019), Table 1.

In this region that averages less than 0.51 m of rainfall annually, the aquifer is being depleted beyond sustainable levels (Kansas State University 2019). To cope with the limited water availability, producers are considering more efficient irrigation systems as a feasible method of reducing water use. The application efficiency of irrigation methods varies considerably between systems. Amosson et al. (2011) reported traditional furrow irrigation systems to have only 60% efficiency whereas subsurface drip irrigation (SDI) is the most water-efficient irrigation system overall with an application efficiency of 97%. In between these systems, low elevation spray application (LESA) from a center pivot provides a nominal reported application efficiency of 88%. While the effectiveness of an SDI system is a definite advantage, the significant costs associated with the installation and maintenance of an SDI system can be prohibitive to producers. A relatively new development in irrigation, mobile drip irrigation (MDI), has been reported in research trials to provide similar application efficiency to SDI. O'Shaughnessy and Colaizzi (2017) reported the efficiency of MDI to be greater than that of LESA. Although the authors discussed MDI and SDI, there are no current direct comparisons

---

Communicated by Daran Rudnick.

✉ Bridget Guerrero
bguerrero@wtamu.edu

[1] Department of Agricultural Sciences, West Texas A&M University, Canyon, TX 79016, USA

[2] Department of Agricultural Economics, Kansas State University, Meridian, TX 76665, USA

[3] Texas A&M AgriLife Research and Extension Center, Amarillo, TX 79106, USA

Table 1 Average prices and yields for alternative crops, 2014–2018 (National Agricultural Statistics Service 2019; Texas A&M AgriLife Extension Service 2019)

Crop	Unit	Price ($/kg)	Yield (kg/ha)
Corn	kg	0.15	12,428
Cotton	kg	1.41	1222
Sorghum	kg	0.14	5837
Wheat	kg	0.17	3497

between these systems reported in the literature. However, the efficiency of MDI reported by O'Shaughnessy and Colaizzi (2017) for corn was comparable to the efficiency of SDI for corn reported by Howell et al. (1997). Of significance, Howell et al. (1997) discussed that efficiencies of SDI are dependent on crop emergence. In semi-arid environments with variable precipitation, it is often challenging to germinate a crop with SDI, whereas higher germination may be possible with MDI. Additionally, the installation cost of MDI is lower per hectare, including the advantage of using center pivots that may already be in place. While these new application systems have increased water use efficiency for many producers, it must be economically feasible for widespread adoption.

This study examines the economic feasibility of producers investing in the conversion to MDI. Specifically, three levels of investment for converting an existing center pivot to MDI are evaluated, and the changes in total variable costs per hectare when converting from LESA to MDI are calculated for low, medium, and high-water use crops. Under each level of investment, the discounted payment method was used to determine the number of years for payback of the investment in MDI technology for each crop, holding yield and commodity prices constant.

Materials and methods

Study area

The study area was the central region of the Ogallala Aquifer, and the researchers specifically focused on the Texas Panhandle and Southwest Kansas, Fig. 1. The Handbook of Texas (Rathjen 2010) outlines the Texas Panhandle as the 26 northernmost counties bounded by New Mexico to the west, Oklahoma to the north and east, and the southern border of Swisher County to the south. Southwest Kansas is defined in this study as the 12 counties that comprise Kansas Groundwater Management District 3, which stretches from the northernmost border of Hamilton County, east to Finney County, and then south to the Oklahoma border and also includes Ford County. The Ogallala Aquifer is the primary source of water for irrigated agricultural production in the region, accounting for approximately 30% of all groundwater used for irrigation in the United States. Underlying portions of eight states in the Great Plains, the aquifer stretches across roughly 453,248 square kilometers of land that produces nearly a fifth of the United States' wheat, corn, cotton, and cattle (National Resources Conservation Service 2012; McGuire 2017).

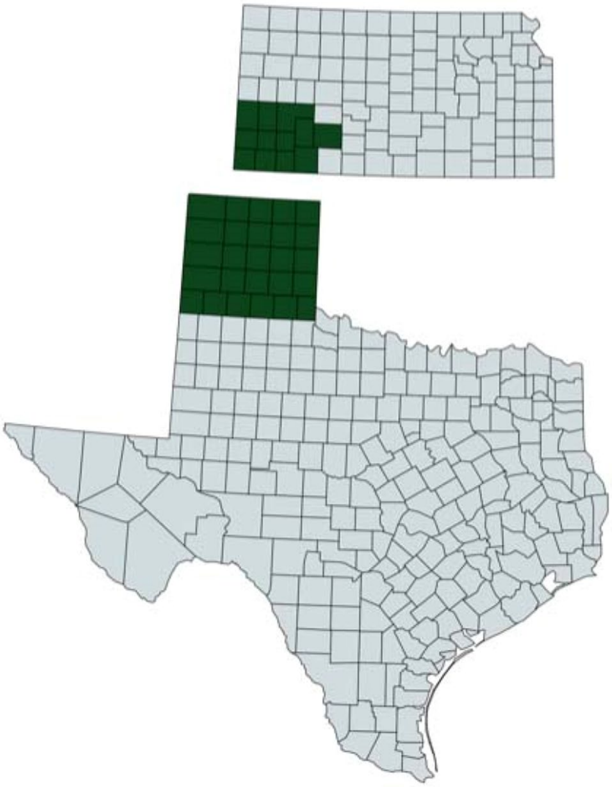
Fig. 1 Central Ogallala Region Study Area

Characteristics of LESA and MDI irrigation systems

In this study, LESA was used as the baseline irrigation application system. This system utilizes a center pivot that disperses water from an applicator 0.30 to 0.46 m above the soil surface, ideally spaced no more than 2.03 m apart (Amosson et al. 2011). Each of the applicators is connected to a drop hose extending from a furrow arm off the mainline with a weight directly above the nozzle to assist with limiting hose movement from wind and allowing the applicators to work even with crops planted in straight rows. Generally, LESA systems wet less foliage allowing for greater water use efficiency and, potentially, less insect damage on damp crops. LESA application efficiency rates are between 85 and 90%; however, it may be lower on broadcast or lower profile crops (Amosson et al. 2011). In this study, an application efficiency rate of 88 percent was used for analysis. As the application rate may exceed that of the rate of soil infiltration, low soil–water uniformity has been observed with the redistribution of applied water (Kisekka et al. 2017).

MDI technology combines the high irrigation efficiency of SDI with more conventional center pivot technology. Initial work was done as early as the 1970s, but current MDI technology was first patented in 2001 (Thom 2001). In this type of system, existing sprinkler nozzles are replaced with drip hoses which drag behind the center pivot such that water is applied directly on the soil surface. In theory, this process should reduce evaporation losses and possibly increase crop yields. Overall, this system has the potential to reduce water losses significantly due to reduced wind drift, soil water evaporation, and canopy evaporation due to the more direct application of water with the goal of capturing the efficiency of drip irrigation at a lower cost than some other micro-irrigation methods, particularly in lower-value crops (Kisekka et al. 2017).

Additionally, with many soils and cropping systems, excessive center pivot wheel track depth can be problematic. Since MDI drip hoses apply irrigation water behind the wheels, the tires run on dry ground, preventing or reducing expensive drive train repairs and end of season wheel track maintenance. The MDI system contains weights on the lower end of the draglines which serve to provide consistent placement of the hoses as they move around the center pivot (Thom 2001). However, Olson and Rogers (2008), Kisekka et al. (2017), and O'Shaughnessy and Colaizzi (2017) all noted the potential problem of MDI hoses traveling into the crop; although in field trials, this damaged corn leaves but did not harm the ears. Reversing the pivot system can also be an issue with MDI, particularly on the outer regions of the pivot where hose length is longer. Other issues that have been noted by producers are that of varmint damage to the draglines (Yost et al. 2019). Maintenance estimates for these MDI based issues have not been documented.

Initial studies of MDI systems indicated positive efficiency advantages were not significant enough to overcome management issues that occurred such as decreased water flow due to clogging (Olson and Rogers 2007). More recent studies have shown design improvements to overcome these initial issues with no significant yield or labor differences, and MDI was shown to increase soil water storage levels (Kisekka et al. 2016, 2017). Moreover, the additional benefits of reduced wheel track rutting, improved field conditions, and reduced runoff potential have resulted in considerable producer interest (Olson and Rogers 2019).

Economic analysis

The economic comparison relies on techniques developed by Delano et al. (1997), O'Brien et al. (1998), Amosson et al. (2011), and Lamm et al. (2015). Partial budgeting and net present value (NPV) analysis were applied to assess the economic feasibility of modifications to the new irrigation technology. Net present value comparison is a standard method used to compare long-term projects. The calculation discounts future cash flows to present values and sums the flow of all money over time, to be evaluated in present-day dollars. The use of net present value is a reasonable method to use when comparing investments or project costs. Comparable to Guerrero et al. (2016), a cost–benefit analysis was performed to assess the number of years of use that would be required to cover the cost of conversion to MDI.

Investment costs vary significantly between producers. Based on communication with producers and irrigation equipment distributors, a range of investment costs from $185 to $556 per hectare was established (Dragonline Irrigation Personal Communication 2019; Teeter Irrigation Personal Communication 2019; H. Grall Personal Communication 2019; T. Moore Personal Communication 2019; Gaines 2017). Furthermore, T-L Irrigation (Personal Communication 2018) quoted an extensive partial retrofit of an existing 0.40 km center pivot at just over $20,250, or $400 per hectare for a 51 hectare field. The actual cost incurred by an individual producer is dependent on several factors including the design and age of the current center pivot, the spacing of drip hoses, location and size of fields, filtration or chemical requirements of wells, and any additional equipment required for conversion. To account for these varying levels of investment cost, a baseline cost of $371 per hectare (medium) was used, in addition to $185 per hectare (low) and $556 per hectare (high) in conversion costs. This allowed for the payback period to be calculated based on several different levels of investment to provide a range of possible outcomes.

Discount rates of 0, 3, and 6% were used to calculate the net present value at each level of investment. The discount rate varies by producer depending on if conversion funds were borrowed for payment of the system, the amount borrowed, and the interest rate obtained. Moreover, the producer's level of risk adversity or uncertainty about future cash availability will also change the effective discount rate. A higher discount rate results in a higher net cost under each level of investment. Amosson et al. (2011) estimated a useful life for center pivot and subsurface drip irrigation systems to be 25 years with a salvage value of 20%. Although some system components can last 25 years or more, depending on many factors such as care and maintenance, conservative measures for MDI system life and salvage value were utilized in this study. Thus, a 10% salvage value, the useful life of 10 years for the MDI components (Yost et al. 2019), and a 15% marginal tax rate were assumed. With an investment cost of $371 per hectare, the net investment after including both the discounted salvage value and discounted net tax

Table 2 MDI net investment cost (\$/hectare)[a]

Conversion cost	Discount rate		
	0%	3%	6%
185 (small)	141.79	148.86	154.37
371 (medium)	283.55	297.74	308.73
556 (large)	425.34	446.59	463.10

[a] Assumes a marginal tax rate of 15%, a useful life of 10 years, and a salvage value of 10% of the cost of conversion

Table 3 Irrigation water application and variable costs for LESA and MDI by crop

	Corn	Cotton	Sorghum/wheat
LESA[a]			
Irrigation applied (m^3/ha)[b]	5080	2032	3556
Variable costs (\$/m^3)	0.12	0.13	0.12
Total variable costs (\$/hectare)	605.58	261.02	433.30
MDI[c]			
Irrigation applied (m^3/ha)[b]	4656	1862	3259
Variable costs (\$/m^3)	0.12	0.13	0.12
Total variable costs (\$/hectare)	553.07	237.22	395.05

[a] 88% application efficiency (Amosson et al. 2011)

[b] Baseline crop water application (Amosson et al. 2011)

[c] 96% application efficiency assumed

benefits was \$283.55, \$297.74, and \$308.73, under a 0, 3, and 6% discount rate, respectively, Table 2. Both the three and six percent discount rates are used for the remainder of the analysis.

To assess crops with differing water use, corn, cotton, sorghum, and wheat were analyzed. Cotton represents a low water use crop, wheat and sorghum represent an intermediate level of water, and corn represents high water use. LESA irrigation application in m^3/ha by crop was used as the baseline (Amosson et al. 2011). To calculate the relative application for MDI, the ratio of application efficiencies for the two systems was applied to the baseline LESA irrigation application, assuming MDI has a 96% application efficiency rate. While there is limited field trial data available in the study region, the efficiency is assumed to greater than LEPA (95%) due to the more concentrated application, as discussed above, but less than SDI (97%) likely due to potential surface evaporation, particularly in the early part of the growing season. It was also assumed that MDI would have the same variable costs per hectare as LEPA. Variable costs of the two systems were obtained (Amosson et al. 2011) and updated to current dollars using the Producer Price Index from the Bureau of Labor Statistics (2019). As in Guerrero et al. (2016), the pumping costs were obtained for a 107-m pumping lift. Variable costs included fuel, lubrication, maintenance, repairs, and labor. Total variable costs (TVC) per hectare were then calculated by multiplying the cost per m^3 applied by the total m^3 applied per hectare by crop, Table 3.

MDI systems may initially require more time for management than a conventional center pivot setup. While MDI systems may not be more complicated than that of a center pivot system, they do require a different set of procedures and as a result, may have higher operating costs. Earlier systems required increased maintenance throughout the year (O'Shaughnessy and Colaizzi 2017), but the redesigned system and hoses as explained by Kisekka et al. (2017) has been able to overcome this, showing little to no difference in labor costs. One of the primary concerns was clogging of the hoses, but O'Shaughnessy and Colaizzi (2017) found that nearly all clogging was eliminated through the use of a disk filter. There is additional labor at the end of the season, where producers have found that the hoses should be tied up or removed for storage over the winter to prevent damage from rodents or deer when the system is not in use (Dragonline Irrigation Personal Communication 2019). However, in several aspects, the labor required for an MDI system will be lower. Notably, wheel tracking problems are significantly reduced or eliminated, which accounts for a considerable portion of reduced costs.

Based on Amosson et al. (2011), the only difference in variable costs per m^3 applied to a single crop when pumping from a set depth was due to differences in labor. In this study, the difference in variable costs due to labor was minimal and dependent upon the crop when comparing LESA to MDI. However, field trials comparing irrigation systems conducted at T&O Water Technology Farm in Southwest Kansas in 2016 demonstrated an additional average savings of \$14.38 per hectare as the result of the lack of drive train repairs for pivots retrofitted with MDI technology. This was added to the change in variable costs due to decreased labor, resulting in cost savings ranging from \$16.43 to \$16.53 per hectare, depending on the crop, Table 4. The more prominent change in variable costs was due to increased efficiency, which ranged in savings from \$21.75 to \$50.46 per hectare, with more savings resulting from the high water use crop, corn. This additional savings per hectare resulted in total reduced variable costs of MDI when compared to LESA, of \$66.89, \$38.18, and \$52.63 per hectare for corn, cotton, and sorghum/wheat, respectively, Table 4.

To be economically feasible, the costs of converting to a MDI irrigation system must be counteracted by decreased variable costs, including the cost of labor and increased water application efficiency. The net present value of the cost of conversion combined with the decreased TVC was used to determine the payback period in years that would be required for each of the three levels of investment for each crop, using the discounted payback method (Bhandari 1986).

Table 4 Change in variable costs from LESA to MDI ($/hectare)

	Corn	Cotton	Sorghum/wheat
Change in TVC due to decreased labor	−16.43	−16.43	−16.53
Change in TVC due to increased efficiency	−50.46	−21.75	−36.10
Total change in TVC	−66.89	−38.18	−52.63

Table 5 MDI payback period (years) for alternative crops with a three percent discount rate

Gross investment ($/hectare)	Net investment ($/hectare)	Corn	Cotton	Sorghum/wheat
185	149	2.3	4.2	3.0
371	298	4.9	9.0	6.3
556	447	7.6	14.6	9.9

Results and discussion

Comparing MDI to LESA, the crops representing three water-use levels averaged a savings in TVC of $52.57 per hectare. The reduced TVC can be split into the changes as the result of decreased labor and increased efficiency. The majority of the cost advantage comes from increased efficiency, particularly in intermediate and high-water use crops, Table 4. The water-use efficiency of MDI allows for 424 fewer m^3/ha to be applied to corn and 297 fewer m^3/ha to be applied to sorghum/wheat while maintaining the productivity of the crop, Table 3.

Results indicate that for the high-water use crop, corn, a payback period of 2.3, 4.9, and 7.6 years for the small, medium, and large investment costs, respectively, is required. As the water use of the crop drops, the payback period rises as it takes longer to realize the gain in system efficiency. For sorghum/wheat, the intermediate-water use crops, a payback period of 3.0 years is required for the small investment cost. As the level of investment rises, 6.3 and 9.9 years is required for the medium and large levels, respectively. The lowest water use crop, cotton, showed the longest payback period. Cotton required 4.2, 9.0, and 14.6 years for the small, medium, and large investment costs, respectively. The increased efficiency of MDI provides for greater cost savings as the amount of irrigation water applied increases as this accounts for the majority of the change in variable costs per hectare. This is particularly important to note for producers or areas where less water than assumed is applied as it will increase the payback period for each crop. Results of this study show that the payback period, under the three percent discount rate, can range from as little as 2 years to more than 14 years, depending on the crop and investment level (Table 5).

Table 6 MDI payback period (years) for alternative crops with a six percent discount rate

Gross investment ($/hectare)	Net investment ($/hectare)	Corn	Cotton	Sorghum/wheat
185	154	2.6	4.8	3.3
371	309	5.6	11.4	7.4
556	463	9.2	22.3	12.9

The payback period was also calculated using a 6% discount rate, Table 6. The increased discount rate results in an increased payback period, particularly as the investment cost rises. The crop representing the highest water use, corn, requires 2.6, 5.6, and 9.2 years for the small, medium, and large investment costs, respectively. On the other hand, cotton, the lowest water use crop, requires 4.8 years for the small investment cost and 11.4 years for the medium investment cost. The years rise considerably under the high investment cost, requiring more than 22 years to payback the system. Thus, the actual cost of conversion for an individual operation should be carefully considered before MDI is installed on a center pivot to ensure an accurate payback period calculation based on the actual net investment cost and water application by crop.

One of the benefits of the MDI system is improved water use efficiency as measured by either decreased costs or increased yield per m^3 of applied irrigation. The benefits of MDI technology may even be more apparent in a dryer year, as found by O'Shaughnessy and Colaizzi (2017). In their two-year study, yield remained similar between both MDI and LESA irrigation systems, but, in the drier year of the study, MDI showed significantly higher water use efficiency. With water application being concentrated to a smaller area, there is a greater amount of dry soil that is still available to capture rainwater to take advantage of any precipitation during the growing season. Lamaoui et al. (2018) noted decreased plant stress with increased frequency of irrigation application, which is especially important in a limited water-use area or in areas with coarse soils. While typically the main benefit is seen as increased water-use efficiency, some producers have seen yield increases with the installation of an MDI system (Gaines 2017; T Moore Personal Communication 2019). In this study, yields and prices were held constant to allow for analysis of the payback period as a result of decreased variable costs. However, if producers are able to increase yields or if prices were to rise, the payback period for MDI conversion could be reduced, and this is certainly an area where additional work would prove valuable.

Additionally, there is the possibility that MDI technology will be approved for the United States Department of Agriculture—Natural Resources Conservation Service (NRCS) Environmental Quality Incentives Program (EQIP) cost-share payments (Washington, D.C., USA). Since this analysis does not account for several potential factors, including EQIP or other potential government cost-share payments, the results are considered to be conservative estimates of the investment payback period considering the potential benefits of an MDI system.

Particularly in heavily water-limited areas, MDI shows the potential to increase the productivity of agricultural land and increase the efficiency of reduced water application without the extensive capital investment required from SDI systems. While the results of this study evaluate a pumping lift of 107 m, producers should consider that a lower pumping lift will increase the payback period and a higher pumping lift will decrease the payback period. Finally, with little long-term use of MDI there are still questions about the longevity and performance of the system over time. In this study, the payback period for cotton under the $556 per hectare investment exceeds the assumed useful life of 10 years. Additional research and demonstration efforts in this area could provide new data for a more accurate assessment, particularly if MDI systems are proven to have a longer average useful life.

Conclusions

Depletion of the Ogallala Aquifer and diminished well capacities will make irrigating crops to their full water requirements impossible, as many have already been seen in some areas of the Central Ogallala region. The challenge is to manage the demands on the Ogallala, balancing economic success and the conservation of natural resources. MDI is one such technology that is bridging the gap between increased water use efficiency and economic productivity. However, producers can be reluctant to invest in a new irrigation system when the initial investment costs are high. The overall savings from labor and increased efficiency may warrant an investment in conversion to a MDI application system, particularly in areas where water is drastically limited or for producers who are facing reduced well capacities currently or in the future.

This study evaluates the economic feasibility of converting to MDI under several crop scenarios and investment levels. The payback period for conversion varies considerably under these different conditions and is shortened with higher-water use crops as the change in total variable cost saving rises from increased water use efficiency. Consequently, crops such as corn would provide the most feasible scenario for adoption by producers in the Central Ogallala region. Intermediate-water use crops, sorghum and wheat, are also feasible for producers, particularly under lower investment levels. Thus, producers growing high-value, high-water use crops are the most feasible operation in which to convert to MDI.

Conversion to any irrigation system is one that requires careful evaluation of multiple aspects of an operation. The analysis conducted was based on average producer information for the study area, but this may not accurately reflect every potential situation. Careful assessment should be made as to how the assumptions and scenarios match a producer's operation. Future research should be conducted with MDI addressing other alternative crops, government programs, pumping rates, and long-term usage.

Acknowledgements This research was supported in part by the Ogallala Aquifer Program, a consortium of the USDA Agricultural Research Service, Kansas State University, Texas A&M AgriLife Research, Texas A&M AgriLife Extension Service, Texas Tech University, and West Texas A&M University. A portion of funding for this research was provided by USDA to Project No. 2016-68007-25066, through the National Institute for Food and Agriculture's Agriculture and Food Research Initiative, Water for Agriculture Challenge Area. Project website: ogallalawater.org.

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest. The funding sponsors had no role in the design of the study, analysis or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

References

Amosson S, Almas L, Girase J et al (2011) Economics of irrigation systems B-6113. Texas, College Station

Bhandari S (1986) Discounted payback: a criterion for capital investment decisions. J Small Bus Manag 24:17–22

Bureau of Labor Statistics (2019) Producer price index for farm machinery and equipment manufacturing. http://www.bls.gov/data/. Accessed 10 Aug 2019

Delano D, Williams J, O'Brien D (1997) An economic analysis of flood and center pivot irrigation system modification. Am J Agric Econ 79:1734–1734

Gaines T (2017) Cut water costs and boost yields with drag hose system. In: Success. Farming. https://www.agriculture.com/machinery/irrigation-equipment/cut-water-costs-and-boost-yields-with-drag-hose-system. Accessed 1 Aug 2019

Guerrero B, Amosson S, Almas L et al (2016) Economic feasibility of converting center pivot irrigation to subsurface drip irrigation. J ASFMRA. https://doi.org/10.22004/ag.econ.236655

Howell T, Schneider A, Evett S (1997) Subsurface and surface microirrigation of corn - southern high plains. Trans ASABE 40(3):635–641

Kansas State University (2019) Kansas climate. In: Weather data libr. http://climate.k-state.edu/basics/. Accessed 15 Aug 2019

Kisekka I, Oker T, Nguyen G et al (2016) Mobile drip irrigation evaluation in corn. Kansas Agric Exp Stn Res Rep 2:1–10. https://doi.org/10.4148/2378-5977.1253

Kisekka I, Oker T, Nguyen G et al (2017) Revisiting precision mobile drip irrigation under limited water. Irrig Sci 35:483–500. https://doi.org/10.1007/s00271-017-0555-7

Lamaoui M, Jemo M, Dalta R, Bekkaoui F (2018) Heat and drought stresses in crops and approaches for their mitigation. Front Chem 6:1–14

Lamm F, O'Brien D, Rogers D (2015) Economic comparison of subsurface drip and center pivot sprinkler irrigation using spreadsheet software. Appl Eng Agric 31:929–936

McGuire VL (2017) Water-level and recoverable water in storage changes, High Plains aquifer, predevelopment to 2015 and 2013–15. Reston, VA

National Agricultural Statistics Service (2019) 2014–2018 historical yields for the Northern high plains district in Texas and Southwest District in Kansas. http://www.nass.usda.gov/. Accessed 2 Aug 2019

National Resources Conservation Service (2012) Ogallala aquifer initiative 2011 report

O'Brien D, Rogers D, Lamm F, Clark G (1998) An economic comparison of subsurface drip and center pivot sprinkler irrigation systems. Appl Eng Agric 14:391–398

O'Shaughnessy S, Colaizzi P (2017) Performance of precision mobile drip irrigation in the Texas High Plains region. Agronomy 7:13. https://doi.org/10.3390/agronomy7040068

Olson B, Rogers D (2007) Center pivot precision mobile drip irrigation. In: Proceeding central plains irrigation conference, pp 107–113

Olson B, Rogers D (2008) Comparing drag hoses verses sprinklers on corn irrigated by a center pivot. Appl Eng Agric 24:41–45. https://doi.org/10.13031/2013.24159

Olson B, Rogers D (2019) Evaluation of mobile drip irrigation (MDI) and other sprinkler packages. In: 31st Annual central plains irrigation conference, pp 98–107

Rathjen F (2010) Panhandle. In: Handb. Texas. http://www.tshaonline.org/handbook/online/articles/ryp01. Accessed 28 July 2019

Texas A&M AgriLife Extension Service (2019) Basis data: average monthly cash and futures prices for 2014–2018. http://agecoext.tamu.edu/resources/basis-data.html. Accessed 2 Aug 2019

Thom D (2001) Mobile drip irrigation system. Patent No US6343749B

Yost M, Holt J, Reid C et al (2019) Mobile drip irrigation for pivots and laterals. Ag Extension Utah State University AG/Irrigation/2019-02pr. https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3011&context=extension_curall. Accessed 10 Aug 2019