NITROGEN MANAGEMENT AND WATER PRODUCTIVITY OF GRAIN CROPS UNDER DROUGHT OR LIMITED IRRIGATION

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ABSTRACT

The interactions of nitrogen management and water have been the subject of many studies that have improved crop management practices. Water scarcity however, has become a pressing contemporary challenge for agricultural and food sustainability, especially in many arid and semi-arid regions of the world. As the amount of available water for irrigation decreases, more studies must shift their focus to how nitrogen fertilizers influences water use efficiency. Numerous strategies are currently employed to protect nitrogen from loss in wet environments, including improvements in irrigation strategies, timing of N fertilizer application, and use of nitrification inhibitors and slow or controlled release nitrogen sources. This review aims to provide sufficient examples to illustrate how these nitrogen protection strategies used within water-limiting environments can provide higher crop yields. When assessing the crop water productivity, a measurement of yield per unit of water consumed by the crop, this productivity can lead to management decisions to promote long-term sustainability under water-limiting conditions. Tools such as controlled-release nitrogen, which controls N supply to the crop and prevents excessive N supply and luxury vegetative growth, may reduce water consumption during vegetative growth conserving more water for reproductive periods resulting in higher yields.

BACKGROUND

Water scarcity is one of the most pressing contemporary challenges for agricultural and food sustainability. In many arid and semi-arid regions of the world, irrigation has been developed to allow stable, high yield agriculture and avoid the effects of drought. But water scarcity in many of these regions is now a pressing issue due to declining groundwater levels, increasing competition for water by municipal and industrial users, increasing frequency and severity of drought, and declining water quality due to pollution and salinity (Gleeson et al., 2012; Vorosmarty et al., 2000). For example, increasing demand for water by a growing urban population in Colorado is expected to drive a loss of 175,000 ha of irrigated farmland by 2030 (Colorado Water Conservation Board, 2004). Severe yield losses have also occurred throughout much of the U.S. Great Plains during recent droughts due to low capacity irrigation wells failing to meet crop water demand. Similar concerns are observed in arid and semi-arid regions worldwide, including key food production regions in China, India, and Africa (Alghariani, 2007; Basch et al., 2012; Kahlon et al., 2012).

Innovative cropping systems that increase resilience to drought and improve crop water productivity are needed. Key elements of drought resilient cropping systems include tillage practices, soil fertility management, drought tolerant crops, crop rotation, and irrigation scheduling. Some crops have been developed with enhanced drought tolerance, most notably drought tolerant corn hybrids. For example, DuPont Pioneer developed drought tolerant corn hybrids (trait branded as Optimum AQUAmax) using a complex of native genes from a wide background of maize genetics. These hybrids have shown yield advantages under drought stress (Joel Schneekloth, Colorado State University, personal communication). However, increasing water-limited crop yield must go beyond drought *tolerance* toward increasing *crop water productivity* in water scarce environments. Water productivity is the amount of crop yield per amount of water used, often referred to as the amount of "crop per drop". Improving crop water productivity depends not only on new genetics, but also on a comprehensive set of environmental and management factors. For example, DuPont Pioneer's new Optimum AQUAMax maize hybrids reach their water-saving potential only when grown under recommended management practices (Jeff Schussler, DuPont Pioneer, personal communication). This paper is being developed to evaluate the role of nitrogen management in addressing crop water productivity in water scarce environments. Specifically, a literature review is being conducted to evaluate the interaction of plant nitrogen fertility status and water scarcity on crop water productivity for crops typically grown in water scarce environments.

NITROGEN MANAGEMENT IN WATER SCARCE ENVIRONEMNTS

The vast majority of the thousands of studies on the interactions of nitrogen and water in cropping systems have focused on the ***ways that water influences nitrogen use efficiency***. It is well established that excess soil water leads to low nitrogen use efficiency due to nitrate leaching and denitrification. Numerous strategies are employed to protect nitrogen from loss in wet environments, including improvements in irrigation strategies, timing of N fertilizer application, and use of nitrification inhibitors and slow or controlled release nitrogen sources. Much less has been studied on the ***nitrogen influence on water use efficiency***. In many arid and semi-arid regions, and even in more humid regions during drought conditions, water is the most yield limiting factor. In such environments, there is value is assessing the crop water productivity, a measurement of yield per unit of water consumed by the crop. Assessing crop water productivity can lead to management decisions to promote long-term sustainability under water-limiting conditions. Tools such as controlled-release nitrogen, which controls N supply to the crop and prevents excessive N supply and luxury vegetative growth may reduce water consumption during vegetative growth conserving more water for reproductive periods.

SMALLGRAINS IN ARID AND SEMI-ARID ENVIRONMENTS

A variety of studies on small grain corps illustrate that in dry environments, higher rates of N applied in the early season can result in yield decline relative to lower rates of N. The yield decline relates to depletion of soil moisture during early season growth, leaving less soil water available for reproductive growth and seed development. One study, conducted in Maricopa, AZ over two years varied the amount of irrigation and N supplied to durum wheat (*Triticum durum Desf.*). Nitrogen was split applied three times during stem elongation as UAN (32%). Yield functions maximized at intermediate rates that depended on the amount of irrigation water supplied (Figure 1). At higher rates of N, yield consistently declined from intermediate N levels where peak yields were observed. This same result is seen in the response of barley in a study conducted in Syria that varied N rates with contrasting split application timing (Figure 1). Maximum yield levels were obtained at lower N rates when N was applied at tillering than when applied at planting. Declining yield above N rates that maximized yields were especially apparent with N applied at tillering. As for the durum wheat study, the higher N rates result in yield declines because they stimulate vegetative growth and consume stored soil water before reproductive growth stages.

Studies conducted in the semi-arid U.S. Great Plains provide further evidence that high rates of early season N can negatively affect dryland wheat yields (Halvorson et al., 2004; Nielsen and Halvorson, 1991; others). The observation of yield loss at high N rates is most common when water limitations are high and when N is applied at planting. Under these circumstances, plants with high, early season N rates compared to plants with moderate or split applied N rates develop larger leaf area and biomass. This results in the depletion of soil water prior to flowering and grain fill. As an illustration, note a declining yield function at high N rates in a dry year but not in a wet year as observed in a 9-year study near Akron, CO (Figure 1; Halverson et al., 2004). In this study, all N was applied at planting as anhydrous ammonia. Growing season precipitation was below the long-term average in 1992 and was above average in 1986. In addition to early water depletion, high N applied at planting can lead to lodging, disease, and freeze damage. Delayed nitrogen availability through split application or controlled release fertilizers in water scarce environments would reduce the risk of yield loss at high N rates.

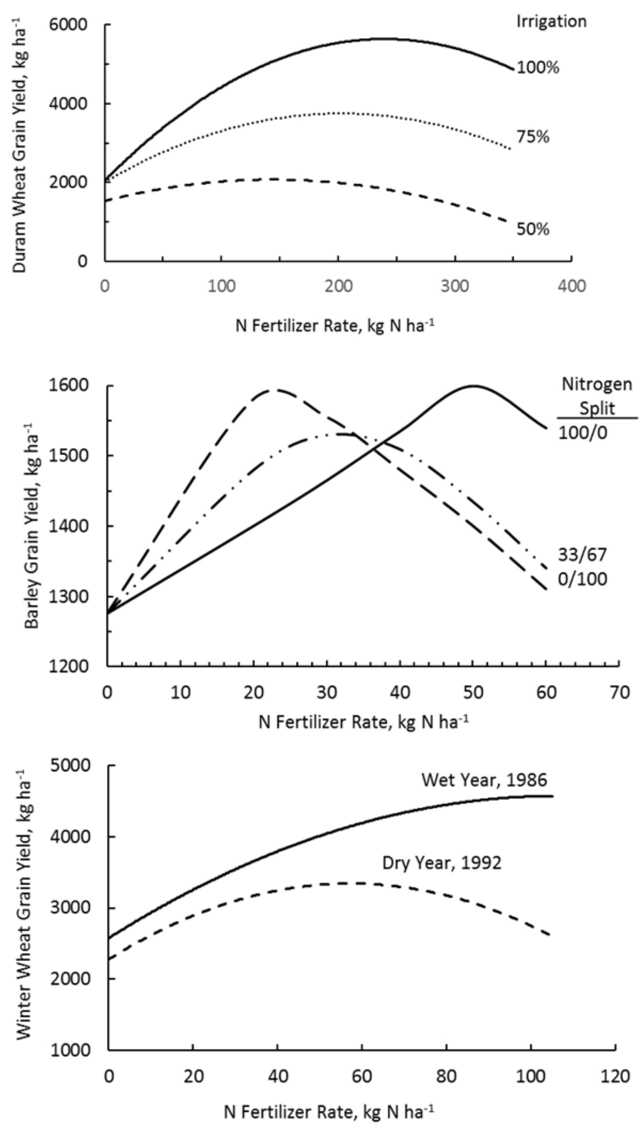


Figure 1. Upper chart - Grain yield of durum wheat as affected by rate of applied N at varying levels of sprinkler irrigation at a study in Maricopa, AZ. (Modified from Mon et al., 2016).

Center chart - Grain yield of barley as affected by rate and ratio (planting/tillering) of applied N in northern Syria. (Modified from Anderson, 1985).

Lower chart - Winter wheat yields from a wheat-corn-fallow rotation study in Akron, Colorado as a function of N fertilizer rate. The chart compares a wet and dry year from the study. Modified from Halvorson et al. (2004).

MAIZE

The observation of a declining yield function for water scare environments with high N at planting is more prevalent for small grains than for maize. In maize, some similar observations have been made, but only under extremely water limited conditions. For example, in a study performed in Xianning, China, corn with three different rates of N applied at planting were subjected to increasing periods of time without irrigation. At moderate drought, yields increased with N rate, but when conditions were very dry, increasing N resulted in reduced yield (Figure 2).

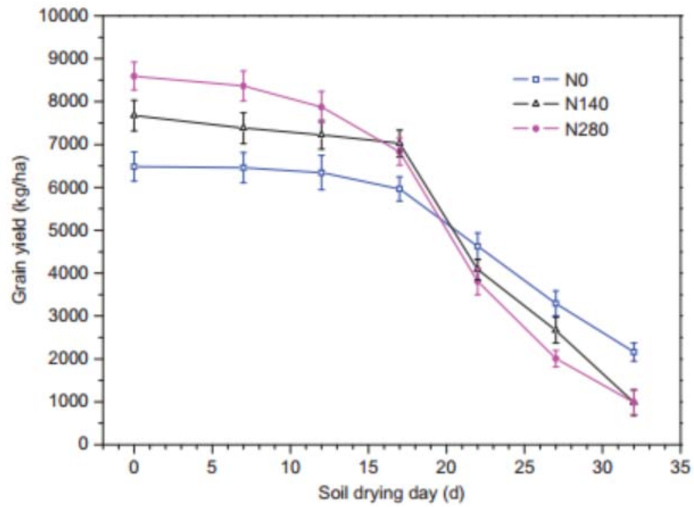


Figure 2. From Lirong et al. (2012). A study in Xianning, China evaluated the interaction of N rate and drought on grain yield. Drought was simulated using increasing periods of soil drying time (days since irrigation).

A pilot study was conducted in Provo, Utah in 2013 to evaluate the interaction of N and water stress. The study was based on the concept of controlled deficit irrigation, a management approach that targets application of a limited supply of irrigation water to reproductive crop growth stages. While the potential benefits of limited irrigation have been documented (DeJonge et al., 2011; Saseenndran et al., 2008), less is known about how limited irrigation practices interact with the nitrogen fertility status of crop plants. In the study, growth was limited for plants with low, early season N, which translated into lower water stress under limited irrigation compared to plants with high N (Figure 3). Yields were more negatively affected by early season N deficiency than by water stress. An ESN treatment had the highest nitrogen use efficiency and water use efficiency in the study (Figure 3).

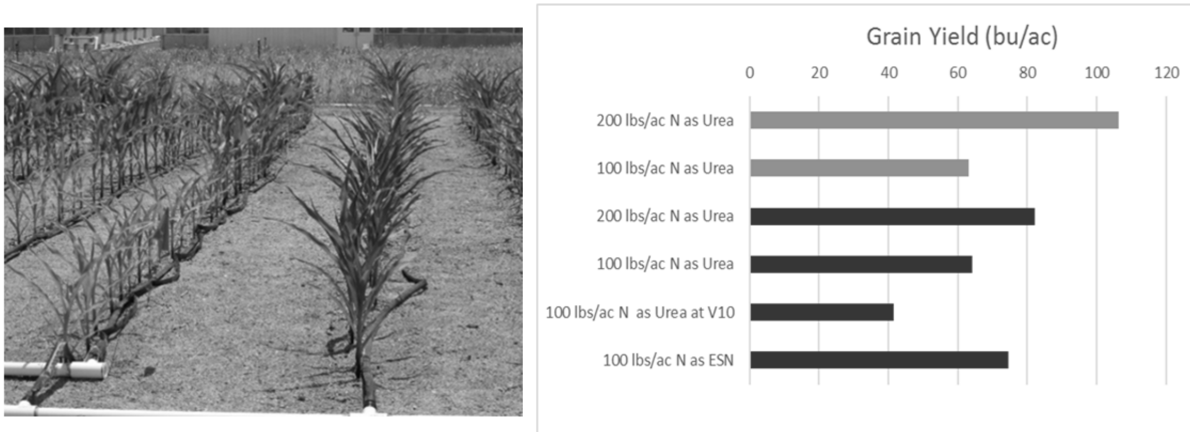
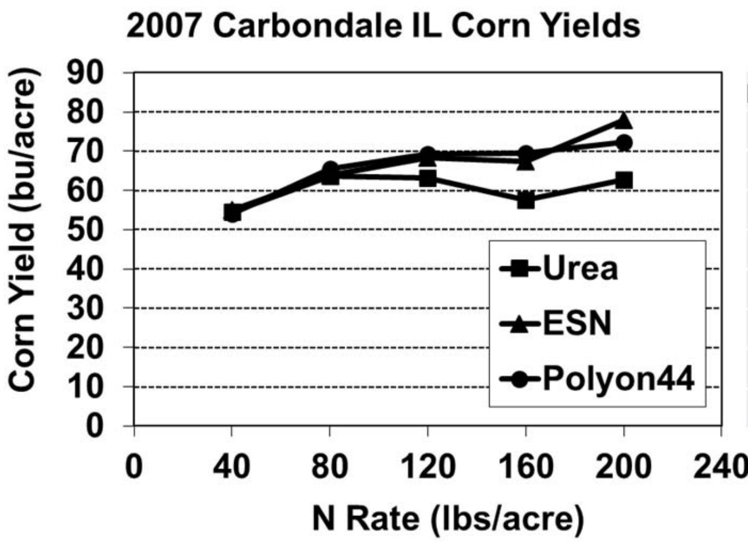


Figure 3. In a pilot study of limited irrigation in Provo, Utah, low N maize (front, left rows) have reduced growth but also reduced water stress compared to adequate N plots (front, right rows). Yields are shown for plots with daily irrigation (blue bars) compared to plots with limited irrigation (red bars).

Some past studies comparing ESN with urea as N sources for corn may support the hypothesis that when moisture stress occurs during vegetative growth, controlling N supply can improve yields. The primary use of ESN is generally to control N exposure to N loss conditions. ESN has been shown in numerous studies to reduce N losses and increase yields when excessive moisture is present. In some studies where early summer rainfall was very limited and N loss was not obvious, ESN has produced greater yields than urea. While exact data to confirm the above hypothesis was not collected, the yield increase in the apparent absence of N loss could indicate that controlled N supply with ESN reduced drought stress, controlled vegetative growth, and conserved moisture for later reproductive growth.

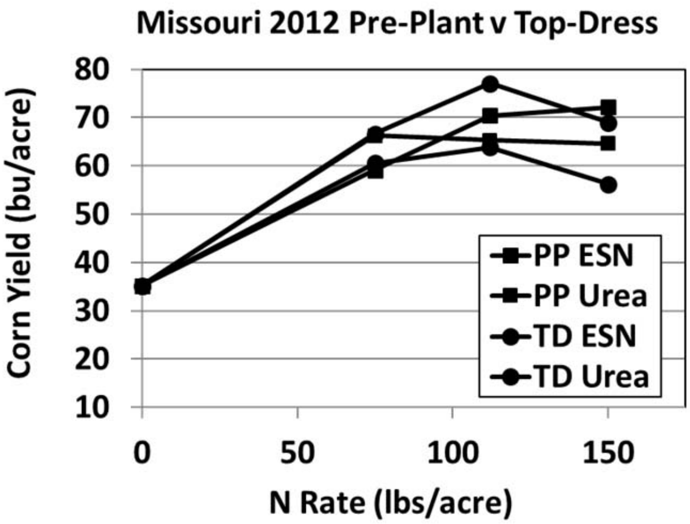
Corn grown at Carbondale, IL in 2007 under limited rainfall was fertilized with urea, ESN, and Polyon 44 (a controlled-release fertilizer similar to ESN). All three fertilizers increased yields up to 80 lbs N/acre (Figure 4, D. Hernandez, So. Illinois Univ, 2007, unpublished data). Above 80 lbs N/ac, urea decreased yields while ESN and Polyon yields were not similarly penalized by higher N rates. Under moisture stress, high rates of urea pre-plant might be expected to increase vegetative growth and vegetative moisture consumption thereby increasing moisture stress during tasseling and silking and decreasing yields. The two controlled-release fertilizers increased yields, even at high N rates. This study seems to support the hypothesis that controlled N supply during early season moisture stress can improve water-use efficiency.



Rainfall (in)	
March	1.52
April	2.69
May	2.64
June	2.97
July	3.14
August	2.01
September	2.50
Total	17.47

Figure 4. Corn yields under limited rainfall with three N sources at Carbondale, IL in 2007. Monthly rainfall totals are shown to the right of the figure.

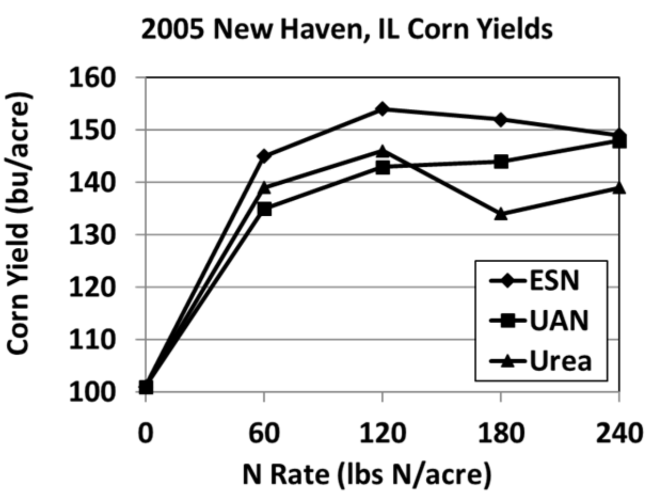
A Missouri study compared ESN, urea, and SuperU applied pre-plant and ESN or urea top-dressed at V6 (Figure 5, Nelson, Univ of Missouri, unpublished data). Pre-plant urea and SuperU yields declined above 75 lbs N/acre while pre-plant ESN yields increased up to 150 lbs N/acre. It is possible that yield results in this study are confounded by short-duration denitrification events during May and the increased yields with ESN could be partially a result of reduced denitrification losses and reduced moisture stress with limited May-July rainfall. SuperU, which contains a nitrification inhibitor should have minimized denitrification losses during this part of the growing season. That SuperU produced yield patterns similar to urea suggests that N loss should not be the major reason for the yield increases seen with ESN. These treatments in 2013 under excessive May rainfall did not produce similar yield decreases at high N rates; yields in 2013 increased with increasing N rate for both sources and application times. Further evaluation of specific rainfall events could help clarify the nature of the specific ESN effects, but the yield patterns seem to agree with the hypothesis that controlled N supply during periods of limited rainfall can reduce moisture stress.



Rainfall (in)	
March	2.34
April	4.69
May	2.49
June	2.23
July	0.73
August	2.99
September	3.56
Total	19.03

Figure 5. Corn yields under limited rainfall for two N sources applied pre-plant (PP) or top-dress at V6 (TD) at Novelty, MO in 2012. Monthly rainfall totals are shown to the right of the figure.

Corn yields measured at New Haven, IL in 2005 (Figure 6, S. Ebelhar, Univ of Illinois, unpublished data) follow patterns similar to Illinois (Figure 4) and Missouri (Figure 5). In the absence of apparent N loss events, ESN maintained greater yields at higher N rates than either UAN or urea. Urea yields were particularly depressed at high N rates. Several other ESN studies in corn not shown here produced similar yield increases with minimal rainfall and limited potential for N loss. These examples, while not entirely consistent with other ESN studies where little, if any, benefit of ESN was observed in dry conditions, seem to support the general hypothesis that controlled N supply during periods of limited rainfall can improve N- and water-use efficiency.



Rainfall (in)	
March	3.17
April	3.08
May	1.9
June	2.08
July	2.7
August	8.76
September	2.11
Total	23.8

Figure 6. Corn yields under limited rainfall for three N sources applied before planting at New Haven, IL in 2005. Monthly rainfall totals are shown to the right of the figure.

CANOLA

A recent Canadian study evaluating N sources on canola illustrates the potential for improved canola productivity under moisture stress by reducing N supply during early vegetative growth (Figure 7, McKenzie Applied Research Assoc., Alberta, unpublished data). The study was conducted at Fort Vermillion in N. Alberta in 2014 and 2015. Both years were characterized by drought in the early summer. Canola planted in May of 2015 was exposed to the greatest stress during early vegetative growth. Canola planted in July 2014 received some rain in July and August during vegetative growth. This rainfall pattern seems to correlate with yield differences between urea and ESN, a controlled-release urea (Figure 8). While there may be other causes of these yield patterns, they seem to support the hypothesis that controlling N supply in times of stress during vegetative growth as observed in the other studies cited herein. Some benefit was observed for urea treated with urease and nitrification inhibitors only in 2015 (data not shown). The yield increase with inhibitors was significantly less than that observed with ESN. Rainfall neither year would have been sufficient to cause significant leaching or denitrification losses, so the yield results cannot be attributed reduced N losses with the treated N sources.

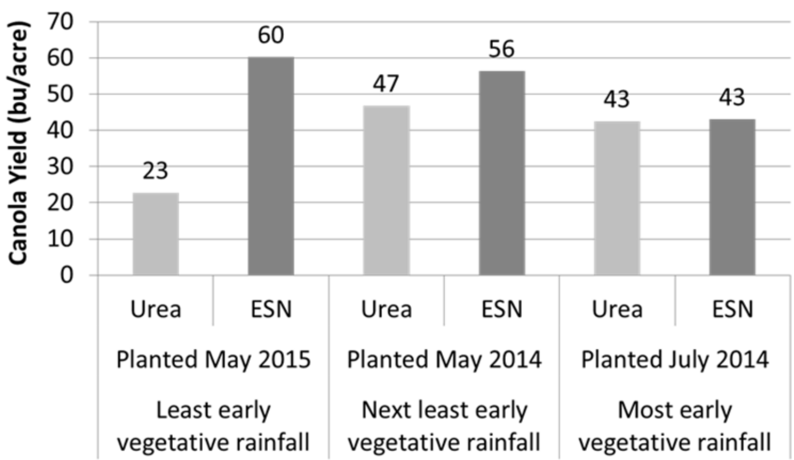


Figure 7. Canola yield response to urea and controlled-release urea (ESN) at Fort Vermillion, AB. N was applied at 60 lbs N/acre at planting in a band three inches from the seed and four inches deep.

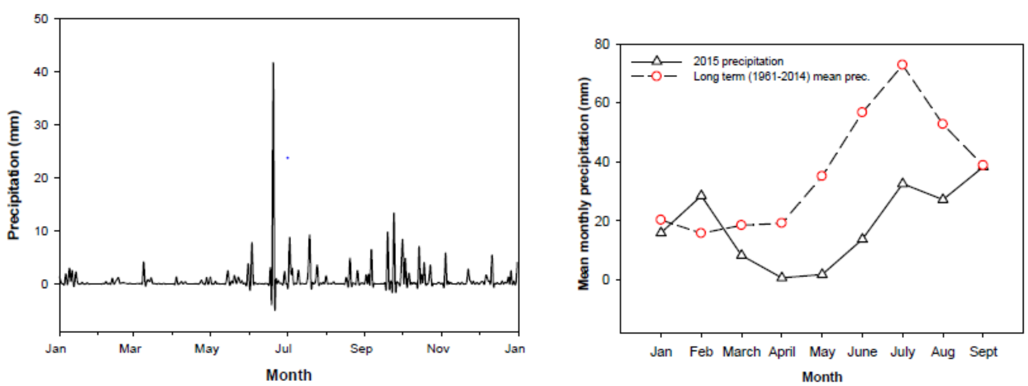


Figure 8. Growing season precipitation at Fort Vermillion, AB in 2014 (left) and 2015 (right).

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