APRIL 2007
VOLUME 26
ISSUE 1

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Colorado State University Cooperative Extension

FROM THE GROUND UP

Agronomy News

Limited Irrigation Management – Getting the Most Crop per Drop

Principles and Practices

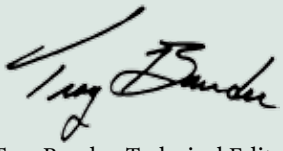
by Joel Schneekloth, Extension Northern Region Water Resource Specialist

Colorado producers irrigate approximately three million acres of pasture, hay, and row crops yielding receipts worth more than five billion dollars per year. However, irrigation water availability for these enterprises is declining. Dwindling agricultural water supplies due to drought, compact compliance requirements, urban transfers, alluvial well pumping restrictions, and declining ground water from non-renewable aquifers has reduced the water available to irrigated agriculture. These water shortages have been occurring in almost every irrigated watershed and

FROM THE GROUND UP

Agronomy News is a quarterly publication of the Extension Unit, Department of Soil & Crop Sciences, Colorado State University, Fort Collins, Colorado.

Web Site: http://www.extsoil.crop.colostate.edu/Newsletters



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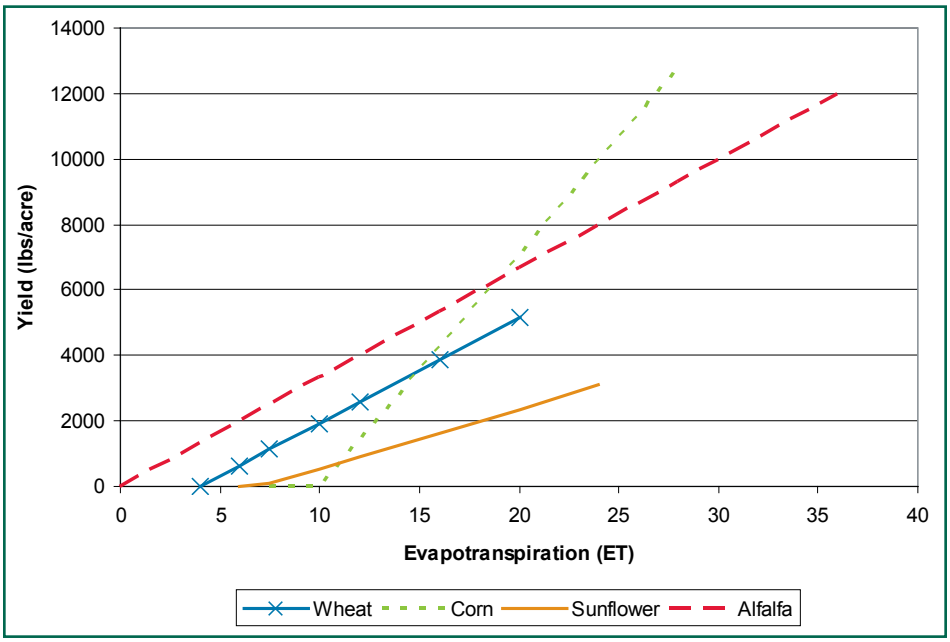

Figure 1. Crop yield and seasonal evapotranspiration relationships.

ground water basin in some degree for the past several years.

The purpose of this newsletter is to build upon concepts and suggestions for limited irrigation management, provide updates on limited irrigation research projects around the state, and suggest further resources for managing under tight water supplies. This is the second issue of *Agronomy News* that has focused on limited water. Readers are encouraged to review the *Drought* issue of April 2003 available at the URL address provided on page 2 for more information on this topic.

Full irrigation results when applied irrigation water is sufficient to meet the crop water demand or evapotranspiration (ET) not supplied by natural precipitation and soil water storage. Limited irrigation occurs when water supplies are restricted, either in timing and/or amount so that full ET demands cannot be met for the entire growing season. Limited irrigation situations include:

1. Reduced surface water supplies or storage due to drought or low snow pack.
2. Restricted pumping allocations in alluvial aquifers. In some instances, the allocations are considerably less than what is required to fully irrigate the crops typically grown.
3. Low capacity irrigation wells due to limited saturated depth of the aquifer. Well yields are then insufficient to meet the peak ET demands of the crop.

Under limited irrigation using typical management practices, yields and returns from the irrigated crop will generally be reduced as compared to a fully irrigated crop. Management strategies that can help minimize yield loss and preserve net return when coupled with careful input management include: understanding the relationships between grain yield and water use (evapotranspiration); irrigation timing to manage water stress to crops during critical growth stages; crop residue management for water conservation; plant population management; crop rotations to balance water use; and improved irrigation efficiency.

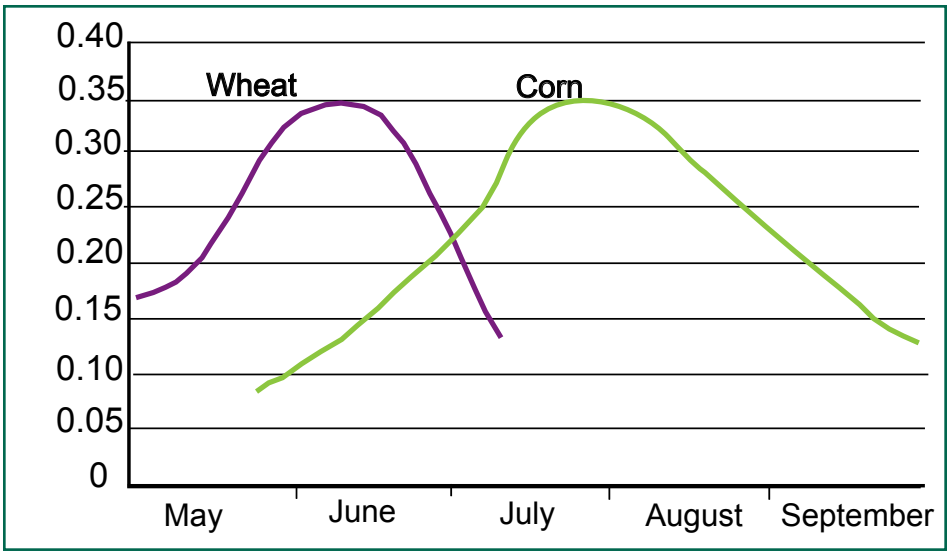

Figure 2. Example of daily ET patterns of wheat and corn through a typical growing season.

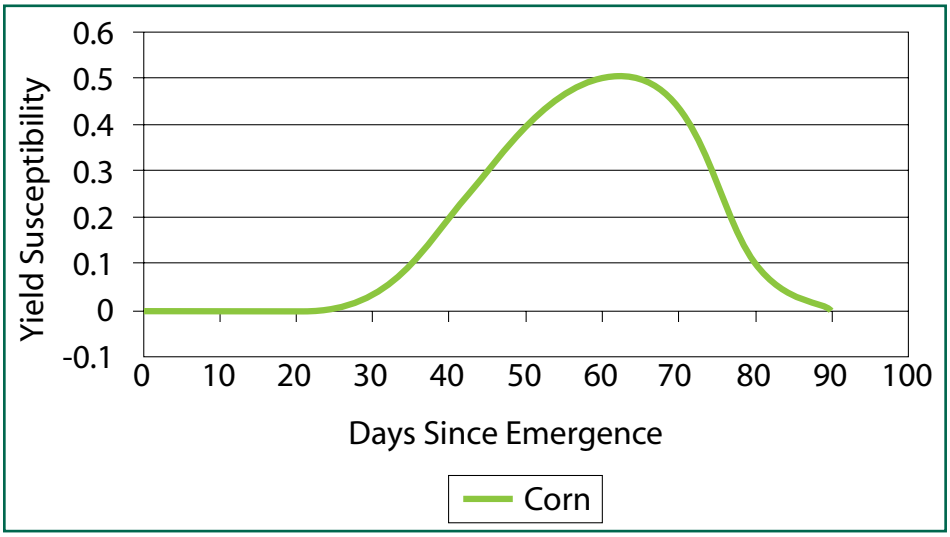

Figure 3. Yield susceptibility to moisture stress for corn (Sudar et al., 1981).

Yield and Evapotranspiration and Water Timing

Evapotranspiration (ET) is the driving force behind crop yields (Figure 1). Crops such as corn, respond with more yield for every inch of water of ET as compared to winter wheat or sunflowers. However, corn requires more water for development or maintenance and requires approximately 10 inches of ET to produce the first increment of yield as compared to 4.5 and 7.5 inches of ET for wheat and sunflowers, respectively. These crops also require less ET for maximum production. Forage crops such as alfalfa produce harvestable yield with the first increment of ET and thus are reasonable crop choices for many producers under limited water. See the article *Estimated Yield of Some Alternative Crops under Varying Irrigation in Northeast Colorado* on page 8 for a more detailed explanation of crop response to water.

Crops respond to water stress differently at several growth stages. Most grain crops are not as impacted by water stress during the vegetative growth stage and during late reproductive or grain fill growth stages (Figure 3). However, crops are sensitive to water stress during the reproductive growth stages and water stress during these stages will significantly impact yields. When producers have control over when they can irrigate, limiting water during the growth stages that are least sensitive to water stress while saving water for the critical growth stages is important to maximizing the return to water. When restricted upon the total amount of water that can be applied, saving that water for the reproductive growth stages is the most advantageous to grain yield.

Crop rotations that include lower water use crops such as sunflowers or winter wheat can reduce irrigation needs. Schneekloth et al. (1991) found that when limited to 6 inches of irrigation, corn following wheat yielded 13 bu/acre (8 percent) more than continuous corn. The increased grain yield following wheat was due to increased stored soil moisture during the non-growing season that was available for ET during the growing season. With low capacity wells, planting multiple crops on smaller acreages within a field allows for water to be applied at amounts and times when the crop needs the water. Crop rotations also spread the irrigation season over a greater time period as compared to a single crop. When planting multiple crops such as corn and winter wheat under irrigation, the irrigation season is extended from May to early October as compared to continuous corn, which is predominantly irrigated from June to early September. Crops such as corn and wheat have different timings for peak water use (Figure 2). The net effect of irrigating fewer acres at any one point in time is that ET demand of that crop can be better met. Irrigation management can be as needed rather than in anticipation of crop ET.

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Other resources for understanding crop rotations under limited irrigation include: *Cropping options for limited water supplies in Northeast Colorado, 2003* available at: http://www.extsoilcrop.colostate.edu/Newsletters/2003/croppingoptions_2003.htm and *Seasonal Water Needs for Colorado Crops* at http://www.extsoilcrop.colostate.edu/Newsletters/2003/Drought/seasonal.html.

Residue management in limited irrigated systems for capturing and storing rain and snow becomes as critical as dryland systems. Crop residues and reduced tillage can significantly increase the capture and storage of water due to reduced evaporation from tillage operations and runoff and increased snow catch. Standing residue is more effective than flat residue for snow catch. Studies in Akron found that standing sunflower residue increased the amount of snow captured nearly 2 inches in increased soil moisture over flat residue (see http://www.extsoilcrop.colostate.edu/Newsletters/2003/Drought/stubble.html). During the growing season, residue can also have important impact upon water conservation. Researchers in Kansas found that wheat residue reduced the amount of evaporation from the soil during the growing season for irrigated corn as compared to bare soil. The reduction in evaporation amounted to nearly 2.5 inches for the growing season. Most of these saving occurred before the corn crop reached full canopy (see http://www.extsoilcrop.colostate.edu/Newsletters/2003/Drought/residue.html). Residue also reducers runoff from precipitation allowing for better infiltration and decreases rainfall and irrigation impact upon surface sealing which increases infiltration rates.

Efficient application is critical when irrigation water is limited. Thus runoff, deep percolation, and evaporative losses must be minimized by tweaking the existing or upgrading to a different irrigation system. Center pivot irrigation efficiency can vary depending upon management and system design, so seek the advice of an irrigation professional to make sure your nozzle package correctly fits your pumping capacity and soil characteristics. Surface irrigation systems are inherently inefficient, but can be improved by shortening row length, increasing stream size and cutback, using optimum set times, packing furrows and/or using surge valves or manually surging rows. A longer discussion of these adjustments can be found at: http://www.extsoilcrop.colostate.edu/Newsletters/2003/Drought/tips.html.

Pre-irrigation is a strategy that is often recommended under limited irrigation, particularly under low capacity systems to ensure that the soil profile is filled to field capacity before the growing season. However, producers should remember that the storage efficiency of pre-irrigations is low. Lamm and Rogers (1985) found that the storage efficiency of non-growing season precipitation was reduced as the fall available soil water content was closer to field capacity. Although pre-irrigation may be needed in years with low precipitation, decisions on whether to pre-irrigate are more reliable in the spring to take advantage of non-growing season precipitation.

Crop yields and gross returns from limited irrigation will generally be lower than a fully irrigated crop production system. However, changes in agronomic and irrigation management practices can help maintain respectable yields and net returns. A combination of management strategies such as rotations with lower water use crops, reduced tillage, water timing, and improved irrigation efficiency can help stretch limited water supplies in many situations.

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Upcoming Events

May 7-11, 2007: Rocky Mountain Compost School
Website: www.rockymountaincompostschool.info

June 11-14, 2007: Wheat Field Days
Website: www.csucrops.com

Irrigated Agriculture is an Engine for Economic Activity in Rural Communities

by James Pritchett, Assistant Professor, Agricultural and Resource Economics

Water is an important natural resource that contributes to the Colorado's economic, cultural and social well-being. But as recent events have shown, our limited water supply has many competing uses and is undergoing many rapid changes. Water rights are being voluntarily transferred from irrigated agriculture to municipal use, groundwater supplies are being sufficiently depleted so that pumping is too costly relative to the value of the crops and wells without sufficient augmentation are being retired. Ultimately, this means fewer irrigated acres, and the economic impacts of this reduced activity are a key concern for rural communities.

How important is irrigated agriculture to rural communities? Quantifying cash receipts is one way to measure the impact of irrigated agriculture to Colorado's economy. When tallied as sales at the farm gate, agricultural receipts generated roughly $5.4 billion in 2005 or about 2 percent of Colorado's general economic output. About 40 percent is derived from crop sales with the remainder from livestock sales. Irrigated cropping generates approximately $1.62 billion in a year, or about ¾ of all crop receipts.

Of course, the economic contribution of agriculture doesn't stop at the farm gate. For example, irrigated crop production supports commercial livestock, meat-packing, and dairy industries. These primary industries encourage economic development directly, through the purchase of inputs, and indirectly, through the wages and salaries of employees. Without other viable local base industries, a reduction in the revenue generated in the agricultural sector will have adverse economic impacts throughout the regional economy. This begs the question, "How important is irrigated agriculture's activity to the regional economy?"

Table 1. Irrigated Agriculture and Economic Activity for Colorado Regions

Region	Farm Gate Receipts as a Percent of Total Regional Output[a]	Economic Activity Generated per Acre of Irrigated Cropland	Representative Cropping Pattern
East Arkansas	31%	$428	Forage Crops
Republican	37%	$678	Continuous Corn, Alfalfa
Rio Grande	48%	$1,127	Potatoes, Barley, Alfalfa
East South Platte	2%	$690	Corn, Alfalfa, Sugar Beets

[a]All receipts from production agriculture

Recent research from Colorado State University and the Colorado Water Resources Research Institute provides insights[1]. First, irrigated agriculture's contribution to economic activity varies by region (Table 1). The second column of Table 1 indicates the proportion that all agricultural receipts (crops and livestock) make of the region's total economy. Measured at the farm gate, production agriculture makes a significant portion of sales for the Rio Grande basin at 48 percent of the total output. In the South Platte, production agriculture is significant industry but *relative* to all economic activity, it makes a smaller proportion. Simply put, the South Platte basin economy has more sources of economic activity when compared to the Rio Grande region.

The third column of Table 1 includes farm gate sales, but also measures the inputs purchased to support irrigated cropping. More specifically, economic activity includes the following.

- **Direct activity:** Revenue flows from the sale of crops.
- **Indirect activities:** The revenue generated by the demand for inputs from other industries. For instance, a farmer indirectly supports businesses supplying inputs such as fertilizer, seed, etc.
- **Induced activity:** The revenue generated as labor spends its wages in the regional economy in areas such as supermarkets, pharmacies, banks, etc.

In the third column of Table 1, the direct, indirect and induced activity has been summed and then averaged for each acre of the regions' cropland. The lowest value is found in the Arkansas at $428 per acre and the highest is in the Rio Grande at $1,127 per acre. The crop mix describes, in part, the difference. The primary crop in the Rio Grand (in terms of its value) is

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[1] J. Thorvaldson and J. Pritchett. "Economic Impact Analysis of Irrigated Acreage in Four River Basins in Colorado." Colorado Water Resources Research Institute Completion Report. Fort Collins, Colo. Located at http://www.cwrri.colostate.edu/pubs/series/completionreport/crlist.htm

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potatoes, a high value crop that requires significant inputs to be grown, and is exported almost exclusively out of the region. Forage crops are typical in the Arkansas, and these perennial require relatively fewer inputs. In addition, much of the forages used in the Arkansas Valley are used locally.

So when is economic activity high? When high value crops are sold outside the region, when revenues from the crop sales are spent on locally produced inputs and when local support industries use local labor and inputs.

What about limited irrigation versus 'buy and dry' of irrigated land?

Limited irrigation is better for the regional economy when compared to fallowing or converting large swaths of land to dryland cropping. Simply put, limited irrigation provides greater direct, indirect and induced economic activity. While not as large as the economic activity shown under full irrigation in Table 1, the economic activity generated by limited irrigation is greater than that for dryland cropping.

The economic activity in Table 1 is a snapshot of irrigated agriculture's contribution today, but it cannot be interpreted as "lost" economic activity as water leaves agriculture. As an example, we would expect farms to adapt and improvise when confronted with a limited water situation – that is, they might convert to dryland cropping or rangeland. Likewise, agribusiness may innovate – it's common for wholesalers (such as cooperatives) to provide more small acreage services as large agriculture shifts out of the region. Of course, this is viable near larger urban areas than those that are more distant.

This table does not address distributional effects, two in particular. First, if the irrigated acres that are fallowed happen to be clustered (which is likely given legal transactions costs), the economic consequences will be localized and severe, even though they appear to be smaller when viewed at a regional scale. In addition, the effects will be more intense for particular businesses that are solely designed to support irrigated agriculture and individuals whose work skills are cannot be shifted from agriculture to other industries.

Finally, the economy's tipping points aren't represented Table 1 – that is, a critical mass is needed to support businesses in rural economies If revenues slide below the tipping point, then businesses may closed down in spite of efforts to shift to other revenue streams. Lost property taxes are also not included in the analysis, which may be severe given the large difference between assessed values of irrigated vs. dryland.

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Meet the Faculty


Dr. Neil Hansen

Dr. Neil Hansen joined the Colorado State University faculty in 2004 as an associate professor in the department of soil and crop sciences. His teaching responsibilities include SC420 and SC421, Crop and Soil Management Systems I and II. Dr. Hansen earned his bachelor of science in agronomy in 1992 and his masters of science in agronomy in 1994 from Brigham Young University. He completed his doctorate in soil physics at the University of Minnesota in 1998. Neil comes to CSU from the University of Minnesota where he worked in the department of soil, water and climate as a soil scientist and water quality specialist.

Although Dr. Hansen has a great deal of interest in dry land cropping systems, he quickly realized the need to address the loss of irrigation water in his research and outreach programs. Neil subsequently developed a cooperative research and demonstration project with the objective of sustaining profitable cropping systems in the environment of increasing competition for a limited water supply.

Limited Irrigation Alfalfa

by Neil C. Hansen, associate professor, Department of Soil and Crop Sciences

Alfalfa has several traits that allow some flexibility in managing a limited irrigation water supply. First and foremost, an established alfalfa crop has a root system that is efficient at exploring deep in the soil for water. Like most crops, alfalfa roots will develop most where soil moisture is available. As a result, alfalfa root systems look different under furrow and sprinkler irrigation systems. Because alfalfa roots deeply, it can use water that would move below the root zone of many other crops.

A second trait of interest is the ability of alfalfa as a perennial crop to go dormant during drought conditions and remain viable so that it can resume growth when water becomes available. This trait comes from alfalfa's origination in the semi-arid lands of Mesopotamia, where annual cycles of arid conditions are interrupted by seasonal precipitation. Finally, alfalfa hay quality is generally higher when yields are reduced from moisture stress. The higher quality can partially offset the loss in yield.

Beginning in 2005, Colorado State University and Northern Colorado Water Conservancy District (NCWCD) teamed up to study limited irrigation strategies for alfalfa. As part of the project, a careful study was made of past irrigated alfalfa research throughout the U.S. Great Plains region. Information was also combined from six individual studies conducted in an area from the Texas panhandle to North Dakota and a fairly consistent relationship was found between alfalfa yield and consumptive water use (Figure 1). The slope of the line relating yield to consumptive water use tells us it takes about 7 inches of consumptive water use to produce each ton of alfalfa dry matter. The consumptive water use is evapotranspiration of water obtained from irrigation, precipitation and stored soil moisture. There will be some deviation from this line based on local conditions, with Colorado likely requiring less water per ton than the average. Another lesson learned from past alfalfa research is that alfalfa uses water more efficiently during the cool conditions in spring and fall than during the hot summer months.

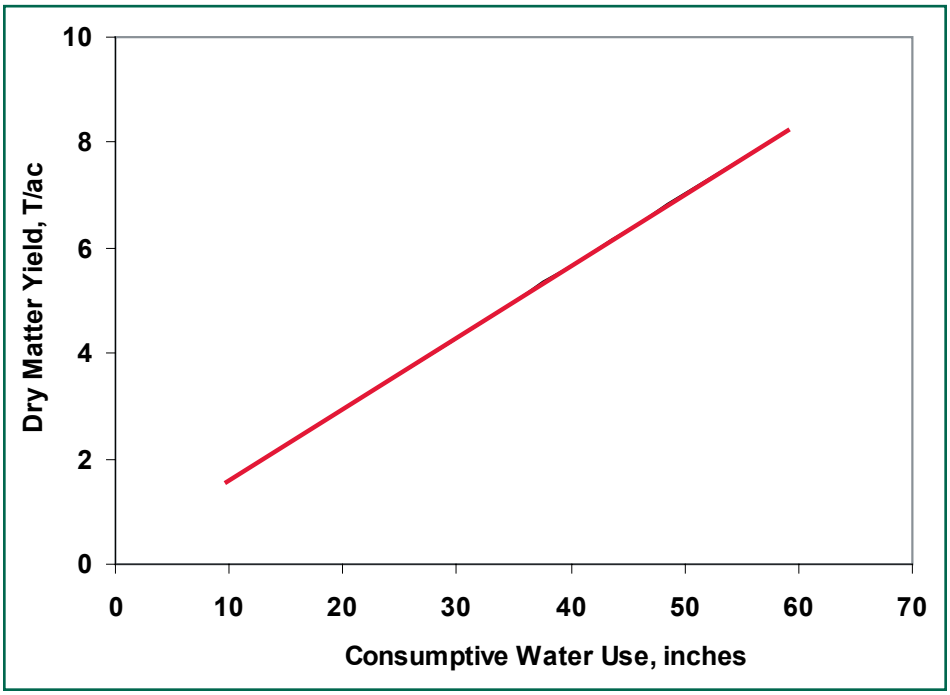

Figure 1. Relationship of alfalfa yield to consumptive water use based on six published studies in the Great Plains.

Based on the lessons of the past, we designed an experiment that evaluates alfalfa growth and yield with different irrigation regimes. The experiment is located at the NCWCD headquarters under a linear move sprinkler irrigation system on a two-year old alfalfa stand.

Our water management comparisons were:

1. Full irrigation reference
2. Terminate irrigation after first cutting
3. Terminate irrigation after second cutting
4. One additional irrigation after first cutting plus irrigation in late summer and fall

These reduced water approaches, called partial season irrigation, seek to get the most return per unit of applied water by irrigating during the cooler parts of the growing season and withholding irrigation during the hotter part of the summer. Our results for the 2006 growing season are shown in Figure 2. Applied irrigation amounts were 27 inches, 14 inches, 13 inches, and 5 inches for treatments 1 through 4 listed above, respectively. Total growing season precipitation between March and October was 7.1 inches. When irrigation water is limited, yields decline as expected. Notice that in the third treatment where irrigation was stopped and was later resumed, the fourth cutting yield was the same as that for the full irrigation treatment, illustrating alfalfa's ability to resume growth when water becomes available.

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Estimated Yield of Some Alternative Crops Under Varying Irrigation in Northeast Colorado

by David C. Nielsen, Research Agronomist, USDA-ARS, Central Great Plains Research Station

Much of the irrigated acres in northeastern Colorado are devoted to corn grain production. Diversifying irrigated agricultural production in this region could result in water savings if alternative crops were grown that have lower water requirements than corn. Making such crop choice decisions initially requires knowledge of how yields of new crops respond to water.

Over a number of years, water use/yield production functions have been developed at the Central Great Plains Research Station near Akron. Such functions predict yield based on a linear relationship between total water use and crop yield. Water use is considered to be the sum of soil water extracted from the soil by the crop, growing season precipitation, and irrigation applied during the growing season. Production functions for three oilseeds, four legumes, three forages, and corn grain are shown in Table 1. These 11 production functions (along with six others) are available for easy use in a simple Excel spreadsheet (the Central Great Plains Yield Calculator, available from the author) that also includes average growing season precipitation for 15 locations in eastern Colorado, western Nebraska, and western Kansas. The calculator assumes that water is the controlling factor for yield, and that other factors (such as date of planting, fertility, weed control, insect control, timing of precipitation and irrigation, and harvest efficiency) are optimal. The calculator also assumes that there are no significant weather influences such as hail, frosts, or excessive wind that would adversely affect yield.

Using the Yield Calculator can give a farmer an idea about the yield response of an alternative crop to the irrigation water that he would apply. Table 2 shows estimated yields for the crops whose production functions were given in Table 1 for four irrigation levels and assuming 6 inches of water was used from the soil. Average growing season precipitation was assumed for three locations in northeastern Colorado (Briggsdale, Limon, and Wray).

Oilseed Response to Irrigation

Of the three oilseed crops shown in Table 1, canola exhibits the largest response to water (175 lb/a/inch) while safflower shows the smallest response (121 lb/a/inch). Predicted yields at Briggsdale range from 1568 lb/a with 3 inches of irrigation to 3145 lb/a with 12 inches of irrigation. Yields at all irrigation levels are lower for safflower and sunflower compared with canola, and greater in Limon and Wray compared with Briggsdale as precipitation increases moving west to east. The highest predicted yield (3548 lb/a) comes from canola grown at Wray with 12 inches of irrigation.

Legume Response to Irrigation

Legume seed response to water ranges from 148 lb/a/inch for soybean to 240 lb/a/inch for chickpea (Table 1). With 3 inches of irrigation, the greatest legume seed yield at Briggsdale was predicted for pea (2598 lb/a) and the least from dry bean (1823 lb/a). With 12 inches of irrigation, the greatest seed yield was predicted for chickpea (4645 lb/a). As with predicted oilseed yield,

Table 1. Production functions used in the Central Great Plains Yield Calculator for three oilseed crops, four legumes, three forage crops, and corn.

Crop	Production function
Oilseeds	
canola	lb/a = 175.2*(inches water use – 6.22)
safflower	lb/a = 121.4*(inches water use – 3.02)
sunflower	lb/a = 150.6*(inches water use – 6.88)
Legumes	
pea	lb/a = 181.4*(inches water use – 0.85)
chickpea	lb/a = 240.4*(inches water use – 5.80)
soybean	lb/a = 148.1*(inches water use – 0.68)
dry bean	lb/a = 193.0*(inches water use – 5.50)
Forages	
forage triticale	lb/a = 748.4*(inches water use – 3.39)
foxtail millet	lb/a = 664.4*(inches water use – 3.07)
corn silage	lb/a = 548.8*(inches water use – 5.31)
Starchy Grain	
corn	lb/a = 582.2*(inches water use - 9.13)

Table 2. Yields predicted with the Central Great Plains Yield Calculator assuming 6 inches of soil water use and average growing season precipitation at three northeastern Colorado locations.

	Irrigation	canola	safflower	sunflower	pea	chickpea	soybean	dry bean	forage triticale	foxtail millet	corn silage	corn
	---in---	----------lb/a----------							----------T/a----------			lb/a (bu/a)
Briggsdale	3	1568	1497	1315	2598	2491	2531	1823	4.81	3.66	3.10	**5032 (90)**
	6	2093	1861	1767	3142	3212	2975	2402	5.94	4.66	3.92	**6778 (121)**
	9	2619	2225	2218	3686	3933	3420	2981	7.06	5.66	4.74	**8525 (152)**
	12	3145	2590	2670	4230	4654	3864	3560	8.18	6.65	5.57	**10271 (183)**
Limon	3	1690	1575	1393	2725	2678	2611	1993	5.18	3.95	3.35	**5346 (95)**
	6	2216	1939	1845	3269	3400	3055	2572	6.30	4.95	4.17	**7093 (127)**
	9	2742	2303	2297	3813	4121	3500	3151	7.42	5.95	5.00	**8839 (158)**
	12	3267	2667	2749	4357	4842	3944	3730	8.55	6.94	5.82	**10586 (189)**
Wray	3	1971	1743	1508	3015	3070	2809	2113	5.91	4.10	3.63	**6126 (109)**
	6	2496	2108	1959	3559	3791	3254	2692	7.03	5.10	4.45	**7873 (141)**
	9	3022	2472	2411	4103	4513	3698	3271	8.15	6.09	5.27	**9619 (172)**
	12	3548	2836	2863	4647	5234	4142	3850	9.28	7.09	6.09	**11366 (203)**

predicted yields of legumes are greater at Limon and Wray because of greater average growing season precipitation. Soybean yield at Wray with 12 inches of irrigation is predicted to be 4142 lb/a (69 bu/a).

Forage Response to Irrigation

Forage dry matter response to water ranges from 549 lb/a/inch for corn to 748 lb/a/inch for triticale (Table 1). Predicted dry matter yields range from 3.10 T/a for corn grown at Briggsdale with 3 inches of irrigation to 9.28 T/a for triticale grown at Wray with 12 inches of irrigation.

Comparisons with Corn Grain Predictions

Table 2 shows predicted corn grain production with four irrigation levels at the three eastern Colorado locations assuming 6 inches of soil water use and average growing season precipitation. Corn grain yields at all irrigation levels and all three locations are predicted to be much greater than oilseed or legume seed yields because of the much greater production function response of grain yield to water use for corn (582 lb/a/in) compared with the other crops (Table 1). This is due to the much more efficient photosynthetic mechanism in corn that turns carbon dioxide, water, and sunlight into carbohydrates compared with oilseeds and legumes. Much more energy is required to produce the proteins and oils in legumes and oilseeds than to produce the starches in corn.

The predicted yields in Table 2 give farmers a starting place to determine the consequences of growing a crop other than corn under irrigation in their quest to grow a profitable crop while lowering water use. The current high prices for corn, however, do not promote the production of any of these alternative crops.

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Yield Impact of Growth Stage Irrigation of Sunflowers

by Joel Schneekloth, Extension Northern Region Water Resource Specialist

Sunflowers are native to the Colorado Central High Plains. Sunflowers are a crop that has a deep root system that can utilize soil moisture that most crops can not access. Producers within Northeast Colorado have asked questions about irrigation management of sunflowers under limited water conditions. However, little is known about irrigation management of sunflowers.

In 2002, research was initiated to look at the response of sunflowers to growth stage irrigation. Irrigation management strategies looked at comparing a range of timings from full irrigation to dryland. Limited irrigation strategies including irrigating only during time periods during the reproductive growth stages which are generally the most susceptible to water stress. Theses included irrigating from bud initiation (R1) to beginning bloom (R3), bud initiation to petal drop (R5), beginning bloom (R4) to petal drop and petal drop to beginning maturity (R7). Irrigation was applied at a maximum of 2 inches per week during those growth stages. The sunflowers were planted into dryland winter wheat stubble which did have an impact on beginning soil moisture two of the four years (2002 and 2004). Oil seed sunflowers were planted in late May or early June depending upon conditions at a rate of 24,000 seeds per acre.

Grain yields are shown in Figure 1. Grain yields in 2002 were impacted by drought, rodent damage and severe hail. These events limited yields in 2002 as compared to the remaining years. In years such as 2002 and 2004, full irrigation of sunflowers resulted in the highest yields as compared to all other irrigation strategies. Limiting irrigation at any growth stage resulted in lower yields. In each of these years, beginning soil moisture was limited as compared to 2003 and 2005 which were at field capacity to a depth of 6 feet or more. Limiting water during years with less than an adequate profile resulted in yield reductions. However, limiting water to the beginning bloom to petal drop resulted in similar grain yields as compared to irrigating during the bud initiation to petal drop in 2004. Precipitation in 2004 was near average during the June to August time period.

In years with a soil moisture profile at or near field capacity to a depth of 6 feet, limiting irrigation in the vegetative and early reproductive growth stages resulted in greater yields than full irrigation (2003 and 2005). Irrigating during the R4 to R5 growth stages utilized the stored soil moisture during the vegetative growth stages and positively responded to irrigation during the pollination time period. Irrigation during the early reproductive and vegetative growth stages reduced grain yields by 200 to 300 pounds per acre as compared to irrigation during the R4 and R5 growth stages. It is still unknown why there is this type of positive response to limited irrigation during the R4 to R5 growth stage when beginning soil moisture is adequate.

Another major issue with oil type sunflowers is the impact of oil content with irrigation management. Oil type sunflowers are paid a premium for oil contents above 40 percent and a deduction is charged when oil is below 40 percent. Increasing oil contents can have a major impact on the economics of irrigated sunflowers. For every 1 percent increase in oil content, yields can be 2 percent less and still have the same gross revenue.

Figure 2 shows the oil content for the irrigation strategies. In three of the four years, oil contents increased as irrigation was initiated later in the growth stage as compared to full irrigation. Withholding irrigation until after the R5 growth stage increased oil significantly as compared to

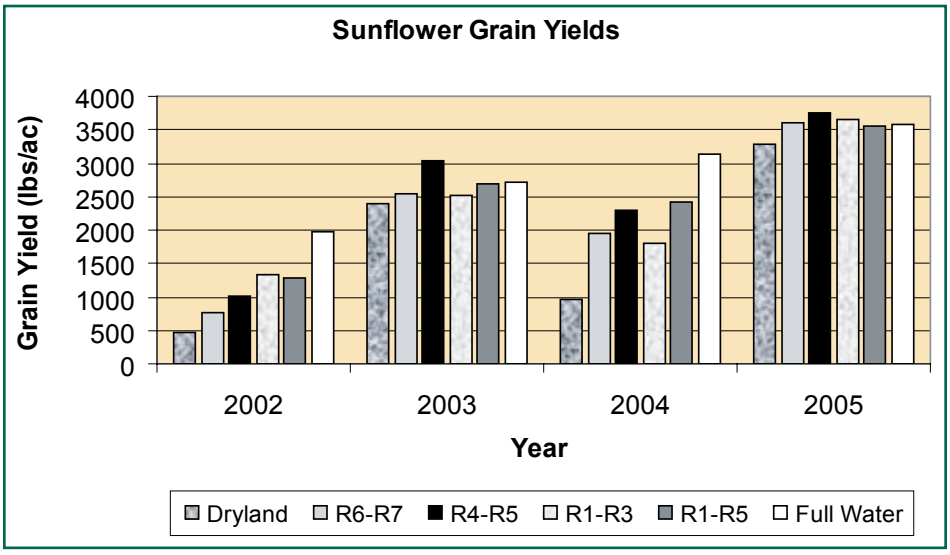

Figure 1. Sunflower grain yields affected by irrigation timing at Akron.

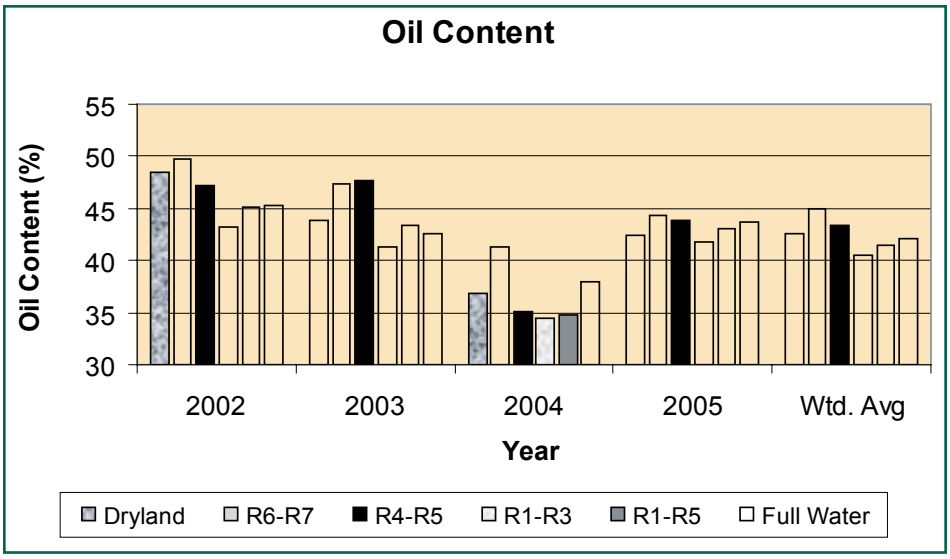

Figure 2. Sunflower oil content affected by irrigation timing at Akron.

full irrigation management. Oil content of the R6 to R7 strategy averaged 2 percentage points more oil as compared to the next optimal strategy. This strengthens the philosophy that oil is "laid down" after pollination. However, irrigating prior to end of pollination generally decreased oil content as compared to this strategy. The next optimal strategy was irrigating during the R4 and R5 growth stage. This strategy averaged 1.5 percentage points more oil than compared to full irrigation.

Irrigating at the beginning of the bud initiation growth stage and ending irrigation at either the beginning bloom or petal drop significantly reduced oil content. When ending irrigation at beginning bloom, the oil content was reduced by 1.5 percentage points as compared to full irrigation. Irrigating during the early reproductive growth stages and ending prior to the R6 growth stage generally resulted in larger plants that required more water. In most years, this resulted in water stress during the R6 to R8 growth stage.

By limiting irrigation, how much water was saved. Full irrigation of sunflowers averaged more than 10 inches of irrigation per year. Limiting irrigation to the R4 to R5 growth stage reduced the amount of irrigation applied by 60 percent as compared to full irrigation. Only irrigating during the R1 to R5 growth stage resulted in an irrigation reduction of 35 percent as compared to full irrigation. The current recommendation for irrigating oil sunflowers is, 1.) if soil moisture is at or near field capacity to a depth of 5 feet, limit irrigation to the R4 to R5 growth stage, 2.) if soil moisture is limited, practice full irrigation during the growing season.

Although confection sunflowers were not discussed in this article, results from this study found that the optimal irrigation strategy for confection sunflowers was irrigating during the R1 to R5 growth stage. Grain yields seed sizes were similar to that of full irrigation. Confection sunflowers responded to water earlier as compared to oil sunflowers. This may be due to the fact that seed size is much more important than oil and seed size may be determined earlier in the reproductive growth stages.

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The Effects of Drip Irrigation on Corn Yield and Soil Salinity in the Arkansas Valley

by Abdel Berrada, Research Scientist, Arkansas Valley Research Center

The sale and transfer of water to municipalities along the Front Range, coupled with recent droughts, have prompted interest in water conservation in the Arkansas Valley of southeastern Colorado (Ark Valley). Furrow irrigation is still the predominant irrigation system in the Ark Valley, but more efficient systems such as drip irrigation are gaining in importance. Drip irrigation is mostly used for the production of vegetable crops such as cantaloupes and onions, which often are rotated with corn. Research in western Kansas has demonstrated the feasibility of subsurface drip irrigation (SDI) for corn production if the system is maintained for 10 years or longer. However, the impact of SDI on salt accumulation in the soil profile and potential crop loss is not well known. Salinity is a serious concern in the Ark Valley and increases from West to East.

A field experiment was initiated at the Arkansas Valley Research Center (AVRC) in 2005 to study the effects of SDI on corn yield and the movement of salts in the root zone. Water was applied through SDI or via furrows as often as possible (full-irrigation regime) or at selected growth stages (deficit irrigation). Other variables were N (0, 60, 120, and 180 lb/acre) and manure rates (0, 10, 20, and 30 T/acre). Drip tapes were placed 8 inches below ground, at 5-foot intervals. Furrows were also 5 feet apart. Corn was planted in late April at approximately 33,000 seeds/acre, in 30-in rows.

There were no significant differences in corn yield between SDI and furrow irrigation (FrI) in 2005 and 2006 (Figure 2), in spite of the fact that 76 and 57 percent more irrigation water was applied with FrI than with SDI in 2005 and 2006 (Figure 1). Full irrigation produced on average 20 bu/acre more corn than deficit irrigation in

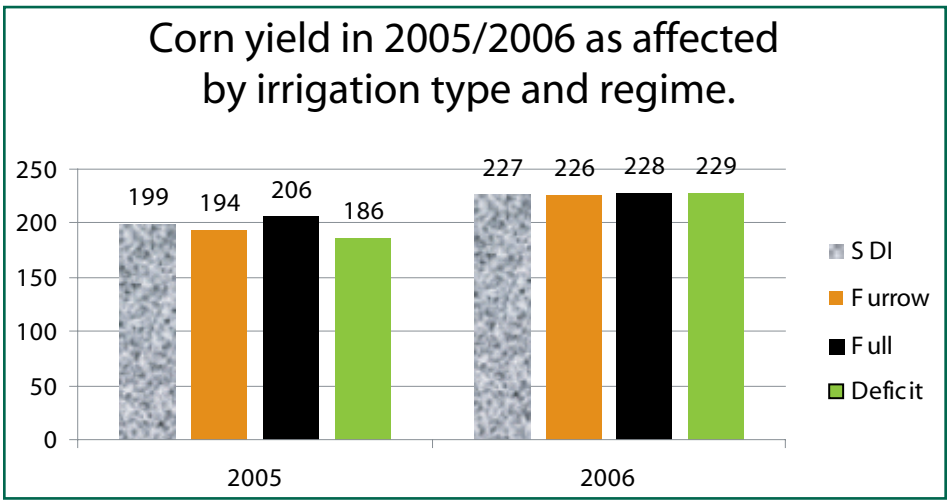

Figure 1. 2005-2006 Corn Yields.

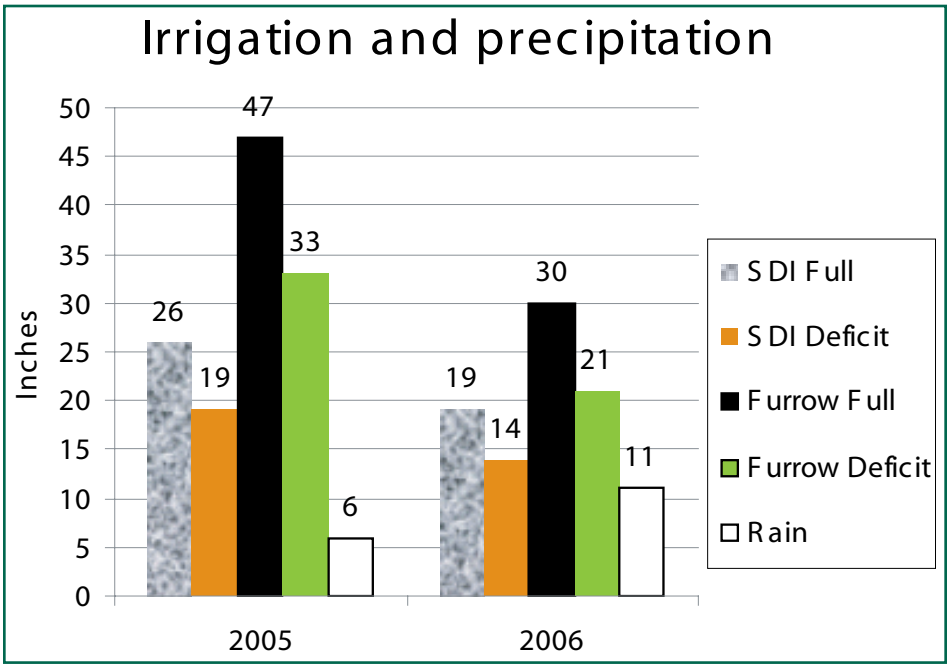

Figure 2. Total irrigation and precipitation during the 2005 and 2006 corn seasons.

2005 (Figure 3). There was no significant difference between the two irrigation regimes in 2006 (Figure 3), probably due to higher rainfall and more targeted deficit irrigation in 2006.

The manure treatments resulted in much higher ECe values than the non-manure treatment of 120 lb N/acre in the top 4 to 12 inches of soil, early in the season (Figure 4). Lower ECe values were observed after corn harvest in 2005 and 2006 (Table 1) due to salt movement and redistribution in the soil profile. In general, there was greater salt concentration

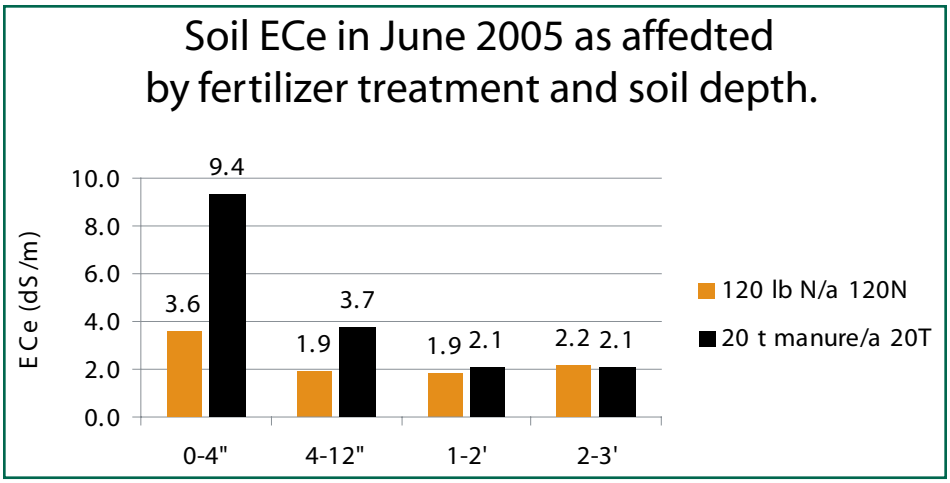

Figure 3. June 2005 Soil ECe levels.

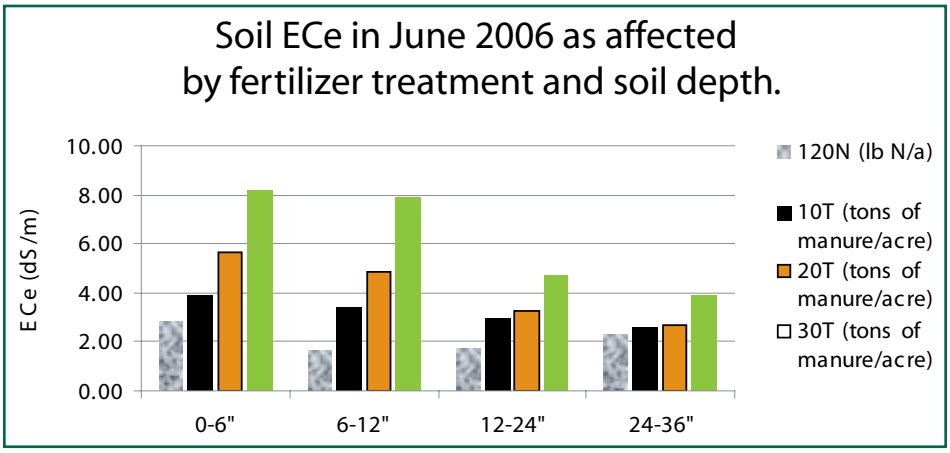

Figure 4. June 2006 Soil ECe levels.

(higher ECe) away from the drip tape (located in the middle of the bed) e.g., in the furrow under SDI. Similarly, greater ECe values were measured in the bed center than in the furrow under FrI (Table 1). Another striking difference was the apparent salt accumulation under SDI in the 3 foot to 6 foot depth, compared to FrI, which could be due to the higher leaching potential of FrI. Salt accumulation under SDI is a concern in the Ark Valley, particularly when well water is used (well water is generally more saline than ditch water) and may require periodic flushing.

This study was supported by the Colorado Department of Public Health and Environment (Water Quality Control Division), the Colorado Agriculture Experiment Station, and the Soil Plant Nutrient Research Unit of USDA-ARS in Ft. Collins, Colo.. It will be continued for at least one more year to further assess salt and N movement under SDI and FrI. Concurrently, a new experiment will be started in 2007 to examine in more detail the effects of irrigation scheduling, based on crop ET, on corn DM and grain yield.

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Table 1. Post-harvest soil ECe (dS/m) under SDI and FrI as affected by sampling depth and position.

Soil Depth	SDI						FrI					
	Furrow		Row		Bed Center		Furrow		Row		Bed Center	
	Nov. '05	Nov. '06	Nov. '05	Nov. '06	Nov. '05	Nov. '06	Nov. '05	Nov. '06	Nov. '05	Nov. '06	Nov. '05	Nov. '06
0-6"	2.59	1.10	1.53	1.26	1.95	2.17	1.38	1.10	2.01	1.72	4.25	3.81
6-12"	2.01	1.39	1.49	1.57	1.28	1.71	1.61	1.28	1.28	1.51	2.62	4.86
1-2'	2.06	1.94	2.38	1.86	1.12	1.32	2.02	1.27	1.49	1.38	1.83	2.95
2-3'	2.46	2.67	2.94	2.96	1.28	1.36	2.03	1.35	1.91	1.38	1.52	2.52
3-4'	2.65	2.91	2.85	3.91	1.95	2.11	2.30	1.75	2.23	1.73	1.65	2.46
4-5'	3.32	4.04	3.63	4.77	3.26	3.58	2.76	2.29	2.85	2.45	2.09	2.67
5-6'	3.35	4.13	3.72	4.66	3.49	3.92	2.58	2.35	2.94	2.60	2.01	2.34

Effects of Water Stress on Corn Production

by Joseph Benjamin, USDA Agricultural Research Service, Akron

Competition between agricultural and urban water uses in the semi-arid west often leaves agricultural producers with short water supplies. Better irrigation management must be used to maximize the economic benefit of the water available to agricultural producers. Maximum irrigation water efficiency is obtained when water is applied so that water stress on the crop is minimized and over watering is eliminated.

The first step to determine how much water to apply and the interval between watering is knowledge of soil characteristics. Over watering can be as detrimental to crop production as under-watering. Soils will retain only a limited amount of water so over-watering can cause excessive leaching of water and nutrients. Excessive water application can lead to low oxygen levels caused by lack of air-filled pore space and limited oxygen exchange with the atmosphere. Under-watering can cause high soil strength and may limit root proliferation if the soil is too hard for roots to penetrate. Lack of water can cause plant stress when the plant can no longer assimilate sufficient water to meet evapotraspiration demand, either due to limited root development or low water content in the soil.

A way to determine the range of water contents that provide a suitable environment for crop production is to plot these limiting soil physical characteristics on a graph and determine the range of water contents where the detrimental effects of these factors are minimized. The range of water contents that provide minimal soil physical limitations for these properties is called the Least Limiting Water Range (LLWR). An example of the LLWR for a Weld silt loam is shown in Figure 1. The crosshatched area represents the range of water content at various bulk densities that would not cause physical limitations to plant growth.

The objective of irrigation management is to maintain the soil water content within the LLWR. In this example, if the soil had a bulk density of 1.3 g/cm^3, the desirable soil water content range would be between 22 and 38 percent volumetric water content. Irrigation would be scheduled based on crop water use and irrigation application to keep the water content within this range at all times.

Significant water savings can occur by not irrigating too early in the growing season. If there was sufficient water recharge over winter and there is sufficient water to germinate the seed, irrigation may not be needed until corn gets to the knee-high growth stage. Delaying watering allows the producer to take full advantage of spring rainfall and water stored in the soil.

After irrigation starts, one must be careful not to over water. Irrigation scheduling based on crop water use determined from crop growth stage and current weather conditions is the most efficient method to determine water application rate. As a rule of thumb, water use at the seedling stage is < 0.05" per day. When corn gets to 1 ft. high the water use rate is about 0.10" per day. Corn at silking uses between 0.30" and 0.50" of water per day. During grain fill, corn will use water at about 0.30" of water per day.

Any water stress can cause lower corn yield. Figure 2 shows the reduction in irrigated corn yield at Akron, Colo., caused by the cumulative water stress. The term

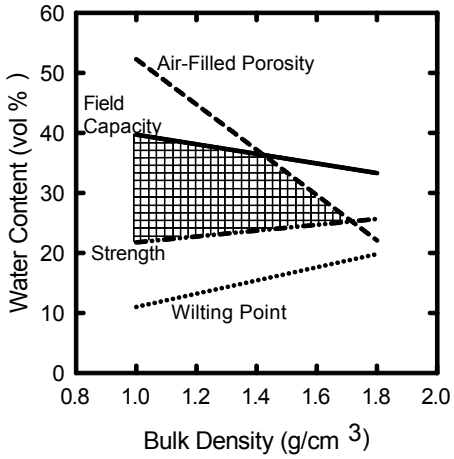

Figure 1.

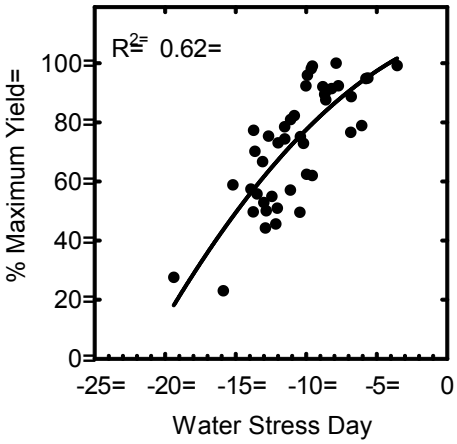

Figure 2.

Water Stress Day (WSD) is the number of days where the water content in the surface 2' feet of soil is outside of the LLWR. Corn withstood about 5 WSD before significant yield reductions occurred.

The timing of water stress influences the magnitude of the effects. Water stress during the vegetative growth stage reduces leaf and stem elongation and results in a shorter plant with smaller leaves. Water stress during the reproductive growth stages can delay silking and inhibit pollination. Water stress during grain filling may

reduce the time for grain filling and lead to lower test weights. The most critical time for water stress to occur is during silking. In several studies across the western United States, water stress during the vegetative growth stage lowered corn yield by about 7 bu/inch of irrigation water while water stress during silking lowered corn yield by about 16 bu/inch of irrigation water.

In conclusion, less than adequate water supplies need not prohibit growing corn under irrigation. While some yield loss will occur with less irrigation, proper irrigation management for the soil conditions and better timing of irrigation to minimize stress during critical periods can minimize the adverse effects of lower water supplies.

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Limited Irrigation Alfalfa

continued from page 7

An initial economic analysis suggests that the two intermediate irrigation levels in this study may remain profitable, while yields in the driest system were not adequate for a profitable system. Partial season irrigation may be a viable strategy for limited irrigation of alfalfa. This strategy of fully irrigating alfalfa for a partial season is a better approach than deficit irrigation throughout the full growing season because it focuses irrigation and growth during the cooler time periods when water use is more efficient. This study will be continued for several more growing seasons to evaluate profitability and alfalfa stand quality over time. However, our initial results suggest that alfalfa is a crop that provides flexibility for irrigation water management when supplies are limited.

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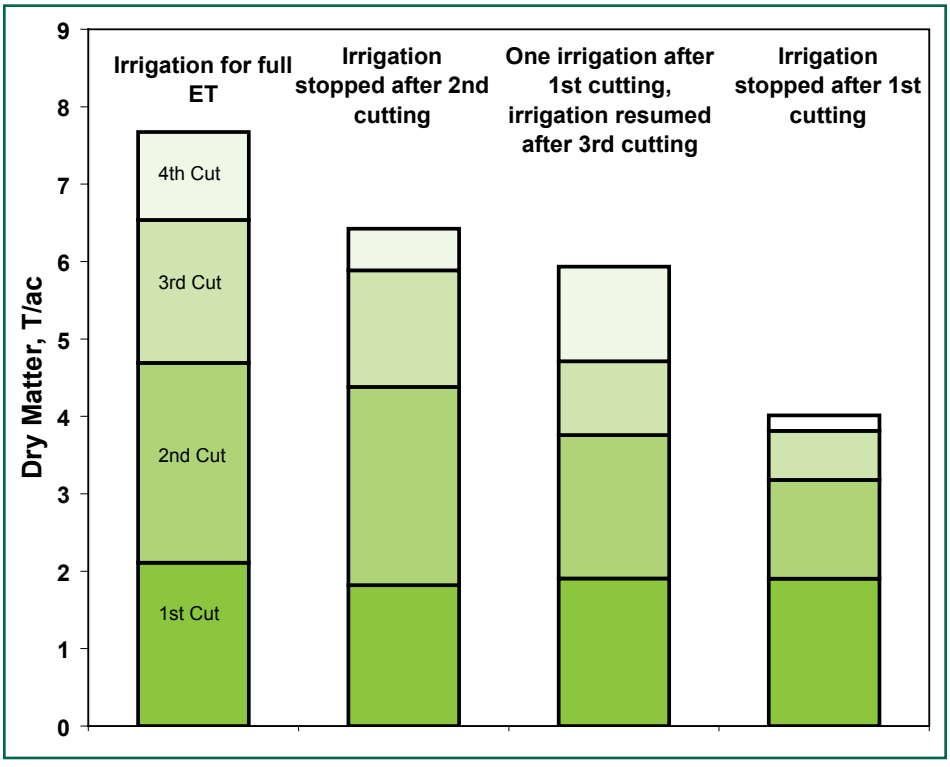

Figure 2. 2006 Alfalfa Yields With Different Irrigation Strategies, Berthoud, Colorado

Limited Irrigation and Crop Rotation Project Studies Methods to Reduce Consumptive Use

by Joel Schneekloth, Extension Northern Region Water Resource Specialist

An on-farm demonstration and research project was initiated in 2006 near Burlington, Colo. to cropping practices to reduce consumptive use in the Republican River Basin. Colorado needs to find ways to reduce consumptive use in this basin to meet compact compliance with Kansas and Nebraska and also preserve the life of the High Plains (Ogallala) aquifer. This need was accentuated in 1998, when Kansas brought suit against Nebraska for using more than its allocation of the three-state Republican River compact. The Kansas claim was largely based on the use of groundwater for irrigation. Nebraska brought Colorado into this suit as a third party and the suit was settled in 2002 with an agreement that groundwater pumping be included in the calculations for stream flow depletion.

Corn is the primary irrigated crop in the Colorado High Plains. Approximately 70 percent of the irrigated acres are grown as irrigated corn followed by hay as the next largest irrigated acreage. Acreage of lower water use crops such as winter-wheat, beans, sunflower, and others was approximately 10 percent of the irrigated acreage. Fully irrigated corn has a seasonal evapotranspiration (ET) requirement (consumptive use) of 25 to 27 inches per acre while low water use crops require approximately 18 to 23 inches of ET per acre.

To demonstrate crop rotations to reduce consumptive use and aquifer depletion, we split a 130-acre center pivot is split into four zones. Each zone contains a different crop: winter-wheat, corn, sunflowers, or soybean grown in that order. This rotation incorporates low water use crops such as wheat with high water use crops such as corn and medium water use crops such as sunflower and soybean. The use of this rotation should reduce average ET, as compared to fully irrigated corn, of the irrigated acres by 16 percent with a reduction in calculated net irrigation requirements of 25 percent when all crops are fully irrigated.

Three irrigation management treatments are incorporated for each crop. These treatments range from an allocation averaging 9 inches per year to full irrigation, and an intermediate water treatment that will use less water than full irrigation. The allocation and intermediate irrigation treatments withhold irrigation until the reproductive growth stages for each crop unless soil moisture depletions reach approximately 70 percent depletion of available soil moisture in the active root zone. The full irrigation management will irrigate according to current best management practices for each crop, irrigating to meet ET demands unmet by precipitation.

The 2006 growing season at Burlington received near-average precipitation for the entire growing season, but precipitation for June and July was above normal by 1.5 and 1.0 inches, respectively. Although water stress was evident on the intermediate allocation corn during the later half of June, the stress associated with the corn was not severe enough to reduce grain yields (Table 1), but did reduce plant height as compared to full irrigation. At maturity, the allocation corn was approximately 2

Table 1. Grain yields for corn and sunflowers.

	Corn		Sunflower	
	Irrigation (inches)	Yield bu/ac	Irrigation (inches)	Yield lbs/ac
Allocation	8	193	4	2486
Interm.	10	203	6	2583
Full	12	198	8	2387

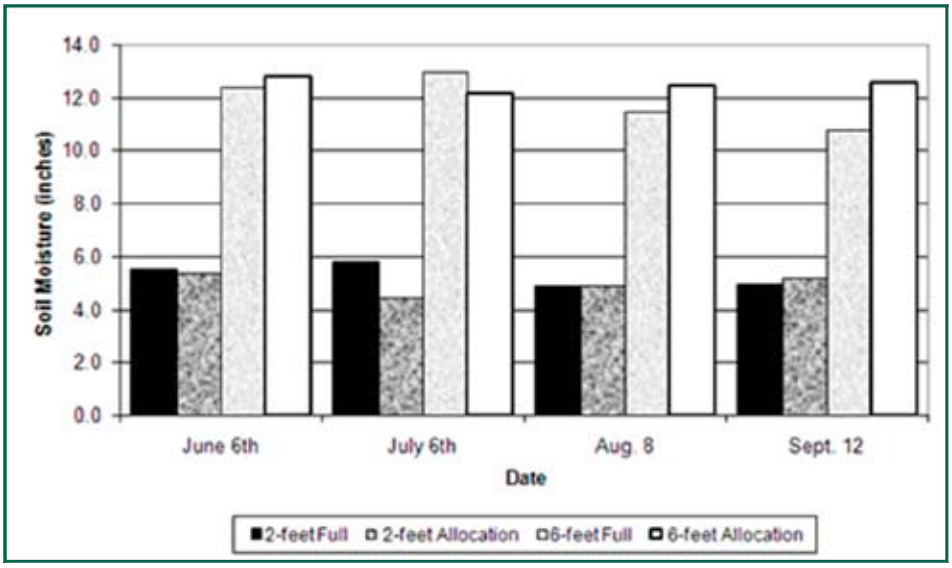

Figure 1. Volumetric soil moisture (inches/inch)

feet shorter than the corn in the fully irrigated treatment.

Volumetric soil moisture (inches/inch) for full and allocation corn (Figure 1) shows the changes in soil moisture during the growing season. Soil moisture in the upper 2 feet for allocation corn was much drier than compared to full irrigation corn. The difference in moisture between full irrigation and allocation corn was more than 1.5 inches difference in water availability. Although irrigation and precipitation for full and allocation irrigation were similar after the week of July 10, soil moisture for full irrigation was declining as compared to allocation. Much of this may have been due to difference in the leaf area between the treatments available for transpiring water.

Grain yields for irrigated sunflowers are shown in Table 1. The intermediate irrigation management yielded approximately 200 pounds per acre more than full irrigation with an irrigation savings of 2 inches. Allocation sunflowers had 4 inches of irrigation applied as compared to 8 inches for full irrigation and averaged approximately 100 pounds per acre more than full irrigation. Oil contents for allocation and intermediate management strategies averaged 47 percent oil as compared to 42 percent for full irrigation. These results are similar to research on irrigation timing conducted at Akron, Colo. (see sunflower article on page 10). Early irrigation of sunflower did not increase yield and reduced oil content as compared to timing the irrigation to the beginning flower growth stage.

In 2006, with average to above average precipitation, reducing irrigation during the vegetative growth stages did not reduce grain yields as compared to full irrigation. However, having adequate irrigation capacity to bring crops out of water stress prior to entering the reproductive growth stages is important. This is the first year in a multi-year research and demonstration plot which will continue thru 2008 with current funding. The 2007 rotation includes winter-wheat after soybeans, corn after corn, sunflowers after corn, and soybeans following sunflowers. Funding for this project was with the USDA-NRCS Conservation Innovation Grant and the Republican River Water Conservation District.

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USDA-Agricultural Research Service Initiates Limited Irrigation Project

by Tom Trout, Research Leader, Water Management Research Unit, USDA-Agricultural Research

The Water Management Research Unit of the USDA-Agricultural Research Service in Fort Collins is initiating a five-year study on limited irrigation at a Colorado State University field site near Greeley. This group of agricultural engineers and weed scientists will be measuring water production functions (crop yield response to declining amounts of irrigation) and weed management of four crops in rotation – wheat, sunflower, corn, and dry beans. The crops will be monitored how the crops respond to limited irrigation and measure stress indicators such as canopy temperature, stomatal closure, leaf water potential and soil water content. These indicators should show when a crop is being damaged by the lack of water and how plants respond to water stress at different growth stages. By carefully timing irrigations, we hope to develop strategies for obtaining the maximum yield from an available water supply. Throughout these trials we will be working with crop simulation modelers from the ARS Agricultural Systems Research Unit to improve the ability of models to predict the crop response to water stress. We will then use these models to extend the field trial results to other soils and climates. The field trials will be carried out under both minimum and conventional tillage to compare how much rain and irrigation water is stored and preserved for crop use under the two tillage systems.

While the engineers are monitoring the crops, the weed scientists will measure how weed populations vary under limited irrigation and determine how to manage the weeds so they don't compete with the crop for the limited water. We expect that dry soil conditions and reduced crop canopies will result in changes in the composition and populations of weeds. Reduced irrigation will likely result in changes in herbicide activity, effectiveness and seasonal carry-over compared to well watered conditions.

The expected outcome of these studies will be information that, when combined with results from CSU limited water studies, can be used to develop decision support aids for growers. These aids will help growers choose which crops to plant, schedule irrigations, and manage weeds so they can maximize their income with available water supplies.

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Limited and Full Irrigation Comparison for Corn and Grain Sorghum

by Kevin Larson, Research Scientist; Dennis Thompson, Technician; and Deborah Harn, Research Associate, Plainsman Research Center, Walsh, Colorado

The importance of limited irrigation (supplemental irrigation) has traditionally been associated with very low capacity irrigation wells. The current high fuel prices and associated pumping costs places new emphasis on limited irrigation as a replacement for full irrigation when commodity prices are low. At the Plainsmen Research Center, we define limited irrigation on corn and grain sorghum as applying one in-season, furrow irrigation of less than 10 a-in./a, or a similar amount or water applied with a sprinkler. Applying less than 10 a-in./a of in-season irrigation assumes that the soil water profile is full from sufficient winter moisture, or, if winter moisture is lacking, the soil water profile is filled by pre-irrigation.

Limited irrigation becomes a more profitable choice, as fuel costs increase and commodity prices remain low. Our research (http://www.colostate.edu/depts/prc/pubs/LimitedandFullIrrigationComparisonforCorn.pdf) suggests that the decision point for conversion from full irrigation to limited irrigation with our current costs, and the target price ($2.63/bu for corn and $2.57/bu for grain sorghum) as the expected grain price, is $5.00/a-in. pumping cost for corn and $6.00/a-in. pumping cost for grain sorghum (Figure 1). This past season, research the pumping cost in the Southern High Plains Groundwater District was between $6.50 a-in./a to $7.50 a-in./a for a typical 600 gpm, 300 ft. well with a natural gas power plant.

An economic comparison between corn and grain sorghum under full and limited irrigation is dependent on commodity price and input costs. Having a similar target price for corn ($2.63/bu) and grain sorghum ($2.57/bu) provides corn with higher net income than grain sorghum under limited irrigation and nearly identical net income under full irrigation. However, when corn and grain sorghum commodity prices are above the target price, corn frequently has a $0.30/bu price advantage compared to grain sorghum in the local market. Corn priced $0.30/bu higher than grain sorghum provides corn with higher net income than grain sorghum under both full and limited irrigation.

With the current commodity prices, full irrigation has the income advantage over limited irrigation even with relatively high pumping costs. The current demand for corn and grain sorghum for ethanol production has increased the new crop contract price to over $4.00/bu. With these high commodity prices ($4.00/bu for corn and $3.70/bu for grain sorghum), pumping costs would have to exceed $9.50/a-in. for grain sorghum and $11.00/a-in. for corn in order to make limited irrigation more profitable than full irrigation.

When input costs, particularly pumping costs, are high and commodity prices are low, limited irrigation is more profitable than full irrigation. Inputs such as fertilizer and seed, which differ between full and limited irrigation regimes, favor limited irrigation when these input costs increase. When commodity prices are high and input costs are low, full irrigation is more profitable than limited irrigation. Currently, full irrigation is more profitable than limited irrigation because the high commodity prices more than compensate for the moderately high input costs.

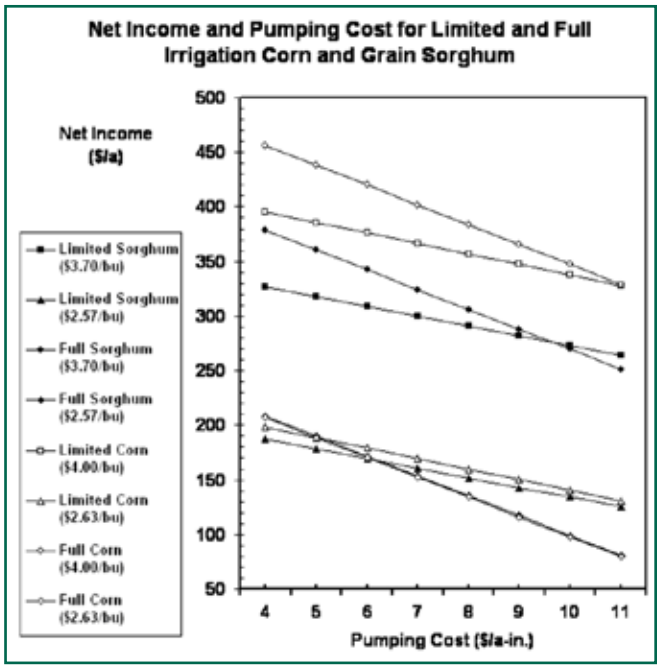

Figure 1. Full and limited sprinkler irrigation comparison of net income for corn and grain sorghum. Assumptions: yield: 151 bu/a for full irrigation grain sorghum, 123 bu/a for limited irrigation grain sorghum, 182 bu/a for full irrigation corn, and 144 bu/a for limited irrigation corn; grain price: $2.63/bu and $4.00/bu for corn, and $2.57/bu and $3.70/bu for grain sorghum; irrigation: 17 a-in./a for full irrigation corn and grain sorghum, 8 a-in./a for limited irrigation grain sorghum, and 9 a-in./a for limited irrigation corn; production costs: pumping cost varies from $4 to $11/a-in., all other costs remain constant.

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Research/Outreach Team to Develop Rural-Urban Water Model

by Tom Holtzer, Department Head and Professor, Department of Bioagricultural Sciences and Pest Management

Colorado State University is partnering with the Parker Water and Sanitation District (PWSD) in a research and outreach project aimed at developing ways to sustain irrigated agriculture while meeting the increasing water demands of urban areas. Results from this three-year, $1 million-plus project are expected to provide crucial information that can be used in the development of water policy and ways to establish rural-urban water partnerships. The study will develop and investigate cropping system options to determine how much water can be saved. The water saved can be made available for possible urban use, while at the same time sustaining viable economic returns to the agricultural and rural communities.

A 14-member multidisciplinary research and outreach team will investigate cropping system options such as rotational cropping (fallowing of a portion of the land); limited irrigation; using drought-tolerant crops and crop varieties; and adoption of optimal irrigation technology and alternative farming practices that reduce demand for water. All three of these methods would make water available for urban use. Various strategies will be characterized and compared from the perspectives of farm profitability and economic activity in the agricultural and rural sectors, the amount of water made available for other uses, and practical feasibility.

Funding from PWSD includes more than $850,000 plus the use of more than $200,000 in equipment for the research. Experiments will be carried out on land owned by PWSD near Iliff, Colo., at CSU's Agricultural Research Development and Education Center north of Fort Collins, and in on-farm demonstrations performed by local farmers near Iliff. The combination of small scale experimental studies, larger scale controlled experiments, and on farm demonstrations, are designed to more quickly and efficiently provide robust results. Project results will be made available during demonstration field days, and as part of the Colorado State University Extension fact sheets, technical reports and this newsletter.

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Limited Irrigation References and Resources on the Web

Agronomy News – Crop Production with Limited Water:
http://www.extsoilcrop.colostate.edu/Newsletters/2003/Drought/drought.pdf

Irrigating for Maximum Economic Return with Limited Water:
http://www.ianrpubs.unl.edu/epublic/live/g1422/build/g1422.pdf

Irrigating with Limited Water Supplies – A Practical Guide to Choosing Crops Well-Suited to Limited Irrigation: http://waterquality.montana.edu/docs/Publications/irrigatingsmallerfile.pdf

Cropping options for limited water supplies in Northeast Colorado:
http://www.extsoilcrop.colostate.edu/Newsletters/2003/croppingoptions_2003.htm

Seasonal Water Needs and Opportunities for Limited Irrigation for Colorado Crops:
http://www.ext.colostate.edu/pubs/crops/04718.html

Crop Water Use and Growth Stages:
http://www.ext.colostate.edu/pubs/crops/04715.html

Estimating Soil Moisture:
http://www.ext.colostate.edu/pubs/crops/04700.html

Colorado State University Extension Drought Resource page:
http://www.ext.colostate.edu/menudrought.html

Past proceedings from the Central Plains Irrigation Conference contain several studies on limited irrigation:
http://www.oznet.ksu.edu/irrigate/OOW/CPIADocs.htm

Conventional, Strip, and No Tillage Corn Production Under Different Irrigation Capacities: http://www.oznet.ksu.edu/irrigate/Reports/Lamm07ICTRev.pdf

Presentations from a Limited Water Conference are available at:
http://wsprod.colostate.edu/cwis435/WQ/presentations.htm

Univ. of Neb. Decision Support Tool for Producers with Limited Water:
http://real.unl.edu/h20/

KSU Crop Water Allocator computer program:
http://www.oznet.ksu.edu/mil/cwa/

Multiple links to water and water quality information:
www.csuwater.info