Agronomic Impacts of Reduced Irrigation in the Upper Colorado River Basin

A Review of the Literature for Informing a Demand Management Program

Prepared for The Nature Conservancy by Culp & Kelly, LLP

August 2019

Agronomic Impacts of Reduced Irrigation in the Upper Colorado River Basin

A Review of the Literature for Informing a Demand Management Program

Contents

I. Introduction

Significant research has been conducted in the last decade on the agronomic impacts of reduced irrigation in the Upper Colorado River Basin. However, much of this research is difficult to access or otherwise not readily available to stakeholders currently investigating the feasibility of a demand management program. This paper reviews and synthesizes the identified, compiled body of research work to highlight key findings related to agronomic impacts of limited irrigation or other methods to reduce consumptive use of irrigation water and identify the factors that are showing up with some regularity. The concluding section identifies remaining research questions and suggests some potential implications and possible next steps for a demand management program. The appendix summarizes the parameters of several of the studies reviewed.

II. Overview

Agricultural productivity on irrigated land is affected by a wide variety of factors, many of which are outside of the producer's control. Weather, snowpack, and equipment malfunction, just to name a few, will impact field operations, yields, returns, and water use (and water savings) (Brummer 2015) (Smeal, et al. 1994). **A unifying theme across the reviewed research is that site-specific variables can lead to large variations in water use efficiency and crop yield—critical factors in evaluating potential water savings and financial returns of changed irrigation practices**. Nevertheless, a viable demand management program based on compensation for reduced consumptive use must have some degree of predictability as to expected water savings, in order for producers and program managers/funders to know what to expect.

A significant amount of the research reviewed for this paper has focused on alfalfa – both because it covers a large percentage of irrigated acreage and because it represents a significant amount of the irrigation water used in the Colorado River Basin (and broader Western United States). Alfalfa also stands out as one of the crops most tolerant to limited irrigation with less residual effect on stand recovery or land in years following limited or deficit irrigation. A few other crops have also been shown to have potential for limited or reduced irrigation: grass hay/pasture, corn (grain and silage), wheat, and sunflowers. Research has also been conducted on the effects of limited irrigation on barley, dry beans, potatoes, and sugarbeets. Finally, a few crop types stand out as absolutely not tolerant to limited irrigation: vegetables, orchards, and vineyards (both in terms of tolerance and in value).

This paper describes various agronomic impacts related to limited irrigation methods (typically split-season irrigation, rotational or temporary fallowing, and deficit irrigation) that have been identified in research to date. The majority of the research described here relates to alfalfa, but where agronomic affects for other crops are described, those are specifically noted. The agronomic impacts evaluated in most studies include changes in: yield; quality; crop water use efficiency; same season and later year recovery; soil health; weeds, disease and pests; and agricultural operations. These various impacts are summarized to assist decision makers in navigating the space between agricultural risk/uncertainty and moving forward with a viable demand management program.

III. Agronomic Impacts of Limited Irrigation

1. Yield

Yield is by far the agronomic affect most addressed in the research. In general, studies noted that yields typically increase linearly with the amount of water used by the crop. Crops respond to water stress differently during different growth stages (Schneekloth, Bauder and Hansen 2003 (rev. 2009)). Many studies have used this concept to study limited irrigation across different growth stages. For crops like alfalfa and grass hay, limited irrigation is typically studied across seasonal harvests and across years. This section focuses on yield impacts on alfalfa and grass hay/pasture, but includes a table noting various yield studies and results for other crops, including corn, barley, wheat, sunflowers, beans, and tuber/root crops. It is worth noting that much of the research related to these crops describes managing irrigation in response to limited water availability or to meet specific crop management goals, and not on limited irrigation as a water savings tool for something like a demand management program.

Alfalfa yields have been found to be responsive to irrigation level, decreasing with reduced irrigation (N. Hansen 2008); (D. P. Cabot, et al. 2017). Correspondingly, yield increases as irrigation and evapotranspiration increase (Smeal, et al. 1994). One author noted that deficit irrigation of alfalfa can reduce yield by approximately 1 ton per acre in high elevations and approximately 5 tons per acre in lower elevations. (Allen 2011).

As noted above, limited irrigation of alfalfa is typically done across seasonal harvests in part because yield varies across seasonal cuttings. Focusing irrigation on the first and second cuttings can maintain good yield, even if slightly reduced under limited irrigation. (Orloff, et al. 2005). "The grower is still able to harvest the more valuable and higher yielding spring cuttings and, while total alfalfa yield for the season would be reduced, a significant proportion of the annual production is still obtained." (Orloff, et al. 2005).

Limited irrigation can affect the stand density of alfalfa, (Udall and Peterson 2017), but this impact is especially related to certain soil and temperature conditions. Stand loss has been observed in sandy soil, arid geographies, and lengthy deficit irrigation periods during hotter temperatures. (Udall and Peterson 2017); (Lindenmayer, Hansen, et al., Deficit Irrigation of Alfalfa for Water-Savings in the Great Plains and Intermountain West: A Review and Analysis of the Literature 2011). One study noted that alfalfa stands and biomass yields may be reduced after summer termination of irrigation even after irrigation is resumed (Lindenmayer, Hansen, et al., Deficit Irrigation of Alfalfa for Water-Savings in the Great Plains and Intermountain West: A Review and Analysis of the Literature 2011), while another study noted that yield quickly returned and quality was not affected once irrigation resumed (Udall and Peterson 2017). This variability could be related to climate and soil factors; for example, one study noted that stand density and yield were reduced after irrigation was resumed in areas with sandy soils and more arid, hotter climates. (Bauder, et al. 2011) (citing (Ottman, Tickes and Roth, Alfalfa yield and stand response to irrigation termination in an arid environment 1996)).

Similar yield results are noted in studies of limited irrigation of grass pasture. Like alfalfa, forage production for well-managed pastures can be reduced by approximately 1 ton per acre in high elevations and approximately 5 tons per acre in lower elevations. (Allen 2011). A study in Colorado found that withholding irrigation for a full season for grass pasture reduced grass yields by 70%. (Jones 2015). Yield impacts in this instance continued into the recovery year once full irrigation resumed. (Jones 2015). However, even with reduced yield, the study found that forage quality actually slightly increased with moderate water stress. (Jones 2015).

Yield Impacts of Limited Irrigation on Other Crops	
Corn	As summarized in (MWH 2013), studies suggest that a 50% decrease in irrigation will only reduce corn yield by 25%. (citing (Hansen, Westfall and Herman 2011)). Corn is more water sensitive during reproductive stages, indicating that irrigation can be restricted during early stages and saved for more critical stages. (Kirkpatrick, et al. 2006).
Barley	Water stress prior to or just after flowering most impacts yields for barley. Yield recovery from stress during this period is lower than stress in early vegetative stages, and each day of severe stress during heading was equal to a one-bushel per acre reduction in yield. Late season moistures stress can reduce kernel weight and yield. (Kirkpatrick, et al. 2006).
Wheat	Water stress occurring during or following heading or during the maturing processes causes the greatest yield reductions for wheat "Stress during maturing resulted in about a 10 percent yield reduction, while moderate stress during the aerial vegetative stage had essentially no effect on yield." (Kirkpatrick, et al. 2006).
Sunflower	Water stress during reproduction and seed development has the most impact on yield, while water stress during vegetative stages has the least. "A 20 percent reduction in applied irrigation water during the early vegetative period reduced yield by only 5%, while the same reduction in irrigation during the flowering stage resulted in a 50% yield reduction." (Kirkpatrick, et al. 2006).
Beans	Water stress during reproductive stages, especially flower and pod fill, has the greatest impact on yield. A Colorado study found that moisture stress during reproductive stages could result in a 27% decrease in yield. (Kirkpatrick, et al. 2006) (citing (Bandaranayake 1990)).
Tuber and Root Crops	Indeterminate crops can endure 4-5 day periods of moisture stress throughout the growing season without much reduction in yield or quality, and yield may not even suffer from longer periods of stress, though quality may decline. (Kirkpatrick, et al. 2006). For potatoes, "any depletion past 60-80 percent [maximum allowable depletion] leads to decreases in quality and/or yield." (Kirkpatrick, et al. 2006).

2. Quality

Some studies found that limited irrigation of alfalfa has resulted in improved quality of forage. Improved quality was based on reduced total fiber content and increased digestibility. (P. Cabot, et al. 2017); (Jones 2015). Similar quality improvements were found in grass hay. (Jones 2015).

3. Water Use Efficiency

Water use efficiency is a measure of how effectively a plant converts water to biomass and is a variable that fluctuates based on a variety of factors including location, soil type, season, and management practices. (Bauder, et al. 2011); (Lindenmayer, Hansen, et al., Deficit Irrigation of Alfalfa for Water-Savings in the Great Plains and Intermountain West: A Review and Analysis of the Literature 2011). The measure is useful in maximizing crop yield based on water use efficiency, but it is an impractical factor for most growers and for a demand management program design because it requires sophisticated lab analyses. The main consideration for purposes of this summary is to note that, in general, applying less water than a crop's full rate of evapotranspiration will cause a reduction in water use efficiency. (Bauder, et al. 2011).

4. Recovery

Alfalfa generally shows full recovery when irrigation is returned following limited irrigation (whether within a year's seasonal cuttings or across years). (N. Hansen 2008); (P. Cabot, et al. 2017); (Orloff, et al. 2005); (Udall and Peterson 2017). After deficit irrigation, one study found no stand or yield effects the following year. (Orloff, et al. 2005). A MWH summary memorandum noted that, after deficit irrigation, alfalfa and grass pasture both had no significant loss of plant population nor long-term crop damage. (MWH 2013).

However, as noted above, recovery may be more difficult in arid climates with sandy soils, where reduced irrigation can reduce stands and biomass yields, even once full irrigation is resumed. (MWH 2013) (citing (Ottman, Tickes and Roth, Alfalfa yield and stand response to irrigation termination in an arid environment 1996)). One study found this risk especially high where deficit irrigation occurred for several consecutive years. (Orloff, et al. 2005).

For grass hayfields, two studies indicated that it may require at least 2 years of full irrigation to recovery following one season of no irrigation. (Brummer 2015); (Jones 2015).

Recovery time is an important consideration for growers in deciding whether to participate in a demand management program. Damage to crops or fields (including plant death, bare ground, recovery time, etc.) was an often-cited concern from farmers and ranchers interviewed on the feasibility of a rotational fallowing or reduced irrigation program. (Gangwer 2011).

5. Soil Health

Several components of soil health are important when considering limited irrigation practices:

Soil Health Considerations of Limited Irrigation	
Salinity	Salt will move to the surface of the soil during periods of fallowing. When returning from fallowing, some fields may need a pre-planting leaching irrigation, which could reduce the water savings from fallowing. (Udall and Peterson 2017).
Nutrients	Soil fertility is a factor that can affect alfalfa yields. (Smeal, et al. 1994). Recovery from limited irrigation may be affected by micronutrient availability (low oxygen can lead to iron and other micronutrients being unavailable for plant growth), and nutrient carryover (reduced irrigation prevents nitrogen losses). (D. P. Cabot, et al. 2017).
Stored Water	Alfalfa, with its deep roots, will utilize moisture from the soil profile to a greater degree under limited irrigation, which could result in reduced water savings as well as impacts on the water table and/or nearby streamflow. (Lindenmayer, Hansen, et al., Deficit Irrigation of Alfalfa for Water-Savings in the Great Plains and Intermountain West: A Review and Analysis of the Literature 2011). Corn can also utilize moisture from deep in the soil profile. (Kirkpatrick, et al. 2006).
Tillage	"No-till increases the amount of water stored in the soil due to reduced evaporation from tillage operations, improved infiltration and reduced runoff, and increased snow catch during winter snowstorms. Changes in tillage management have allowed producers to change rotations from the conventional wheat-fallow rotation to more intensive rotations such as wheat-corn-fallow. The changes in tillage management can be successfully used in irrigated production for moisture conservation." (Schneekloth, Bauder and Hansen 2003 (rev. 2009)).

6. Weeds, Diseases, & Pests

Water stress can exacerbate disease and insect problems, which can in turn affect stand density and recovery. (D. P. Cabot, et al. 2017); (Bauder, et al. 2011) (citing Lauriault 2011). If water stress causes reduction in stand density for alfalfa, weed control can become more of a challenge. (Bauder, et al. 2011). As noted above, damage to crops or fields (weed and tree encroachment, etc.) was an often cited concern from ranchers on feasibility of a rotational fallowing or deficit irrigation program (Gangwer 2011).

7. Agricultural Operations

Several operational factors are important when considering limited irrigation:

Ag Operations Considerations of Limited Irrigation	
Flexibility in Management	Alfalfa has many traits that give producers management flexibility in limited water situations. Its resistance to drought and quick recovery allow producers to adjust water application and harvest intervals to balance yield quantity and quality to suit water use and market needs. (Bauder, et al. 2011).
Crop Rotations	Crop rotations can extend irrigation seasons and allow for longer operation of irrigation systems with proper irrigation management. (Schneekloth, Bauder and Hansen 2003 (rev. 2009)). As described above (and summarized in **Appendix A – Table of Studies**), various combinations of crop rotations, together with limited irrigation practices, can be tailored for water use and market needs.
Residue Management	Residue management (capturing, storing, and preserving every possible source of water in production system, including rainfall, snowfall, and irrigation water) can have a significant impact on increasing the availability of water (Schneekloth, Bauder and Hansen 2003 (rev. 2009)). This can supplement crop water use needs when implementing limited irrigation.
Land Management / Tillage	All fallowing programs require management of bare fields to prevent weeds, avoid topsoil erosion, and control dust. (Udall and Peterson 2017). As described above, no-till increases the amount of water stored in the soil, and changes in tillage management can allow producers to change rotations from convention to more intensive rotations. (Schneekloth, Bauder and Hansen 2003 (rev. 2009)).
Herd Size	For grass sites that support cattle operations, any reduction in grass/alfalfa yield can impact the size and quality of the herd. Importing feed could help address this issue, but there remain issues of weed control on the site with reduced irrigation, reliability of imported supply, and the cost and challenge for planning for imported supply. No or reduced irrigation may be feasible for cattle operations that are not size-limited (i.e., summer range limited or operations which sell extra hay). (CRWB Work Group 2018).
Equipment / Infrastructure Maintenance	Costs of maintaining equipment and infrastructure continue even when limiting irrigation. Ranchers cited this maintenance as a concern when interviewed regarding the feasibility of a rotational fallowing or deficit irrigation program. (Gangwer 2011).

IV. Identified Research/Information Needs and Next Steps

The studies identified several research/info needs that could better develop understandings of agronomic impacts of limited irrigation, and which could help reduce the uncertainty of these impacts when developing a demand management program:

Research/Information Needs	
Continuing limited irrigation studies	*Impacts over a variety of geographies* Studies related to limited irrigation of grass pastures have mostly been performed at low elevation sites. Additional research studies at high elevation sites may be required to investigate the behavior of grass pastures under deficit irrigation. (MWH 2013).
	Crop varieties Not much is known about the potential role of alfalfa variety on partial season irrigation. (Lindenmayer, Hansen, et al., Deficit Irrigation of Alfalfa for Water-Savings in the Great Plains and Intermountain West: A Review and Analysis of the Literature 2011).
	Recovery Impacts may go beyond the year of fallowing/deficit irrigation, and growers need a better understanding of how land recovers. (CRWB Work Group 2018); (Gangwer 2011).
Management & Operations	*Better understand the benefits of rotational fallowing and reduced irrigation* "Rotational fallowing to conserve water should provide many of the benefits of traditional land fallowing for soil health, future yield increases and pest management. These benefits, however, have been much less studied than the water conservation savings, and remain mostly unquantified." (Udall and Peterson 2017).
	Better understand the role of crop switching In theory, crop switching is a way to save water, but it is difficult to implement due to capital costs of conversion, access to processing facilities and markets and other factors. (Udall and Peterson 2017)
Verification of consumptive use savings	There is an ongoing question of how to verify consumptive use savings, which we do not address in this summary, but will nevertheless be an important consideration in developing and implementing a demand management program.

These studies and the identified research needs illustrate the wide range of variability in agronomic impacts across geographies, irrigation methods, and crop types. One thing that is clear from this variability is the need for larger, multi-year projects, particularly, but not exclusively, in the areas where producers have already expressed interest in participating in demand management programs. Similarly, decision-makers charged with designing a demand management program will likely have to consider how this variability, yield impacts, recovery, and other agronomic factors will impact program contracts, payments, and other program design features.

References

Allen, L. Niel. 2011. "Draft White Paper – Colorado River Water Bank."

Bandaranayake, M.W. 1990. "Effects of soil moisture on growth and yield of beans." *M.S. Thesis.*

Bauder, Troy, Nil Hansen, Brad Lindenmeyer, Jim Bauder, and Joe Brummer. 2011. "Limited Irrigation of Alfalfa in the Great Plains and Intermountain West."

Bowman, Alison, and Brendan Scott. 2009. "Water use crops and pastures in southern NSW." *Prime Facts, NSW Government, Industry & Investment.*

Brummer, Dr. Joe. 2015. "Summary: Agronomic Responses to Partial and Full Season Fallowing of Alfalfa and Grass Hayfields."

Cabot, Dr. Perry, Dr. Joe Brummer, Dr. Greg Litus, Dr. Abdel Berrada, Dr. Jose Chavez, Sumit Gautam, Aman Vashisht, Farmer Participants, and Jesse Kruthaupt. 2017. "Phase IIC Water Bank Projects: Colorado Water Congress Update."

Cabot, Perry, Joe Brummer, Sumit Gautam, Lyndsay Jones, and Neil Hansen. 2017. "Benefits and Impacts of Partial Season Irrigation on Alfalfa Production ." *2017 Western Alfalfa & Forage Symposium.*

Castle, Anne, MaryLou Smith, John Stulp, Brad Udall, and Reagan Waskom. 2017. "Where Now with Alternative Transfer Methods - ATMs - In Colorado?"

CRWB Work Group. 2018. "An Overview of Previous Studies & Reports."

Gangwer, Kristin. 2011. "Challenges in Prospective Temporary Fallowing of Irrigated Agriculture in the Upper Colorado River Basin." *Environmental Defense Fund.*

Hansen, N.C., D.G. Westfall, and J.R. Herman. 2011. "Demonstrating limited irrigation technology as an approach to sustain irrigated agriculture while meeting increasing urban water demand in Colorado." *A report to U.S. Bureau of Reclamation by the Department of Soil and Crop Sciences, Colorado State University.*

Hansen, Neil. 2008. "Strategies for Reducing Consumptive Use of Alfalfa." *https://www.ksre.k-state.edu/irrigate/oow/p08/Hansen08.pdf.*

Jones, Lyndsay P. 2015. "Agronomic responses of grass and alfalfa aayfields to no and partial season irrigation as part of a Western Slope Water Bank." *M.S. Thesis.*

Kirkpatrick, Amber, Linzy Browning, James W. Bauder, Reagan Waskom, Matt Neibauer, and Grant Cardon. 2006. "Irrigating with Limited Water Supplies: A practical guide to choosing crops well-suited to limited irrigation." *MSU Extension Service.*

Lindenmayer, R. Bradley, Neil C. Hansen, Joe Brummer, and James G. Pritchett. 2011. "Deficit Irrigation of Alfalfa for Water-Savings in the Great Plains and Intermountain West: A Review and Analysis of the Literature." *CSU.*

MWH. 2013. "Review of Available Research on Limited/Deficit Irrigation."

Orloff, Steve, Dan Putnam, Blaine Hanson, and Harry Carlson. 2005. "Implications of Deficit Irrigation Managment of Alfalfa." *U.C. Davis Cooperative Extension.*

Ottman, Michael J., Barry R. Tickes, and and Robert L. Roth. 1996. "Alfalfa yield and stand response to irrigation termination in an arid environment." *Agron. J. 88:44-48.*

Schneekloth, J., T. Bauder, and N. Hansen. 2003 (rev. 2009). "Limited Irrigation Management: Principles and Practices." *CSU Extension, Fact Sheet No. 4.720.*

Smeal, D., E.J. Gregory, R.N. Arnold, and J. Tomko. 1994. "Water Use and Yield of Alfalfa in Northwestern New Mexico." *N.M.S.U Agric. Exp. Sta. Bull. 770.*

Udall, Brad, and Greg Peterson. 2017. "Agricultural Water Conservation in the Colorado River Basin: Alternatives." *CSU.*

Appendix A – Table of Studies

Note – This table does not include all cited references; it focuses on primary sources and includes some secondary sources that had specific study information

Study Citation	Primary / Secondary Source	Location	Method	Crop	Results / Notes
Bauder, Troy, Nil Hansen, Brad Lindenmeyer, Jim Bauder, and Joe Brummer. 2011. "Limited Irrigation of Alfalfa in the Great Plains and Intermountain West."	Secondary - reviews available studies; highlights one recent research example	Colorado - Fort Collins	Deficit Irrigation - irrigation applied throughout growing season but with a capacity limitation of one irrigation per week and max weekly irrigation of 1.5' Partial Season Irrigation - irrigation focused on the first hay cutting and then terminated later in season	Alfalfa	"Alfalfa offers producers many opportunities to maintain production under limited water situations, not available with other forages and grain crops… most research has shown that targeting water applications during this [cooler spring] period and forgoing irrigations during mid-summer cuttings is a better conservation strategy than full season deficit irrigation in semi-arid areas."
Brummer, Dr. Joe. 2015. "Summary: Agronomic Responses to Partial and Full Season Fallowing of Alfalfa and Grass Hayfields."	Primary	Colorado - Eckert (Kehmeier Farm, Lower Gunnison) - Fruita (Western CO Research Center, Lower Colorado) - Yellow Jacket (Southwestern CO Res. Center, San Juan/Dolores)	- Fully irrigated (control) - Stop irrigation after 1st cutting - Stop irrigation after 2nd cutting Treatments repeated on same plots in 2014	Alfalfa	- 1st year yield reductions: irr. Stopped after 1st cutting - reduced 42-71% irr. Stopped after 2nd cutting - reduced 0-54% for complete fallowed area - reduced 77% - 2nd year yield reductions irr. Stopped after 1st cutting - reduced 55-82% irr stopped after 2nd cutting - reduced 4-39% - alfalfa appears to be very conducive to partial season irrigation
		Colorado - Hayden (Carpenter Ranch - Upper Yampa) - Steamboat Lake (Fetcher Ranch, Upper Yampa) - Gunnison (Trampe Ranch, Upper Gunnison) - Kremmling (Blue Valley Ranch, Upper Colorado) - Cimarron (Western Rivers Conservancy, Gunnison) - Gunnison (Peterson Ranch-Razor Creek, Upper Gunnison)	- Fully irrigated (control) - Fallowed one whole season Both plots fully irrigated in 2014-2015 to document recovery	Grass	- 1st year, avg. yield reduction was 48% with reductions ranging from 24-70% - 2nd year, yield reduction ranged from 81-93% for 2 fallowed sites - 2nd year, for 3 sites returned to full irrigation, yields were still 39-54% below fully irrigated areas - appears that it will require at least 2 years of full irrigation following one season of complete fallowing for high elevation grass hayfields to recovery to full productivity.
Cabot, Dr. Perry, Dr. Joe Brummer, Dr. Greg Litus, Dr. Abdel Berrada, Dr. Jose Chavez, Sumit Gautam, Aman Vashisht, Farmer Participants, and Jesse Kruthaupt. 2017. "Phase IIC Water Bank Projects: Colorado Water Congress Update."	Primary	Colorado			- Alfalfa exhibits better yields during first, second cuttings - significant reductions during stress period - carryover effects depend on soil and plant conditions (e.g., alfalfa with deep roots vs. grasses with shallow roots) - lower WUE as plant uses more water to cool itself in summer - modest gains in forage quality from reduced irrigation
		- Eckert	- Full - WA1 - SA2	Alfalfa	
		- Yellow Jacket	- Full - SA2 - SA1	Alfalfa	
		- Orchard Mesa	- Full - SA1	Grass hay	
		- Montrose	- Full - SA1	Grass hay	

Study Citation	Primary / Secondary Source	Location	Method	Crop	Results / Notes
Cabot, Perry, Joe Brummer, Sumit Gautam, Lyndsay Jones, and Neil Hansen. 2017. "Benefits and Impacts of Partial Season Irrigation on Alfalfa Production." 2017 Western Alfalfa & Forage Symposium.	Primary	Colorado, Western Slope - Fruita (CSU research center) - Loma - Eckert - Yellow Jacket (CSU research center)	6 established alfalfa fields subjected to irrigation treatments: - Normal irrigation - Irrigation stopped later in growing season - Irrigation stopped early in the growing season for 2 consecutive years All fields then received consistently full irrigation in the third and final year	Alfalfa	"...results suggest that reduced irrigation may improve forage quality slightly, but will significantly reduce yields. When irrigation is returned the following year, alfalfa yields may fully recover depending on length and severity of reduced irrigation."
Hansen, N.C., D.G. Westfall, and J.R. Herman. 2011. "Demonstrating limited irrigation technology as an approach to sustain irrigated agriculture while meeting increasing urban water demand in Colorado." A report to U.S. Bureau of Reclamation by the Department of Soil and Crop Sciences, Colorado State University.	Primary (cited in MWH memo)	Colorado, South Platte River - Iliff	Rotational cropping and limited irrigation		
			- Full irrigation, continuous corn	Corn	
			- Corn-fallow-combination	Corn	- showed 30% increase in yield than full irrigation - fallowing not considered an efficient way of storing water in soil profile due to high evap rates
			- Corn-fallow-dryland wheat	Corn, wheat	- corn produced same yield as corn-fallow system - dryland wheat generated higher yield than fallow - shows advantage of dryland farming over fallowing of an irrigated area
			- sugarbeet-hay millet combination (rotational cropping and limited irrigation)	Sugarbeet, hay millet	no clear understanding of water savings between these systems, but a modest increase in yield was observed in the rotational cropping system vs. the limited irrigation system
			- Corn-soybean-wheat-canola combination (rotational cropping and limited irrigation)	Corn, soybean, wheat, canola	- Average yield and ET for full irrigated corn were observed similar to corn yield and ET in other rotational cropping systems - Soybean yield was moderate and suggested its use as a good alternative crop for both rotational and limited irrigation practices. - Canola was not observed to be a preferred alternative based on relatively high ET and low yield
			- Corn-soybean-wheat-triticale combination (rotational cropping and limited irrigation)	Corn, soybean, wheat, triticale	- corn yield was observed to decrease by 4-10% - dryland wheat yield decreased by 24% and 19% from the other systems
Hansen, Neil. 2019. "Strategies for Reducing Consumptive Use of Alfalfa."	Primary	Colorado, Northern Colorado Water Conservancy District headquarters (Berthoud)	Deficit Irrigation - Full irrigation - Stop Irrigation after 2nd Cutting - Spring and Fall Irrigation - Stop Irrigation after 1st Cutting	Alfalfa	"Alfalfa yields were responsive to irrigation level, decreasing with reductions in irrigation amount… "

Study Citation	Primary / Secondary Source	Location	Method	Crop	Results / Notes
Jones, Lyndsay P. 2015. "Agronomic responses of grass and alfalfa hayfields to no and partial season irrigation as part of a Western Slope Water Bank. M.S. Thesis.	Primary	Colorado - Eckert (Kehmeier Farm, Lower Gunnison) - Fruita (Western CO Research Center, Lower Colorado) - Yellow Jacket (Southwestern CO Res. Center, San Juan/Dolores)	Partial Season Irrigation - Full irrigation (control) - Irr. Stopped after 1st cutting (SA1) - Irr. Stopped after 2nd cutting (SA2) (two consecutive years)	Alfalfa	"...results suggest that reduced irrigation may improve forage quality slightly, but will significantly reduce yields. When irrigation is returned the following year, forages may have increased quality"; "grass yields will likely not fully recover while alfalfa yields may recover depending on length and severity of reduced irrigation."
		Colorado - Cimarron - Gunnison - Hayden - Kremmling - Razor Creek - Steamboat Lake	- Full irrigation - No irrigation	Grass	
Lindenmayer, R. Bradley, Neil C. Hansen, Joe Brummer, and James G. Pritchett. 2011. "Deficit Irrigation of Alfalfa for Water-Savings in the Great Plains and Intermountain West: A Review and Analysis of the Literature."	Secondary - review and analysis of the literature:			Alfalfa (Medicago sativa L.)	Alfalfa biomass yield exhibits a linear relationship to ET. Because early season harvests have greater WUE, combining full irrigation in spring with no irrigation during less efficient water-use growth periods may be more effective in savings water than season-long deficit irrigation.
	Daigger et al., 1970	Nebraska	Full irrigation		
	Bauder et al., 1978	North Dakota	Dryland; Deficient; Optimum; Excessive; Average		
	Retta and Hanks, 1980	Utah	Line source average		
	Sammis, 1981	New Mexico	Line source average		
	Carter and Sheaffer, 1983	Minnesota	High; Med. High; Med. Low; Dryland; Average		
	Undersander, 1987	Texas	Line source average		
	Wright, 1988	Idaho	Full irrigation		
	Bogler and Matches, 1990	Texas	Average		
	Smeal et al., 1991	New Mexico	Line source average		
Orloff, Steve, Dan Putnam, Blaine Hanson, and Harry Carlson. 2005. "Implications of Deficit Irrigation Management of Alfalfa." U.C. Davis Cooperative Extension.	Primary	Intermountain area (Klamath Basin and Scott Valley)	Deficit Irrigation - normal full-season irrigation - no irrigation after first cutting - no irrigation after second cutting	Alfalfa	"...results suggest that early curtailment of alfalfa irrigation to conserve water is agronomically feasible. Assessing how much water is actually saved and assigning a value to the water are complex tasks that are regionally specific."
		Sacramento Valley (Yolo County)	Deficit Irrigation - normal full-season irrigation - irrigation cut-off in mid summer (July) - irrigation cut-off in mid summer (July) with resumption of irrigation in fall	Alfalfa	
Ottman, Michael J., Barry R. Tickes, and Robert L. Roth. 1996. "Alfalfa yield and stand response to irrigation termination in an arid environment." Agron. J. 88:44-48.	Primary (cited in MWH memo)	Arizona - Yuma - Maricopa	Deficit irrigation - Irrigation terminated seasonally: summer and winter in Yuma summer in Maricopa summer, fall, and winter in Maricopa	Alfalfa (Medicago sativa L.)	termination of summer irrigation in regions with arid climates and sandy soils can reduce alfalfa stands and biomass yield

Study Citation	Primary / Secondary Source	Location	Method	Crop	Results / Notes
Smeal, D., E.J. Gregory, R.N. Arnold, and J. Tomko. 1994. "Water Use and Yield of Alfalfa in Northwestern New Mexico." N.M.S.U Agric. Exp. Sta. Bull. 770.	Primary	New Mexico, NMSU Agricultural Science Center (Farmington)	Decreasing irrigation gradient across subplots to study the relationship between alfalfa yield and water use In last year of study, one-half of plot was irrigated uniformly to evaluate alfalfa's capability to rebound in growth after being subjected to varying degrees of deficit irrigation for several years	Alfalfa (variety WL-309)	- Alfalfa yield increased as irrigation and ET increased during all growing periods - Developed a CU curve for growers in Farmington area to estimate water use for effective irrigation management without using climatic data.
Udall, Brad, and Greg Peterson. 2017. "Agricultural Water Conservation in the Colorado River Basin: Alternatives." CSU.	Secondary - review of case studies	- Colorado, Colorado Water Trust studies in southwestern CO - Upper Colorado River Basin, Colorado Compact Water Bank workgroup studies - Upper and Lower Colorado River Basin, Colorado River System Conservation Pilot Program - Colorado, CSU studies in Arkansas and South Platte Basins - Colorado River Basin, Ongoing studies	Deficit Irrigation - Regulated deficit irrigation - Split season deficit irrigation		"Alfalfa… is an obvious candidate for saving water through deficit irrigation. Although it is also possible to partially irrigate alfalfa throughout the growing season, split season irrigation results in higher relative yields, better quality, and lower labor than other forms of deficit irrigation, and thus has been the focus of almost all deficit irrigation studies." (4)
		- California, MWD/PVID Rotational Fallowing program - California, MWD/Bard Irrigation District (Yuma) summer Fallowing - California, San Diego/IID Fallowing program - Colorado, Superditch Fallowing program, Arkansas River valley - Colorado, Aurora Arkansas Basin fallowing program (joined later by Colorado Springs)	Rotational Fallowing		"Unlike some of the other methods of saving water… temporary land fallowing is a proven, successful strategy for conserving significant amounts of water with a long history of on-the-ground projects in the [CRB]. Although there can be significant issues with quantifying the actual water savings from fallowing, there is little doubt that fallowing does save water." (6)
		- Wyoming, Walker River Basin - California, nut crops - Arizona, Yuma growers switching from citrus, cotton and other crops to sophisticated multi-cropping oriented around winter vegetables	Crop Switching		"While in theory this technique is appealing as a way to save water, numerous studies and publications have shown that crop switching is difficult to implement because there are many complicated and potentially expensive issues to resolve." (8)
		- California, MWD/IID efficiency program - Arizona, Yuma, springs, high flow turnouts, laser leveling, and other efficiency - Colorado, Grand Junction ID canal lining, automated head gates, check structures, end-of-canal reservoir	Irrigation Efficiency and Water Conservation		" Each concept has different physical and legal ramifications, especially in terms of how they affect other uses and users. Both concepts can potentially provide water for municipal or environmental purposes from agriculture." (11)