Project Background

This document is one of four separate reports created under a grant from the Walton Family Foundation to investigate ways to minimize harm to agriculture as water scarcity in the Colorado River Basin forces growing municipal and environmental water users to look at existing uses as potential sources of supply. Agriculture, the largest water user in the basin, is a frequent target in these efforts. The project, "Agricultural Water Conservation in the Colorado River Basin: Alternatives to Permanent Fallowing Research Synthesis and Outreach Workshops" was undertaken to create detailed reports of the four common methods used to temporarily transfer water from agriculture to other purposes. The four reports consider the following methods:

- Deficit Irrigation of Alfalfa and other Forages
- Rotational Fallowing
- Crop Switching
- Irrigation Efficiency and Water Conservation

After the reports were drafted, three workshops were held, one in the Upper Basin in Grand Junction on November 4, 2016, one in the Lower Basin in Tucson on March 29, 2017, and one in Washington, DC on May 16, 2017. All of the reports are available from the Colorado Water Institute website.

Acknowledgements

First, Greg Peterson and I thank the Walton Family Foundation for making this project possible. Without their funding and support, the project would not have happened.

Many people assisted with this project by reading and providing comments on drafts. We want to especially thank Perri Benemelis, Mike Bernardo, Perry Cabot, Aaron Citron, Michael Cohen, Bonnie Colby, Terry Fulp, Robert Glennon, Bill Hasencamp, Chuck Howe, Carly Jerla, Dave Kanzer, Doug Kenney, Kelsea MacIlroy, Jan Matusak, Sharon Megdal, Peter Nichols, Wade Noble, Michael Ottman, Ron Raynor, Adam Schempp, Tina Shields, MaryLou Smith, Pete Taylor, Reagan Waskom, John Wiener, and Scott Wilbor. Paul Kehmeier contributed a lovely photograph and important story. The final product was much improved by these insightful comments. It must be noted that any mistakes are solely mine.

Nancy Grice at the Colorado Water Institute provided critical support with financial reporting, travel assistance and working with Colorado State University. MaryLou Smith was instrumental in organizing and chairing the outreach workshops. Reagan Waskom provided much needed intellectual support throughout the project. Beth Lipscomb assisted with overall editing at the end. Finally, a very special thanks goes to my co-author, Greg Peterson, who did much of the early, difficult research and writing. Much of the value of this project is in the extensive bibliographies that Greg created by painstakingly acquiring, reading and summarizing hundreds of documents.

We thank Senator Michael Bennet and his staff for acquiring a room at the Capitol Visitor Center for the DC event. Finally, we extend our sincere appreciation to the approximately 100 participants who shared their precious time to join us for our outreach workshops. Thank you, all.

Brad Udall

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Abbreviations

AF	Acre-feet
CRB	Colorado River Basin
CWCB	Colorado Water Conservation Board
CWT	Colorado Water Trust
DI	Deficit Irrigation
ET	Evapotranspiration
MAF	Million Acre-feet
NASS	National Agricultural Statistics Service
RDI	Regulated Deficit Irrigation
TNC	The Nature Conservancy
USBR	U.S. Bureau of Reclamation
USDA	U.S. Department of Agriculture
WUE	Water Use Efficiency

1 Summary

Irrigation is generally designed to meet the full water requirements of crops. ***Deficit irrigation*** is the generic term for applying less water than the full needs of a crop; it can take many forms. It can be a planned, sophisticated strategy or an unplanned, natural consequence when water scarcity arises. Planned deficit irrigation is widely used with grapes, to improve quality. Unplanned deficit irrigation occurs commonly on forage crops that depend on diversions from mountain streams as the runoff pulse declines in late summer.

1.1 Different Methods of Planned Deficit Irrigation

Regulated Deficit Irrigation (RDI) is the term used to apply less water than needed during less critical life stages, with the general goal of improving the quality of the crop. RDI is practiced widely on certain crops like fruit and nut trees.

Another planned deficit irrigation strategy is used with perennial hay crops, especially alfalfa. By completely ceasing water application for part of the year, some perennial crops can be forced to enter dormancy and thus survive a lack of water. This method has been most consistently called “**split season” deficit irrigation.**

1.2 Why Alfalfa and Deficit Irrigation?

Alfalfa, because of its large consumptive use relative to other crops, its extensive acreage in both the Lower and Upper Basins, and its ability to go dormant when water is removed, 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.

1.3 Alfalfa’s Importance in the Colorado River Basin

Alfalfa, when combined with all hays, is the nation’s third largest crop by production value. It is very commonly grown in the West where nearly 40% of the nation’s alfalfa hay is produced from 11 western states. Because it is an animal food, it is sometimes called the “corn and soybeans” of the West. It is a major crop in each of the Colorado River Basin states and is 28% of the total acreage in the basin in these states. In most years, it makes up more acreage than any other crop in the Imperial and Palo Verde Valleys of California. Alfalfa is an important crop in a rotation because it is a nitrogen-fixing legume.

1.4 Critical Alfalfa Facts

Alfalfa yields range from under two tons per acre in the high mountain valleys of Colorado and Wyoming where only one cut is done, to over 10 tons per acre with 10 cuts per year in the low deserts of the Colorado River Basin. Harvesting and field drying is the one area where alfalfa has elevated risk for the grower because for storage the hay must be dry. The plants last for several years in the field, especially if a dense stand with little room for weeds is established. Few pesticides and herbicides are used. The soil is left unplowed several years, for a positive effect on soil health. Alfalfa fixes nitrogen and thus the crop rarely needs nitrogen and it also provides nitrogen for the next crop. Because alfalfa fields are left undisturbed for years, they have significant wildlife benefits not present with annual row crops. Alfalfa is very easy to grow. It is adaptable to different climates from sweltering deserts to the highest mountain valleys, and can be planted at different times of the year.

Alfalfa is a cool season crop, meaning it is optimized to growing in the colder parts of the year. The spring and fall generate the highest yields, and the highest nutritional content. In Arizona, the term "summer slump" historically was used to mean the period in July and August when alfalfa generated little yield while using lots of water. In the 1960s before laser leveling, it was common to deficit irrigate during this period to save water ("summer dry down"), and to avoid root scalding from water ponding in fields when temperatures are above 100 F.

1.5 Alfalfa's Important Ties to the Beef and Dairy Industries

Alfalfa is a critical input to the beef and dairy industries. Since 1970, the dairy industry in the West has grown enormously, and alfalfa production has commensurately increased. The number of dairy cattle has increased significantly in California, central Arizona, southeastern New Mexico, and the Front Range of Colorado. In California, alfalfa is a $1B/year crop feeding a $5B/year dairy industry, the largest agricultural sector in the state. California is now the #1 dairy state, while New Mexico (#9), Arizona (#13), Colorado (#15), and Utah (#21) are also key national dairy producers. Alfalfa is grown near where it is used because it is bulky and hence has a relatively high cost of transportation. It provides significant nutritional advantages compared to other forages with its high protein content.

1.6 Alfalfa Deficit Irrigation Studies

There have been numerous studies on deficit irrigation of alfalfa dating to the 1960s. Alfalfa has a natural ability to go dormant when water is reduced or cut off. Stand loss, the loss of some of the plants, has occurred in a few studies. Stand loss is especially related to sandy soils with little water holding capacity, and lengthy deficit irrigation periods during very high temperatures. In general, yield returns quickly once irrigation resumes and the hay quality does not appear to be affected. Deeper soils are generally better when water is cut off as they hold more water. Alfalfa's deep taproot can often obtain at least some water to keep the plant alive with deep soils.

1.7 Deficit Irrigation of Pasture

Irrigated pasture makes up approximately 15% of all irrigated lands in the 11 Western states. There is very little research on deficit irrigation of the grasses present in these pastures. Cow-calf operators are highly dependent on this resource. Grasses can also go dormant, but have much shallower root systems and are thus unable to tap deep moisture like alfalfa.

1.8 Case Studies on Deficit Irrigation

There are several recent case studies on deficit irrigation in the Colorado River Basin. The Colorado Water Trust has been pursuing its use in Southwestern Colorado. The Colorado Compact Water Bank workgroup has been studying this issue as a way of saving water for post compact water rights in the event of an Upper Basin “compact call”[1]. Additionally, the recent Colorado River System Conservation Pilot Program has utilized deficit irrigation in the Upper and Lower Basins. Colorado State University has studied this issue in both the Colorado’s Arkansas and South Platte Basins, and studies are ongoing in the Colorado River Basin.

2 Introduction

Irrigation is generally designed to meet the full water requirements of crops[2]. Irrigators, however, may under-irrigate crops when water is scarce, or over-irrigate when water is plentiful or inexpensive. Deficit irrigation is the generic term for applying less water than the full needs of a crop and can take many forms. It can be a planned, sophisticated strategy or an unplanned fact of life when water scarcity arises. Planned deficit irrigation is widely used with grapes to improve quality. Unplanned deficit irrigation occurs widely on hay crops that depend on diversions from mountain streams as the runoff pulse declines in late summer. Planned deficit irrigation has made it possible for many farmers around the world to increase water productivity and profits (Elias Fereres & Soriano, 2007; Geerts & Raes, 2009).

Depending if land or water is limited, deficit irrigation can increase profits depending on the price of crops and water (Marshall English & Raja, 1996). Deficit irrigation has been investigated because economists have long known that maximizing crop yield is not the same as maximizing profits. Applying less water could result in financial savings on labor, water, and other inputs, assuming that there is a charge for water. In theory, a farmer could increase profits by optimizing the use of all of these inputs (M. English, 1990). In recent years, deficit irrigation has been studied because of water scarcity issues, not profit maximization (E. Fereres & Soriano, 2006; R. B. Lindenmayer, Hansen, Brummer, & Pritchett, 2011a; Pritchett, Thorvaldson, & Frasier, 2008).

There are different methods of planned deficit irrigation. Regulated Deficit Irrigation (RDI) is the term used to apply less water than needed during less critical life stages with the general goal of improving the quality of the crop. RDI is practiced widely on certain crops like fruit and nut trees including almond, peaches, pistachio, citrus, apple, apricot, wine grapes, and olives. RDI can also be used to save water with the goal of not damaging the yield or crop quality. Different plants have different tolerances for reductions in water depending on their life cycle.

Another planned deficit irrigation strategy is used with perennial hay crops, especially alfalfa. By completely ceasing water application for part of the year, some perennial crops can be forced to enter dormancy and water can be saved. This method has been most consistently called split season irrigation

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[1] The Colorado River Compact contains a provision stating that the Upper Basin shall not deplete the flows of the river below 75 million acre-feet every ten running years. Were this to occur, the Upper Basin would have to reduce consumption and this reduction has been likened to an in-state river “call”. In a river call, diversions from junior users are reduced in order to supply water to more senior users. Upper Basin “post compact” water rights – those with priority dates after the compact – would in theory be subject to curtailment under this “compact call” scenario.

[2] Agronomists define full irrigation as “when irrigation water is applied to completely meet crop water demand or evapotranspiration (ET) that is not supplied by natural precipitation and soil water storage”.

although other names have been used as well[3]. Although it is also possible to partially irrigate alfalfa throughout the growing season, split season irrigation results in higher relative yields and better quality than partial irrigation the entire season and thus is the focus of this chapter. Most studies of deficit irrigation for alfalfa have promoted split season irrigation for these very reasons. (S. Orloff, Putnam, Hansen, & Carlson, 2014).

Despite RDI's success with crops like grapes, the real opportunity in the Colorado River Basin to utilize deficit irrigation to save water is with alfalfa, because of its large water consumption, its widespread cultivation, and its ability to tolerate water reductions. Deficit irrigation of alfalfa is currently being used in Reclamation's System Conservation Pilot Projects (See Carpenter Ranch Case Study below) and is also a key feature of Colorado's Compact Water Bank studies. Deficit irrigation of alfalfa may be a helpful tool to address potential compact curtailments in the Upper Basin and the structural deficit in the Lower Basin. Deficit irrigation generally limits the amount of biomass production, thus reducing the yield of forage crops like alfalfa and hence farmer profits (S. Orloff, Putnam, et al., 2014). Thus, any plan to utilize deficit irrigation with alfalfa would have to compensate growers for lost profits.

Even though deficit irrigation has not yet been used on a wide scale to conserve water, there is considerable research on the topic that could prove invaluable. Research conducted in the basin states over the last 50 years shows that deficit irrigation is a viable option although there are numerous hurdles to its successful widespread implementation[4]. This chapter surveys the current research and issues related to DI, especially concerning its use with alfalfa. The chapter concludes with three cases of actual deficit irrigation in the Basin.

3 Alfalfa Overview and Deficit Irrigation

Alfalfa is a major cash crop in every western state and the nation's fourth largest crop commodity (Putnam et al., 2000). In 2014, alfalfa made up almost 80 percent of crop value of production of all hay crops. Alfalfa by itself is only behind corn, soybeans, and wheat in total value of U.S. production (USDA Crop Summary, 2015). Nationally, there are 23 million acres of the crop. Combined with all other hay crops, it is the third highest crop in value after corn and soybeans, a position it has held for years (NASS, 2016).

Alfalfa is the Western equivalent of corn and soybeans. Its widespread production in the United States, and especially in the West, reflects the preferences of American consumers to eat beef and dairy products. It grows in many regions and climates. Deficit irrigation of alfalfa provides opportunity for

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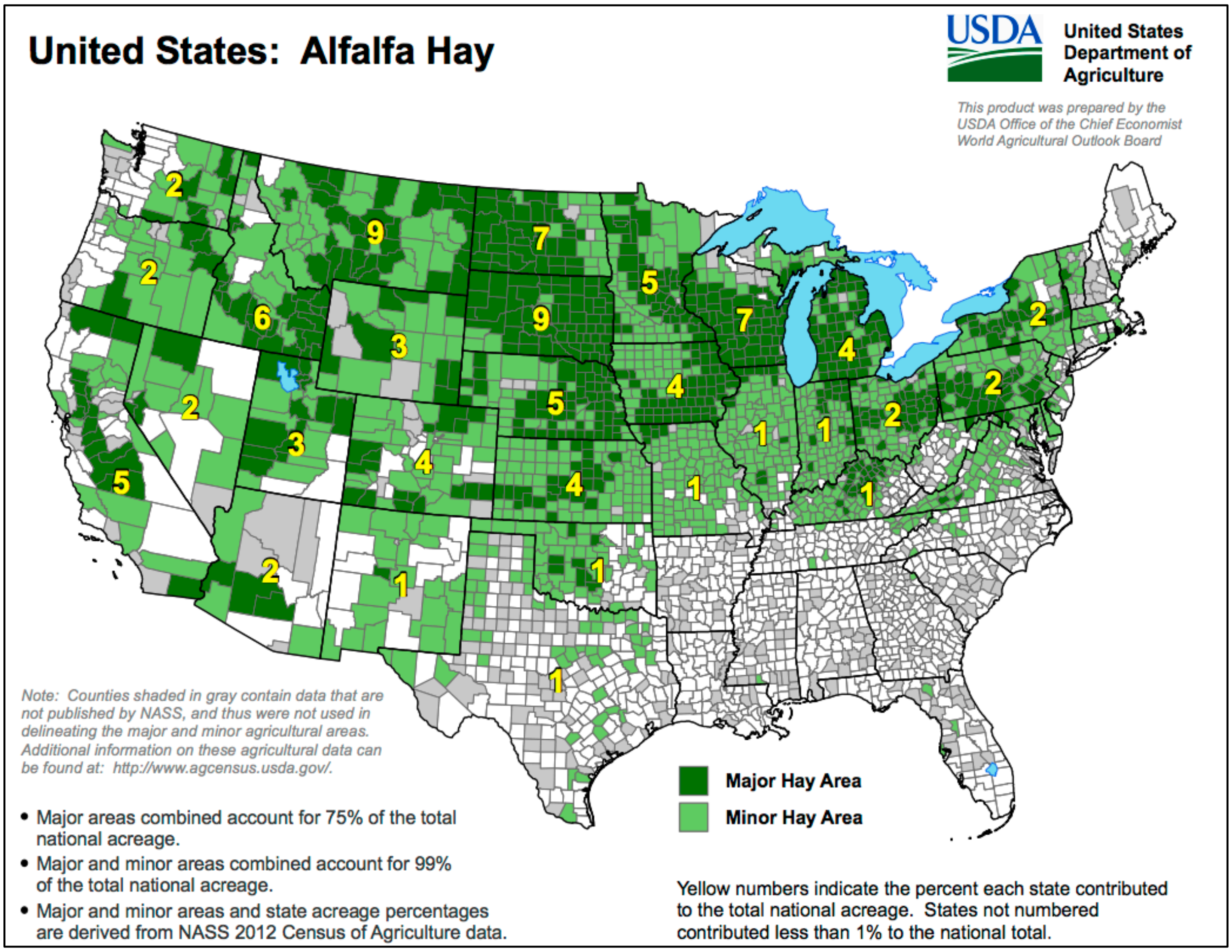
[3] Some of these terms are summer fallow, partial-season irrigation, early irrigation, summer dry-down, or even "cold turkey cutoff".

[4] This chapter is concerned with agronomic issues of deficit irrigation. There are also significant legal hurdles associated with the use of deficit irrigation to move saved water to another user. In both the Upper and Lower Basins, for example, the doctrine of prior appropriation means that water not used is legally available to the next in priority diverter. Legal methods to 'shepherd' the water saved from deficit irrigation to its intended target use around potential next in priority diverters (who can be located upstream as well as downstream) would be needed for deficit irrigation to be a success. Although critical, these are not a focus of this document.

significant water savings because of its widespread cultivation, because of its significant water use, and because of the drought tolerance of the plant.

3.1 History

Alfalfa originated in the Middle East more than 4000 years ago. The name is said to mean “best horse fodder.” From the Middle East, it spread to Greece and other Mediterranean locations. In Europe it was named “lucerne” and that name is currently still used in many counties (Putnam, Summers, & Orloff, 2007). Within the U.S. it first appeared in Georgia in 1736 but these early efforts in the East were mostly unsuccessful. Alfalfa was likely brought to California from Chile during the Gold Rush (1849-1852) at a time when everything was animal-powered and cattle were the focus of western ranching. With irrigation, it thrived in the hot and dry climate of California, and it had a ready local market for high-quality forages. Unlike other California crops that had to be shipped far away, it was sold as a cash crop locally used (Putnam et al., 2000). From California, it spread east to other Western states where it also grew well. Its movement from West to East in the United States is highly unusual for a crop.



This product was prepared by the USDA Office of the Chief Economist World Agricultural Outlook Board

Note: Counties shaded in gray contain data that are not published by NASS, and thus were not used in delineating the major and minor agricultural areas. Additional information on these agricultural data can be found at: http://www.agcensus.usda.gov/.

- Major areas combined account for 75% of the total national acreage.
- Major and minor areas combined account for 99% of the total national acreage.
- Major and minor areas and state acreage percentages are derived from NASS 2012 Census of Agriculture data.

Yellow numbers indicate the percent each state contributed to the total national acreage. States not numbered contributed less than 1% to the national total.

Figure 1: Locations where alfalfa is grown in the United States. Source: NASS (2012).

3.2 Alfalfa Agronomic Studies

There are hundreds of studies and even complete books on alfalfa production dating back to the early 1900s (Coburn, 1908; S. B. Orloff, Carlson, & Teuber, 1997; Peterson, 1972; Stanberry, 1955; Summers, Charles G. & Putnam, Dan, 2007; Undersander, Dan J. et al., 2000; Wing, 1909). Researchers from agricultural colleges and the USDA Agricultural Research Service have analyzed all aspects of its production including water consumption, yield, quality, differences among cultivars, irrigation practices, drought tolerance and many other plant characteristics throughout the United States, including the Northeast and Southeast. Most of these studies, however, have taken place in western states where alfalfa thrives like Nebraska, Texas, Colorado, Nevada, Oregon, Arizona, and especially California. Alfalfa is widely grown throughout the world and studies have also been conducted in Lebanon, Israel, Cyprus, and Spain among other international locations.

Considerable knowledge on alfalfa has come from state extension services and unpublished conference papers although there are also numerous peer-reviewed papers. Since 1971, the California Alfalfa and Forage Symposium (now the Western Alfalfa & Grains Symposium) has produced a multitude of reports on alfalfa that range from deficit irrigation to nutritional quality to the economic impact of alfalfa production ("Alfalfa Symposium Proceedings," 2016). Most Extension Services have multiple publications to assist growers ("Alfalfa Symposium Proceedings," 2016; S. B. Orloff et al., 1997; Summers, Charles G. & Putnam, Dan, 2007; Undersander, Dan J. et al., 2000). A list of the studies surveyed in this effort is included as an appendix to this chapter. In recent years, due to drought and competition for water, many of these studies have focused on deficit irrigation field trials as a way of saving water. Most of these field trials provide support to the idea that split season deficit irrigation can save water and can be done without long-term harm to the crop, with some caveats pertaining to groundwater use, overly long termination, and suitable soils (T. Bauder, Hansen, Lindenmeyer, Bauder, & Brummer, n.d.; Frate & Roberts, 1988a; Hansen, 2008; B. Lindenmayer, Hansen, Crookston, Brummer, & Jha, 2008a; R. B. Lindenmayer et al., 2011a; S. B. Orloff, Putnam, Hanson, & Carlson, 2003).

3.3 Alfalfa Acreage and Production Value

Alfalfa's total acreage and economic relationship with western livestock and dairy industries makes alfalfa one of the most important crops in the West. Nearly 40 percent of the nation's alfalfa hay is produced in the 11 western states (Putnam et al., 2001). There are many other crops grown in the West, but none are produced on the same scale and with the same geographic range. In the West, alfalfa acreage is greatest in Montana, followed by Idaho, California, and Colorado. However, total production is greatest in California due to higher yields, where more than 80 percent of the hay is grown in areas that have 7-10 harvests ("cuttings") a year (Putnam et al., 2000).

Areas that often have wet soil with high humidity show significant declines in alfalfa productivity. Diseases of the root and crown occur under excessively wet conditions (S. B. Orloff et al., 1997). The arid climate in the western United States is thus ideal for production.

Table 1: Forage and alfalfa acreage (1000s) in the Colorado River Basin. Source: Cohen et al. (2013).

	Total All Crops Harvested Acreage	**Forage Harvested Acreage (includes alfalfa)**	**Forage Acreage as % of Total Harvested Acreage**	**Total Alfalfa Harvested Acreage**	**Alfalfa Acreage as % of Total Harvested Acreage**
AZ	754	307	41%	257	34%
CA	452	289	64%	181	40%
CO	641	332	52%	157	24%
NV	25	17	68%	-	0%
NM	64	37	58%	29	45%
UT	277	124	45%	104	38%
WY	339	208	61%	55	16%
US Total	2555	1315	51%	783	31%
Mexico	443	79	18%	79	18%
CRB Total	3077	1394	45%	863	28%

Alfalfa is a major crop in all of the Colorado River Basin States, especially in states like Nevada and Utah, where alfalfa is approximately 54 percent of the total acreage of principal crops (Table 2). In the Colorado River Basin, alfalfa makes up more than one-quarter (26 percent) of all major crops in the basin (. The acreage of alfalfa in the basin is highest in California and Arizona, where the long growing season and extensive acreage alfalfa contributes to its large total consumptive use.

Table 2: Alfalfa acreage compared to other principal crops in Colorado River Basin states. Note: Principal crops included in the area planted are corn, sorghum, oats, barley, rye, winter wheat, Durum wheat, other spring wheat, rice, soybeans, peanuts, sunflower, cotton, dry edible beans, sugar beets, canola, and proso millet. Harvest acreage is used for all hay, tobacco, and sugarcane in computing total area. Source: USDA June 30, 2015 Acreage Report.

State	Alfalfa Area Harvested	Principal Crop Area	% of Principal Crop Area
Arizona	260	666	39.0%
California	820	3,086	26.6%
Colorado	700	5,986	11.7%
Nevada	240	445	53.9%
New Mexico	220	1,008	21.8%
Utah	510	944	54%
Wyoming	490	1,447	33.9%

Alfalfa is the single largest user of agricultural water in California, making up nearly 20 percent of applied water (S. Orloff, Putnam, et al., 2014). Most years, it makes up more acreage than any other crop in the Imperial and Palo Verde Valleys. The subtropical desert climate is ideal for growing alfalfa year-round. Sunlight occurs more than 90 percent of the possible hours every year and even in the winter sunshine exceeds 8 hours a day. In the low desert areas of California and Arizona, the consumptive use of alfalfa in the early to mid-1990s was approximately 1.8 maf annually because of extensive acreage and year-round production of the crop. This amount was 45 percent more than cotton, 65 percent more than wheat, 66 percent more than sorghum, 89 percent more than lettuce, and 75 percent more than cantaloupe (Takele & Kallenbach, 2001a).

In California, alfalfa is worth over $1 billion/year and is a fundamental input to California's large dairy and beef industries. The dairy and beef cattle industries are reliant this locally-grown alfalfa. Unlike other crops like cotton, it receives no crop subsidy. Comparatively, these industries provide more jobs and economic activity than TV and movies and the wine industry in California. Often, alfalfa is compared to high-value crops that generate more value per acre. Even though the value of alfalfa produced from an acre is less than other crops, the overall value of the downstream uses of alfalfa is comparable. For example, almonds are a high-value crop with water use per acre similar to alfalfa. The dry matter yields of alfalfa are six times greater than that of almonds. The value of consumer products produced per acre is only marginally better for almonds (alfalfa can produce 2,459 gallons of milk/acre and an almond orchard makes 1,464 cans of nuts/acre) (Putnam, 2010). This hidden value of alfalfa is a necessary part of the understanding the crop's significance in the region.

3.4 Connection to Dairy and Beef Industries

Alfalfa is a critical input into the dairy and beef industries and cannot be separated from this value chain. Farmers will grow alfalfa if these industries continue to demand the crop. In just the last few decades, alfalfa production has changed dramatically. "It has gone from a relatively low-value rotation and pasture crop grown largely to feed dairy cows on-farm, to a cash hay business, being grown and managed professionally, shipped long distances, even overseas, to multiple markets, with exacting demands on quality factors. It has risen from a “Rodney Dangerfield” of crops (“don’t get much respect”), to a crop which can effectively compete economically with a wide range of irrigated crops in the West, including potato, tomato, and some specialty crops, as well as corn, grains, and oilseeds” (Putnam, 2009).

As many western states have expanded their dairy industries, the need for high quality hay has also increased significantly. The demand for alfalfa is mostly local and regional, not international, although some alfalfa is now being exported (Glennon, 2012; “My Turn”, 2015, “Saudi dairy company Almarai buys land in California to grow fodder”, 2016). Due to the expanding dairy industry in states like Idaho, New Mexico and California, and lack of profitable alternative crops, alfalfa acreage increased significantly around the year 2000 (Putnam et al., 2000). Growth of the dairy industry has been significant in Western states over the last 40 years. In 1970, the only Western states in the top ten of dairy production were California and Texas. By 2008, Idaho, New Mexico, and Washington were also top ten dairy states (Figure 1).

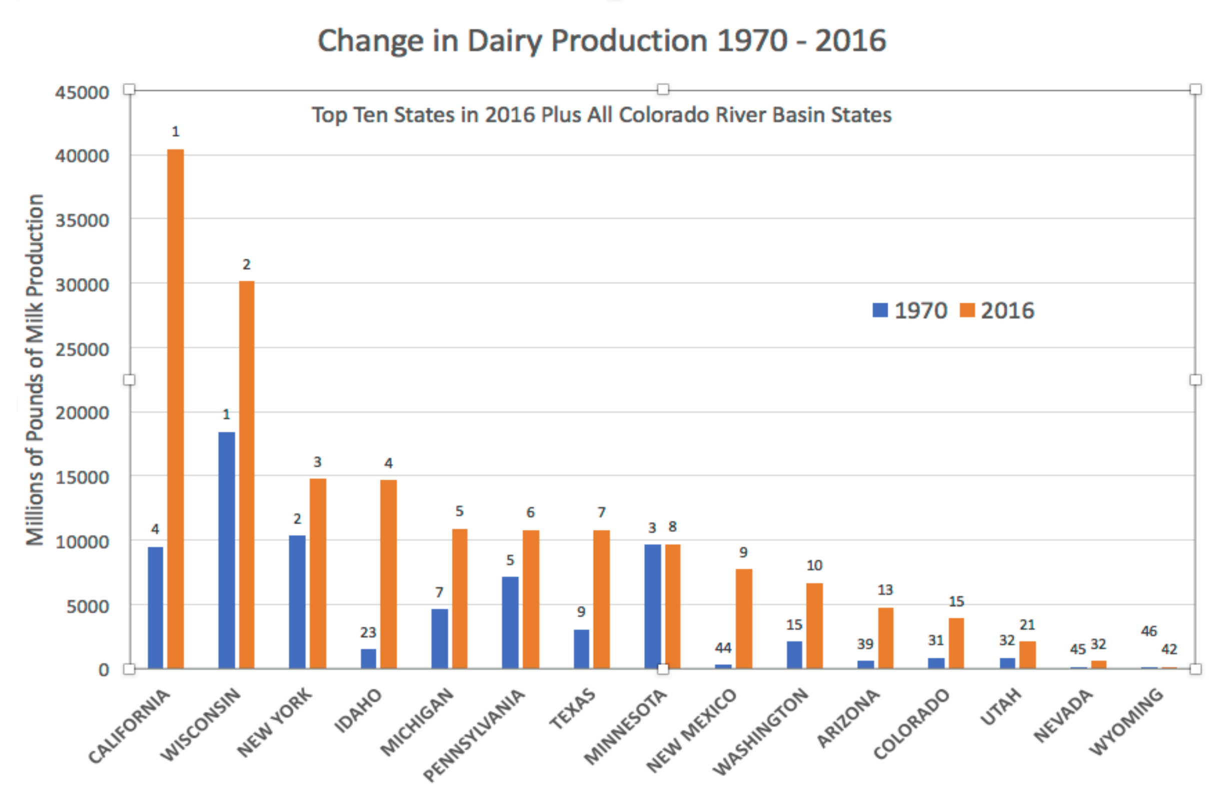


Figure 2: Top ten milk production states, plus CRB States, 1970 and 2016. National ranks shown at top of the column. Source: NASS (2017).

During this period, national milk cow numbers declined from 12 million to 9.3 million while western states added cows. (Production per cow during this period has significantly outpaced the decline in total cows and thus total milk production has increased). Alfalfa production has struggled to keep up and been outpaced significantly by demand. In California, about the same amount of alfalfa hay is produced now as in 1970, but dairy production has quadrupled. Alfalfa is a preferred feeding ration for cows, especially young and lactating cows, comprising in some cases more than 25% of the diet (Foster, 1992; Robinson, 2014; Schoneveld, 1992). Dairies have found other ways to meet their demand for forage despite the lack of alfalfa production: increased use of corn and small grain silage, alfalfa by-products and fermentation by-products; and improvement of alfalfa quality factors that increase milk production. In addition, there has been a reduction in the amount of alfalfa fed to beef animals (Putnam, 2009).

Though dairies have found some solutions to meet the lack of alfalfa production, alfalfa provides significant nutritional advantages compared to other forages. Modern dairy production monitors the digestion (and rumen, especially) of cattle carefully. Exact percentages of crude protein, fiber, and other plant nutrients are required to maintain the pH in a cow's stomach for optimum milk production and prevent rumen acidosis, a decline in the rumen pH that can cause depression, lack of appetite, elevated heart rate, diarrhea, and death in animals. Compared to corn and cereal silages, alfalfa has much better nutritional qualities like high buffering capacity, chewing stimulation, and pectin, which all help regulate the pH in the rumen. Alfalfa is also closer to the ideal level of crude protein, which supports growth and milk production. Other important amino acids like lysine are higher in the alfalfa. Compared to silages, it also has more good ash (inorganic matter) like calcium (Robinson, 2014). Studies have shown that a diet that is two-thirds alfalfa is optimal for milk production. Higher alfalfa diets also produce less nitrogen excretion per unit of milk produced. Alternative diets with less alfalfa require expensive supplements to match the nutritional value of the crop (Martin, Brink, Hall, Shewmaker, & Undersander, 2006).

Since the dairy and livestock industry provides a consistent source of demand, alfalfa is a relatively low-risk crop choice for farmers with the ability to provide a reasonably stable income. Higher-value crops always have the risk of overproducing for narrow markets. (Putnam, 2010). Unlike most other crops, alfalfa can be harvested multiple times during the year, providing a dependable income stream. Alternatively, it can be stored onsite in simple structures to be sold when market conditions improve.

3.5 Agronomic Practices and Considerations

Alfalfa's adaptability explains its widespread cultivation; no other U.S. crop can be grown in such diverse locations. It is grown throughout the western United States almost regardless of climate, elevation, and precipitation. Specialized cultivars exist for cool high mountain valleys and hot, dry deserts near sea level and it flourishes in both locations (Putnam, Orloff, & Teuber, 2007). It can grow in a wide array of soil types, from heavy clay soils to sandy soils, to organic or volcanic soils (S. B. Orloff et al., 1997; Putnam et al., 2000).

Alfalfa is a relatively easy crop to grow. In many Intermountain Regions, a seedbed can be prepared without plowing (S. B. Orloff et al., 1997). It requires much less labor compared to high value crops like vegetables and fruit trees. There is no ideal planting date; it can be planted successfully at several different times. Most often, planting occurs in the late-summer or early-spring (S. B. Orloff et al., 1997). Planting in the late-summer can take advantage of upcoming winter precipitation to help establish the plant. Often, when alfalfa is planted in the spring, an application of water is necessary after planting to support initial root growth (Guitjens, 1990; S. B. Orloff et al., 1997).

Throughout the growing season, alfalfa is irrigated 1-3 times between cuttings and the amount of water applied annually varies greatly from region to region, ranging from 2 af in cool mountain climates to 7-8 AF in the deserts per acre per year (Putnam et al., 2001). The growth process dictates when to harvest, usually every 30 to 50 days. After a cutting, alfalfa relies on its root reserves for approximately 2 to 3 weeks (roughly 6 to 8 inches of plant height) after which it then adds surplus carbohydrates back to the roots (S. B. Orloff et al., 1997). Normally, irrigation is discontinued some time before cutting to allow equipment access to the field without compacting the soil or damaging the plants.

The post cutting drying of alfalfa requires several days without irrigation, too. Watering is resumed after the hay bales have been removed (Guitjens, 1990). The cutting schedule is adjusted based on the intended use of the alfalfa hay. Shorter cutting periods result in lower yields but higher quality hay, which is ideal for dairies, growing calves, or yearlings. Alfalfa harvested before bloom produces higher quality hay than after bloom (Putnam et al., 2001). Longer cutting periods will have higher yields but lower quality (Putnam, Robinson, & DePeters, 2007). This hay is better suited for beef cows and “hobby” horses (S. B. Orloff, 2007). Even though immature alfalfa may be the highest quality, the greatest financial return may be harvesting mature alfalfa to maximize yield, reduce harvest costs, or ensure stand survival (Mueller, 1992).

In general, alfalfa requires fewer chemical inputs than other crops (Table 3). Rarely does the crop need nitrogen application, and, because it fixes nitrogen like all legumes, it provides a significant source of the nutrient for subsequent crops (Putnam et al., 2001; Putnam, 2010; Wrona, 1992). It has also been used to mitigate contamination problems by absorbing nitrates from groundwater, recycling dairy or municipal waste, and mitigating industrial compounds that could contaminate groundwater (Putnam, 2010; Putnam et al., 2001). With more government regulations that require nutrient management plans for soils high in nitrate nitrogen and or phosphorus, crops that can remove excessive nitrate will become more important (Martin, Mertens, & Weimer, 2004). Finally, there are millions of acres of alfalfa in the US that do not receive any pesticides (Putnam et al., 2001).

Table 3: Alfalfa fertilizer and chemical inputs. Source: Orloff et al. (2007).

Element Needed	**Symbol**	**Fertilizer Required**
Phosphorus	P2O5	Frequently
Sulfur	S	Frequently
Boron	B	Less Frequently
Molybdenum	Mo	Less Frequently
Iron	Fe	Seldom
Nitrogen	N	Seldom
Calcium	Ca	Never
Chlorine	Cl	Never
Cobalt	Co	Never
Copper	Cu	Never
Magnesium	Mg	Never
Manganese	Mn	Never
Nickel	Ni	Never
Zinc	Zn	Never

3.6 Harvesting and Yields

Compared to other crops, alfalfa is one of the most difficult to harvest. Not only must it be cut, but alfalfa must be dried to lower the moisture content from usually 75 to 85 percent to less than 20 percent before baling (S. B. Orloff & Mueller, 2007). To produce a ton of hay at 20 percent moisture, seven tons of water must be extracted from eight tons of fresh forage. Most of the moisture loss occurs from leaves through open stomata, representing 75 percent of the moisture loss during approximately 20 percent of the total drying time. Then the pores of the leaf and stem close, slowing the rate of drying considerably. There are many different management practices to speed up the second phase of the drying process. Mechanical methods can lightly crimp or crush the forage, breaking the stems and increasing water loss. Chemical drying agents allow moisture to exit more easily, but are not popular due to their cost and lack of effectiveness in cool weather when they are needed most. Having wider and thinner windrows[5] as opposed to conventional narrow thick windrows is another technique to decrease drying time. Wide windrows dry faster because more of the alfalfa is exposed to the sun (S. B. Orloff, 1992). The last step of the haying process is for the alfalfa to be baled and then collected for storage or shipping (S. B. Orloff et al., 1997).

The climatic variability in growing locations throughout the region is reflected in the yield, irrigation amount, cuts per year, fall dormancy and stand life of alfalfa (Table 4). Cooler regions with shorter growing seasons and higher precipitation like Wyoming, Utah and Colorado have lower yields, fewer cuttings per year, and alfalfa varieties that become dormant earlier in the fall and have delayed growth in the spring. Alfalfa stands in this environment can last up to eight years. In the hotter areas of southern California and Arizona, alfalfa requires more irrigation water, has higher yields, more cuttings per season, and many of the alfalfa cultivars are less fall dormant, which allows for a longer growing season. Unfortunately, stands must be replaced every 3-4 years in these climates.

Table 4: Alfalfa characteristics by state. Source: Summers et al. (2007).

State	Average Yield (tons/acre)	Economic Rank in State	Acreage Under Irrigation	Cuts/Year	Fall Dormancy Classes	Stands Replaced Every
Arizona	7.9	-	98%	8-10	8-9	3 years
California	6.8	5-7	100%	3-10	3-10	3-4 years
Colorado	3.8	3	89%	1-4	2-4	3-8 years
Nevada	4.1	1	100%	3-4	3-5	8 years
New Mexico	5.2	3	90%	3-8	3-9	3-5 years
Utah	4.4	3	67%	3-5	3-6	3-5 years
Wyoming	2.7	-	68%	1-4	2-4	4 years

3.7 Dormancy

Alfalfa's adaptability includes its ability to survive prolonged periods of drought. Alfalfa plants go into drought-induced dormancy and generally recover once moisture is returned (S. Orloff, Putnam, et al., 2014). Alfalfa is relatively drought tolerant because of its deep root system. It is able to access moisture lower in the soil profile that other crops cannot (S. Orloff, Putnam, et al., 2014). When alfalfa becomes drought-stressed, it will rely on the water deeper in the soil profile, if available. Roots can grow and penetrate soil to a depth of 9 meters (K. B. Jensen, Waldron, Peel, & Hill, 2007; Shewmaker, Allen, & Neibling, 2015). However, 60 to 70 percent of the total root mass is in the upper 15 cm of the soil;

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[5] A windrow is the gathered linear pile of cut alfalfa that is left to dry in the sun. "Make hay while the sun shines" could easily be "make windrows while the sun shines."

keeping that section of the soil profile moist is important (K. B. Jensen et al., 2007). Approximately 70 percent of the water is extracted by the upper half of the root system (S. Orloff, Putnam, et al., 2014) (Colorado Water Conservation Board & Colorado Division of Water Resources, 2013; S. Orloff, Bali, & Putnam, 2014). In the fall, the plants enter dormancy when the days shorten and temperatures drop. The plants will begin to grow again when soil temperatures warm. While dormant, alfalfa is much less susceptible to cold and frost (S. B. Orloff et al., 1997).

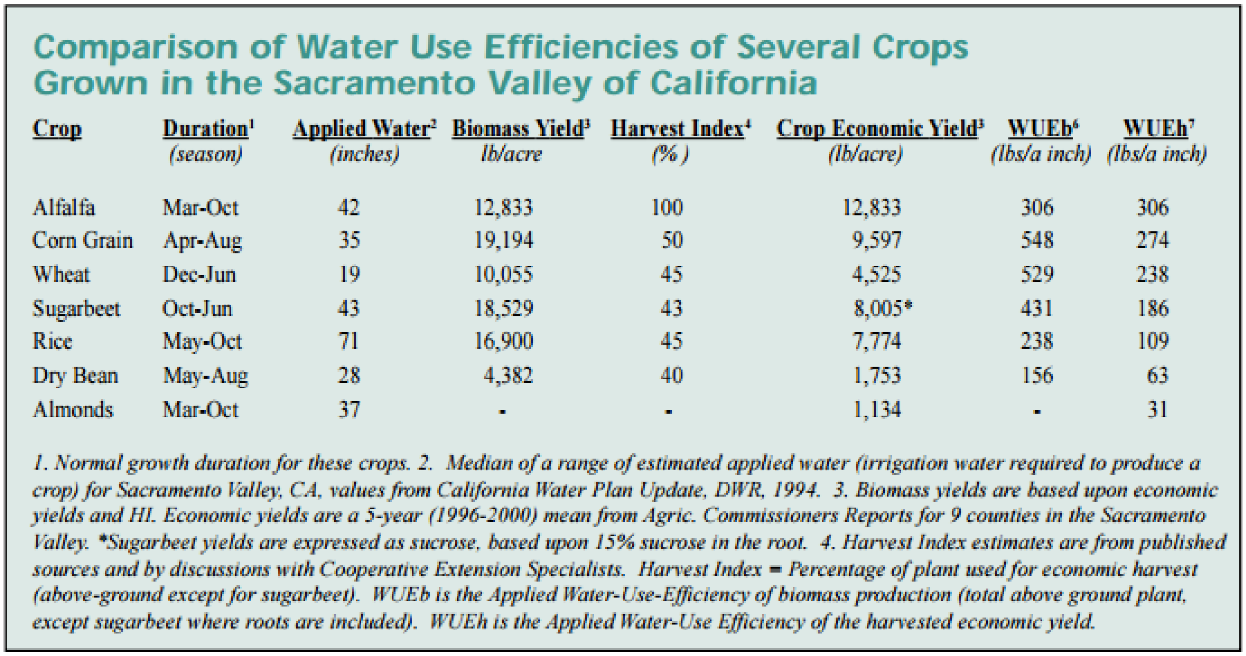
Cutting management is the primary method for increasing stand health during drought periods. Starch stored in the crown and roots feed new branch and crown bud growth in the spring (Fransen & Kugler, 2003). This stored starch is also important during regrowth periods after cuttings. One extension study suggests that as long as the plant roots remain white, moist and pliable the plant can survive drought (McWilliams, 2002). A 1997 study in Tucson looked at crown moisture as a relatively easy way of predicting survivability during summer irrigation termination (SIT). At the end of an 84-day SIT, 42% crown moisture was identified as a critical threshold for crown survivability (Matthias Wissuwa, Smith, & Ottman, 1997).

Figure 3: Five-year-old alfalfa after two years of drought. Source: Orloff et al. (2014). Note: A field study on alfalfa in Five Points, CA was stopped after three years. In both 2013 and 2014 there was no water applied from April to November, but the stands mostly survived by relying on subsurface moisture.

3.8 Water Use Compared to Other Plants

The most often cited criticism of alfalfa is that it consumes more water than almost any other crop except rice when comparing consumptive use across different plants. The large water consumption is due to the long growing season of perennial crops (S. Orloff, Putnam, et al., 2014). Alfalfa provides a high tonnage of usable dry matter for the water applied (Putnam et al., 2001). In the Sacramento Valley of California, the water use efficiency[6] (WUE) of alfalfa compares well to other commonly grown and high-value crops in the same area (Table 5). Even though the biomass yield is not as high as other crops like corn and rice, alfalfa has a very high “harvest index”, the percentage of plant used for economic harvest. Its water use efficiency of biomass production is average, but the WUE of the harvested economic yield is higher than any of the other crops listed.

Table 1: Water use efficiency comparison of Sacramento Valley crops. Source: Putnam et al. (2001).



Comparison of Water Use Efficiencies of Several Crops Grown in the Sacramento Valley of California

Crop	Duration[1] *(season)*	Applied Water[2] *(inches)*	Biomass Yield[3] *lb/acre*	Harvest Index[4] *(%)*	Crop Economic Yield[3] *(lb/acre)*	WUEb[6] *(lbs/a inch)*	WUEh[7] *(lbs/a inch)*
Alfalfa	Mar-Oct	42	12,833	100	12,833	306	306
Corn Grain	Apr-Aug	35	19,194	50	9,597	548	274
Wheat	Dec-Jun	19	10,055	45	4,525	529	238
Sugarbeet	Oct-Jun	43	18,529	43	8,005*	431	186
Rice	May-Oct	71	16,900	45	7,774	238	109
Dry Bean	May-Aug	28	4,382	40	1,753	156	63
Almonds	Mar-Oct	37	-	-	1,134	-	31

*1. Normal growth duration for these crops. 2. Median of a range of estimated applied water (irrigation water required to produce a crop) for Sacramento Valley, CA, values from California Water Plan Update, DWR, 1994. 3. Biomass yields are based upon economic yields and HI. Economic yields are a 5-year (1996-2000) mean from Agric. Commissioners Reports for 9 counties in the Sacramento Valley. *Sugarbeet yields are expressed as sucrose, based upon 15% sucrose in the root. 4. Harvest Index estimates are from published sources and by discussions with Cooperative Extension Specialists. Harvest Index = Percentage of plant used for economic harvest (above-ground except for sugarbeet). WUEb is the Applied Water-Use-Efficiency of biomass production (total above ground plant, except sugarbeet where roots are included). WUEh is the Applied Water-Use Efficiency of the harvested economic yield.*

3.9 Environmental Benefits

Alfalfa has some environmental benefits not present in other crops. Due to the long stand life of the plant, it provides habitat for wildlife and beneficial insects. Many animal species use alfalfa for reproduction, cover, or feeding (Putnam et al., 2001). Alfalfa improves the soil characteristics and contributes to less erosion due to its extensive root system and long life. Most alfalfa fields are not tilled for 3 to 6 years and the root structure helps maintain the soil in place. The thick canopy covers most of the soil and prevents water from loosening the soil (Putnam, 2010; Putnam et al., 2001). Many alfalfa fields are not sprayed with pesticides or herbicides.

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[6] Water Use Efficiency is a measure of how well the plant generates biomass per unit of applied water. The biomass can be the total plant biomass, or the biomass of the economic part of the plant. Because the entire harvested amount of alfalfa is used, the plant scores high by this measure of water use.

3.10 Yield, Water Consumption, and Quality Relationships

There have been many studies on the relationship between alfalfa ET and yield in numerous locations around the country. Alfalfa yield has a linear relationship with evapotranspiration (ET). The more water is applied, the higher the yield until the full ET is reached. Consistently, yield increases with increased irrigation to the point of meeting maximum ET. (J. W. Bauder, Bauer, Ramirez, & Cassel, 1978; Carter & Sheaffer, 1983; Davis, Fry, & Jones, 1963; Donovan & Meek, 1983, 1984; Hanson, Putnam, & Snyder, 2007; E. H. Jensen, Miller, Mahannah, Read, & Kimbell, 1988). Even in locations like western New York that are not ideal for alfalfa growth, increased irrigation results in higher yields (Lathwell & Vittum, 1962). Other studies have shown that yield is also a function of growing degree-day accumulation, average daily solar radiation, year and harvest number within year, but ET is the most significant factor (Hanks, 1974; Smeal, Kallsen, & Sammis, 1991).

Deficit irrigation will reduce yield significantly because ET and yield are linearly related. Indeed, this result holds for all forms of deficit irrigation where biomass growth is the objective. Many studies (see appendix) have investigated the impacts of split-season deficit irrigation or continuous deficit irrigation on alfalfa yield. (Cohen, Bielorai, & Dovrat, 1972; Guitjens, 1990; Hugh Barret & Skogerboe, 1980; R. B. Lindenmayer, Hansen, Brummer, & Pritchett, 2011b; Retta & Hanks, 1980; Sammis, 1981; Smeal et al., 1991; Wright, 1988). All feature significant yield declines when the plants truly received less water; in some cases, the plants were able to access groundwater and thus show lower declines than would otherwise occur.

Interestingly, alfalfa that is water stressed often has improved quality because the plant is not as mature and contains a higher percentage of leaf material and fewer stems. Multiple deficit irrigation studies have found drought stressed alfalfa to be higher in crude protein and lower in non-digestible fiber, both desirable characteristics (Davis et al., 1963; Donovan & Meek, 1983, 1984; Hanson et al., 2007; E. H. Jensen et al., 1988; McWilliams, 2002; Mueller, 1992).

The relationship between ET and yield shifts depending on the climate (Figure 4). Hotter climates with more evaporative losses will produce significantly less alfalfa at the amount of ET than alfalfa grown in cooler climates, though the relationship is still linear. (Sanden, Klonsky, Putnam, Schwankl, & Bali, 2011).

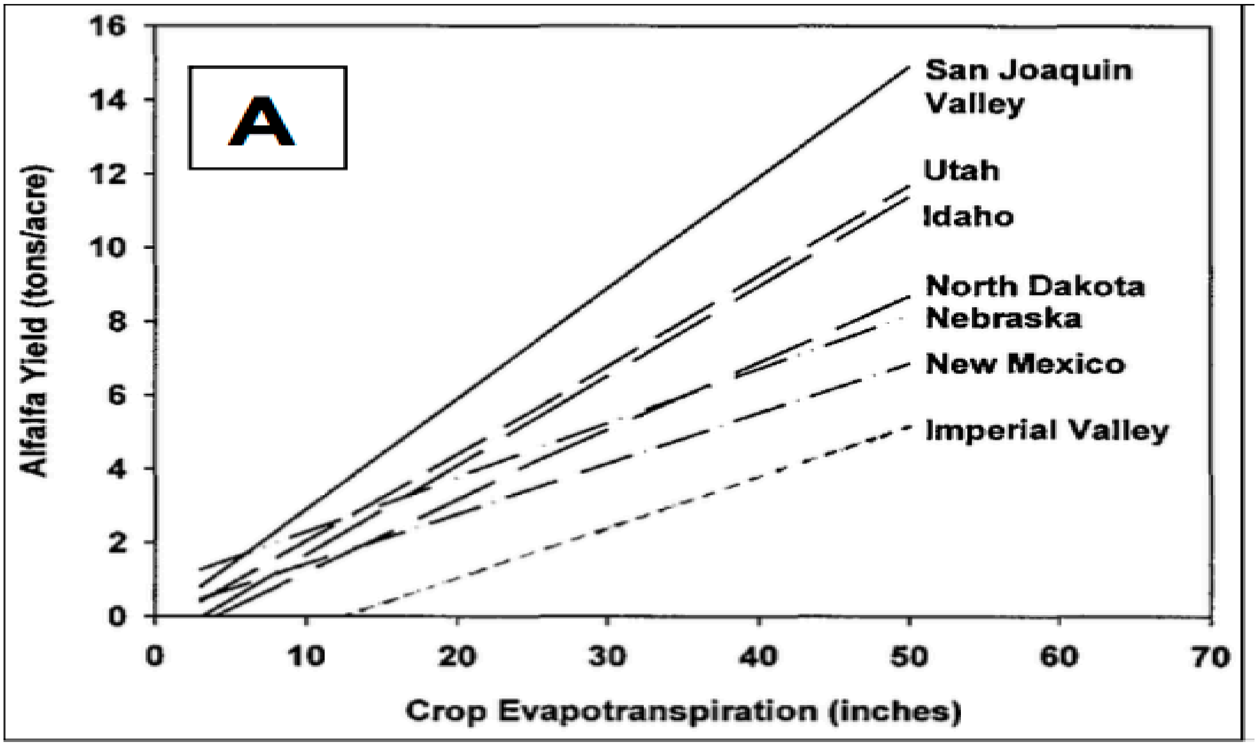

Figure 4: ET vs. yield of alfalfa in different locations. Source: Sanden et al. (2011).

Water applied in excess of water required by the crop does not produce extra yield (Shewmaker et al., 2015). Indeed, over-irrigation can lead to stand loss and declining yields (Rice, Quisenberry, & Nolan, 1989). Early in the irrigation season crop requirements can often be met with limited irrigation. Consistently, studies have found little response of alfalfa yield to applied water for the first cutting due to stored water in soil from normal winter and spring precipitation (Hanson & Putnam, 2000; Shewmaker et al., 2015).

Most studies have found very little difference in the relationship between yield and ET in different cultivars. A study in Bushland, Texas found little difference in yields between cultivars, but water use generally increased with yield (Undersander, 1987). In the San Joaquin Valley of California, one study found some differences between alfalfa varieties in the early spring and late summer, but total seasonal yields were not different among the cultivars (Grimes, Wiley, & Sheesley, 1992). In Logan, Utah, more variation in yield was documented between years than between difference cultivars (Retta & Hanks, 1980). However, some yield differences were found between seven cultivars grown in the Imperial Valley (Hanson & Putnam, 2000).

3.11 Seasonal Yield

Alfalfa consistently produces the highest yields of the best quality at the highest water use efficiency in the spring. This is why many emphasize split season deficit irrigation for alfalfa, terminating irrigation after most of the quality yield has been produced (S. Orloff, Putnam, Hanson, & Carlson, 2003a) (R. B. Lindenmayer et al., 2011a; S. Orloff, Putnam, Hanson, & Carlson, 2003b).

Yields throughout the West are often highest early in the season, making up a disproportionate amount of the total annual yield. Spring to early summer cuttings produce approximately two-thirds of the annual yield (Guitjens & Goodrich, 1994; S. Orloff, Putnam, et al., 2014). In Arizona, alfalfa is generally harvested from March 1st through November 1st, but 65 percent of the total production comes before mid-May (Husman, 1992). In North Dakota, yields declined with each successive harvest. That trend increases with magnitude for unirrigated alfalfa (J. W. Bauder et al., 1978). In Washington, in a four-cut harvest system, the first cutting usually makes up about 35 percent to 38 percent of the year's total forage produced. In a five-cut harvest system, the first cutting yields are about 27 percent (Fransen & Kugler, 2003). In the Central and Imperial Valleys of California, about two-thirds of the annual production occurs by July. This increases to 75 percent in the Intermountain Regions of California (S. Orloff, Putnam, et al., 2014). In Idaho, the first cutting of a 4-cut system makes up 35-38 percent of the year's total forage yield and in a 5-cut system the first cutting is about 27% of the total yearly yield (Shewmaker et al., 2015).

Orloff et al. (2014) documents the significant decline in yield as a percent of total production in two locations in California (Figure 5). In the Intermountain region, yields after the second cutting only make up 25 and 41 percent of the total annual yield in a three- and four-cut system, respectively. By the second cutting (when split-season deficit irrigation could occur), 75 and 60 percent of total alfalfa is harvested in a three- and four-cut system, respectively. In Fresno County, a region where seven harvests can occur in one season, production declines in late July and August.

Regardless of location or climate, alfalfa yields decrease during the hot summer season because it is a cool season crop[7]. This occurs in all major production areas in North America, including the Colorado River Basin (Evans & Peaden, 1984). In some studies the amount of forage harvested from the midsummer cutting is 50 percent lower than the spring cutting, even with irrigation (Cohen et al., 1972). In Washington, over a two-year study the ratio of yield over the four harvests throughout the season was 37:27:24:12 (Evans & Peaden, 1984). In the Imperial and Palo Verde Valleys, summer yields drop to ½ to ¾ ton per cutting on a 24 to 28 day cycle (Wrona, 1992).

3.12 Seasonal Nutritional Characteristics

Alfalfa's nutritional characteristics, especially its high protein and digestibility, make it the preferred forage for lactating dairy cows. One important factor affecting quality is the content of the cell wall. In high quality alfalfa, there is less cell wall material, making it more nutritious and digestible. With low-quality alfalfa, there is a higher proportion of cell wall material containing indigestible compounds like lignin. This "lignification" of the cell wall occurs as alfalfa plants mature (S. B. Orloff et al., 1997).

Spring is when the highest quality alfalfa is produced. This difference in quality is significant such that it is highly desired by dairy farmers and commands a higher price (Foster, 1992; S. Orloff, Putnam, et al., 2014; Robinson, 2014; Schoneveld, 1992). Forage quality declines after the first harvest. In some regions the decline can be severe (Martin et al., 2006), in part due to higher temperatures.

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[7] Cool season crops are adapted to cool climates and are often less sensitive to frosts. When temperatures warm too much for the plant, they will produce flowers and seeds.

According to Mueller (1992), forage quality declines as the summer progresses and recovers in the fall. Alfalfa harvested in the spring or fall has a higher leaf and protein content than summer produced alfalfa. High temperature increases the rate of plant maturation and cell wall lignification (the strengthening of the plant vascular body). This causes structural components to form much faster at the expense of metabolites in the cell contents. Lignification of the cell wall is the primary factor limiting forage digestibility. During April and May, hay quality is excellent and prices are usually highest. In June, July, and August, alfalfa hay yields are high but quality is lower. The table below shows the change in yield and total digestible nutrients (TDN).

Alfalfa produced in the summer months brings a lower price due to its poor quality compared to spring or fall hay. Summer biomass created is thicker in the stem and not as digestible (T. Bauder, Hansen, Lindenmeyer, Bauder, & Brummer, 2014; Martin et al., 2006; S. Orloff, Putnam, et al., 2014; Wrona, 1992). This type of alfalfa is suited for dry cows, feedlot animals, or horses, not lactating dairy cows (M. Ottman & Mostafa, 2013).

3.13 Seasonal Water Use Efficiency

Alfalfa yields more dry matter per unit of water use during the spring and late fall than the summer, but fall periods do not have the same water use efficiency or quality as the spring. Sunlight and plant physiology are why alfalfa produces the best quality hay in the spring. The amount of sunlight (measured by solar irradiance) is greater in the spring than in the fall. Biomass growth per unit of ET increases with solar irradiance up to a maximum level, after which yields decline. The combination of high light intensity and low temperatures that suit cool season crops only occurs in the spring. This combination results in high levels of photosynthesis and low levels of evaporation. Another factor is that in the spring alfalfa has a reserve of carbohydrates from the previous fall that can used for growth. Finally, in the spring more photosynthetic growth goes to biomass yield than root reserves (T. Bauder et al., 2014).

WUE declines during the season due to changes in solar irradiance and the carbohydrate reserve flux in alfalfa (R. B. Lindenmayer et al., 2011b). In some regions, 40 percent of annual irrigation is applied in July to August, with only 20 percent of the yield being produced during that time. Not irrigating in July and August noticeably increased water-use efficiency for the whole year (Metochis & Orphanos, 1981).

Since yields are typically highest in the spring and the ET rate is less than the summer, the water use efficiency of alfalfa is greater in the spring than mid-summer and fall (Daigger, Axthelm, & Ashburn, 1970; S. Orloff, Putnam, et al., 2014). The water use efficiency decreases with each subsequent harvest later in the growing the season (T. Bauder et al., 2014). Guitjens and Goodrich (1994) found the average water use efficiency to be greater in the early and late season, when temperatures are cooler. They also found that the production capacity for the first harvest was the greatest for a given amount of water.

Decreasing WUE in the hot summer months is driven by the increase of ET of fully irrigated alfalfa. ET for alfalfa is often highest in July and August (Wright, 1988). One study found that ET increased gradually from the start of the season to the first part of July, reaching maximum values of 7.5 mm and 8 mm a day (Hanson et al., 2007). In an alfalfa study in Bushland, Texas, water efficiencies were highest when daily evaporative demand was lowest (spring) (Undersander, 1987). In Nebraska, the average consumptive use of water per day increased for each harvest: 4.1 mm for the first harvest, 5.6 mm for the second, and 5.9 mm for the third. The amount of water use per cutting increased from 9.6

cm/metric ton (first cutting), to 11.2 cm/metric ton to (second cutting), to 15.4 cm/metric ton at the final cutting. The amount of water applied increased to achieve the same yield, resulting in a decline in water use efficiency (Daigger et al., 1970). Similar to difference in yields, there is little evidence to support that alfalfa varieties vary widely in water use efficiency. There may be some differences during parts of the season, but the total-season water use efficiency is not that different (R. B. Lindenmayer et al., 2011b).

3.14 Summer Slump

As discussed above, while springtime is ideal for alfalfa production, quality, yields, and WUE all decline sharply during the hot late summer (July and August), a time known as the "summer slump." The alfalfa grown during this period is of lower quality and lower yield, but requires the most amount of water applied during the season (Hanson & Putnam, 2000; Metochis & Orphanos, 1981). Orloff et al. (2003a) asserts that summer deficit irrigation has the most potential to conserve water because it allows some forage production in the spring and the established alfalfa cover minimizes the potential for wind erosion and weed encroachment during the summer dry-down period.

Summer slump is associated with higher temperatures (especially during the night), shorter days, and increased humidity (T. Bauder et al., 2014; Cohen et al., 1972; Evans & Peaden, 1984; Husman, 1992; M. Ottman & Mostafa, 2013). Alfalfa is a cool season crop and the higher than normal temperatures are not ideal for optimum growth. The leaves are not able to cool themselves and transpire enough water to the same extent during the spring and fall (M. Ottman & Mostafa, 2013). When this occurs, the structural development of alfalfa is accelerated, shortening the time to maturity when the plants flower (Evans & Peaden, 1984). A lack of height and stem numbers reduce yield. After a cutting, the plant replenishes the root carbohydrates for about two weeks to prepare for the next growth cycle (M. Ottman & Mostafa, 2013). The crown, roots, and reproductive structures of alfalfa receive more growth than leaves and stems (Smeal et al., 1991).

There are strategies to partially mitigate the effects of summer slump. Some research has found more dormant varieties of alfalfa are more resistant to the characteristics of summer slump. However, many semi-dormant alfalfa varieties in the low elevation deserts do not produce yields comparable to non-dormant varieties. Studies have had mixed results with increases and decreases in yields when excess nitrogen is applied. Due to the decrease in alfalfa growth, weeds become more competitive for water. The most effective method to prevent weed encroachment is a healthy and dense stand. Cutting height is also important. A height of 1-inch is recommended on a 4-week harvesting interval, but cutting at 4 inches has some advantages. A small amount of carbohydrates may be stored in the stem, aiding regrowth. Also, since less stem is harvested, the quality also increases (M. Ottman & Mostafa, 2013).

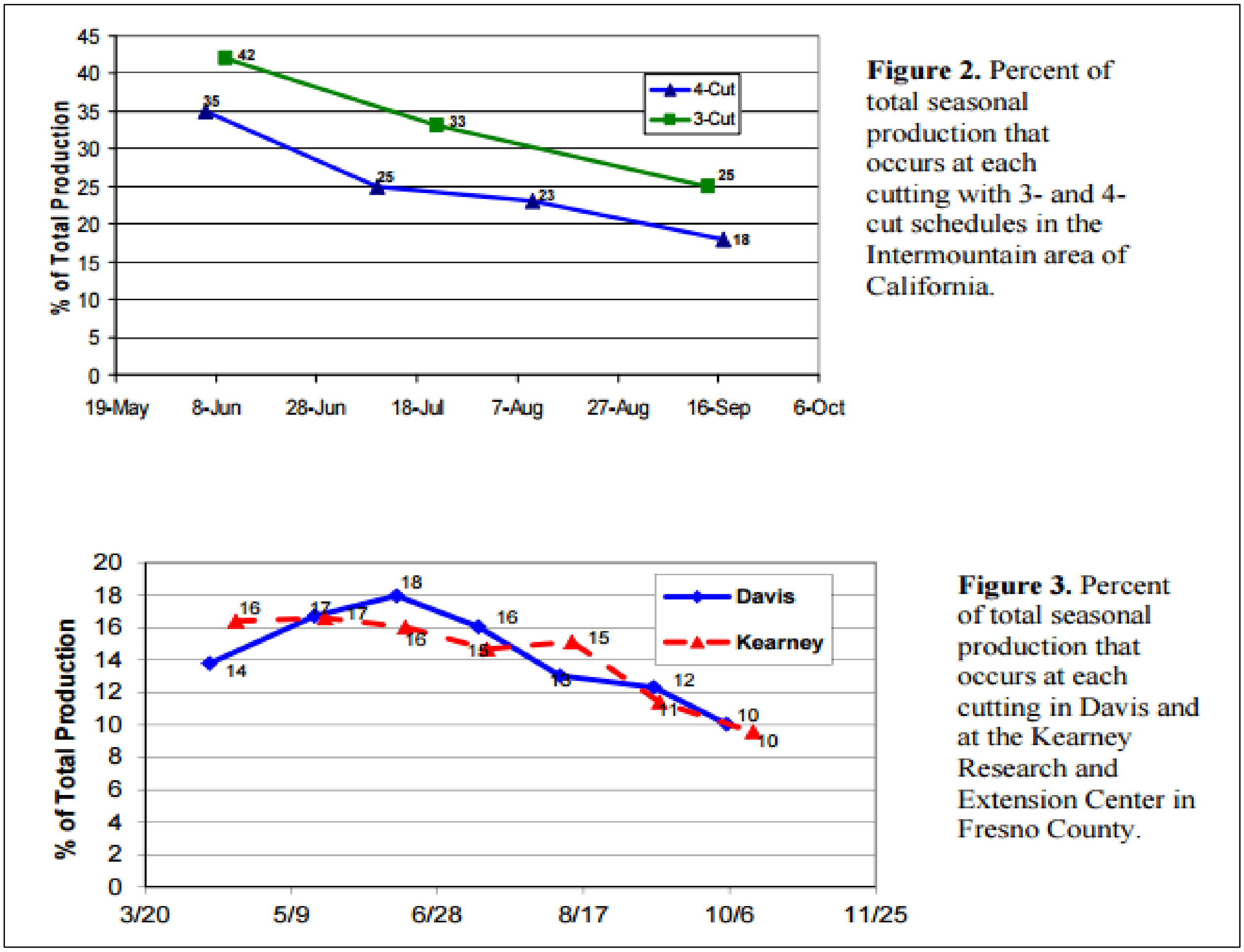

Figure 2. Percent of total seasonal production that occurs at each cutting with 3- and 4-cut schedules in the Intermountain area of California.

Figure 3. Percent of total seasonal production that occurs at each cutting in Davis and at the Kearney Research and Extension Center in Fresno County.

Figure 5: Percent of annual yield per cutting in the Intermountain Area and Fresno County, California. Source: Orloff et al. (2014).

This period of marginal alfalfa production presents a great opportunity to reduce consumptive use, with less harm that full season deficit irrigation or fallowing. In fact, terminating irrigation during the late summer has often been practiced in the past and was referred to as “summer dry-down.” In southern California in the 1950s, it was common for growers to terminate irrigation over the summer. This practice was tried again in the early 1990s. Alfalfa would be cut in July and irrigation withheld until October. There was little loss to alfalfa stands in the 1950s, but many growers’ stands were harmed by this practice in 1991-1992. This was likely due to the different cultivars of alfalfa grown at the time and that the alfalfa was already weakened by a whitefly invasion (Wrona, 1992).

The same practice was common in southern Arizona, where farmers ceased irrigation from July through August and alfalfa went dormant (Schonhorst, Thompson, & Dennis, 1963). Withholding summer irrigation was common in the 1960s and resulted in less stand loss due to scald and fewer problems from encroaching summer grasses. Improved land leveling techniques and effective herbicides significantly reduced these negative effects. (M. J. Ottman, Tickes, & Roth, 1996). Before laser leveling, farmers often resisted irrigating because the increased water necessary to meet ET during the late summer would often pond in the un-level parts of the fields. This would lead to scalding and severe loss of stand. Laser leveled fields allowed farmers to apply just as much water and not worry stand loss from water ponding (M. Ottman & Mostafa, 2013).

3.15 Deficit Irrigation Induced Stand Loss

One of the most important issues with deficit irrigation of alfalfa is stand loss (the loss of some or all of the plants). It is a given that yields will decline when irrigation is withheld, but stand loss would result in future declines in production from the remaining alfalfa. An irrigator is more likely to forego irrigation if there were no long-lasting effects on the plant. Alfalfa survivability depends on the environment, length of growing season, duration of drought period, soil type, depth to water table, salinity, and even alfalfa variety (S. Orloff, Putnam, et al., 2014).

A few studies have shown that terminating irrigation during summer can cause permanent reduction in forage yield due to stand loss, especially in very hot climates with sandy soils (Shewmaker et al., 2015; Matthais Wissuwa & Smith, 1997). However, the bulk of the alfalfa studies show that short periods of deficit irrigation will not cause stand loss when compared to fully irrigated plots. Studies conducted in cooler regions with shorter growing seasons had the best results. In some cases, deficit irrigation could even be implemented on newly planted alfalfa or for two years in a row with few losses. Stand loss was more common when irrigation was terminated for long periods of time, multiple years in a row, or in sandy soils.

In the Intermountain region of California, deficit irrigation studies have found no observed difference in stand density in the year after split season deficit irrigation. This may be because Intermountain regions are cooler and have a shorter growing season. The exception was when the experiments were performed the year alfalfa was seeded. In that case, there was stand loss, indicating that alfalfa needs time to establish itself before it can survive periods of deficit irrigation. Stand loss has also occurred when water was withdrawn for most of the year in areas of shallow soil where the plants were weakened and had lower root reserves (S. Orloff, Putnam, et al., 2014). In Fresno County, California, a study by Frate and Roberts (1988b) concluded that alfalfa planted in early fall can survive irrigation termination in the midsummer in the first and second year. There appeared to be little to no stand loss in trials in the Klamath and Sacramento Basins (S. Orloff et al., 2003a).

On the Front Range of Colorado in Berthoud, the number of crowns that survived was higher in experimental treatments when irrigation was terminated after the 1st or 2nd cutting than a full irrigation control plot or when water was only withheld during the summer (B. Lindenmayer, Hansen, Crookston, Brummer, & Jha, 2008b). At three sites on the western slope of Colorado, stand density was not affected by terminating irrigation after the 1st or 2nd cutting for two years (Jones, 2015). Another study in Fort Collins, Colorado found no decline in stand density in later years of the experiment (T. Bauder et al., 2014).

A study in southern Arizona in the 1960s-withheld irrigation in July and August. There was little difference in stand loss over the three-year study between irrigated and non-irrigated plots. Both plots had significant stand loss during that time, but at this time fields were not laser-leveled and high plant mortality was common in alfalfa due to scalding (Schonhorst et al., 1963).

In Tucson, Arizona, Wissuwa and Smith (1997) terminated irrigation for 84 days, resulting in 24 percent plant mortality. In another test, water was terminated for 42 days one year and 75 days the next. In this test, there was only 1.5 percent plant mortality, which was comparable to the stand loss in the control plots. They also found that crown mortality was significantly correlated with the concentration of total nonstructural carbohydrates (TNC), the nutrients stored in the crown and the root reserve for future growth. When the amount of TNC drops below a certain level, it is unlikely the plant will survive. Similarly, Takele and Kallenbach (2001a) found that stands declined more rapidly when water is withheld for periods greater than 35 days in the summer.

Significant stand loss sometimes occurred in other very hot low desert regions. A Palo Verde Irrigation District study had stand loss due to the sandy soils (S. Orloff et al., 2003a). A similar case occurred in Yuma, Arizona where stand loss was so severe that alfalfa didn't recover after the first-year termination. Summer irrigation termination did not have as dramatic an effect in Maricopa, Arizona, which received more rainfall, was slightly less hot, and the soil had a higher water holding capacity (M. J. Ottman et al., 1996). Soil type appears to be the determining factor in many cases where stand loss is an issue. (S. Orloff et al., 2003a).

3.16 Post Deficit Irrigation Yields and Recovery

In many cases, alfalfa has shown to be quite resilient to split-season deficit irrigation. Soil, climate, and length of irrigation termination are factors which determine the recovery period. Many studies have found little to no impact on yields once irrigation resumed. Alfalfa appears to be very resilient and quick to recover from induced drought. At the Intermountain sites, there was no observed difference in yield the following year (S. Orloff, Putnam, et al., 2014). In the Berthoud, Colorado study, the first cutting was very similar regardless of whether the previous year's irrigation treatment was full irrigation, or irrigation termination after the 1st or 2nd cutting (B. Lindenmayer et al., 2008b). In western Colorado, alfalfa that was not irrigated after the 2nd cutting produced similar yields in the 1st and 2nd cutting the following year when compared to fully irrigated alfalfa (Jones, 2015). In Fallon, Nevada, fields fully recovered after three years of deficit irrigation regardless of whether irrigation was withheld after the 2nd or 3rd cutting (Guitjens, 1993).

Alfalfa studies in Cyprus found that when irrigation resumed, alfalfa not irrigated for one or two growth periods produced similar yields to the control (Metochis & Orphanos, 1981). Frate and Roberts (1988b) found that alfalfa planted in early fall can survive induced first and second year midsummer deficit irrigation. After two years of different deficit irrigation regimes, all treatments were irrigated twice per cutting for a third year. These fields produced as well as the standard application of water. Better hay quality was a result for some deficit irrigation treatments in the first harvest after irrigation was reapplied. In Davis, California, after deficit irrigation in July and August, alfalfa yields recovered with the subsequent crop (Hanson et al., 2007).

In some cases, harvests do not fully recover or take time to equal yields on fully-irrigated plots. If irrigation is withheld for a long period, yields can be reduced significantly. In the western Colorado study, alfalfa harvests were significantly reduced the following year when irrigation was terminated after the 1st cutting, as opposed to the 2nd (Jones, 2015). In the Cyprus study, alfalfa not irrigated for three growth periods produced 20 percent less forage than the control the following season (Metochis & Orphanos, 1981). The study in Fort Collins, Colorado found that yields of spring harvests following dry summers of partial season irrigated alfalfa average 85 percent of irrigated alfalfa (T. Bauder et al., 2014). In the Palo Verde Valley, the yield was less than the control at the first harvest after water was withheld for 70 days, but not for 35 days. Yields did recover after one of two normal growth periods with irrigation (Takele & Kallenbach, 2001b). The case is similar in the Maricopa, Arizona study, where yields recovered the first growth cycle after irrigation resumed in October and during the second growth cycle the following year (M. J. Ottman et al., 1996).

3.17 Soil Factors

The biggest factor with alfalfa survivability after deficit irrigation seems to relate to soil types (K. B. Jensen et al., 2007; S. Orloff et al., 2003a). Consistently, soils with higher water holding capacity and infiltration are better for alfalfa in general, especially when deficit irrigation is being practiced. Sandy loam to clay loam are best because they are the optimum choice for water holding capacity and water infiltration (S. B. Orloff et al., 1997). Sands and loamy sands have a low water capacity (Table 2). Less water in the soil profile means less water the plant can draw upon during drought or DI. Also, the hydraulic conductivity (ability of water to move through the soil profile) is too fast in these soils (S. Orloff, Putnam, et al., 2014). Alternatively, soil with a high water holding capacity, like fine textured clays, are also problematic for alfalfa. In these types of soils, water drainage and conductivity are slow (S. B. Orloff et al., 1997). The right hydraulic conductivity allows water to move upward from the water table to root system at the right rate (S. Orloff, Putnam, et al., 2014). Soils with slow infiltration properties and low hydraulic conductivity are prone to water logging (Guitjens, 1990). In medium textured soils with a shallow water table, alfalfa can survive no matter what hydrologic conductivity exists (S. Orloff, Putnam, et al., 2014).

Table 2: Different soil types and water holding capacity. Source: Jensen et al. (2007).

Soil Type	Water Holding Capacity mm/m
Coarse sand	42
Loamy sand	83
Silt loam	146-167
Silty clay loam	167
Clay loam	167
Clay loam	167
Heavy clay loam	146-167

Even for normal alfalfa growth without deficit irrigation, soil can have a significant impact depending on the water holding capacity. In places with enough winter precipitation, irrigation may not have any significant influence on the first two cuttings of alfalfa due to stored soil moisture. The plant can rely significantly on water stored in the profile (Davis et al., 1963). Sandy soils have the opposite effect. They have too little water-holding capacity to produce a full first cutting without irrigation. Regardless of the amount of winter precipitation, the profile cannot contain a sufficient amount to assist alfalfa in meeting its ET demand in the early spring (Shewmaker et al., 2015).

Soil depth is another issue. A shallow soil profile provides less room for root development and less capacity for water storage (Guitjens, 1990). Ideally, soil depth should be greater than 6 feet deep with a minimum depth of 3 feet (S. B. Orloff et al., 1997). This can be an issue in the Intermountain Region, where shallow soils can hinder root growth (S. B. Orloff et al., 1997).

3.18 Water Table Height, Taproots, and Survivability

Alfalfa has a taproot that commonly extends four to six feet, but can go as deep as 30 feet. However, even though alfalfa roots can extend to great depths compared to other plants, the majority of the root is within two to four feet of the soil surface. Generally, the effective rooting depth for irrigation is the first 4 feet of the soil profile (S. B. Orloff et al., 1997). This area is often critical for irrigation in the spring and throughout the growing season (Berrada & Reich, 2011; Daigger et al., 1970). This is also where most water is absorbed in the soil profile (Figure 6).

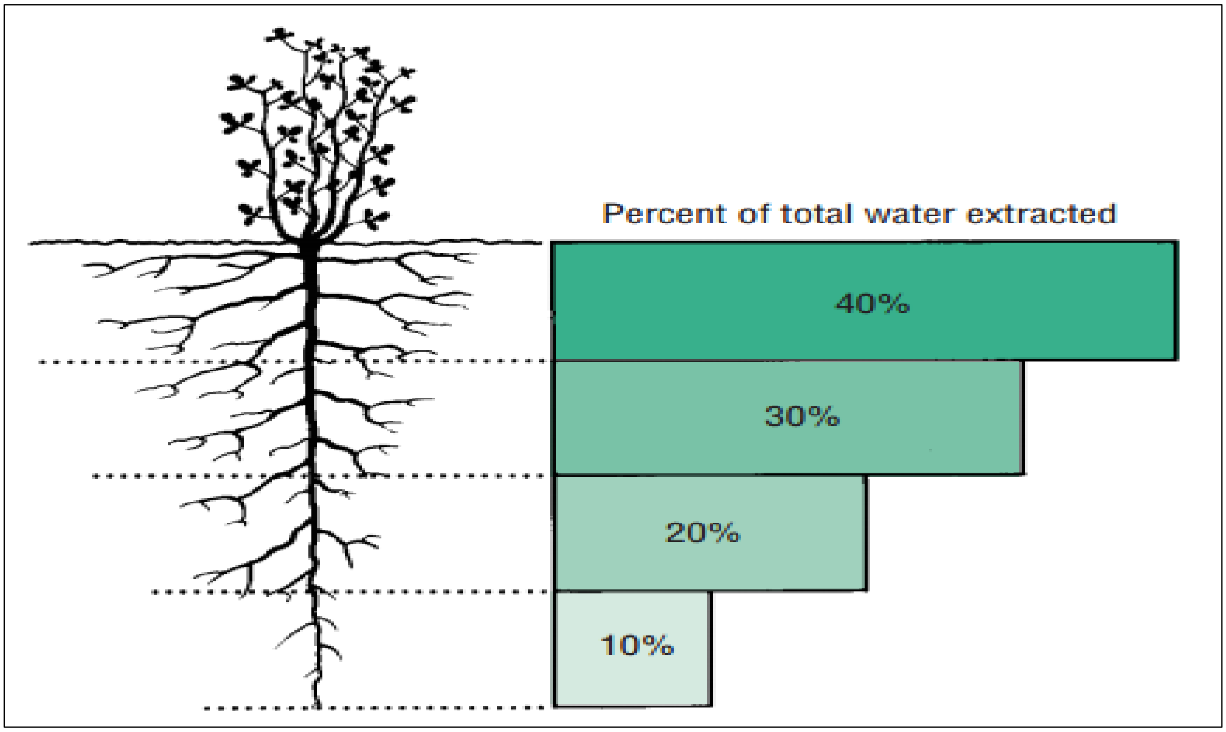

Figure 6: Unit-less schematic showing amount of water extracted compared to root depth. Note: 70% of the water is extracted by the upper half of the root system. Source: Orloff, 1997.

Keeping the upper soil profile properly irrigated is essential. As more water is extracted, soil particles hold stored water more tightly. For alfalfa, the "maximum allowable depletion," the amount of water loss that can occur before water extraction becomes too difficult, is 50 percent (S. B. Orloff et al., 1997). The deepest roots absorb less water and thus can transport less water to the above ground portions of the plant.

Even though a shallow (but not too shallow) water table is seen as beneficial for alfalfa growth, especially during DI the research provides conflicting results. A study in North Dakota found that ET was affected by the water table depth and irrigation level. Another study in western Colorado found that water from the water table made up 62 and 76 percent of seasonal ET at a depth of 60cm. At 105 cm water table depth, the water table supplied 27 and 28 percent of seasonal ET. The ET contribution from groundwater declined rapidly as the water table depth increased (R. B. Lindenmayer et al., 2011b). Auckly and Guitjens (1995) in western Nevada studied alfalfa yield response to groundwater after irrigation was terminated. They found that shallow groundwater was not a substitute water source for alfalfa and water-table depth did not have a significant influence on yield even though the water-table was only around 1.5 meters deep. Another study concluded that favorable aspects for growth included a stable and shallow water table, periodic rainfall, and acceptable groundwater quality (Guitjens, 1990).

4 Deficit Irrigation of Other Forage Crops

Even though alfalfa is the most widely grown crop in the Colorado River Basin, other forages and irrigated pastures make up a significant area in the region. According to the 2012 Census of Agriculture, irrigated pasture makes up 14.5 percent of all irrigated land in the eleven western states (Table 7). Cow-calf and beef industries are highly dependent on this pasture (S. Orloff, Putnam, et al., 2014). In the high elevation areas of Colorado and Wyoming, pasture is the dominant water and land use, given the very short growing season that significantly limits what can be grown.

Table 3: Irrigated pasture acreage in western states and U.S. Source: Orloff et al. (2014).

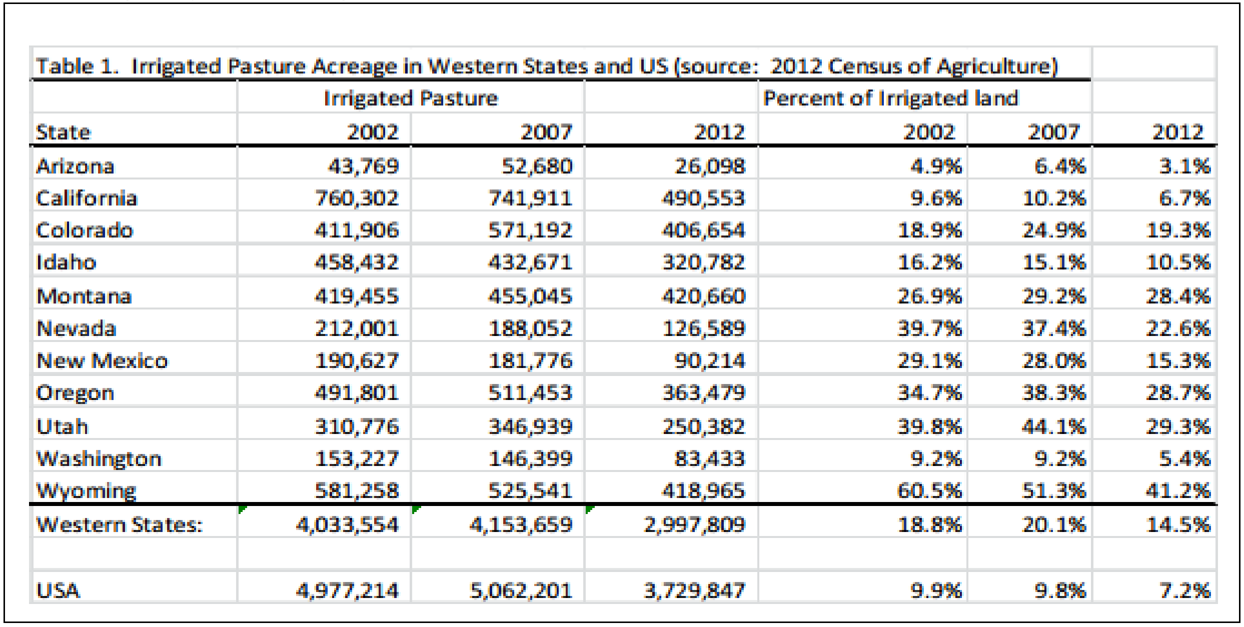

Table 1. Irrigated Pasture Acreage in Western States and US (source: 2012 Census of Agriculture)

	Irrigated Pasture			Percent of Irrigated land		
State	2002	2007	2012	2002	2007	2012
Arizona	43,769	52,680	26,098	4.9%	6.4%	3.1%
California	760,302	741,911	490,553	9.6%	10.2%	6.7%
Colorado	411,906	571,192	406,654	18.9%	24.9%	19.3%
Idaho	458,432	432,671	320,782	16.2%	15.1%	10.5%
Montana	419,455	455,045	420,660	26.9%	29.2%	28.4%
Nevada	212,001	188,052	126,589	39.7%	37.4%	22.6%
New Mexico	190,627	181,776	90,214	29.1%	28.0%	15.3%
Oregon	491,801	511,453	363,479	34.7%	38.3%	28.7%
Utah	310,776	346,939	250,382	39.8%	44.1%	29.3%
Washington	153,227	146,399	83,433	9.2%	9.2%	5.4%
Wyoming	581,258	525,541	418,965	60.5%	51.3%	41.2%
Western States:	4,033,554	4,153,659	2,997,809	18.8%	20.1%	14.5%
USA	4,977,214	5,062,201	3,729,847	9.9%	9.8%	7.2%

Perennial pasture grasses are not as drought tolerant as alfalfa, and do not compare in terms of nutritional quality. Studies have involved tall fescue, orchardgrass, brome, wheatgrass, and festulolium. Under deficit irrigation, there are severe declines in yield and sometimes there was no forage to harvest for many varieties. Alternatively, drought tolerant species like brome and wheatgrass cannot tolerate full-season irrigation (S. Orloff, Putnam, et al., 2014). The shallow root systems of grasses provide fewer reserves to withstand drought. There is a lack of literature on this topic.

5 Deficit Irrigation Case Studies

5.1 Colorado Water Trust

Since 2001, the Colorado Water Trust (CWT) has been working to restore rivers by acquiring water rights for instream flows and facilitating creative water transfers between water right users and the Colorado Water Conservation Board's (CWCB) instream flow program. CWT uses water right sales, water right donations, long-term leases, short-term leases, conservation easements, and structural and alternative solutions to increase stream flows (CWT, 2015).

Two recent pieces of Colorado legislation have given CWT and agricultural water right holders much more flexibility towards temporarily transferring water from agricultural users to meet environmental needs. A 2003 state statue allowed agricultural water users to loan water to the CWCB for instream flow purposes. These lease agreements allow transfers to occur three out of ten years and often only require the approval of the State Engineer's Office. Participants do not usually have to go through the water court process to complete such an agreement (Colo. State Stat. § 37-83-105). The statute was modified in 2008 to remove these loan periods from historical consumptive use analyses for a water transfer right case. In addition, the water rights are protected from abandonment. In 2013, Senate Bill 13-019 provided a "safe haven" for agricultural water right holders in the Colorado, Gunnison, and Yampa River Basins to temporarily transfer water without the lower consumptive use affecting their overall historical consumptive use of the water right, as long as they are participating in a state-sponsored program[8].

The CWT has brokered some agreements between water right holders and the CWCB, in which an irrigator fallows their land in the late season and transfers a certain amount of water for instream flow purposes. One agreement, which was the first in the state to invoke the 2013 law, allowed a rancher on Willow Creek to divert less water during times of low flows. The rancher was able to transfer water for five out of ten years without lowering the value of his water right (Holm, 2015; Postel & Reeve, 2015). In a project on Deep Creek, water was not diverted in August to increase stream flows. A rancher reduced his irrigated acreage in the summer, and the CWT paid him the value of the foregone hay and alfalfa. A similar lease agreement on the Tomichi Creek stipulates that the landowners can use early season water to irrigate hay meadows and pasture grass but in July or August diversions will cease and the foregone water will be used by the CWCB's instream flow program (CWT, 2015).

The CWT is in the process of establishing the first permanent water-sharing agreement for agricultural and environmental purposes in Colorado. A 5-mile section of the Cimarron River below the McKinley Ditch is often dried up in late summer. Under the proposed agreement, farmland on the ditch will be irrigated only in the first half of the irrigation season with no irrigation later in year (Buchanan, 2015; CWT, 2015). The ranch that irrigates the land is owned by a conservation organization, Western Rivers Conservancy. The CWT believes that this arrangement can serve as a model for private agricultural water users (Ross, 2015b). The CWT and CWCB have filed in Water Court for a change of use to add an

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[8] In Colorado, the value of a water right is determined by its actual historic consumptive use, not by the total diversion amount in the water right decree. The determination of historic consumptive use is part of the process of changing the water right in a sale.

instream flow right. Two nearby landowners have filed statements of opposition to make sure that their water rights are not impacted by the transfer (Gardner-Smith, 2015).

5.2 Colorado Compact Water Bank

Under the Colorado River Compact, if the Upper Basin states were to cause the flow at Lee Ferry, Arizona to fall below 75 MAF during any consecutive 10-year period, the Upper Basin states would have to curtail their diversions. Known as “compact curtailment”, these reductions would in theory fall on post-compact diverters, a class that includes most of Colorado’s Front Range cities. The Water Bank Work Group is currently examining the feasibility of a water bank in Colorado to mitigate the negative effects of a compact curtailment. The group is made up of representatives from the Colorado River Water Conservation District, Colorado Water Conservation Board, Front Range Water Council, Southwestern Water Conservation District, and The Nature Conservancy. The bank would compensate agricultural water users to conserve water through deficit irrigation or split-season fallowing. This “saved” water would come from pre-Compact (pre-1922 or possibly pre-1929) water rights than are not subject to curtailment and these diverters would then lease the saved water to users who rely on post-Compact water rights. (Moving Forward, 2015; MWH, 2012).

The study is broken up into three phases: (1) quantifying potential supply and demand, (2) analyzing the feasibility of deficit irrigation on current irrigation systems and how to measure reductions in consumptive use, and (3) examining regional economic and environmental effects. Deficit irrigation would be the best suited method to reduce consumptive use because much of the area in the study involves alfalfa and grass pasture (over 90 percent). After calculating the maximum potential consumptive use available from deficit irrigation and full fallowing, and applying a series of supply-use scenarios, the Water Bank could potentially provide up to 200,000 acre-feet of water per year. The bank could not provide water for all Colorado River depletion curtailments, but it would still be a significant amount. The Water Bank, however, would require a high level of participation among West Slope irrigators to provide such a large amount of water. To produce such savings, the amount of land put under deficit irrigation would be significant: 130,000 to 260,000 acres (MWH, 2012).

Phase 2 of the study examined how participating in the bank would affect irrigation system operations and included an outreach program toward the agricultural community. The study used eight test case irrigation systems that were representative of the systems in Western Colorado and consisted of irrigation organizations that were private, public, federal, tribal, small, large, high elevation, low elevation, and different crops.

One finding is that using deficit irrigation on land used to grow alfalfa and grass hay for cow-calf operations may be difficult. High-elevation grass pastures only have 1-2 cuttings per season and are generally used to feed cattle. There are concerns that reductions in forage yields may affect the size and quality of herds. Ranchers are reluctant to import hay as opposed to using their own. On lower elevation ranches and farms, alfalfa and grass is treated more as a commodity and has much more potential for deficit irrigation and split-season fallowing. The Water Bank would need to be able to quantify the unused consumptive use on farms and ranches on the West Slope, which could be challenging to do if there were broad participation. It is unlikely that any irrigation system has the measurement capabilities or historical data to compute consumptive use savings (MWH, 2014).

Another component of this phase looked at the agronomic effects of deficit irrigation on alfalfa and grass hayfields and found that deficit irrigation may slightly improve quality but will significantly reduce yields. Grass fields will have more difficultly recovering from limited irrigation, but alfalfa fields can recover depending on the length and severity of the deficit irrigation regime. The best scenario in the Upper Basin may be stopping irrigation after the second cutting of alfalfa fields for two consecutive years (Jones, 2015). Lower Basin plants will likely require additional cuttings and water application before ceasing irrigation.

5.3 Colorado River System Conservation Pilot Program

In 2014, the Central Arizona Project, Denver Water, the Metropolitan Water District of Southern California, Southern Nevada Water Authority, and the Bureau of Reclamation provided $11 million to fund water conservation projects in the Colorado River System. This approach attempts to address a possible future water shortage through a basin wide effort, where projects in the Upper Basin can help reduce the threat of Upper Basin Compact curtailment and projects in the Lower Basin can help alleviate the structural deficit in Lake Mead. The Bureau solicited proposals from agricultural, municipal, and industrial water users to create temporary and voluntary projects to reduce demand for water on the river and restore water levels in Lakes Mead and Powell. The Upper Colorado River Commission administers the program in the Upper Basin, while the Bureau administers program in the Lower Basin (USBR News Release, 2014).

For 2015, five projects were approved in Wyoming and five in Colorado. For the Lower Basin, there were two projects in Arizona and one in Nevada. Nine of the Upper Basin projects were agricultural. Full information on the projects is not yet available, especially Lower Basin projects, but some limited information on the Upper Basin projects has been provided by various participants.

In Colorado, two of the five projects involved split season irrigation. The Carpenter Ranch, operated by The Nature Conservancy, was the first to be awarded funding from the program. The ranch experimented with split season-fallowing and terminated irrigation in fields at the beginning of July to measure the impacts on the river and ranch (Ross, 2015a). A total of 197 acres of hay were involved in the project (Ross, 2016). A two-year project also began in the Lower Uncompahgre and Lower Gunnison Rivers, where alfalfa was only irrigated for half the season on four properties (Henrie, 2016). Also, included in these projects were two fallowing projects (corn) and a municipal transbasin project. For Colorado, a total of 829 AF was conserved at a cost of $379 per acre-foot (Henrie, 2016).

In Wyoming, five split season fallowing projects were implemented along the Green River and its tributaries. Participating irrigators agreed to fallow alfalfa and native grass in the late summer to increase flows in the Green River. In return, they were compensated roughly 200% of what they would have earned from the hay produced. This sum included an amount per acre for weed abatement and a premium for being willing to participate in the program (Toye, 2015). A total of 2,178 acres were fallowed, saving 1644 AF at a cost of $200 per acre-foot (Henrie, 2016).

5.4 Colorado State Engineer Rules on Alfalfa and Grass for Temporary Fallowing

Colorado’s HB13-1248, codified at CRS 37-60-115(8), allows for pilot fallowing-leasing projects within the state. The guidelines say that “All parcels containing alfalfa or pasture grass shall be subject to a reduction in the approved amount of transferrable consumptive use if the field is subirrigated”

(Colorado Water Conservation Board & Colorado Division of Water Resources, 2013). The State Engineer's calculations, shown below, significantly reduce the transferable consumptive use if groundwater for sub-irrigation is available. At one foot depth, the reduction for alfalfa is 100% and pasture grass is 85%, and at four feet the reduction is 50% for alfalfa and 20% for pasture grass.

Table 4: Colorado state engineer reduction for alfalfa and pasture grass consumptive use credits based on depth to groundwater. Source: Colorado State Engineer (2013).

	Percent Reduction in Consumptive Use Credit	
Depth to Groundwater (ft)	Pasture Grass	Alfalfa
1	85%	100%
2	50%	90%
3	30%	75%
4	20%	50%
5	15%	35%
6	10%	20%
7	5%	15%
8	0%	10%
9	0%	0%

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7 Appendix: Alfalfa Studies Investigated

	Type of Study	Location	Time Period	Soil	Cultivar	Method	Findings
Deficit Irrigation (Alfalfa)							
1	Split-Season (Orloff et al., 2014)	Intermountain California		Medium texture		DI after 1st and 2nd cutting	No observed difference on future yield or stand loss
2	Split-Season (Orloff et al., 2014)	Sacramento Valley, California		Medium texture		DI in early summer (July) and early summer with fall irrigation	
3	Split-Season (Orloff et al., 2014)	Palo Verde Valley, California		Sandy soil		No summer irrigation and a single irrigation in July	One field recovered and one field had significantly reduced future yields and stand loss
4	Split-Season (Hanson et al., 2007)	Davis, California	2003-2006	Clay loam		DI in July and August w/o fall irrigation, and deficit irrigation in July and August with fall irrigation	No significant difference in the future spring yields of DI and fully irrigated plots. DI Alfalfa had lower NDF and higher crude protein
5	Split-Season (Metochis & Orphanos, 1981)	Athalassa, Cyprus	1978-1980	Fine sandy loam	Local (composite of Provence)	DI for 1st growth period, 1st and 2nd, 1st and 3rd, and all 3	Only impact on future yields was when DI was withheld for all 3 growth periods.
6	Split-Season (Takele &	Palo Verde Valley, California	1997-1998	Silty clay loam	UC Cibola	Water withheld for 35, 70, and 105 days	DI longer than 35 days impacted future yields by at

	Kallenbach, 2001)						least 20% and increased stand loss
7	Split-Season (Orloff et al., 2003)	Malin, Oregon	2003	Fine sandy loam		DI after 1st and 2nd cutting	No observed difference on future yield or stand loss
8	Split-Season (Orloff et al., 2003)	Tulelake, California	2003	Silt loam with a high organic matter content		DI after 1st and 2nd cutting	No observed difference on future yield or stand loss
9	Split-Season (Orloff et al., 2003)	Sacramento Valley, California	2003	Clay loam		DI midsummer and DI midsummer with fall irrigation	No observed difference on future yield or stand loss
10	Split-Season (Orloff et al., 2014)	Yuma, Arizona	1990-1992	Supersition sand	CUF 101	DI from July - Oct, and Nov - Feb	Significant stand loss and severe reduction in yields
11	Split-Season (Ottman et al., 1996)	Maricopa, Arizona	1990-1992	Sandy loam	CUF 101	DI from Aug - Mar and Aug - Sept	Yields recovered in the first regrowth. Stand loss similar to normal irrigation
12	Split-Season (Guitjens, 1993)	Fallon, Nevada	1981-1984	loamy sand to a loamy fine sand	Pacer	Irrigation for only 2, 3, and 4 harvests	All yields recovered when normal irrigation resumed
13	Split-Season (Lindenmayer et al., 2008)	Berthoud, Colorado	2006-2007	Clay loam	Dairyland Magna Graze	DI after 1st and 2nd cutting, and DI during summer	

14	Split-Season (Wissuwa & Smith, 1997)	Tucson, Arizona	1994-1995	Clay loam	Arizona 91 Arabian Composite	DI for 84 days, and DI for 42 days year one and 75 days year two	High plant mortality for 84 days, but normal decline (1.5%) for second treatment. Higher yields after 42 days than control. Crown mortality related to concentration of total nonstructural carbohydrates
15	Split-Season (Schonhorst et al., 1963)	Southern Arizona	1959-1962		Moapa	DI from July - Aug	Not a significant different in yield or stand loss
16	Split-Season (Jones, 2015)	Western Colorado (Fruita, Eckert, Yellow Jacket)	2013-2014	Loam, clay loam, and silty clay		DI after 1st and 2nd cutting	Lower yields in first cutting next spring
17	Regulated Deficit Irrigation (RDI) (Carter & Sheaffer, 1983)	Becker, Minnesota	1980-1981	Loamy sand	Iroquois	Treatments were a percent (0, 33,66, and 100) of keeping soil water levels at optimal capacity	66% irrigation had similar yields to 100%
18	RDI (Bauder et al., 1978)	Southeastern North Dakota	1973-1976	Sandy loam (moderately coarse)	Vernal	No irrigation, and deficient, optimum and excessive of required ET	Harvest of deficient treatment was slightly lower than optimum and excessive treatments

19	RDI (Davis et al., 1963)	Davis, California	1962	Silty clay	Lahontan	A percent (25, 50, 75, 100, 150, and 200) of depth of irrigation to achieve optimum soil moisture, and an additional 75 and 100 % with no winter irrigation	Treatments over 100% did not produce significant gains. A slight decrease in yield with 75%. Treatments without winter irrigation did not have significant decreases in yield. First 2 cuttings, not influenced by irrigation. Protein and carotene were lower as applied water increased
20	RDI (Jensen et al., 1988)	Wadsworth, Nevada	1984-1985	Sandy loam	Lahontan and L-720	A percent (50, 75, 100, and 125) of FAO Pan Evaporation	Decrease in yields for 125% treatment
21	RDI (Donovan & Meek, 1983)	Imperial Irrigation District, California	1975-1978	Clayey loam	Mesa Sirsa and Salton	A percent (56, 66, 75, 84) of pan evaporation and 56 and 75% with a winter leaching treatment	The 84% treatment had extensive stand loss and lower yields. 75% had the highest yields. The 75% with winter leaching had lower yields but the 56% with leaching had higher yields than the standard 56%
22	RDI & Split-Season (Frate & Roberts, 1991)	Fresno County, California	1986-1988	Sandy loam	CUF 101	Irrigation 2 times per cutting and 3 during summer (wet), 2 times per cutting (standard), 1 time per cutting (dry), DI in July and August, and July termination	No treatments had a negative impact on future yields. Standard irrigation produced higher yields than wet

23	RDI & Split-Season (Robinson & Teuber 1992)	Imperial Valley, California	1991-1992	Clay over sandy texture	CUF 101	Limited water in Aug, DI in Aug -July, and DI Aug - Sep	
24	RDI & Split-Season (Bauder et al. 2014)	Fort Collins, Colorado	2007-2009	Clay loam		RDI was once a week and only 1.5 inches of water and DI termination after 1st cutting	No significant stand loss for both treatments. DI after 1st cutting caused a 15% decline in next spring harvest
Yield and ET (Alfalfa)							
25	ET (Wright, 1988)	Southern Idaho	1969-1975	Sily loam	Ranger		ET was highly variable on a daily basis and seasonal ET was about 50% greater than previously reported for the area. ET was highest in July and Aug
26	Yield (Sammis, 1981)	Las Cruces, New Mexico	1978-1979	Fine sand to clay loam	Mesilla, Moapa, and Hairy Peruvian, and Acala cotton 1517-V		Yield is linear of ET for alfalfa and cotton. Similar water-production function throughout NM
27	Yield related to ET, growth stage, and environment (Smeal et al., 1991)	Farmington, New Mexico	1981-1987	Sandy loam	WL 309	Uniform irrigation	Seasonal yield is a function of ET and year. Yield is maximized during the fifth year and minimized during the first. Yield/ET increases with more solar radiation.

28	Yield and cultivars (Undersander, 1986)	Bushland, Texas	1983-1985	Clay loam	Vanguard, Cody, Zia, and Dawson		No significant difference between 4 cultivars. CU increased with yield.
29	Yield and cultivars (Grimes et al., 1992)	San Joaquin Valley, California	1985-1986	Sandy loam	WL 318, CUF 101, and Moapa 69	Variable irrigation was applied across the cultivars	WL 318 had a greater yield in the spring, but lower in the summer. Total seasonal yields were not different
30	Yield and ET of alfalfa and corn (Retta & Hanks. 1980)	Logan, Utah			Alfalfa: Ladak, Washoe, and Masilla, and 5 corn varieties	Cultivars were treated with variable irrigation levels to see response in yield	Linear relationship between yield and ET for both crops. More variation in yield between different years than between the different varieties in a given year
31	Yield and ET (Fransen & Kugler, 2003)	Central Washington	two years	Silt loam	Vernal		A greater growth rate and shorter growth period with increased temperatures contribute to reduced yield
32	Seed yield and ET (Cohen et al., 1972)	Coastal Plain Israel		Clay loam	Hairy Peruvian	Irrigation timing at day 10 or 23 or both	Irrigation shortly after cutting helped regrowth and likely increased seed yield potential
33	Consumptive Use (Daigger et al., 1970)	Western Nebraska	1966-1968	Sandy loam			WUE was higher in early season than summer. CU increased with each harvest while yields declined

34	ET and WUE during dormancy and nondormancy (Guitjens & Goodrich, 1994)	Nevada	1973-1978				Yield declined throughout the season. WUE was lowest in the summer. Some water is "lost" during dormancy because excess water than soil profile can hold
Other Alfalfa Studies							
35	Forage quality (Mueller, 1992)						Quality declines as summer progresses and recovers in the fall
36	DI and ground water (Auckly and Guitjens, 1995)	Western Nevada	1981-1983	Loamy sand		Irrigation for first two harvest, first three harvest, and all four harvests	Shallow groundwater was not a substitute water source. Water-table depth did not have a significant influence on yield
37	Weed encroachment (Bell, 1992)		1987 and 1989				Grasses had little direct impact on alfalfa by competition. Herbicide does not increase alfalfa yield. Best to maintain a dense alfalfa crop stand because weeds are moving into vacant areas
38	Subsurface drip irrigation (SDI) (Hutmacher et al., 2001)	Imperial Valley, California	Five years	silty clay			Increased yields, uneven irrigation, and some surface ponding

39	Cost vs. efficiency of alfalfa irrigation systems (Sanden et al., 2011)					Examined flood, sprinkler, pivot, and SDI	Pivot and SDI significantly increase yield and efficiency, but the costs are too high. Requires much more maintenance. Improving distribution uniformity does increase yields
40	WUE and alfalfa genetics (Ray et al., 1999)	Las Cruces, New Mexico	1995-1996	Clay loam	30 varieties	Examined agronomic and physiological traits with WUE under water-limited conditions	Higher yields correlated with higher C isotope discrimination, lower canopy temperatures, low ash concentration, taller shoots, early maturity, and reduced leaf-to-stem ratio
41	Dormancy types and water stress (Hattendorf et al., 1990)	Prosser, Washington	One year	Loam (coarse-silty mixed)	Vernal (dormant), Vernema (intermediate dormancy), and CUF 101 (nondormant)	Water was applied at different values of the Crop Water Stress Index	CU and yields were not significantly different among cultivars. CUF 101 at full canopy cover can help develop more WUE alfalfa
42	Stage growth on yield (Robinson & Massengale. 1968)	Tucson, Arizona	1963-1964	Sandy loam	Moapa	Examined differences between stubble height and if stems had buds or flowers at harvest for impact on yield	Yield and stand declined when harvested at 50% bud state than 25% bloom stage. Greatest decline in yields during highest night temperatures

43	Reduced-runoff surface irrigation method (Bali et al., 2001)	Imperial Valley, California	Three years	Alluvial clay	CUF 101	Tailwater runoff reduced to <2% through a water balance model, reducing water application by 28%	No loss in hay yield. Increased soil salinity. Less stand loss
44	DI and yield/cost functions (English & Raja, 1996)	Northwestern USA, California, and Zimbabwe			Wheat in northwestern USA, cotton in CA, and maize in Zimbabwe	Examined yield and cost functions that would produce the max net income in each situation	In land-limiting situations, optimal DI is 15-16%. In water-limiting cases, optimal DI were 44 and 68% because value of water outweighs value of agricultural production
45	Leaching requirements (Bernstein & Francois, 1973)		1967-1968	Sandy loam	Sonora	Grown in greenhouse lysimeters. Water was applied with different amounts of NaCl and $CaCl_2$	Yield response is more related to salinity of irrigation water than the salinity of the drainage water
Adaptive Studies (Alfalfa)							
46	Irrigation (Rice et al., 1989)	South Carolina (Piedmont and Coastal Plain)		Sandy loam and loamy sand	Vanguard and cultivars with greatest adaptive potential to region	Normal irrigation	Significant stand loss. Irrigated alfalfa is a marginal practice in the area
47	Irrigation (Lathwell & Vittum, 1962)	Geneva, New York	Eight years	Silty loam	Grimm and DuPits	Normal irrigation	Must use irrigation to achieve maximum yields in the region

Other Crops							
48	Split-Season DI on pasture grasses (Orloff et al., 2014)	Tulelake, California		Organic clay loam	26 perennial grasses	DI after 1st and 2nd cutting	For most crops, dramatic losses of future yields and stand loss. Tall fescue performed the best
49	Split-Season DI on pasture grasses (Jones, 2015)	Multiple sites in western Colorado	2013-2014	Loam and sandy loam	Cool-season grasses and legumes	No irrigation	Grasses did not fully recover, second year produced 49% of control
50	Moisture use of forage crops (Cohen & Strickling, 1968)	Upper Marlboro, Maryland	1959	Sandy loam	Alfalfa, tall fescue, and bermudagrass	Examined CU and yield	Alfalfa and tall fescue require similar amounts of water for the same yield. Crops did not extract much water from deeper in the soil profile