THESIS

AGRONOMIC RESPONSES OF GRASS AND ALFAFA HAYFIELDS TO NO AND PARITAL SEASON IRRIGATION AS PART OF A WESTERN SLOPE WATER BANK

Submitted by

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ABSTRACT

AGRONOMIC RESPONSES OF GRASS AND ALFAFA HAYFIELDS TO NO AND PARITAL SEASON IRRIGATION AS PART OF A WESTERN SLOPE WATER BANK

Prolonged drought and increasing demand for water resources has caused growing concern over Colorado's ability to fulfill legal water obligations as identified in the Colorado River Compact. A Western Slope Water Bank, which would entail agricultural water users entering into short-term leases and temporarily withholding or reducing irrigation, could be a partial solution to free up water to fulfill these obligations. Grass and alfalfa (*Medicago sativa* L.) hayfields may be ideal for inclusion in a water bank as they are the primary users of agricultural water in this region and may have a greater ability to withstand water stress in comparison to other crops. This study was conducted to determine effects of withholding irrigation for a full season from high elevation grass hayfields and implementing partial season irrigation on lower elevation alfalfa hayfields on forage yield, nutritional quality, and associated recovery period to confirm if this approach is worth pursuing. In Year 1, five established grass hayfields on the Colorado Western Slope were split into side-by-side plots, one of which was irrigated according to the manager's normal practices as the control while the other was subjected to total cessation of irrigation. Both plots were irrigated in Year 2. In Year 1, average dry matter yields in non-irrigated plots were reduced to 39% (2497 kg ha^{-1}) of the control (6377 kg ha^{-1}). Neutral detergent fiber (aNDF) concentration in non-irrigated plots was 5% lower while crude protein (CP) content was 30% greater than the control. In-vitro true digestibility (IVTD) was unaffected by irrigation treatment. Yields of non-irrigated plots did not fully recover when returned to irrigation in Year 2 producing 49% (3623 kg ha^{-1}) of the control (7442 kg ha^{-1}). When returned to irrigation, aNDF concentrations were still reduced by 8% and CP contents were similar to that of the control. In the single site sampled after returning to full irrigation for 2 years, yields had fully recovered. It is probable that participation by producers in a water bank would be largely influenced by compensation for reduced yields the season of withholding irrigation as well as the following year when irrigation is returned to grass hayfields.

Three established alfalfa fields were subjected to irrigation treatments including irrigation according to the manager's normal practices (control), irrigation stopped after the 1st cutting (SA1), and irrigation stopped after the 2nd cutting (SA2) for 2 consecutive years. Averaged over both years, SA2 plots maintained production similar to the control in the 1st and 2nd cutting while SA1 plots were reduced to 61% (2089 kg ha^{-1}) of the control (3430 kg ha^{-1}) by the 2nd cutting. By the 3rd cutting, SA2 and SA1 yields decreased to 53% (1804 kg ha^{-1}) and 30% (1013 kg ha^{-1}) of the control, respectively. On a total season basis, both plots receiving partial season irrigation were reduced with SA2 plots producing 72% (7880 kg ha^{-1}) and SA1 plots producing 33% (3650 kg ha^{-1}) of the control (11040 kg ha^{-1}). aNDF concentrations were greatest in the control at 34.6% and lowest in SA1 plots at 28.2%. By the 2nd cutting, SA1 plots had the highest IVTD (80%), and by the 3rd cutting, SA2 and SA1 plots were equally greater (80%) than the control (75%). Effects on CP content were inconsistent. These results suggest that reduced irrigation may improve forage quality slightly, but will significantly reduce yields. When irrigation is returned the following year, forages may have increased quality due to reduced fiber content, but grass yields will likely not fully recover while alfalfa yields may recover depending on length and severity of reduced irrigation. Due to its ability to recover, using partial season irrigation similar to that of the SA2 treatment on alfalfa hayfields may be the most practical approach to make water available to a Western Slope water bank.

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CHAPTER ONE

FORAGE YIELD AND QUALITY OF GRASS HAYFIELDS IN WESTERN COLORDO UNDER FULL AND NO IRRIGATION

Introduction 1.1

Insufficient water resources along with increasing demand due to a growing population are of global concern. Irrigated agriculture is the main use of diverted water worldwide and the Colorado River Basin is no exception (Fereres and Soriano, 2007). Distribution and apportionment of these waters are regulated by numerous laws, compacts, and agreements. The Colorado River Compact of 1922 was established between the federal government, 7 basin states, and Mexico to regulate use and management and ensure equitable division of water resources from the Colorado River. In accordance to the compact, over any 10 year period, an average of 9.25 billion cubic meters of water must annually flow past Lee's Ferry which separates the 4 upper basin states, Colorado, New Mexico, Utah, and Wyoming, from the 3 lower basin states, Arizona, California, and Nevada. If the flow falls below the specified amount for a consecutive 10 year period, curtailment of water use in the upper basin is possible (Norviel et al., 1922). Meeting this obligation has not been an issue in the past, but increasing demand along with prolonged drought has increased the probability of future compact curtailments. Rapid population growth in the region is increasing demand for municipal, industrial, and agricultural water. If compact obligations are not met, Colorado and other upper basin states may be forced to reduce or restrict water from certain uses which have not yet been determined (MWH, 2012).

Development of a water banking system to legally reallocate water and continue to meet compact obligations was originally suggested by a group of farmers from Colorado's Western

Slope. The system would be voluntary with participants temporarily implementing regimes of not irrigating fields for an entire season or of using partial season irrigation practices to free up water for other uses. This would be done on a rotational basis to minimize economic and environmental impacts. Participants, required to have pre-compact water rights on the Western Slope, would enter into short-term leases and be compensated for economic losses in crop production. Conserved water, based on curtailment of consumptive use, would be available to the water bank to meet compact obligations or to lease for municipal and industrial uses. Diverted water could also be applied to crops such as orchards and vegetables which would incur significant damage from reduced irrigation (Watson and Scarborough, 2010). Implementing this system would ideally avoid or reduce curtailment possibilities and create additional profit opportunities for agricultural producers with pre-compact water rights. According to Watson and Scarborough (2010), this system treats water as a crop and, in turn, makes water conservation profitable. Adequate participation by agricultural producers would be critical for success of a Western Slope water bank.

Forage crops are ideal for inclusion in water banking projects for multiple reasons. Foremost, these crops are primary users of irrigation water on the Western Slope. In 2012, a reported 252,240 hectares were in grass hay production in the region in comparison to 30,490 hectares in corn, beans, and other crops (MWH, 2012). Forages are also known to be more tolerant to reduced irrigation and water stress and commonly experience significantly fewer long-term effects on future production (MWH, 2012). Grass hayfields on the Western Slope are commonly managed with “wild” flood irrigation systems and are dominated by cool-season grasses with some cool-season legumes. The short growing season generally allows for one harvest annually (Pearson et al. 2011). Due to their prevalence on the landscape and tolerance to reduced irrigation, grass hayfields could be ideal for use in a Western Slope water bank.

While several studies have been conducted comparing tolerance to water stress of various forage species and varieties, limited information is available related to response and recovery of grass hayfields in regions similar to the Western Slope. In a study conducted in northern Utah, Hill et al. (2000) found that increasing water availability resulted in increased forage production of perennial grasses. Similar findings were reported by Smeal et al. (2005) in the dry environment of northern New Mexico where results indicated that there was no significant forage production when less than 350 mm of irrigation water was applied evenly throughout the season. Sheaffer et al. (1992) reported that with drought conditions simulated by maintaining soil moisture at 25 to 50% of field capacity for a full growing season, yield reductions ranged from 24 to 37% of fully irrigated controls. In comparison, the treatment simulating periods of drought followed by well-watered conditions had yield reductions varying from 54 to 81% of control plots when water was returned. Researchers suggested that some species may demonstrate compensatory growth when irrigation is reinitiated.

There have been inconsistent results on the effects of water stress on forage quality. Sheaffer et al. (1992) reported an increase in crude protein (CP) content and reduction in neutral detergent fiber (NDF) and acid detergent fiber (ADF) in perennial grass species experiencing water stress. Researchers concluded that higher forage quality in water stressed plants was due to delayed maturation, increased leafiness, and stem and leaf quality (Sheaffer et al. 1992). In a study comparing various mixtures of perennial grasses and legumes, CP concentrations decreased or were unaffected when plants were under water stress while NDF concentrations were inconsistent between mixtures (Skinner et al., 2004). It was suggested that this was likely due to differences between species rather than effects of water stress (Skinner et al., 2004).

To determine if a Western Slope water bank is worth pursuing, more information is needed on agronomic responses and associated recovery time of high elevation grass hayfields following removal of irrigation for a full season. In a region highly diverse in climate, land characteristics, and management practices, all factors which significantly influence how crops will respond to water stress, it is necessary to determine outcomes in multiple locations throughout the area. This study was designed to determine the impacts of no irrigation for one growing season on forage yield, quality, and recovery period of grass hay crops in different regions of Western Colorado, thereby confirming if this approach is worth pursuing or not.

1.2 Materials and Methods

This study was conducted at sites on the Western Slope of Colorado that encompassed diverse areas throughout the region. Five grass sites were used to compare side by side plots treated with no irrigation and full season irrigation. Each location was unique in climate, land and crop characteristics, and management practices.

1.2.1 Study Site Locations

In 2013, grass hayfield sites included 4 locations (Table 1.1, 1.2, and 1.3). In 2014, a site near Cimarron, Colorado was added. In addition, a hayfield near Razor Creek, west of Gunnison, which had been sampled during the drought in 2012, was resampled in 2014 to determine crop recovery after a two year period. Research plots were irrigated according to the manager’s regular practices and water availability. Cool-season grasses along with some legumes dominate the meadows. In 2013, side by side plots were treated with full irrigation or no irrigation. Both plots were irrigated as normal in 2014. Some alterations, which are described in the following section, were made at specific sites.

Table 1.1. Characteristics of grass sites used to evaluate the impact of no irrigation on forage yield, quality, and recovery on the Western Slope of Colorado.

Location	County	Elevation (m)	Annual Precipitation (mm)	Growing season length (days)*	Irrigated area (ha)	Non-irrigated area (ha)
Cimarron	Montrose	2,102	338	101	6.07	0.40
Gunnison	Gunnison	2,348	265	90	1.21	0.81
Hayden	Routt	1,932	432	123	2.39	2.39
Kremmling	Grand	2,245	300	107	1.62	1.01
Razor Creek	Saguache	2,316	265	90	19.93	19.93
Steamboat Lake	Routt	2,499	605	60	3.24	2.39

*Growing season was estimated using length of freeze-free (-2.2˚C) season probabilities as estimated by the *Western Regional Climate Center* (http://www.wrcc.dri.edu).

Table 1.2. Precipitation measurements from spring to harvest and following harvest from grass sites used to evaluate the impact of no irrigation on forage yield, nutritional quality, and recovery on the Western Slope of Colorado.

	2013		2014	
Location	**Dates**	**Precipitation (mm)**	**Dates**	**Precipitation (mm)**
Cimarron*	N/A	N/A	6/4-8/6	8.25
	N/A	N/A	8/6-10/11	116.2
	Total	**N/A**		**124.45**
Gunnison	4/26-7/29	73.4	4/24-7/17	55.6
	7/29-9/21	78.5	7/17-10/11	162.1
	Total	**151.9**		**217.7**
Hayden	5/2-7/2	39.9	5/1-7/3	59.4
	7/2-9/22	47.0	7/3-8/26	108.2
	Total	**86.9**		**167.6**
Kremmling	5/7-8/29	97.8	5/1-8/29	81.0
	8/29-9/22	73.4	N/A	N/A
	Total	**171.2**		**81.0**
Steamboat Lake	5/22-8/16	55.9	6/1-8/26	100.6
	8/16-9/8	25.9	N/A	N/A
	Total	**81.8**		**100.6**

*Precipitation measurements were not collected at the Cimarron site in 2013.

Table 1.3. Reference evapotranspiration (ET) measurements from spring to harvest and following harvest from grass sites used to evaluate the impact of no irrigation on forage yield, nutritional quality, and recovery on the Western Slope of Colorado.

	2013		**2014**	
Location*	**Dates**	**ET (mm)**	**Dates**	**ET (mm)**
Gunnison	4/26-7/29	321.3	5/29-7/17	238.8
	7/29-9/21	190.5	7/17-9/2	221.0
	Total	**511.8**		**459.8**
Hayden	5/22-7/2	457.2	5/1-7/3	248.9
	7/2-9/22	193.0	7/3-8/21	248.9
	Total	650.2		497.8
Kremmling	5/29-8/29	414.8	6/2-8/29	81.0
	8/29-9/22	62.2	N/A	N/A
	Total	**477.0**		**81.0**
Steamboat Lake	5/22-8/16	343.7	6/1-8/26	229.9
	8/16-9/8	76.2	N/A	N/A
	Total	**419.9**		**229.9**

*ET measurements were not collected from the Cimarron site in 2013 or 2014.

1.2.2 Study Site Descriptions

Cimarron, CO:

This site in Montrose County was added in 2014. The test plots are located approximately 9.5 km southeast of Cimarron, CO, near the Little Cimarron River in the Gunnison River Basin. Test plots were not adjacent to each other but were approximately 1.6 km from one another on adjoining ranches. The control (38°22'36.55"N, 107°29'22.55"W) was approximately 2.0 km south of the plot where irrigation was withheld in year 1 (38°23'23.39"N, 107°30'5.38"W). No soil data is available. Sedges (*Carex* spp. L.) and rushes (*Juncus* spp. L.) are common in the both fields in addition to timothy (*Phleum pratense* L.), Kentucky bluegrass (*Poa pratensis* L.), smooth brome, (*Bromus inermis* L.), and red (*Trifolium pratense* L.) and alsike clover (*Trifolium hybridum* L.). The non-irrigated plot is used for haying and grazing while the control field is primarily used for hay production. The irrigated control is flood irrigated from late-May to late-June. After the field is harvested, irrigation is returned and runs through early-October.

Gunnison, CO:

This hayfield site in the Upper Gunnison River Basin was located 11.3 km northeast of the town of Gunnison on the Trampe Ranch (38°37'50.32"N, 106°52'25.20"W). The plots are on Fola cobbly sandy loam soil (loamy-skeletal, mixed Borollic Camborthid) with 1 to 8% slopes. Meadow foxtail (*Alopecurus pratensis* L.) dominates the field with scattered alfalfa (*Medicago sativa* L.) plants mixed throughout. Red clover, smooth brome, orchardgrass (*Dactylis glomerata* L.), and Kentucky bluegrass are also present. Cattle are grazed on the field in the fall if regrowth is adequate. Treatments were unique at this location. During 2013, the west plot was not irrigated and the east plot was treated with normal irrigation. However, the non-irrigated plot was accidentally irrigated twice. As a result, treatments were switched in 2014 and the west plot went back to full irrigation while the east was not irrigated. Therefore, data from 2013 was not included in statistical analyses and data from 2014 was used as year 1.

Hayden, CO:

This site was located on the Carpenter Ranch which is owned and operated by The Nature Conservancy (40°29'35.3"N, 107°10'48.2"W) and is 7.1 km east of Hayden, CO. The ranch, which is in the Upper Yampa River Basin, is dominated by Zoltay loam soil (fine, smectitic, frigid Pachic Argiustoll) with 0 to 5% slopes. Stands are comprised of a wide variety of forages including smooth brome, Kentucky bluegrass, orchardgrass, alfalfa, and red and alsike clover. Unlike the other grass sites, 2 harvests are taken at this location each year. Water is typically applied by border flood irrigation with in 12 hour sets, twice per season, the first in early-May and the second in early-June.

Kremmling, CO:

This site was located on the Blue Valley Ranch (39°58'19.35"N; 106°21'59.55"W) approximately 7.4 km south of Kremmling, CO in the Upper Colorado River Basin. The plots are dominated by Leavitt loam soil (fine-loamy, mixed Argic Cryoboroll) with 0 to 6% slopes. Cool-season grasses such as smooth brome, Kentucky bluegrass, quackgrass (*Elymus repens* L.), and meadow foxtail are common. Ammonium nitrate fertilizer (34-0-0) is annually applied at 44.8 kilograms per hectare. The plots are periodically used for grazing livestock in the fall and winter. Plots are typically irrigated from early May through mid-July. Water is usually on the plots for 4 to 5 days with periods of 1 to 2 days between applications.

Razor Creek, CO:

The site near Razor Creek (38°26'2.04"N, 106°39'0.39"W) is located 8 km southwest of Doyleville, CO in the Upper Gunnison River Basin. In 2012, this hayfield was in poor condition resulting from severe drought conditions. With reduced water availability, only about half of the field received irrigation. Samples were collected and analyzed from the irrigated and non-irrigated sections. Full irrigation was applied to the entire field the following 2 years and samples were collected and analyzed again in 2014 to determine longer-term recovery of grass hayfields. Soils are Bosler sandy loam (fine-loamy over sandy or sandy-skeletal, mixed Borolic Haplargid) and Irim loam (loamy-skeletal, mixed, frigid Typic Haplaquoll) with 1 to 8% slopes. The field contains a variety of grasses, legumes, and forbs including meadow foxtail, timothy, tufted hairgrass (*Deschampsia cespitosa* L.), alsike clover, sedges, rushes, dandelion (*Taraxacum officinale* F.H. Wigg.), and herbaceous cinquefoil (*Potentilla pulcherrima* L.).

Steamboat Lake State Park, CO:

Also in the Upper Yampa River Basin, this mountain meadow hayfield (40°47'36.64"N, 106°58'53.60"W) is 19.0 km northwest of Clark, CO. The field is bordered by Steamboat Lake on 3 sides and is at a higher elevation and has a shorter growing season than the Hayden site. Soils are composed mainly of Rabbitears loam (fine-loamy, mixed, superactive Pachic Argicryoll) with some Menbar-like loam (fine-loamy over sandy or sandy-skeletal, mixed, superactive Aquic Cumulic Haplocryoll) with up to 12% slopes. Smooth brome, Kentucky bluegrass, clovers, and sedges dominate the plots. Cattle usually graze the field in spring and fall. The plots are flood irrigated from the first week of June to the first week of July each year.

1.2.3 Treatments and measurements:

In year 1, side by side plots were either not irrigated for the entire season or normally irrigated (control). Both plots were fully irrigated in year 2 to determine carryover effects and recovery of grass hayfields.

In mid to late-April of each year, wooden fence posts were inserted near the border of irrigated plots to secure Stratus™ rain gauges (Productive Alternatives®, Fergus Falls, MN) and ETgage (evapotranspiration (ET) gage) Model A™ atmometers (ETgage Company®, Loveland, CO). A minimum of 1 mm of baby oil was added to each rain gauge to avoid water loss to evaporation. Atmometers, which estimated reference ET, were set with the top of the instrument 1 m above ground and filled with distilled water (Bauder, 1999). Green canvases specific for grass crops were fixed to the top to simulate the canopy. Atmometer and rain gauge readings were taken periodically throughout the growing season. South facing temperature loggers (Hobo Pro Series, Model H8, Onset Computer Corp., Bourne, MA) with radiation shields were set up on T-posts at each location. Loggers were programmed to record ambient temperature at 10 minute intervals. Fifteen soil samples were taken to 15 cm from each plot and separated into 7.5 cm depth increments. Samples were analyzed at the Colorado State University (CSU) Soil-Water-Plant Testing Laboratory for chemical properties and extractable nutrients using the routine analysis (pH, electrical conductivity, organic matter, nitrate-nitrogen, phosphorus, potassium, and particle size analysis). In each plot, plant species composition and cover data was collected by taking 100 random samples using a modified step-point method (Owensby, 1973). The subsequent spring, samples were taken and instruments set up using the same methods.

Prior to each hay harvest by the producer, 10 samples were collected in each treatment area for yield using a 0.25 m^2 frame. Samples were hand clipped at 7.5 cm to simulate approximate cutter-bar height. Plant material was dried in a forced-air oven at 55°C for a minimum of 72 hours. After plant samples reached a constant dry weight, they were weighed, and yields were converted to kilograms per hectare. Following weighing, individual samples were ground through a Thomas Model 4 Wiley® Mill (Philadelphia, PA) with a 2 mm screen followed by a Foss™ Tecator Cyclotec Sample Mill Model 1093 (Eden Prairie, MN) with a 2 mm screen to homogenize the sample.

Ground samples were used to determine dry matter (DM) and quality factors, including neutral detergent fiber (aNDF), *in-vitro* true digestibility (IVTD), and CP concentration, for each treatment. To determine DM, 1 gram of sample was weighed into an aluminum dish, dried for a minimum of 24 hours at 102˚C, and reweighed. Each of the 10 samples from all treatments was used to determine aNDF, which differs from NDF as it involves alpha amylase in the rinsing procedure. One duplicate, blank, and standard (mixed cool-season grass hay) bag were included in each set of 24 samples that were run through an Ankom® 200 fiber analyzer (Method 6)

(ANKOM Technology, Macedon, NY). To determine IVTD, 4 samples were randomly selected from each set, and duplicates of these samples were tested. Rumen fluid was collected from 2 rumen fistulated steers that were being fed a mixed forage and corn diet. Samples were incubated in a Daisy II Incubator (Method 3) (ANKOM Technology, Macedon, NY) for 48 hours and then run through an Ankom® 200 fiber analyzer using the same procedure as above for aNDF. Crude protein content was measured using a LECO TruSpec® CN268 Elemental Combustion Analyzer (LECO Corp., St. Joseph, MI) to determine N content. All 10 samples from every treatment were analyzed. Crude protein was estimated by multiplying percent N by a factor of 6.25. If there were insufficient amounts of sample available for measurement, the initial 10 were combined to no less than 4 samples.

Statistical analysis

Statistical analyses were conducted using the MIXED procedure of SAS® 9.3 (SAS® Institute Inc., 2012). An analysis of variance (ANOVA) was performed on yield, aNDF, CP, and IVTD with irrigation treatment and year as fixed factors. Site was considered a random factor. Least square means (LSM) were estimated using the LSMEANS statement (SAS® Institute Inc., 2012). When significant effects were observed ($P \leq 0.15$), differences in LSM were determined using the PDIFF statement in SAS.

1.3 Results and discussion

1.3.1 Dry Matter Yield

Dry matter yields responded to irrigation treatments both years of the study (Table 1.4). When irrigation was withheld for a single season and only natural moisture was available, average grass yields were severely reduced to 30% of the irrigated control ($P=0.0184$). These results are consistent with previous studies (Sheaffer et al., 1992; Smeal et al., 2005; Xu and

Zhou, 2006). Yields continued to be affected by irrigation treatments in the recovery year (P=0.0355). When returned to irrigation the following year, yields were still reduced and produced 49% the control, which was irrigated both years. Averaged across years, plots that were not irrigated the first year produced 39% of the control (P=0.0457). Results indicated that withholding irrigation for a season will have a significant impact on yields the following year when returned to irrigation. Additional years of data are needed to determine how long it takes for yields to fully recover.

Table 1.4. Forage yield, neutral detergent fiber (aNDF) concentration, crude protein (CP) content, and *in vitro* true digestibility (IVTD) from high elevation grass hayfields in western Colorado under full or no irrigation in year 1 and after one year of recovery (year 2).

Treatment	Dry Matter Yield (kg ha^{-1})	aNDF (%)	CP (%)	IVTD (%)
Year 1				
Irrigated	5394^{a}*	54.9^{a}	7.6^{b}	73.5^{a}
Non-irrigated	1643^{b}	51.9^{b}	10.8^{a}	75.4^{a}
Year 2^{+}				
Irrigated	7442^{a}	58.0^{a}	8.6^{a}	74.7^{a}
Non-irrigated	3623^{b}	53.3^{b}	8.0^{a}	74.4^{a}

*Means with the same letter within a year and variable comparing irrigated to non-irrigated are not significantly different at the P=0.15 level.

$^{+}$Both plots were fully irrigated in year 2.

1.3.2 Nutritional Quality

Irrigation treatments had an effect on both aNDF and CP in year 1 (Table 1.4). Forage quality in non-irrigated plots generally increased as measured by a 5% decrease (P=0.1416) in aNDF and 30% increase (P=0.0203) in CP concentrations. With moderate water stress, plant maturation is slowed, resulting in higher forage quality (Buxton, 1996; Bittman et al., 1988). This is likely due to a higher leaf-to-stem ratio as well as increased concentration of N and other nutrient dense compounds caused by reduced biomass. Nutrients and nonstructural carbohydrates also accumulate and can be used to stimulate growth when water is restored (Bittman et al., 1988; Busso et al., 1989; Dina and Klikoff, 1973; Kigel and Dotan, 1982). Digestibility was unaffected by irrigation treatment.

aNDF

Water stress led to a decrease in total fiber (Table 1.4) which has been demonstrated by many researchers (Bittman et al., 1988; Grant et al., 2014; Sheaffer et al., 1992; Wilson et al., 1980). Grant et al. (2014) suggested that increased forage digestibility could be the result of a greater proportion of metabolic tissue to structural tissue. When returned to irrigation in year 2, total fiber content as measured by aNDF was still reduced by 8% (P=0.1283). The lower aNDF concentrations following a return to irrigation were likely due to several factors. First, because the effects of water stress carried over to the following year and growth was still stunted, slowed maturation partially contributed to the reduced fiber content. Second, it has been demonstrated that, during severe drought conditions, nonstructural carbohydrates accumulate at higher levels which are then utilized by the plants to stimulate regrowth and recovery when water is returned (Bittman, 1985; Busso et al., 1989).

CP

Generally, CP content increased in water stressed plants (Table 1.4). Effects of water stress on forage protein are inconsistent. Some studies have also shown an increase in CP with decreased water (Grant et al., 2014; Islam et al., 2012; Sheaffer et al., 1992; Rostamza et al., 2011). In contrast, Bittman et al. (1988) observed a seasonal decline in N concentration in water stressed grasses, while others reported no effect (Ul-Allah et al., 2014; Wilson, 1983). Differing results may be caused by many factors including severity and duration of water stress, plant species, soil type, and soil fertility (Bittman et al., 1988; Buxton, 1996; Grant et al., 2014). When irrigation was restored the second year, CP values decreased and were similar to those of the control. CP content was not significantly affected by the previous irrigation treatment. This is likely due to plant maturity and diluted N concentrations with increasing plant growth (Grant et al., 2014; Wilson and Ng, 1975; Xu and Zhou, 2006).

IVTD

Digestibility as measured by IVTD increased slightly in the non-irrigated plots but did not differ statistically (Table 1.4). Differing results have been reported in previous research. Skinner et al. (2004) observed a decrease in digestibility in forage mixtures of cool season perennials with the exception of a mixture dominated by chicory. In comparison, Bittman et al. (1988) reported that water stress increased digestibility but also increased leaf senescence suggesting no relation to leaf-to-stem ratio. In addition, Boschma and Scott (2000) found an increase in digestibility in moderately stressed (406-440 mm) perennial grasses and a decrease when more severely stressed (276-333 mm). Increased leaf loss in grasses subjected to extreme water stress likely contributed to the reduced digestibility (Buxton, 1996). Conflicting results may be due to variability in location, severity of water stress, time of harvest, and plant composition of hayfields.

Yield and Quality after 2 Years of Recovery

While results indicate that production will still be reduced the first year irrigation is returned following a season of no irrigation, data collected from a single site near Razor Creek demonstrated a return to full production during the second year of recovery (Table 1.5). In 2012, severe drought resulted in only half of this field receiving irrigation. The half receiving no irrigation produced only 13% of the irrigated side with yields of 440 and 3270 kg ha^{-1}, respectively. In 2014, after 2 years of irrigation water being applied to the entire field, yields had completely recovered with the previously non-irrigated portion producing 5760 kg ha^{-1} and the irrigated producing 5670 kg ha^{-1}. Quality was slightly higher in the non-irrigated portion the year of no irrigation and continued to be greater after 2 years of recovery (Table 1.5). More data is needed on dry matter yields and nutritional quality of fields in the second year of recovery to determine if a return to full production is expected in other locations.

Table 1.5. Forage yield, neutral detergent fiber (aNDF) concentration, crude protein (CP) content, and in vitro true digestibility (IVTD) from a hayfield near Razor Creek in Doyleville, CO under full or no irrigation in year 1 and after two years of recovery (year 3).

	DM (kg ha^{-1})		NDF (%)		CP (%)		IVTD (%)	
Treatment	Year 1	Year 3	Year 1	Year 3	Year 1	Year 3	Year 1*	Year 3
Fully Irrigated	3,270	5,670	60.5	59.1	9.9	7.3	N/A	69.1
Non Irrigated (year 1)	440	5,760	57.9	54.7	10.9	8.4	N/A	72.3
% Change	-87%	2%	-4%	-7%	9%	13%	N/A	5%

*IVDT not measured on forage samples from year 1.

1.3.3 Plant Composition and Ground Cover

Irrigation treatment had little impact on plant composition and ground cover (Tables 1.6 and 1.7). Plant composition demonstrated a higher percentage of legumes in irrigated plots (Table 6) (P=0.0923) while percentage of cool-season grasses, and forbs and weeds did not statistically differ between treatments (Table 6). Prevalence of clover species likely resulted in reduced performance of legumes in water stressed plots. Skinner et al. (2004) also observed a reduction of legumes, specifically red clover, with increasing water stress. Others have also reported poor drought tolerance of various clover species (Neal et al., 2011; Ohlsson, 1991). In a study on root distribution and response to water stress, Skinner and Comas (2010) found that, on average, grasses had larger root systems than legumes which may have resulted in improved persistence in drought conditions and no change in percentage of grass species.

Species present, and proportion of these species, likely influenced yield and quality responses to water stress (Martin and Hovin, 1980). It is important to recognize that forage species vary widely in productivity, quality, persistence, and response to water stress (Neal et al. 2011; Sheaffer et al., 1992). Test plots in this study contained a variety of grass, legume, forb, and weed species. Previous researchers have reported differences in response to water stress of many of the species present in this study. For example, Ohlsson (1991) determined that timothy and red clover were less tolerant to drought, and smooth brome and alfalfa were more tolerant. Sheaffer et al. (1992) reported that drought reduced persistence of timothy but did not affect smooth brome or orchardgrass. It was concluded that smooth brome may demonstrate compensatory growth when water becomes available (Sheaffer et al., 1992). Neal et al. (2011) reported poor tolerance and persistence of white clover while Wang and Huang (2004) found that Kentucky bluegrass may sustain permanent damage when subjected to water and heat stress. Because these species were prevalent at the sites used in this study, species composition likely affected plant response and recovery.

Table 1.6. Plant composition percentages adjusted for baseline values using year 1 as a covariate in the model from high elevation grass hayfields in western Colorado under full or no irrigation in year 1 and after one year of recovery.

	Treatment	
Cover	Irrigated	Non-irrigated (year 1)
Legumes	13.1^{+a*}	5.9^{b}
Forbs/weeds	17.0^{a}	19.4^{a}
Cool-season grasses	70.0^{a}	74.6^{a}

*Means followed by the same letter within a row do not differ significantly at the P=0.15 level.

In regard to ground cover, results indicated that treatment had no effect on percent of bare ground, litter, or weeds and forbs while the proportion of grasses and legumes was greater in irrigated plots (Table 1.7) (P=0.0369). These results parallel plant composition results which showed better performance of legumes in irrigated plots, while grasses did not appear to be negatively affected. Although not statistically significant, bare ground and litter were slightly higher in water stressed plots. Skinner et al. (2004) observed water stressed mixtures had an increase in proportion of dead material compared to normal and excessive moisture treatments and Neal et al. (2011) reported increased bare ground resulting from plant death. Varying results can be explained by the influence of plant composition, length and severity of water stress, and environmental conditions on changes in ground cover.

Table 1.7. Ground cover percentages adjusted for baseline values using year 1 as a covariate in the model from high elevation grass hayfields in western Colorado under full or no irrigation in year 1 and after one year of recovery (year 2).

	Treatment	
Cover	Irrigated	Non-irrigated (year 1)
Bare Ground	9.7+a*	14.1a
Grasses and Legumes	32.4a	21.2b
Litter	50.2a	54.8a
Forbs and Weeds	8.6a	9.0a

*Means followed by the same letter within a row do not differ significantly at the P=0.15 level.

1.3.4 Soil Properties

There was little change in soil properties between treatments (Tables 1.8 and 1.9) (Appendix A). In the upper sample portion, organic matter (OM) was higher in the irrigated plots (P=0.1017). Reduced growth above and below ground likely resulted in lower organic matter in water stressed plots. Soils in the irrigated plots also had higher levels of potassium (K) (P=0.0735). The reason for this difference was not apparent, but it may be due to differential sampling between years. No significant responses were observed in the lower sample portion.

Table 1.8. Soil properties from the upper sample portion (0 to 7.5 cm) adjusted for baseline values using year 1 as a covariate in the model from high elevation grass hayfields in western Colorado under full or no irrigation in year 1 and after one year of recovery (year 2).

	Treatment	
Soil Property	Irrigated	Non-irrigated (year 1)
pH	6.2^{+a*}	6.1^{a}
Electrical Conductivity (mmhos/cm)	0.4^{a}	0.4^{a}
Organic Matter (%)	12.7^{a}	11.4^{b}
Nitrate-Nitrogen (ppm)	2.6^{a}	5.8^{a}
Phosphorus (ppm)	6.1^{a}	7.5^{a}
Potassium (ppm)	292.1^{a}	192.8^{b}

*Means followed by the same letter within a row do not differ significantly at the P=0.15 level.

Table 1.9. Soil properties from the lower sample portion (7.5 to 15 cm) adjusted for baseline values using year 1 as a covariate in the model from high elevation grass hayfields in western Colorado under full or no irrigation in year 1 and after one year of recovery (year 2).

	Treatment	
Soil Property	Irrigated	Non-irrigated (year 1)
pH	6.1^{+a*}	6.3^{a}
Electrical Conductivity (mmhos/cm)	0.3^{a}	0.4^{a}
Organic Matter (%)	4.7^{a}	4.5^{a}
Nitrate-Nitrogen (ppm)	0.6^{a}	2.0^{a}
Phosphorus (ppm)	1.0^{a}	2.7^{a}
Potassium (ppm)	148.7^{a}	106.9^{a}

*Means followed by the same letter within a row do not differ significantly at the P=0.15 level.

1.4 Conclusion

Findings from this study indicated that withholding irrigation from grass hayfields for a complete growing season will slightly improve forage quality, but will significantly reduce production. This outcome was exhibited not only during the non-irrigated year, but also during the first recovery year when irrigation water is returned to fields. Production of higher quality forage will partially offset losses due to reduced yields, but these gains not compensate for the broader loss of production. Yields may fully recover when water has been returned for 2 growing seasons according to findings at the Razor Creek site. Results showed that withholding irrigation may reduce the percentage of legumes but will not significantly affect other species. Furthermore, soil organic matter will likely be lower in non-irrigated fields due to the reduction in above- and below-ground production. More long-term data is needed to determine potential recovery time and changes in forage quality in subsequent years to determine if reducing irrigation in high elevation hayfields for use in a Western Slope water bank is worth pursuing. With increasing water scarcity concerns and irrigated agriculture being the main source of water use in the region, management practices that reduce irrigation may be an option to make water available for other uses.

CHAPTER 2

ALFALFA YIELD AND QUALITY IN WESTERN COLORADO WITH PARTIAL SEASON IRRIGATION

2.1 Introduction

In the Western United States, rapid population growth along with extended drought has created new challenges in meeting agricultural and municipal water needs. The Colorado River Basin supplies approximately 40 million people with water in addition to irrigating 2.23 million hectares of farmland (Executive Summary, 2012). Increasing strain on water resources in this region may lead to severe environmental, economic, and legal impacts. The Colorado River Compact of 1922 was developed as an agreement between 7 basin states to ensure equitable division of water resources. These states are separated at Lee’s Ferry, Arizona into the Upper Basin and Lower Basin states. Precipitation from the 4 Upper Basin states, which consists of Colorado, Wyoming, Utah, and Arizona, provide approximately 90% of the water flow in the Colorado River (Jacobs, 2011). Under legal requirements stipulated in the compact, the Upper Basin states must not allow less than 92.5 billion cubic meters of water to flow through Lee’s Ferry for any rolling 10 year period. Recent conditions have increased the likelihood of the inability for the Upper Basin states to comply with compact obligations in the future. Reduced use of irrigation is an increasingly common approach to address water issues. A Western Slope Water Bank is one possible system that may help address challenges of increasing demand for a limited and variable water supply in the Colorado River Basin.

As proposed, water banking would be a way to legally transfer water in a market situation. Because the primary use of water on Colorado’s Western Slope is irrigated agriculture, it is likely to be the main contributor of water to the bank. Voluntary participants with pre-1922 water rights would enter into short-term leases and temporarily withhold or reduce use of irrigation water. Purchasers may use water for municipal, industrial, environmental, recreational, or other agricultural uses. Water banking may make water available for other uses while creating a new source of income for agricultural producers.

Over 90% of irrigated land on Colorado's Western Slope is used to produce forage crops with approximately 24% (77,900 hectares) in irrigated alfalfa (MWH, 2012). Because of its abundance in the region and tolerance to water stress, alfalfa may be ideal for inclusion in water banking projects. The deep tap roots of alfalfa are able to access water longer into dry periods and make it relatively tolerant to drought in comparison to other forage species. The ability to go into drought induced dormancy assists alfalfa in withstanding and recovering from water stress depending on intensity and duration (Barnes and Sheaffer, 1995). Previous studies have shown that deficit irrigation of alfalfa results in reduced yields, but crops may fully recover in 1 to 3 years (Hanson et al., 2007; Guitjens et al., 1993). The severity of reduced irrigation in conjunction with environmental conditions influences agronomic responses and recovery period and may result in permanent damage to alfalfa (Ottman et al., 1996).

There have also been previous investigations that determined the effects of water stress on nutritional quality of alfalfa. Several studies have found that severe or prolonged water stress results in increased forage quality. The common finding is that water deficits lead to a reduced rate of maturity and increased leaf-to-stem ratio resulting in higher quality forage (Carter and Sheaffer, 1983; Lindenmayer, 2008; Peterson et al., 1992). Although researchers generally report increased quality, it is important to note that effects of water stress on individual quality parameters differ. Timing, duration, and severity of water stress along with other environmental factors may cause variation in response of individual quality parameters (Buxton, 1996; Mueller and Orloff, 1994; Ohlsson, 1991). Many studies have reported increased digestibility, while effects on crude protein content are more variable (Carter and Sheaffer, 1983; Vough and Marten, 1971). Others have observed no effect on forage quality (Peterson et al., 1992). Much of the past research concentrates on yield response and recovery associated with insufficient water supply with fewer studies reporting quality parameters. Limited information is available on effects and associated recovery associated with partial season irrigation of alfalfa in semi-arid environments similar to those on Colorado's Western Slope.

To determine whether a Western Slope Water Bank is worth pursuing, more information is needed on agronomic responses of alfalfa crops to partial season irrigation. In a region highly diverse in climate, land characteristics, and management practices which significantly influence how crops will respond to water stress, it is necessary to determine outcomes in multiple locations throughout the area. This study was designed to determine the impacts of reduced irrigation regimes on forage yield and nutritional quality of alfalfa hay crops in different regions of Western Colorado. The objective was to provide adequate information to confirm if a water bank is worth pursuing.

2.2 Methods and Materials

2.2.1 Study Site Descriptions

This study was conducted at various sites on the Western Slope of Colorado that encompassed areas diverse in climate, land and crop characteristics, and management practices. Three established alfalfa hayfields were selected for study to compare side-by-side plots treated with full season and 2 partial season irrigation treatments in 2013 and 2014. Sites were located near Fruita, Eckert, and Yellow Jacket, Colorado (Tables 2.1 and 2.2). The Fruita and Yellow

Jacket sites were located at Colorado State University research centers. Each site produced 3 to 4 cuttings of hay each year. Gated pipe furrow and center pivot irrigation systems were used at Fruita and Yellow Jacket, respectively. Furrow irrigation with gated pipe was used at Eckert.

Table 2.1. Characteristics of alfalfa sites used to evaluate the impact of partial season irrigation on forage yield and nutritional quality on the Western Slope of Colorado.

Location	**County**	**Elevation (m)**	**Annual Precipitation (mm)**	**Growing Season Length (days)***	**Total area (ha)**
Eckert	Delta	1,697	318	166	3.48
Fruita	Mesa	1,380	223	173	0.81
Yellow Jacket	Montezuma	2,103	407	136	6.07

*Growing season length was estimated using the *Western Regional Climate Center* freeze-free (-2.2˚C) season probabilities (http://www.wrcc.dri.edu).

Table 2.2. Precipitation and estimated evapotranspiration (ET) from harvest periods of alfalfa sites used to evaluate the impact of partial season irrigation on forage yield, nutritional quality, and recovery on the Western Slope of Colorado in 2013 and 2014.

		Year 1			**Year 2**		
Location	**Cutting**	**Dates**	**Precip. (mm)**	**ET (mm)**	**Dates**	**Precip. (mm)**	**ET (mm)**
Eckert[+]	1st	4/16-6/17	25.5[+]	338.8[+]	4/19-5/29	10.1[+]	191.8[+]
	2nd	6/17-7/29	54.6[+]	350.5[+]	5/29-7/17	4.0[+]	172.7[+]
	3rd	7/29-9/21	85.0[+]	284.5[+]	7/17-8/29	58.1[+]	236.2[+]
	Total		**162.1**	**973.8**	**Total**	**72.2**	**600.7**
Fruita*	1st	3/5-5/20	29.5*	263.7*	4/20-5/22	37.1*	303.5*
	2nd	5/20-6/24	0.0*	263.7*	5/22-7/3	9.9*	343.2*
	3rd	6/24-7/30	38.6*	259.3*	7/3-8/6	21.6*	223.5*
	4th	7/30-9/21	74.4*	232.2*	8/6-8/20	16.0*	51.3*
	Total		**142.5**	**1018.9**	**Total**	**84.6**	**921.5**
Yellow Jacket*[+]	1st	4/15-6/7	16.5[+]	276.9*	4/15-6/12	57.4[+]	313.9*
	2nd	6/7-7/18	16.3[+]	305.3*[+]	6/12-7/24	22.6[+]	344.7*
	3rd	7/18-9/20	204.2[+]	301.8[+]	7/24-8/14	32.3[+]	105.4*
	Total		**237.0**	**884.0**	**Total**	**112.3**	**764.0**

*Crop water use (ET) values were based on the Penman-Kimberly reference ET model specific for alfalfa crops using data collected from The *Colorado Agricultural Meteorological Network* (CoAgMet) weather stations at corresponding locations.

[+] Values from atmometers and rain gauges installed at corresponding locations.

Eckert, CO:

The Eckert site was located 1.6 km west of the town of Eckert in the Lower Gunnison River Basin (38°50'22.09"N, 107°58'48.47"W). Three cuttings were harvested annually from this hayfield which was dominated by Mesa loam soil (fine-loamy, mixed, mesic Typic Haplargids). Water was applied to the field by furrow irrigation starting in mid-May in 2013. Thirteen, 24 hour sets were applied to the control in 2013 with the last one in late October. In 2014, the control received 10 sets with the first one starting on May 14 and the last one ending on July 29. Unlike 2013, plots were not irrigated after the 3rd cutting so the main delivery ditch could be dried in preparation for installing new pipe.

Fruita, CO:

The Fruita site was located 4.7 kilometers (km) northeast of the town of Fruita at the Western Colorado Research Center (WCRC) in the Lower Colorado River Basin (39°10'36.92"N, 108°41'47.72"W). Three soil types comprised the plot area, including Sagers silty clay loam (fine-silty, mixed, active, calcareous, mesic Typic Torriorthents), Killpack silty clay (fine-silty, mixed, active, mesic Typic Haplocambids), and Fruitvale clay loam (fine-loamy, mixed, active, mesic Typic Argigypsids). The field produced 4 harvests each year. Water was applied by furrow irrigation starting in early April. In 2013, 11 furrow irrigation sets of 17 to 24 hours were applied to the fully irrigated control with the last set in early October. Ten sets ranging in time from 7 to 24 hours were applied to the control during the 2014 season with the last set in September.

Yellow Jacket, CO:

The Yellow Jacket site was located 2.4 km northwest of the town of Yellow Jacket at the Southwestern Colorado Research Center (SWCRC) and is in the San Juan/Dolores River Basin

(37°32'13.55"N, 108°44'22.40"W). This site was the most southern studied in the project. A center pivot irrigation system was used. Soils were Wetherill loam (fine-silty, mixed, superactive, mesic Aridic Haplustalfs) with 1-6% slopes. In 2013, the east half of the field was completely fallowed and sampled. This portion was not used in 2014. In 2013, 368 mm of water was applied to the field with the control receiving an estimated 14 applications starting in mid-May and ending in early-October. In 2014, 355 mm were applied with the control receiving 17 applications starting in mid-May and ending in early-September.

2.2.2 Treatments and Measurements

Three side-by-side plots were established at each site and treated as follows for 2 consecutive years: one plot received full irrigation (control), irrigation was stopped after the 2nd cutting for the next treatment (SA2), and for the third treatment, irrigation was stopped after the 1st cutting (SA1). A plot which received no irrigation in year 1 was also sampled at the Yellow Jacket site. Full weather stations were available on-site at the Fruita and Yellow Jacket centers. In the early spring of each season, wooden fence posts were inserted near the borders of irrigated plots to secure Stratus™ rain gauges (Productive Alternatives®, Fergus Falls, MN) and ETgage (evapotranspiration (ET) gage) Model A™ atmometers (ETgage Company®, Loveland, CO) at the Eckert and Yellow Jacket sites. A minimum of 1 mm of baby oil was added to each rain gauge to minimize water loss to evaporation. Atmometers, which measured estimated reference ET, were set with the top of the instrument 1 m above ground and filled with distilled water (Bauder, 1999). Green canvases specific for alfalfa crops were fixed to the top to simulate the crop canopy. Atmometer and rain gauge readings were taken periodically throughout the growing season. Instruments were set up in Yellow Jacket to parallel weather station results because of distance from the weather station and crop canopy dissimilarities. At the Eckert site, a south facing temperature logger (Hobo Pro Series, Model H8, Onset Computer Corp., Bourne, MA) with a radiation shield was set up on a T-post and recorded ambient temperature at 10-minute intervals.

Fifteen soil samples were taken to 15 cm and separated into 7.5 cm depth increments in each plot in the spring of each year. Samples were analyzed at the Colorado State University (CSU) Soil-Water-Plant Testing Laboratory for chemical properties and extractable nutrients using the routine analysis (pH, electrical conductivity, organic matter, nitrate-nitrogen, phosphorus, potassium, and particle size analysis). Plant density data was determined each spring by taking 12 plant counts using 0.1 m^2 sampling frames in each treatment area.

Yield and quality samples were collected prior to each hay harvest at each site. Ten samples were collected in each treatment area using a 0.25 m^2 frame. Samples were hand clipped at 7.5 cm to simulate approximate cutter-bar height. Plant material was dried in a forced-air oven at 55^{o}C for a minimum of 72 hours. After plant samples reached a constant dry weight, they were weighed and yields converted to kilograms per hectare. Following weighing, individual samples were ground through a Thomas Model 4 Wiley® Mill (Philadelphia, PA) with a 2 mm screen followed by a Foss™ Tecator Cyclotec Sample Mill Model 1093 (Eden Prairie, MN) with a 2 mm screen to homogenize the sample.

Ground samples were used to determine dry matter (DM) and quality factors, including neutral detergent fiber (aNDF), in vitro true digestibility (IVTD), and crude protein (CP) concentration, for each treatment. To determine DM, a 1 gram of sample was weighed into an aluminum dish, dried for a minimum of 24 hours at 102˚C, and reweighed. Each of the 10 samples from all treatments was used to determine aNDF. One duplicate, blank, and standard (mixed cool-season grass hay) bag were included in each set of 24 samples that were run through an Ankom® 200 fiber analyzer (Method 6) (ANKOM Technology, Macedon, NY). To determine IVTD, 4 samples were randomly selected from each set, and duplicates of these samples were tested. Rumen fluid was collected from 2 rumen fistulated steers that were being fed a mixed forage and corn diet. Samples were incubated in a Daisy II Incubator (ANKOM Technology, Macedon, NY) using the in vitro true digestibility method (Method 3). Crude protein content was measured using a LECO TruSpec® CN268 Elemental Combustion Analyzer (LECO Corp., St. Joseph, MI) to determine nitrogen content. All 10 samples from every treatment plot were analyzed. Crude protein was estimated by multiplying percent nitrogen by a factor of 6.25. If there were insufficient amounts of sample available for measurement, the initial 10 were combined into no less than 4 samples.

Statistical analysis

Statistical analyses were conducted using the MIXED procedure of SAS® 9.3 (SAS® Institute Inc., 2012). A three-way factorial analysis of variance (ANOVA) was performed for yield, aNDF, CP, and IVTD with the 3 factors being irrigation treatment, cutting, and year. Year was not a statistically significant factor for yield, aNDF, or IVTD, so means were averaged over years. Year showed effects on CP content and, thus, was analyzed accordingly. For consistency, the data from the 4th cutting at Fruita was not included as other sites were harvested only 3 times each year, but the 4th cutting was included when determining and analyzing total seasonal yield. Site was considered a random factor while cutting was included as a repeated factor. Least Square Means (LSM) were estimated using the LSMEANS statement (SAS® Institute Inc., 2012). When significant differences were observed ($P \leq 0.15$), LSMs were compared using the PDIFF option to determine differences between individual values.

2.3 Results and discussion

2.3.1 Dry Matter Yield

Partial season irrigation practices resulted in substantial reductions in dry matter production. Yield was significantly affected by an interaction of irrigation treatment and cutting (P=0.1334) (Table 2.3). Both partial season irrigation treatments reduced plant growth and dry matter yields when compared to the irrigated control which maintained similar yields (3550 kg ha^{-1}) across cuttings. These results are supported by previous reports (Carter and Sheaffer, 1983; Halim et al., 1990; Hattendorf et al., 1988; Lindenmayer, 2008; Peterson et al., 1992). Alfalfa subjected to the SA2 treatment maintained yields similar to the control until the 3rd cutting, where terminating irrigation reduced yields to approximately half of the control. When compared to other cuttings within the same treatment, SA2 plots had similar yields in the 1st and 3rd cuttings. Growth was stunted in the 1st cutting of year 2 due to the effects of water stress from the previous year. The 2nd cutting was highest yielding in SA2 plots with a 35% greater yield than the 1st cutting, suggesting that alfalfa has the ability to recover from water stress. This supported the findings of Lindenmayer (2008) who demonstrated yield recovery of alfalfa subjected to partial season water stress. It has also been suggested that alfalfa has mechanisms, such as extensive tap roots reaching water deeper in the soil profile, to maintain production under high levels of water stress (Hattendorf et al., 1988).

Yields of SA1 plots were lower than the control in all cuttings with increasing differences after each cutting. At the 1st cutting, SA1 plots produced only 61% of the control while SA2 plots had intermediate yields. Reduced yields in the 1st cutting were due to lower yields in year 2, when plants started the season severely water stressed from the previous year's treatment. By the 2nd cutting, production of SA1 plots declined by 24% compared to the previous harvest and produced 42% of the control. By the 3rd cutting, yields had severely decreased in both partial season irrigation treatments with SA1 plots producing only 30% of the control. SA2 yields declined by 48% of the previous cutting and produced approximately half as much as the control (53%).

In regards to total seasonal production, in which yields from the 4th cutting taken at Fruita were included, both partial season irrigation treatments resulted in reduced production (P=0.0228). SA1 plot yields were reduced by 67% (3650 kg ha^{-1}) and SA2 plot yields were reduced by 28% (7990 kg ha^{-1}) of the control (11040 kg ha^{-1}).

Table 2.3. Interaction effect of irrigation treatment and cutting on dry matter yield (kg ha^{-1}) of alfalfa from hayfields in western Colorado under full and partial season irrigation treatments of stopping irrigation after the 2nd cutting and stopping irrigation after the 1st cutting.

	Treatment		
	Fully Irrigated	Stop after 2nd	Stop after 1st
Cutting 1	$3430^{+\ Aa*}$	2470^{ABb}	2090^{Ba}
Cutting 2	3810^{Aa}	3770^{Aa}	1590^{Bab}
Cutting 3	3410^{Aa}	1800^{Bb}	1010^{Bb}
Total	**11040^{A}**	**7990^{B}**	**3650^{C}**

$^{+}$Means averaged over years 1 and 2 due to no interaction with year (P=0.2407).
*Means followed by the same lowercase letter(s) in a column or uppercase letter(s) within a row do not differ significantly at the P=0.15 level.

2.3.2 Nutritional Quality

Forage quality generally increased with partial season irrigation treatments as indicated by reduced total fiber content and increased digestibility (Tables 2.4 and 2.5). Generally, water stress and other factors that stunt plant growth result in higher quality forage while factors that hasten growth result in reduced quality (Mueller and Orloff, 1994). In this study, quality tended to be lowest in the 2nd cutting in regards to increased aNDF and decreased IVTD which was likely due to higher temperatures resulting in an increased rate of lignification (Putnam and Ottman, 2013). Increased growth observed in this cutting may have also contributed to reduced quality (Buxton, 1996; Mueller and Orloff, 1994; Peterson et al., 1992).

aNDF

Increasing water stress generally reduces total fiber content as measured by aNDF suggesting improved dry matter intake potential (Buxton, 1996). Fiber concentrations responded to irrigation treatment (P=0.0900) and differed between cuttings (P=0.0111) (Table 2.4). Results are consistent with previous reports (Carter and Sheaffer, 1983; Halim et al., 1990; Lindenmayer, 2008; Peterson et al., 1992). Fiber concentrations were lowest in SA1 plots and greatest in the control with concentrations of 27.9 and 33.9%, respectively. Enhanced quality is likely due to delayed maturity resulting in a greater leaf-to-stem ratio and finer stems (Lindenmayer, 2008; Peterson et al., 1992). Halim et al. (1990) suggested slowed cell wall development is a result of carbon being used to increase production of sugars and other compounds. Schubert et al. (1995) confirmed that decreased growth of alfalfa due to water stress results in accumulations of glucose, sucrose, and amino acids.

Results also indicated a relationship between fiber content and cutting. When averaged over all treatments, aNDF was greatest in the 2nd cutting with equally reduced concentrations of 15% in the 1st and 3rd cuttings. Similarly, when testing alfalfa for relative feed value (RFV), Lindenmayer (2008) observed lower quality in the 2nd cutting. This was likely due to higher temperatures resulting in more rapid lignification that reduced digestibility (Putnam and Ottman, 2013). Increased growth, plant maturity, management, and environmental factors may contribute to reduced quality observed in the 2nd cutting.

Table 2.4. Neutral detergent fiber (aNDF) and crude protein (CP) concentrations of alfalfa from hayfields in western Colorado under full and partial season irrigation treatments of stopping irrigation after the 2nd cutting and stopping irrigation after the 1st cutting.

	aNDF (%)	CP (%)
Treatment⁺		
Irrigated Control	33.9 ^{a*}	27.4 ^{a}
Stop after 2nd (SA2)	31.0 ^{ab}	26.6 ^{a}
Stop after 1st (SA1)	27.9 ^{b}	27.2 ^{a}
Cutting⁺		
1	29.9 ^{b}	27.0 ^{a}
2	33.8 ^{a}	23.9 ^{b}
3	29.1 ^{b}	25.8 ^{b}

⁺Means averaged over years 1 and 2 due to no interaction with year (P=0.2240 for aNDF and 0.2639 for CP).

*Means followed by the same letter within a column and variable are not significantly different at the P=0.15 level.

CP

CP concentrations were affected by cutting but not by irrigation treatment. Averaged over both years, CP was greatest in the 1st cutting (Table 2.4). An inconsistent response in CP was observed as demonstrated by the year by cutting interaction (P=0.0288) (Table 2.5). In year 1, when averaged across all treatments, CP content was greatest in the 1st cutting. The 2nd and 3rd cuttings were similar with 13 and 15% reduced CP contents, respectively. In year 2, the 2nd cutting generally had the lowest CP content with a value similar to the previous year. By year 2, CP content was 10% lower in the 1st cutting and 7% higher in the 3rd cutting resulting in similar values. Differing protein concentrations were likely due to plant maturity at harvest and environmental factors. No relationship between CP content and irrigation treatment was observed. The relationship between water stress and protein content in alfalfa has been inconsistent in the literature. Many have also reported no relationship (Carter and Sheaffer, 1983; Halim et al., 1989; Hanson et al., 2007; Vough and Marten, 1971), while others have reported mixed findings of both increasing and decreasing forage protein content (Halim et al., 1990; Peterson et al., 1992; Vough and Marten, 1971). In contrast, others have reported greater CP content with reduced water availability (Walgenbach et al., 1981; Gifford and Jensen, 1967). Inconsistent results may also be caused by differences in nitrogen fixation capabilities in plants (Carter and Sheaffer, 1983; Antolin et al., 1995).

Table 2.5. Interaction effect of year by cutting on crude protein (CP) content of alfalfa from hayfields in western Colorado.

	CP (%)	
	Year 1	Year 2
Cutting		
1	28.6^{Aa*}	25.6^{Ba}
2	24.4^{Ab}	23.3^{Ab}
3	24.8^{Ab}	26.8^{Ba}

*Means with the same lowercase letter within a year, or uppercase letter within a cutting do not differ significantly at the P=0.15 level.

IVTD

Digestibility as measured by IVTD demonstrated a treatment by cutting interaction (P=0.1214), but generally improved with increasing water stress (Table 2.6). In the 1st cutting, irrigation treatments did not differ. By the 2nd cutting, SA1 plots were highest in digestibility averaging 6% greater than the control. By the 3rd cutting, the lowest digestibility occurred in the control with SA2 and SA1 plots being equally greater (5%). The control demonstrated the highest digestibility in the 1st cutting at 79% and lowest in the 2nd cutting at 74.3%. Likewise, Sa2 plots had the lowest digestibility in the 2nd cutting at 74.4% with cuttings 1 and 3 being similar with an average of 81.2%. SA1 plots maintained similar values throughout all cuttings, averaging 79.2%. While response of alfalfa digestibility to water stress is inconsistent in the literature, our results are consistent with many previous reports (Snaydon, 1972; Vough and Marten, 1971). Carter and Sheaffer (1983) found that digestibility increased under severe, prolonged water stress, but did not differ with moderate stress, and they determined this was not related to leaf-to-stem ratio. In contrast, Buxton (1996) reported moderate stress resulted in increased digestibility, and severe stress reduced digestibility due to greater leaf loss. Conflicting results may be due to plant maturity at harvest and varying environmental factors. Harvest dates in this study were commonly delayed due to weather. Alfalfa quality can decline significantly by delaying harvest only a few days (Buxton, 1996).

Table 2.6. Interaction effect of irrigation treatment and cutting on in-vitro true digestibility (IVTD) of alfalfa from hayfields in western Colorado under full and partial season irrigation treatments of stopping irrigation after the 2nd cutting and stopping irrigation after the 1st cutting.

	Treatment		
	Fully Irrigated	Stop after 2nd	Stop after 1st
Cutting 1	$79.0^{+\ Aa*}$	82.0^{Aa}	79.8^{Aa}
Cutting 2	74.3^{Bb}	74.4^{Bb}	80.4^{Aa}
Cutting 3	76.7^{Bab}	80.4^{Aa}	80.4^{Aa}

[+] Means averaged over years 1 and 2 due to no interaction with year (P=0.3906).

*Means followed by the same lowercase letter(s) in a column or uppercase letter(s) within a row do not differ significantly at the P=0.15 level.

2.3.3 Stand Density

Stand density was not affected by irrigation treatment indicating no negative influence on stand persistence (P=0.7443). Plots averaged 28 plants per square meter (m^2). These results support those of Orloff et al. (2014), who reported no change in stand density the year following a season of deficit irrigation in studies conducted in the Intermountain Region and Central Valley of California. However, stands were reduced in the low desert area. Sites where alfalfa fully recovered were characterized by cooler climates and shorter growing seasons, similar to conditions on the Western Slope of Colorado. It was suggested that responses are largely dependent on severity of water stress, growing season length, and environmental conditions

(Orloff et al., 2014). Investigations by other researchers have also reported deficit irrigation in hot, arid locations led to plant loss (Ottman et al., 1996; Takele and Kallenbach, 2001). Survival can generally be explained by alfalfa's ability to go into dormancy when water is limiting and resume growth when adequate water is returned (Lauriault et al. 2014; Long and Orloff, 2014). Plants should go into dormancy with sufficient carbohydrate reserves to lessen chances of reduced stands (Orloff et al., 2014). Results from this study indicate the ability of alfalfa to survive up to 2 seasons of water stress with little to no impact on stand density in conditions common to those on the Western Slope.

2.3.4 Soil Properties

Irrigation treatment had little effect on soil properties (Tables 2.7 and 2.8) (See Appendix). In the upper sample portion (0 to 7.5 cm), results indicated that the irrigated control was higher in organic matter content. Lower organic matter in the partially irrigated plots was likely due to reduced root growth and above ground production (P=0.1164). In the lower sample portion, soil pH differed significantly between irrigation treatments (P=0.0110). Both deficit irrigation treatments had a slightly higher pH than the control. Increased leaching in the control likely led to a slight decrease in pH. Walter et al. (1990) determined that when calcium and magnesium were leached from the soil, they were replaced with hydrogen causing lower pH soils in the South Park area of Colorado. In this study, both partial season irrigation treatments probably experienced less leaching and demonstrated a slight increase in pH. Electrical conductivity (EC) also differed between treatments in the lower sample portion with the highest EC in SA2 plots and the lowest in the control with SA1 being intermediate (P=0.1306). It is possible that applying less water reduced the leaching of salts out of soils at that sampling depth in combination with salts moving up in the soil profile in the partially irrigated plots due to capillary action resulting in increased concentrations (Whiting et al., 2014).

Table 2.7. Soil properties from the upper sample portion (0 to 7.5 cm) adjusted for baseline values using year 1 as a covariate in the model from alfalfa hayfields in western Colorado under full and partial season irrigation treatments of stopping irrigation after the 2nd cutting and stopping irrigation after the 1st cutting.

	Treatment		
Soil Property	Fully Irrigated	Stop after 2nd	Stop after 1st
pH	7.4^{+a*}	7.6^{a}	7.6^{a}
Electrical Conductivity (mmhos/cm)	0.5^{a}	0.4^{a}	0.5^{a}
Organic Matter (%)	2.3^{a}	1.9^{b}	1.7^{b}
Nitrate-Nitrogen (ppm)	10.9^{a}	8.6^{a}	8.9^{a}
Phosphorus (ppm)	6.6^{a}	4.4^{a}	4.6^{a}
Potassium (ppm)	149.2^{a}	115.5^{a}	139.4^{a}

*Means followed by the same letter within a row do not differ significantly at the P=0.15 level.

Table 2.8. Soil properties from the lower sample portion (7.5 to 15 cm) adjusted for baseline values using year 1 as a covariate in the model from alfalfa hayfields in western Colorado under full and partial season irrigation treatments of stopping irrigation after the 2nd cutting (SA2) and stopping irrigation after the 1st cutting (SA1).

	Treatment		
Soil Property	Fully Irrigated	Stop after 2nd	Stop after 1st
pH	7.4^{+b*}	7.6^{a}	7.6^{a}
Electrical Conductivity (mmhos/cm)	0.4^{b}	0.6^{a}	0.5^{ab}
Organic Matter (%)	1.9^{a}	2.0^{a}	1.8^{a}
Nitrate-Nitrogen (ppm)	6.1^{a}	8.6^{a}	5.9^{a}
Phosphorus (ppm)	2.3^{a}	2.9^{a}	3.5^{a}
Potassium (ppm)	111.4^{a}	105.2^{a}	120.1^{a}

*Means followed by the same letter within a row do not differ significantly at the P=0.15 level.

2.3.5 Estimated Water Saved

The amount of consumptive water use conserved using both partial season irrigation treatments from this study was estimated using a relationship between total seasonal yield and

ET developed by Lindenmeyer (2008). This relationship was generated by creating a regression line with data from multiple studies evaluating alfalfa yield response to ET in the Great Plains and Inter-Mountain West (Lindenmeyer, 2008). In this study, an estimated 770 mm of water was used to produce the average total seasonal yield of the fully irrigated control (12360 kg ha^{-1}). In contrast, the SA2 treatment used an estimated 560 mm, conserving 210 mm, and the SA1 treatment used 260 mm, saving 520 mm of water.

2.4 Conclusion

Partial season irrigation practices resulted in significant reductions in dry matter production but increased forage quality in terms of reduced fiber and increased digestibility. Based on these results and past reports, alfalfa yields may recover depending on length and severity of water stress. In regard to agronomic responses, irrigating through the 2nd cutting would be a better option to minimize yield loss and allow recovery by the 2nd cutting the following year while reducing overall water use. In comparison, irrigating only through the 1st cutting may not be a feasible practice due to greater yield loss and reduced recovery the following year. However, reduced costs for machinery and labor, along with higher quality forage and compensation for water may offset reduced yields. Participation will likely be influenced by compensation. In a study conducted to determine the willingness of producers in Colorado’s South Platte Basin to participate, Pritchett et al. (2008) recorded that over 77% of the sampled population would require compensation of $90 to $230 per hectare of land not irrigated for a year. The ability of alfalfa plants to survive and recover from water stress may make partial season irrigation of this crop a reasonable option for inclusion in a water bank system. Long-term data is needed to determine effects and recovery of alfalfa subjected to partial season irrigation implemented over multiple years on a rotational basis.

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APPENDIX

Table A1. Soil properties from the upper sample portion (0 to 7.5 cm) from high elevation grass hayfields in western Colorado under full or no irrigation in year 1 and after one year of recovery (year 2).

			Soil Property				
Site	Treatment	pH	EC (mmhos/ cm)	OM (%)	NO_3-N (ppm)	Phosphorus (ppm)	Potassium (ppm)
Cimarron	Irrigated						
	Year 1	5.4	0.3	20.0	17.2	8	215.0
	Year 2	5.6	0.3	23.3	0.5	8.0	369
	Non-irrigated						
	Year 1	6.1	0.3	10.1	0.5	3	192.0
	Year 2	6.2	0.2	13.0	2.0	5.5	260
Gunnison	Irrigated						
	Year 1	6.5	0.3	7.6	0.8	3	182.0
	Year 2	6.9	0.3	13.5	1.2	6.0	305
	Non-irrigated						
	Year 1	6.6	0.2	3.9	0.7	1	194.0
	Year 2	7.0	0.2	8.1	1.5	4.0	194
Hayden	Irrigated						
	Year 1	5.7	0.3	5.3	1.1	0.5	86.8
	Year 2	5.8	0.3	7.9	0.8	9	119.0
	Non-irrigated						
	Year 1	5.8	0.3	6.2	1.2	4.0	114
	Year 2	5.7	0.8	7.6	17.2	14	98.4
Kremmling	Irrigated						
	Year 1	5.8	0.3	13.8	0.8	2.0	186
	Year 2	5.8	0.3	13.0	6.7	4	218.0
	Non-irrigated						
	Year 1	6.5	0.6	11.1	1.2	<0.01	213
	Year 2	6.1	0.3	9.8	3.4	4	256.0
Steamboat Lake	Irrigated						
	Year 1	5.4	0.2	5.6	0.3	<0.01	161
	Year 2	5.2	0.2	6.1	0.3	1.5	121.0
	Non-irrigated						
	Year 1	5.2	0.2	7.3	0.27	<0.01	190
	Year 2	5.3	0.2	7.3	0.6	1	160.0

Table A2. Soil properties from the lower sample portion (7.5 to 15 cm) from high elevation grass hayfields in western Colorado under full or no irrigation in year 1 and after one year of recovery (year 2).

			Soil Property				
Site	Treatment	pH	EC (mmhos/ cm)	OM (%)	NO_3-N (ppm)	Phosphorus (ppm)	Potassium (ppm)
Cimarron	Irrigated						
	Year 1	5.8	0.6	3.8	0.5	2	60.0
	Year 2	5.6	0.2	3.3	<0.1	0.1	134
	Non-irrigated						
	Year 1	6.4	0.3	4.6	0.2	1	128.0
	Year 2	6.3	0.3	5.7	0.2	1.0	145
Gunnison	Irrigated						
	Year 1	6.6	0.2	4.1	0.7	1	135.0
	Year 2	6.8	0.3	5.6	0.5	1.6	225
	Non-irrigated						
	Year 1	6.7	0.3	7.9	1.3	4	249.0
	Year 2	6.9	0.3	5.4	1.4	2.0	151
Hayden	Irrigated						
	Year 1	5.7	0.3	3.3	0.6	<0.01	58.3
	Year 2	5.8	0.6	3.8	0.5	2	60.0
	Non-irrigated						
	Year 1	5.5	0.4	3.5	0.6	<0.01	71.7
	Year 2	5.9	0.9	4.2	5.6	6	64.3
Kremmling	Irrigated						
	Year 1	6.4	0.4	3.0	0.5	<0.01	134
	Year 2	5.8	0.2	5.0	1.1	1	118.0
	Non-irrigated						
	Year 1	6.7	0.4	3.0	0.6	<0.01	149
	Year 2	6.5	0.4	3.7	0.9	1	125.0
Steamboat Lake	Irrigated						
	Year 1	5.3	0.2	3.0	0.3	<0.01	117
	Year 2	5.2	0.1	3.8	0.3	<0.01	92.8
	Non-irrigated						
	Year 1	5.2	0.2	3.9	0.2	<0.01	114
	Year 2	5.0	0.1	4.9	0.3	1	109.0

Table A3. Soil properties from the upper sample portion (0 to 7.5 cm) from alfalfa hayfields in western Colorado under full and partial season irrigation treatments of stopping irrigation after the 2nd cutting and stopping irrigation after the 1st cutting.

		Soil Property					
Site	Treatment	pH	EC (mmhos/ cm)	OM (%)	NO_3-N (ppm)	Phosphorus (ppm)	Potassium (ppm)
Eckert	Irrigated Control						
	Year 1	7.6	0.5	2.7	11.3	<0.01	201
	Year 2	7.6	0.5	2.9	20.6	2	183.0
	Stop after 2nd (SA2)						
	Year 1	7.8	0.4	2.6	9.6	<0.01	221
	Year 2	7.6	0.4	2.6	15.2	2	151.0
	Stop after 1st (SA1)						
	Year 1	7.8	0.4	3.4	7.4	<0.01	201
	Year 2	7.7	0.5	2.5	16.3	3.5	195.0
Fruita	Irrigated Control						
	Year 1	7.6	2.6	1.4	5.9	0.17	92.1
	Year 2	7.8	0.6	2.4	2.3	7.5	97.1
	Stop after 2nd (SA2)						
	Year 1	N/A*	N/A	N/A	N/A	N/A	N/A
	Year 2	8.0	0.6	1.5	1.9	7.0	83.8
	Stop after 1st (SA1)						
	Year 1	7.5	2.4	1.5	8.3	26.0	119
	Year 2	7.9	0.7	1.5	3.1	12.0	87.2
Yellow Jacket	Irrigated Control						
	Year 1	7.0	0.3	1.2	1.1	2.0	142
	Year 2	6.9	0.3	1.6	10.5	8	156.0
	Stop after 2nd (SA2)						
	Year 1	N/A	N/A	N/A	N/A	N/A	N/A
	Year 2	7.2	0.3	1.4	8.3	2	115.0
	Stop after 1st (SA1)						
	Year 1	N/A	N/A	N/A	N/A	N/A	N/A
	Year 2	7.2	0.3	1.6	7.1	3	144.0

*Plots not sampled in year 1.

Table A4. Soil properties from the lower sample portion (7.5 to 15 cm) from alfalfa hayfields in western Colorado under full and partial season irrigation treatments of stopping irrigation after the 2nd cutting and stopping irrigation after the 1st cutting.

		Soil Property					
Site		pH	EC (mmhos/ cm)	OM (%)	NO_3-N (ppm)	Phosphorus (ppm)	Potassium (ppm)
Eckert	Irrigated Control						
	Year 1	7.7	0.4	2.2	8.3	<0.01	146
	Year 2	7.6	0.4	2.3	10.6	1	134.0
	Stop after 2nd (SA2)						
	Year 1	7.6	0.4	2.2	8.5	<0.01	146
	Year 2	7.7	0.5	2.7	20.3	2	193.0
	Stop after 1st (SA1)						
	Year 1	7.8	0.4	2.6	6.4	<0.01	140
	Year 2	7.8	0.5	2.2	13.8	3	145.0
Fruita	Irrigated Control						
	Year 1	7.8	1.2	1.5	1.6	2.00	85.9
	Year 2	7.9	0.6	1.6	1.7	4.5	83.8
	Stop after 2nd (SA2)						
	Year 1	N/A*	N/A	N/A	N/A	N/A	N/A
	Year 2	8.1	0.9	2.1	1.4	5	80.0
	Stop after 1st (SA1)						
	Year 1	7.7	1.9	1.4	4.1	3.00	102
	Year 2	8.0	0.9	1.9	1.6	6	77.3
Yellow Jacket	Irrigated Control						
	Year 1	7.2	0.3	1.0	0.6	<0.01	110
	Year 2	6.9	0.2	1.6	5.1	2.5	104.0
	Stop after 2nd (SA2)						
	Year 1	N/A	N/A	N/A	N/A	N/A	N/A
	Year 2	7.0	0.3	1.2	4.2	1.5	91.1
	Stop after 1st (SA1)						
	Year 1	N/A	N/A	N/A	N/A	N/A	N/A
	Year 2	7.0	0.3	1.6	2.9	0.5	102.0

*Plots not sampled in year 1.