DETERMINATION OF WATER USE EFFICIENCY FOR FORAGE LEGUMES IN SOUTHERN ALBERTA WITH EMPHASIS ON DRYLAND AND IRRIGATED ALFALFA CULTIVARS

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Dedication

This work is dedicated to my wife Mrs. Eunice Attram for her unconditional love, tremendous support and encouragement and also to our lovely daughter Elizabeth Attram who was my source of inspiration. I also dedicate it to my parents Mr. Joshua and Mrs. Patience Tetteh, my siblings Ananda and Isaac Attram and to my in-laws for their prayers, encouragement and the support they gave during my studies.

Abstract

Field studies were conducted at Lethbridge and Picture Butte in 2012 and 2013 to determine the effects of irrigation water application levels on the dry matter yield, water use efficiency (WUE) and forage quality of irrigated and dryland type alfalfa cultivars. These studies indicated that: 1) Alfalfa cultivars developed for irrigated areas could be irrigated at 75% of the volume applied to the optimal treatment, with 40% depletion of available water at the root zone without incurring drastic yield loss; 2) Both the irrigated and dryland alfalfa cultivars can be irrigated at 75% of the volume of water applied to the optimal treatment, with 40% depletion of available water within 60 - 90% of the root zone with a greater prospect of optimizing WUE of these cultivars under southern Alberta growing conditions; and 3) The height of alfalfa and stage of maturity at the time of harvest affects alfalfa nutritional quality.

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List of Abbreviations

%	Percentage
ADF	Acid Detergent Fiber
ADL	Acid Detergent Lignin
AIMM	Alberta Irrigation Management Model
AITC	Alberta Irrigation Technology Centre
ANOVA	Analysis of Variance
ARD	Alberta Agriculture and Rural Development
B.C.	Before Christ
Blue J	AC Blue J
Ca	Calcium
cm	Centimeter
CO_2	Carbon dioxide
CP	Crude Protein
DDM	Digestible Dry Matter
df	Degrees of Freedom
DM	Dry Matter
DMI	Dry Matter Intake
ERZ	Effective Root Zone
ET	Evapotranspiration or Water Use
FC	Field Capacity
ha	Hectare
IMCIN	Irrigation Management Climate Information Network
K	Potassium
K_c	Crop Coefficient
kg	Kilogram
Longview	AC Longview

LSD	Least Significant Difference
LSR	Leaf-to-Stem Ratio
m	Meter
MAD	Management Allowable Depletion
Mg	Megagram
Mg	Magnesium
mm	Millimeter
MPa	Megapascal
NDF	Neutral Detergent Fiber
^{O}C	Degree Celsius
P	Phosphorus
PAW	Plant-available water
Pr	Probability
PWP	Permanent Wilting Point
RCBD	Randomized Complete Block Design
RFV	Relative Feed Value
SMD	Soil Moisture Depletion at Field Capacity
SSRB	South Saskatchewan River Basin
Syn	Synthetic generation
WUE	Water Use Efficiency
Y	Yield
Zn	Zinc

Chapter One: Introduction

Forages constitute plants that are high in protein and fiber, and mostly consumed by livestock or harvested and processed as feed for livestock (Barnes and Baylor, 1995; Lamp et al., 2007). Forage legumes belonging to *Leguminosae* families are preferred as they provide protein to ruminants and so are considered high in forage quality. Most forage legumes grown in the prairie provinces of Canada; are perennials. They are alfalfa (*Medicago sativa* L.), cicer milkvetch (*Astragalus cicer* L.), sainfoin (*Onobrychys viciifolia Scop.*), and red clover (*Trifiolium pratense* L.). Forage legumes are considered essential to sustainability of agriculture because of their ability to form symbiotic relationships with nitrogen fixing bacteria. This ability to fix nitrogen helps increase yield potential of crops and reduces dependence on nitrogen (N) fertilizer.

Alfalfa is the most extensively grown forage legume across the world, basically because of its high feed value and wide adaptation to different climatic conditions and soil types (Soroka et al., 2011). In Canada, alfalfa is considered the most important forage legume and it is cultivated on over 4.5 million hectares (Statistics Canada, 2002). Along with domestic use for cattle feed, Canada annually exports 350,000 tonnes of alfalfa pellets, making it the leading exporter in the world and the second largest exporter of alfalfa cubes (225,000 tonnes; Agriculture and Agri-Food Canada, 2003). In spite of its significance to livestock production, alfalfa is known as a high water-use crop (Stanberry, 1955; Schneekloth and Andales, 2009). This can be attributed to the fact that it has a deep root system and a longer growing season. In southern Alberta, alfalfa grown under ideal conditions uses between 540 and 680 mm of water in a growing season. Available estimates indicate that alfalfa grown under irrigation uses approximately 100 to

125 mm of water for every ton of hay produced (Efetha, 2011). Alfalfa is the largest single forage legume grown under irrigation in southern Alberta, with approximately 907,000 tonnes produced annually (Dill et al., 2007).

In western Canada and other arid and semi arid regions with erratic rainfall patterns, irrigation is extensively used in the cultivation of alfalfa and other perennial crops. Irrigated agriculture is practiced on approximately 500,000 ha of land in the province of Alberta. This accounts for about 64% of the irrigated cropland in Canada (Statistics Canada, 2001b). Additionally, alfalfa is the largest single forage legume grown under irrigation in southern Alberta, with approximately 907,000 tonnes produced annually (Dill et al., 2007). Unfortunately, the erratic rainfall patterns coupled with the increase in demand for water for livestock production, irrigation, industrial and other domestic purposes pose a threat to alfalfa productivity in this region in the foreseeable future. This competing demand and large irrigated agricultural water extraction is approaching its critical limit at some locations (Corkal and Adkins, 2007). Hence, the provincial government has placed a moratorium on new licence applications for the use of irrigation water within the Bow, Oldman River and South Saskatchewan River Basin (SSRB). It is therefore imperative to explore and adopt strategies that can optimize irrigation efficiency within this province.

Improving water use efficiency (WUE) has been suggested as a means of ensuring efficient use of irrigation water and optimising crop productivity, under limited water conditions. Sheaffer et al. (1988) defined WUE as the biomass (Yield, Y) produced per unit area for each unit of crop water used (ET). WUE is considered as a significant factor for determining the productivity of alfalfa and other crops because, it serves as the basis for evaluating the yield a crop produces, against the use of total water applied. Several studies on alfalfa WUE have been reported with mean annual values ranging between 10 and 25.9 kg ha^{-1} mm^{-1} (Abdul-Jabbar et al, 1983; Grimes et al., 1992; Hirth et al., 2001).

Notwithstanding the fact that there is a tremendous stock of knowledge on WUE for many crops in Canada, the greater part of this knowledge base was built on outmoded assumptions and irrigation technologies (Environment Canada, 2008). Therefore, it is essential that studies on WUE of crops under current conditions using current technologies are undertaken to optimize use of this important natural resource.

The overall objective of this project was to find ways that will facilitate more efficient and productive use of southern Alberta's limited water resources for forage production. Most efficient use of water may help a larger area to be irrigated with the same amount of water. Again, the long-term objective was to determine if low water use cultivars need to be developed. In working toward this long term objective, the following short-term objectives were addressed in this study:

1. to determine how different crop varieties and irrigation regimes affect forage yield;
2. to determine the water use (ET) and water use efficiency (WUE) of both irrigated and dryland alfalfa cultivars under different irrigation regimes; and
3. to determine how different crop varieties and irrigation regimes affect forage quality.

Based on the objectives stated above, we hypothesised that, dryland and irrigated alfalfa cultivars grown under different irrigation water regimes and soil textures produce similar forage yield, water use efficiency and quality. Again we hypothesised that, dryland and irrigated alfalfa cultivars can be grown under different irrigation regimes without sacrificing net economic return to the forage producers. We anticipate that this study will generate a quantitative estimate of the ET and WUE of dryland and irrigated alfalfa cultivars in southern Alberta, and how different irrigation regimes affect both yield and forage quality of these alfalfa types. Additionally, this research will provide a better understanding of the economics of growing different forage crops under different levels of irrigation. Lastly, it may also set the stage for serious consideration of breeding alfalfa cultivar that can be used under reduced water availability.

Chapter Two: Literature review

2.1. History of the crop

Alfalfa, also known as the "Queen of forages", has a long cultivation history (Michaud et al., 1988). It was the first crop to be domesticated by man; and was predominately cultivated and used as forage over 3,300 years ago. Archeological records in Turkey indicate that the Hittites (1400-1200 B.C.) recognized alfalfa as a very valuable and highly nutritious forage, and that they used it as the main source of feed for animals throughout the winter seasons (Bolton et al., 1972). According to Michaud et al. (1988), cultivation of alfalfa predates documented history. It is now found growing wild from China to Spain and from Sweden to North Africa. Additionally, it is now acclimatized to grow in many regions including Australia, New Zealand, South Africa, North and South America.

2.2. Origin and Distribution

Alfalfa, an ancient perennial forage legume is considered to have originated in Vavilov's "Near Eastern Center" which encompasses Asia Minor, Transcaucasia, Iran and the highlands of Turkmenistan (Bolton, 1962; McWilliam, 1968; Whyte, et al., 1953; Wilsie, 1962). Bolton et al. (1972) postulated that the cold winter and hot dry summer climate conditions, coupled with the physical and chemical properties of soils in these geographical locations, enhanced the adaptation of alfalfa to these regions. Soils at these locations are characterised as having a near to neutral pH, are well drained, with sub soils having a high lime content (Klinkowski, 1933; Sinskaya, 1950). Studies conducted by Sinskaya (1950) indicated two centers of origin for alfalfa, namely the mountainous regions of Transcaucasia and central Asia. Conversely, Klinkowski (1933) considered

Media, the north western part of modern Persia as the place of origin of alfalfa. However, Iran is mostly regarded as the place of origin of alfalfa (Bolton et al., 1972).

Available historical records make it impossible to be definitive on how and when alfalfa reached various countries and areas. For example, the oldest known reference to alfalfa is from Turkey (1300 B.C.) and Babylonia (700 B.C.) (Bolton et al., 1972; Michaud et al., 1988). However, Hendry (1923) indicated that the maritime trade which was well developed in the Mediterranean region as early as 4000 B.C. could have contributed to the widespread use of alfalfa. Additionally, the advancement of trade, army invasions during the pre-Christian Era, further enhanced the spread of alfalfa to Asia, Africa and Europe, from its supposed center of origin (Iran) (Michaud et al., 1988). Later introduction of alfalfa to the Americas marked the period of rapid expansion and acceptance of the crop.

2.3. Distribution in Canada and the U.S.

Alfalfa was brought to North America as early as 1736 (Stewart, 1926). Early Missionaries from Mexico were believed to have introduced alfalfa into Texas, Arizona, New Mexico and California (Bolton et al., 1972). Due to the suitable climatic and soil conditions in the southwestern plains of the U.S., alfalfa cultivation spread to Utah and then to its adjoining states. Alfalfa cultivation became pronounced in Kansas by the 1890's (Bolton et al., 1972). The period of 1900 to 1950 witnessed a tremendous increase in cultivated area of alfalfa in the U.S. from 2 million acres to 20 million acres (Bagavathiannan et al., 2009).

The introduction of "Grimm", a winter-hardy alfalfa made it possible for alfalfa to be grown in the northern states of the U.S. and in Canada. Alfalfa was first introduced into Canada in 1871, in the province of Ontario (Armstrong et al., 1942) with seed from Lorraine, France. This seed was developed into a strain known as "Canadian Variegated" (Melton et al., 1988) and was used throughout Ontario, Quebec and the Atlantic Provinces. Now alfalfa is extensively grown in Alberta, Saskatchewan, Manitoba, Ontario and Quebec; on approximately 4-5 million ha of land (Goplen et al., 1980).

2.4. Taxonomy of Alfalfa

Taxonomically alfalfa is classified as:

Kingdom - **Plantae**
Subkingdom - **Trachoheobionta (vascular plants)**
Superdivision - **Spermatophyta (seed plants)**
Divison - **Magnoliophyta (flowering plants)**
Class - **Mangoliopsida (dicotyledons)**
Subclass - **Rosidae**
Order - **Fabales**
Family - **Fabaceae (pea family)**
Tribe - ***Trifolieae***
Genus - ***Medicago***
Species - ***sativa***

Alfalfa occurs both as diploid and tetraploid species although tetraploid cultivars are more common (Brummer et al., 1991). The chromosome number of species in the genus *Medicago* is 2n=16 (Lesins and Gillies, 1972). Although aneuploidy in *M.sativa* is rare, Bolton (1962), indicated that 2n= 4x =31 and 35 have been found. According to Quiros and Bauchan (1988), the genus *Medicago* consists of more than 60 different species, two thirds of which are annuals and one third being perennials. Conversely, Small and Jomphe (1989) indicated that the genus *Medicago* comprises 83 species and 18 infraspecific taxa. The taxonomic nomenclature of these authors further classified alfalfa and the alfalfa complex as infraspecific taxa.

Cultivated alfalfa is an autotetraploid (Stanford, 1951) derived from the *Medicago sativa-falcata* complex, which includes a number of species and subspecies that share the same karyotype (Quiros and Bauchan 1988). *Medicago sativa* ssp. sativa (*M. sativa*), *M. sativa* ssp. *falcata* (*M. falcata*) and *M. sativa* ssp. x *varia* (*M. varia*) are recognized sub-species in the *M. sativa* complex (Frame et al., 1998). The other sub-species as reported by Quiros and Bauchan (1988) include subsp. *caerulea*, subsp. *glutinosa,* subsp. x *tunetana,* subsp. x *ploychroa* and x *hemicycla*. Additionally, the taxa included in the complex are differentiated based on morphology (mainly flower colour, pod shape, and pollen morphology) and ploidy. The subspcieces status of the taxa included in the complex was once considered to be contentious (Sinkaya, 1950; Lensins and Lesins, 1979; Ivanov and Brezhnev, 1988), but recently all of the taxa have been given a subspecific status within the *M. sativa-falcata* complex (Quiros and Bauchan 1988), a nomenclature that has been widely adopted (Şakiroğlu et al., 2010).

2.5. Botanical and morphological perspective of Alfalfa

Alfalfa, *Medicago* spp., is a bushy deep tap-rooted perennial legume that grows to a height of 60-100 cm (Goplen et al., 1980). Alfalfa seeds germinate after absorbing about 125 percent of their weight in water. This water absorption causes the seeds to swell, subsequently breaking the seed coat (Undersander, 2011). The radicle (young root) emerges through the seed coat near the hilum and anchors itself in the soil as an unbranched tap root (Grove and Carlson, 1972). The tip of the radicle continues to grow and penetrate deeper into the soil, while the hypocotyl elongates and pulls the cotyledons and epicotyl (growing point) above the soil surface (Undersander, 2011). Emergence of the cotyledons above ground causes the seed coat to fall. The cotyledons again open to expose the epicotyl.

The epicotyl produces the first foliar leaf, which is a simple, single leaflet (unifoliolate) with a slender petiole (Teuber and Brick, 1988). Subsequent leaves produced on the alternative side of the primary stem are trifoliolate or multifoliolate. These leaves are added as a result of growth of the meristermatic region of the epicotyl (Undersander, 2011). As the epicotyl grows, the first secondary stem is formed from the axillary bud of the unifoliolate leaf (Teuber and Brick, 1988). Subsequent secondary stems develop from the axillary bud at the cotyledon nodes (the point where cotyledons attach to the stem) (Undersander, 2011). Stems that arise from the axillary buds are unifoliolate and the cotyledons form the structure that becomes the primary crown.

The leaves of alfalfa are 1.3-3.8 cm long (Goplen et al., 1980). The first leaf is unifoliate; whereas succeeding leaves are alternate, petiolate, and trifoliate (figure 2.2) (Bolton, 1962). The leaflets vary greatly in shape and size from nearly round to ovate (typical of *M*.sativa), through to obovate and lanceolate (typical of *M.* falcata) (Goplen et al., 1980). Normal leaflets are dentate towards the apex and have a mucronate tip (Bolton, 1962).

The stem of alfalfa is erect, slender, either solid or hollow and grows 1m in height rising from the crown (Goplen et al., 1980; Bagavathiannan et al., 2009). It arises through meristematic activities of the shoot apex (Teuber and Brick, 1988). As the stems age, they become woody at the base and gradually form a compact multiple stem or crown (Figure 2.1). This crown formation is also as result of contractile growth that pulls the axillary buds below the soil surface (Undersander, 2011). The crown is the source of new buds when the crop is cut or grazed, or when new spring growth starts.

Alfalfa varieties and climatic conditions determine the nature of crown formation. In warm climates, varieties with crown above ground-level are prominent; whereas varieties in colder climates form crowns that are partially below the surface (Bolton, 1962). Additionally, varieties with the crowns deep below the soil surface tend to be more persistent than those with shallow crowns because they are protected by the soil from extremely cold air temperatures (Undersander, 2011).

Figure 2.1. Crown of alfalfa.

Figure 2.2. Alfalfa exhibiting trifoliate leaves.

The transition from the vegetative to reproductive growth in alfalfa facilitates the initiation of a flower at the shoot apex (Barnes et al., 1972). This transition takes place between the 6th and 14th node (Dobrenz et al., 1965; Medler et al., 1955) depending on both environmental and genetic factors. Alfalfa flowers grow from the leaf axil and are borne in compact oblong racemes or clusters (Goplen et al., 1980). As few as eight flowers may occur or as many as forty to fifty (Bolton, 1962). Its flower colour ranges from purple or blue (*M. sativa*), to white and yellow (*M. falcata*) or variegated (Goplen et al., 1980). The alfalfa flower possesses both female (pistil) and male (stamen) structures. The flower corollas consist of a large standard petal, two lateral wing petals and two petals united to form the keel. The stamens of alfalfa are diadelphous with nine filaments united to form the staminal column, which is held within the keel. The ovary contains up to fifteen ovules and the stigma is located terminally on a covered style of extremely hard tissue (Bolton, 1962).

Alfalfa is typically cross pollinated because of self-incompatibility and self-sterility. Alfalfa pollination is associated with "tripping". Tripping is the release of the stamen and pistil from the keel petals (Undersander, 2011). Tripping is a prerequisite for effective and efficient pollination and is usually caused by nectar or pollen collecting insects such as the honeybee and leaf-cutter bees. Once the process of tripping and pollination occurs, the pollen fertilizes the ovules within 24 to 32 hours. Each alfalfa flower has between 6 and 18 ovules in its ovary, each of which could potentially become a seed. However, only 10 to 12 ovules usually develop (Undersander, 2011).

After fertilization, the fertilized ovules begin to develop into seeds and stretch the ovary, which becomes the pod surrounding the seed. The pod is 5 to 9 mm in diameter and varies from sickle or crescent to spirally coiled in shape (Bagavathiannan et al., 2009). The seed is kidney-shaped and much smaller than the pod (1-2 mm long, 1-2 mm wide and 1 mm thick) with average count of 465 seed g^{-1} (Teuber and Brick, 1988). Alfalfa seed colour is usually yellow or yellowish brown and olive green to brown. However, white and black seeded genotypes have been reported (Barnes et al, 1967).

One of the most important characteristics of alfalfa is its long taproot system, which often extends deeply into the soil (Figure 2.3). Alfalfa roots can be classified into four general types: tap, branched, rhizomatous, and creeping; all penetrate deeply, 3-9 m into the soil (Goplen et al., 1980). The extent to which roots penetrate is dependent on soil type and soil water level. Israelsen (1950) indicated that, although alfalfa roots may extend deeply into the soil, most of the roots are close to the soil surface. Tap-rooted alfalfas have a main root and narrow, protruding crown: whereas the branch-rooted types have a moderately wide crown and a number of primary roots. Again, the rihizomatous-rooted type spread from the broad crown by horizontal stems that may root at the nodes. Alfalfa plants with creeping roots are more persistent under pasture management and general adverse conditions such as extreme cold and are subject to trampling by livestock (Goplen et al., 1980). Alfalfa root hairs are also capable of establishing a symbiotic relationship with soil borne bacterial; (*Rhizobium meliloti)* and form nodules four weeks after germination. The rate of *Rhizobium* infection depends on the soil nitrogen content and rate of seedling growth (Undersander, 2011).

Figure 2.3. A typical alfalfa root.

2.6. Alfalfa water use efficiency (WUE)

Alfalfa is cultivated extensively under both rainfed and irrigated conditions. In arid and semi-arid areas with erratic rainfall patterns, irrigation is mostly used for maximum production: but water availability in these regions has been the limiting factor to production. Increasing water use efficiency (WUE) will therefore be beneficial in ensuring sustainability of alfalfa production in these regions.

Water use efficiency (WUE) is a broad concept and has been defined in many ways by different authors. In a hydrological sense, Bos and Nugteren (1974) defined WUE as the water content of the root zone following irrigation, expressed as a fraction of the total water supplied to the irrigated area. Physiologically, WUE is considered as the ratio of carbohydrate fixation to rate of water transpired (Loka et al., 2011), while in agronomic terms, it is defined as the biomass (dry matter yield) produced per unit area for a unit of crop water used (Sheaffer et al., 1988; Boyer, 1996). Bolger and Matches (1990) also define WUE as the slope of a linear relationship between biomass to the depth of water used.

Most irrigation management studies in the past used WUE as a major criterion for measuring the productive use of irrigation water and crop productivity, under limited water conditions (Saranga et al., 1999). WUE is considered as a significant factor for determining the productivity of alfalfa and other crops because; it serves as the basis for evaluating crop productivity, against the use of total water applied. Several studies on alfalfa WUE have been reported with mean annual values ranging between 10 and 25.9 kg ha^{-1} mm^{-1} (Abdul -Jabbar et al., 1983; Grimes et al., 1992; Hirth et al., 2001; (Table.2.1)).

Table 2.1. Average total seasonal biomass yield, evapotranspiration (ET), and water use efficiency (WUE) from alfalfa studies under variable irrigation in different locations.

Author	Treatment	Yield (Mg ha^{-1})	ET (cm)	WUE (Mg ha^{-1}cm^{-1})
Daigger et al., 1970	full irrigation	11.5	151.7	0.08
Bauder et al., 1978	dryland	5.8	33.9	0.17
	deficit	9.7	60.2	0.16
	optimum	10.3	64.5	0.16
	excessive	10.8	68.6	0.16
Carter et al., 1983	high	7.4	32.6	0.23
	medium high	7	29.9	0.23
	medium low	5.5	26.4	0.21
	dryland	2.1	17.9	0.12
Wright, 1988	full irrigation	14.7	94.2	0.16
Saeed et al., 1997	frequent	15.3	-	0.12
	less-frequent	12.9	-	0.1
	infrequent	11.2	-	0.08
Kuslu, 2010	full irrigation	10.3	68.8	1.49
	irrigation at 80%	7.6	57.8	1.32
	irrigation at 60%	5.6	47.2	1.19
	irrigation at 40%	3.9	37.2	1.05
	irrigation at 20%	2.7	28.2	0.99
	irrigation at 0%	1.6	18.2	0.9

Source: Adopted and modified after (Lindenmayer et al., 2011).

Saeed and El-Nadi, (1997) reported that alfalfa grown under semiarid conditions should be watered lightly and frequently to attain high yield and high WUE. Again, Carter and Sheaffer (1983) recommended that on coarse-textured soils, moderate water application to alfalfa at 50% depletion of available water could be efficient. A linear relationship between alfalfa yield (Y) and water use (ET) with WUE as the slope have also been established in many irrigation management studies (Carter and Sheaffer, 1983; Undersander, 1987; Smeal et al., 1991). Jodari-Karimi et al. (1983) reported that WUE of alfalfa was higher in deep irrigated treatments than in shallow irrigated treatments. This study also indicated that the rate of root growth increased in non-irrigated alfalfa as a result of limited water stress. Lazaridou and Koutroubas (2004) studied the effect of drought on plant water use efficiency at various phenological stages of berseem clover and alfalfa (Lazaridou and Noitsakis, 2003). Their results indicated a reduction of above ground biomass to one third of irrigated plants (2.3 vs. 6.8 g plant^{-1}) under drought conditions.

Recently, Al-Naeem (2008) studied the performance of alfalfa under stress conditions and determined WUE for optimal forage production under arid conditions in the Al-Ahsa region with its limited irrigation water supply. This study showed high WUE at field capacity and a reduction in dry matter yield for irrigation stress treatments. In another study conducted to evaluate potential water saving strategies on the front range of Colorado (Lindenmayer et al., 2008), the effect of four irrigation strategies were evaluated for ET, WUE, stand density, and forage quality. Their results indicated that on average, up to 282 mm of water were saved in the stress treatments, but a reduction in ET also resulted in yield reduction of up to 6.5 Mg ha^{-1}. Even though reduction in yield was recorded, they determined that an increase in WUE and a decrease in ET resulted in more efficient use of water by the crop. The authors also postulated that the increase in forage quality that was observed was enough to demand a higher sale price which could invariably offset the lost income from reduced yield. It should be mentioned here that the crude protein content of alfalfa can be as high as 20% at the bud stage (Marten et al., 1988) and also that alfalfa produces the greatest amount of forage protein per unit area compared to other legumes (Huyghe, 2003).

Considerable variability in WUE within and among cultivars has also been reported in the past (Cole et al., 1970). Carter et al. (1982) and McIntosh et al. (1981) attributed differences in yield response to soil moisture among alfalfa cultivars to their root characteristics and the rate of transpiration (Cole et al., 1970). Additionally, a study conducted by Grimes et al. (1992) to evaluate WUE of three alfalfa varieties indicated that semi dormant WL318 had a relatively higher WUE than two other varieties tested during a cool spring season, whereas CUF101 and Moapa 69 varieties had a higher WUE in hot summer conditions. Conversely, studies conducted by Hattendorf et al. (1990) and Wilson et al. (1983) to determine water use-yield characteristics of cultivars with different dormancy types, indicated inconsistent results. A two year study conducted by Retta and Hanks (1980) showed no significant difference in biomass yield or water use among varieties Ladak, Washoe and Mesilla. Similarly, Undersander (1987) evaluated WUE for the alfalfa varieties Vangard, Cody, Zia and Dawson. Results obtained from this study showed no significant difference in WUE among the alfalfa varieties for any level of irrigation. Sheaffer et al. (1988) indicated that determination of WUE for different alfalfa cultivars should be done under specific local climatic and soil conditions since these factors influence cultivar ET.

Accurate measurement and determination of WUE is quite challenging, especially when attempting to quantify efficiency throughout the growing season (Loka et al., 2011). This challenge can be attributed to the difficulty in measuring whole-plant carbohydrate matter accumulation and transpiration in the field as well as the inaccuracies associated with scaling from occasional leaf photosynthesis measurements to estimate whole-plant growth and water use (Loka et al., 2011). Therefore in agronomic terms, WUE evaluation at the end of the growing season is based on general measurement of total dry matter produced relative to combined soil water, irrigation and rainfall over the growing season (Loka et al., 2011). A number of factors also influence WUE: these factors could be environmental or due to management practices; some of which include radiation load, temperature, humidity, ambient CO_2 concentration, soil type and structure, soil water availability, nutrition and the genetic composition of the plant (Constable and Rawson, 1980; Lin and Ehleringer, 1982; Zur and Jones, 1984; Reich et al., 1985; Reddy et al., 1995; Loveys et al., 2004).

WUE research is attracting attention in parts of the world where water and precipitation are limited. It is clear that water as a resource for agriculture is becoming less available in semi-arid and arid countries, due to competition for this valuable resource for irrigation, livestock production and other industrial and domestic uses. The situation is expected to worsen due to climate change. It is anticipated that changes in climate will result in changes in precipitation and temperature (Lemmen and Warren, 2004). A warmer climate and unstable precipitation patterns will affect soil moisture, evapotranspiration and these changes would in turn negatively affect crop yield and increase the demand for irrigation water (Kulshreshtha, 2011). The challenge for irrigation experts, plant breeders, and forage producers in arid and semi-arid parts of the globe will be to explore and adopt irrigation management practices that will lead to optimization of the limited water resources and thereby improve WUE in forage legumes.

2.6.1. Strategies to enhance water use efficiency of Alfalfa

Enhancing water use efficiency basically implies the effective and efficient use of current available water to optimize crop output (Passioura, 2006; Ali and Talukder, 2008). The growing demand for limited water resources in some countries where alfalfa is extensively grown has necessitated the need to develop strategies that will lead to improvement of water use and WUE of alfalfa; a forage legume regarded as a high water use crop (Stanberry, 1955; Schneekloth and Andales, 2009). These good water management strategies will ensure the sustainable production of alfalfa in these water challenged environments, thereby complementing the sustainability of the livestock industry as well.

Several strategies have been proposed as a means of enhancing alfalfa water use and WUE. One significant strategy proposed by Putnam (2012) is the enhancement of yield and stand persistence through genetic improvement and agronomic practices. This author argued that because WUE is a ratio of dry matter production and amount of water used and that, increasing the numerator (alfalfa yield) would improve WUE as would decreasing the denominator (water used). Again, this author suggested the use of traditional breeding and biotechnology methods as a means of improving yield; by de-linking the negative relationship of yield and quality, improving root and crown characteristics so plants can extract more moisture from a deeper root profile in the soil under water stress conditions, and improving stand persistence resistance to traffic and stand loss. Stand persistence includes tolerance to flooding and disease, winter kill and ability to withstand frequent traffic and tolerance to heat stress.

Some authors have also proposed deficit irrigation of alfalfa as a means of improving its WUE and water use; and thereby saving water in a water scarce environment. Deficit irrigation is an approach that supplies water at a rate below the full crop water requirement (Carter and Sheaffer, 1983; Undersander, 1987; Grimes et al., 1992; Orloff et al., 2005). Also known as irrigation termination or partial season irrigation (Lindenmayer et al., 2011), this approach focuses on irrigation application in the spring when yield and WUE are greatest and seasonal water use is low, followed by no irrigation in mid-summer and fall when yield decreases and WUE is least (Orloff et al, 2005; Lindenmayer et al, 2011). This high yield and WUE in spring is attributed to the solar irradiance being enough during these months to induce high levels of photosynthesis and temperatures being low enough to keep evapotranspiration at a minimum (Delaney et al., 1974; Leavitt et al., 1979; Smeal et al., 1991). Putnam et al. (2005) employed partial season irrigation in some studies in the US. Their results indicated significant water savings with few long-term impacts on alfalfa stands. Though this approach appears very promising, a study conducted by Ottman et al. (1996) indicated a reduction in alfalfa stand and biomass yield during summer irrigation termination in an arid climate and sandy soil.

The use of efficient irrigation systems and irrigation management techniques have also been suggested as other means of ensuring improvement in WUE of alfalfa and other crops (Putnam, 2012; Alberta Agriculture and Rural Development, 2013). Due to the fact that different irrigation systems have different application efficiencies, producers are required to have a thorough understanding of the efficiencies of these systems in order to make critical irrigation management decisions that can lead to high alfalfa yields, quality and improved WUE. Irrigation system efficiencies can be enhanced through proper selection, operation and maintenance of irrigation pumping units and pipes to avoid leakage and waste of energy; i.e., through upgrade of existing gravity or wheel movement irrigation systems to more efficient low pressure center pivot sprinkler systems that ensure uniform distribution of irrigation water on the field (Alberta Agriculture and Rural Development, 2013). The use of new sprinkler nozzles, developed for low pressure drop-tube center pivot systems has the potential to further increase irrigation efficiency. Variable-rate irrigation technology for pivot irrigation systems also provides another opportunity to enhance WUE, reduce energy costs, and increase water conservation (Alberta Agriculture and Rural Development, 2013). These systems coupled with good irrigation management strategies will help reduce over-irrigation, surface runoff, deep drainage, and flooding which can be detrimental to alfalfa growth and WUE.

2.7. Soil-water-plant relationship

Soil serves as a storage reservoir that holds water for plant growth. It is also the storehouse of plant nutrients, soil microorganisms and an anchorage for plants. Through the process of transpiration and photosynthesis, plants are able to extract water from the soil for the purposes of growth and cooling. Soil water intake and storage capacity of different soils are highly variable and influenced by the soil physical properties. Soil texture, porosity and soil chemical constituents all have a direct bearing on the soil physical characteristics. The particle size of sand, silt and clay constitutes the soil texture: whereas the quantity of water or air a soil can hold is its void space or porosity (Ley et al., 2005).

The water content of soil after being saturated by irrigation and rainfall and allowed to drain freely until the internal drainage of water through the soil profile becomes negligible due to gravity, is known as the field capacity (FC) (Alberta Agriculture and Rural Development, 2013; Ley et al., 2005). It is generally considered as the upper limit of plant available water. At the opposite end of the scale is the permanent wilting point

(PWP), which is the point at which the plant can no longer withdraw water from the soil. In other words, the water left in the soil is being held tightly to the soil surface with a greater tension than the plant can overcome. At this stage of soil moisture, photosynthesis in the plant is slowed down. The plant becomes stunted and looses yield potential even if additional water is supplied (Ley et al., 2005). PWP is considered as the lower limit of plant available soil water and depends upon both plant and soil characteristics. The quantity of water held by the soil between FC and PWP is considered as the plant-available water (PAW). It is also the water available for evapotranspiration and plant growth. The amount of PAW stored in the soil reservoir is commonly expressed as the depth of water per unit depth of soil (Evans et al., 1991) and is dependent on soil water-holding capacity and the effective root zone depth (Alberta Agriculture and Rural Development, 2013). Different textural classes of soils have different PAWs. Plant available water-holding capacity of soil can be obtained from charts that provide information based on soil texture (Table 2.2).

As plants continuously extract water from the soil, PAW in the soil decreases (Evan et al., 1991). However, not all PAW is readily available for plant use: mostly soil water near the PWP is not as readily available and plants will be seriously stressed, which in turn leads to reduction in yield and quality, if the soil moisture level is not replenished. In light of this soil management factor known as management allowable depletion (MAD) (also known as maximum allowable depletion) has been defined (Ley et al., 2005).

Table 2.2. Soil physical characteristics for several texture classes.

Soil texture	Total Porosity	Wilting Point	Field Capacity	Available water holding capacity	
	(%)	(%Volume)	(% volume)	(% volume)	mm m^{-1}
Loamy Sand	40	6	16	10	100
Sandy Loam	42	8	22	14	140
Loam	43	12	30	18	180
Sandy Clay Loam	45	13	29	16	160
Silt Loam	45	10	30	20	200
Clay Loam	47	16	36	20	200
Silty lay Loam	47	18	40	22	220
Sandy Clay	45	20	37	17	170
Silt Clay	47	25	46	21	210
Clay	49	23	42	19	190

Source: Adapted from (Alberta Agriculture, Food and Rural Development, 2004a and 2004b).

MAD is the percentage of PAW at FC that an irrigator allows plants to deplete before initiating irrigation (Burt, 2010). In other words it is the percentage of the total available water which may be safely depleted before moisture stress occurs (Ley et al., 2005). It varies with soil, crop type and crop growth stage, and crop stress tolerance. To ensure an effective and efficient irrigation management program that meets crop water demands, a thorough knowledge of the effective root zone depth (ERZ) and MAD is required (Alberta Agriculture and Rural Development, 2013). MAD values as expressed as a percentage of the PAW at FC in the root zone for various crops are provided in Table 2.3.

Table 2.3. Management allowable depletion for major crops grown in Alberta.

Crops	MAD (% of plant-available water)
Alfalfa hay	40
Barley	40
Canola	40
Dry beans	40
Pea	40
Potato[†]	30-35
Silage corn	40
Spring wheat	40
Sugar beet	40
Timothy hey	40
Winter wheat	50

[†] For potatoes, a MAD of 35 per cent is used for most growth stages except tuber initiation, the growth stages at which 30 per cent of plant -available water is used.

Source: Adapted from (Alberta Agriculture and Rural Development, 2013).

2.8. Irrigation scheduling for alfalfa hay

Irrigation scheduling basically includes decision making on when to irrigate and how much water to apply to meet crop water demands (Irmak et al., 2007). Irrigation scheduling ensures consistent availability of water to plants at the appropriate time the plant needs water. The decision of when to irrigate and how much water to apply is usually based on the soil texture, soil water holding capacity, effective root zone and allowable water depletion by the crop. Proper irrigation scheduling ensures improvement in profitability and water use efficiency by maximizing crop yield and quality, decreasing water lost through deep percolation and runoff, and optimizing pumping cost.

2.8.1. Water requirement

On an annual basis, alfalfa uses more water compared to other crops (Krogman and Hobbs, 1965; Blad and Rosenberg, 1976). This is attributed in part to its long growing season and deep root system that enhances its ability to use moisture deep within the soil

(Irmak et al., 2007). The amount of water used by alfalfa depends on the type of cultivar, stage of growth, canopy density, and harvest date (Efetha, 2011). Annual water use varies from season to season and location to location. In southern Alberta, alfalfa is reported to use about 540 to 680 mm of water per growing season. On a daily basis, especially during the peak season in the months of June, August, and September, alfalfa uses 9 mm, 8 mm and 7 mm of water respectively (Alberta Agriculture and Rural Development, 2013). Alfalfa daily water use in Nebraska has been reported to range between 8 to 9 mm for the month of July and August respectively, and can be as high as 12 mm on hot, windy and dry days (Irmak et al., 2007). Shewmaker et al. (1994) indicated that alfalfa grown at Kimberly, Idaho uses about 923 mm of water per year and under extreme conditions 10 mm per day in mid-summer.

Typically about 70-90% of alfalfa water extraction will be from the top half of the effective root zone (30 cm to 90 cm). This is attributable to the fact that the alfalfa root distribution is concentrated near the soil surface, though roots can extend as far as 120 cm deep into the soil profile (Alberta Agriculture and Rural Development, 2013). It is therefore important that particular attention is given to the moisture status in the top section of the soil profile during irrigation scheduling such that irrigation is initiated when about 50-60% of the PAW in this section is depleted. This is to avoid water stress which can lead to loss of yield potential.

Irrigation scheduling methods for alfalfa and other crops are classified into three categories: plant-based, soil based and ET-based method (Alberta Agriculture and Rural Development, 2013). These methods can vary in complexity and hence, may require the use of technology.

2.8.2. Plant-Based Methods

This method of irrigation scheduling is based on the fact that plant growth has a direct relationship with plant water status and only indirectly is related to soil moisture and atmospheric conditions (Alberta Agriculture and Rural Development, 2013). This implies that, the plant is able to integrate its soil water and atmospheric conditions, in its growth process (USDA, 1991). This method involves observation of a crop to assess changes in plant characteristics such as change in leaf colour, curling of leaves and signs of wilting (SIA Platform, 2010). Plants under water stress exhibit slow or no growth (fewer young leaves, darker in colour) (SIA Platform, 2010). Alfalfa grown under an adequate water environment is typically light green but changes to a dark colour as moisture stress develops (Irmak et al., 2007). Though this method of irrigation scheduling is considered quick, popular and easy, it does not indicate the amount of irrigation water to apply at any given time. With this method, water stressed plants which do not manifest stress characteristics in time will lose yield potential by the time water stress becomes apparent in the plant (Jones, 2004).

2.8.3. Soil-Based Methods

The soil-based method involves determination of the amount of water required to bring soil moisture in the root zone to field capacity. This is achieved by directly or indirectly measuring the amount of water in the soil (Alberta Agriculture and Rural Development, 2013). Several tools and techniques for direct and indirect measurement of soil water are available some of which include soil feel and appearance, gravimetric sampling, tensiometers, porous block, neutron probe, and frequency domain reflectometry (Ley et al., 2005). Soil measurement tools and methods have been thoroughly reviewed (Shemugge et al., 1980; Gardner, 1986; Stafford, 1988; Campbell and Mulla 1990; and Phene et al., 1990). These tools are typically calibrated for the soil in which they are used. For an effective and efficient irrigation scheduling, soil water content is monitored on a weekly basis throughout the growing season (Woods, 2006), to determine the right amount of irrigation water and the timing of application.

2.8.4. Evapotranspiration (ET) - based Methods

Evapotranspiration (ET) also referred to as crop water use, is the water used by a crop for growth and cooling purposes (Al-Kaisi, and Broner, 2009). It evaluates loss of water from the surface of the soil and from crops by evaporation and transpiration (Allen et al., 1998). The ET-based method is sometimes referred to as a weather based method (Alberta Agriculture and Rural Development, 2013), the water budget method (SIA Platform, 2010), or check book method (Evans et al., 2004). This method essentially tracks and accounts for water that is lost by crop evapotraspiration (ET) and addition of water by effective rainfall and irrigation (SIA Platform, 2010; Henggelar et al., 2011). ET is influenced by the prevailing weather conditions, available water in the soil, and crop characteristics (Allen et al., 1998; Al-Kaisi and Broner, 2009). The key weather parameters that affect ET include air temperature, solar radiation, humidity and wind speed; whereas crop characteristics include crop type, variety and growth stage. Additionally, crop height, ground cover and crop rooting characteristics results in different ET levels for different types of crops grown under identical environmental conditions (Allen et al., 1998). To standardize ET measurements and calculations, a reference crop ET (ET_o) is used to estimate actual ET for other crops (Al-Kaisi and Broner, 2009). ET_o is the evapotranspiration rate from a reference surface not short of water (Allen et al., 1998). Grass is normally used as the reference ET crop in humid and semi-humid areas, whereas alfalfa is typically used in arid and semi-arid areas due to its deep root system and ability to go into dormancy when water is not available (Al-Kaisi and Broner, 2009).

Crop evapotranspiration (ET_c) refers to evapotranspiration from disease-free, well fertilized crops, grown under optimum soil water conditions in a field, achieving full production under given conditions (Allen et al., 1998). The easiest and most common method to estimate ET_c is to use the water balance method which estimates ET_c as: $ET_c = ET_o$ x K_c; where K_c is the crop coefficient (ie., $K_c = ET_c / ET_o$) (Snyder et al., 2008). ET_o is measured from weather data. ET-based water balance irrigation scheduling methods are gaining prominence and are being used extensively across the world; because they are easy to apply (Jones, 2004). Again, this method indicates “how much” water and “when” to apply as opposed to the plant-based method. Conversely, the ET based method tends to be less accurate when compared to soil water measurements. This is attributable in part to the fact that the ET-based method requires an accurate local estimate of precipitation and runoff, a good estimate of crop and soil coefficients and regular maintenance and calibration of weather monitoring instruments (Alberta Agriculture and Rural Development, 2013).

Several weather station networks are responsible for collecting data that are in turn used for ET-based irrigation management, such as “AgrimMet” in the Pacific Northwest US (Palmer, 2011) and the Irrigation Management Climate Information Network (IMCIN) in Alberta (Alberta Agriculture and Rural Development, 2013). The weather parameter information gathered from these station networks is used to develop models for crop ET estimation. For instance, in Alberta, crop water requirements are typically estimated from the IMCIN website and by the Alberta Irrigation Management Model (AIMM) (ARD, 2011b). The IMCIN calculator, known as IRRI-Cast and the AIMM employs the modified Penman-Monteith equation (Monteith, 1965) to estimate ET (Jensen et al., 1990).

2.9. Alfalfa yield and forage quality

Several authors have defined forage quality in diverse ways: Ball et al. (2001) defined forage quality as the extent to which forage has the potential to produce a desired animal response. It also refers to how well animals consume a forage and how efficiently the nutrients in the forage are converted into animal products (Linn and Martin, 1989). Additionally, Cherney and Hall (2000) defined it as the sum total of plant constituents that influence animal use of feed. High quality forages are crucial for the livestock industry. They furnish essential energy, proteins, vitamins, minerals and fiber to livestock when used as feed. In fact diets of most domestic and commercial livestock consist principally (if not entirely) of forages (Caddel and Allen, 2000).

Alfalfa is one of the forages used extensively in the production of most highly productive livestock. It is considered as superior to other forage crops because of its high crude protein and energy content. Proper management of alfalfa enhances the yield produced at the end of the growing season while maintaining high nutritive value of the forage (Kephart et al., 1989). Alfalfa yield and quality can be influenced by both biotic and abiotic factors; which include growing conditions, effect of harvesting time and frequency, soil fertility, temperature, water deficit, solar radiation and the presence of disease and insect pests (Buxton, 1996; Hill et al., 1988). The stage of maturity and time of harvesting are considered the most important factors that influence alfalfa yield and quality; as the alfalfa plant matures, its fiber and lignin content increases; whereas, there is a decrease in crude protein, digestibility and metabolizable energy plant maturity. According to Buxton (1996), a week delay in harvesting decreases digestibility and crude protein concentration by about 20 g kg^{-1} and an increase in cell-wall concentration of approximately 30 g kg^{-1}. This negative relationship between alfalfa advancing maturity and declining forage quality is well established (Hintz and Albrecht, 1991; Sanderson, 1992; Sulc et al., 1997). Early harvesting improves the quality of alfalfa but often reduces yield. Frequent early harvest also tends to reduce stand longevity.

Although little quality changes occur in forage leaves, a greater portion of the decline in forage quality is mostly attributed to the marked decrease in the quality of the stem (Albrecht et al., 1987; Barnes and Gordon, 1972; Buxton and Hornstein, 1986). Studies conducted by Christian (1977); Griffin et al. (1994) and Kalu et al. (1981) indicated that high summer temperatures also contribute to the decrease in alfalfa quality as it advances in maturity. High temperature normally increases the rate of plant development and thus reduces leaf to stem ratio and digestibility (Buxton, 1996). Additionally, the neutral detergent fiber (NDF) of forages grown under high temperatures tends to be less digestible due to increased lignification (Buxton and Fales, 1994). Water stress has also been shown to affect alfalfa yield (Schofield, 1945; Kramer, 1962; Lucey et al.1965) and quality (Gifford et al., 1967; Jensen et al, 1967).

Alfalfa yield declines once the plant under goes water stress, that results in plant water potential falling below -1.0 to -1.5MPa (Kohl and Kolar, 1976; Carter and Sheaffer, 1983; Grimes et al., 1992). The plant closes its stomata in response to the water stress conditions to maintaining turgor. This stomatal closure prevents CO_2 from entering the plant hence affecting carbon fixation, photosynthesis and growth (Ottman, 1999). Alfalfa forage quality is typically increased by water stress compared to plants grown under well watered conditions (Wilson, 1982, 1983a, 1983b). Water stress slows down maturation (Halim et al., 1989) thus slowing growth (Brown and Tanner, 1983) which results in an increase in the leaf-to-stem ratio (Halim et al., 1989; Bolger, 1988). A study conducted by Halim et al. (1989) indicated an increase in leaf-to-stem ratio (LSR) from 0.60 in an optimally watered treatment to 0.72 in a severely stressed treatment. Conversely, if the water stress is so severe to reduce leaf mass through senescence, forage quality can decrease (Ottman, 1999). Water stress has also been reported to decrease cell wall concentration (Halim et al., 1989; Deetz et al., 1996) but not necessarily cell wall degradability (Deetz et al., 1996). Kidambi et al. (1990) and Buscaglia et al. (1994) observed an increase in mineral concentration (Ca, Mg, Zn, K and P) in whole plants due to water stress; but the effect of water stress on crude protein in some studies has been inconsistent (Vough and Marten, 1971; Snaydon, 1972; Carter and Sheaffer, 1983).

Alfalfa forage quality is determined based on leaf-to-stem ratio, degree of lignification, palatability, digestibility (fiber) and crude protein content (Elliott et al., 1972). The crude protein content is normally determined indirectly by measuring the amount of N in the forage and multiplying that value by 6.25. It is assumed that N constitutes about 16% of tissue protein in the forage (100/16= 6.25) (Newman et al., 2006); whereas the fiber component is divided into two groups: acid detergent fiber (ADF) and neutral detergent fiber (NDF). NDF measures the cellulose, hemicellulose and lignin portion of the cell wall (structural carbohydrates or sugars) within the forage tissues (Newman et al., 2006). NDF is inversely related to intake; in other words the higher the NDF percentage in forage, the lower the intake. Thus a low percentage NDF is desirable. ADF on the other hand is a sub-fraction of NDF (Robinson et al., 2007) and represents the cellulose, lignin, and silicon portion of the cell wall. Silica and lignin in plants are linked with low digestibility. High ADF values are associated with decreased digestibility; hence a low ADF percentage is desired.

Estimated energy values of feedstuff from ADF and NDF is used in the computation of relative feed-value (RFV) index (Table 2.4); which is a forage quality pricing index (Shroyer et al., 1998). It is the most widely used system in predicting forage quality (Rohweder et al., 1978). RFV grades forages based on their predicted dry matter intake (DMI), the product of DMI and percentage of DDM (Hackmann et al., 2008; Table 2.4). Forage quality information generated through testing is essential for formulating nutritional balanced rations, developing and allocating forage inventories, evaluating forage management practices (growing, harvesting and storage) and marketing and pricing forages (Linn and Martin, 1989).

Table 2.4. Market hay grades for legumes, legume-grass mixture quality standards.

Quality standard [β]	**CP**	**ADF % of DM**	**NDF % of DM**	**RFV** [φ]
Prime	>19	<31	<40	>151
1	17-19	31-40	40-46	151-125
2	14-16	36-40	47-53	124-103
3	11-13	41-42	54-60	102-87
4	8-10	43-45	61-65	86-75
5	<8	>45	>65	<75

[β] Standard assigned by Hay Market Task Force of America Forage and Grassland Council; [φ] Relative Feed Value (RFV).

- Reference hay of 100 RFV contains 41% ADF and 53% NDF.

Source: Adopted from (Kiraz, 2011).

2.10. Alfalfa Breeding Methods

Alfalfa is a primitive perennial forage legume; i.e., an autotetraploid with a base chromosome number of x=8 that exists at two ploidy levels (diploid , 2n=2x=16 and tetraploid 2n=4x=32) (Li and Brummer, 2012). Alfalfa is naturally an outcrossing species mostly cross-pollinated by leaf cutter bees. It exhibits genetic self-incompatibility or self-sterility and therefore successful self-pollination or inbreeding is minimal (Viands et al., 1988). Occurrence of self-pollination in alfalfa leads to inbreeding depression in most cases, resulting in a dramatic reduction in forage and seed yield potential (Rumbaugh et al., 1988). Consequently, commercial alfalfa breeding programs are designed in a way to prevent significant inbreeding and the resulting negative effects of inbreeding depression (Rumbaugh et al., 1988). In most of these breeding programs, alfalfa varieties are bred as synthetic varieties. These varieties are maintained through multiple seed generations via open-pollination of their progenies in isolation from other pollen sources; hence making each individual plant within the synthetic varieties genotypically and phenotypically different.

Alfalfa breeding involves the use of simple methods of selection such as mass selection, recurrent phenotypic selection, backcrossing method and progeny test selection (Milić, 2011). Though mass selection was the initial method for genetic improvement of alfalfa genotypes; recurrent phenotypic selection is extensively used in most alfalfa breeding programs (Wiersma, 2001). Recurrent phenotypic selection method of breeding involves intercrossing of selected parents to produce a synthetic variety (Hill, 1987; Riday and Brummer, 2002). The selected intercrossed parents (Sny 0) produce the first synthetic generation (Syn 1) which is further used to advance subsequent generations (i.e., Syn 3 or Syn 4) (Rumbaugh et al., 1988; Casler et al., 1996; Brummer, 1999).

Chapter Three: Evaluation of forage yield of both irrigated and dryland type alfalfa cultivars under different irrigation treatments in southern Alberta

Abstract

Field studies were conducted at Lethbridge in 2012 and 2013 and at Picture Butte in 2012 to determine the effects of irrigation on the dry matter (DM) yield of two types of alfalfa cultivars. The irrigated cultivars (Longview and Blue J) and dryland cultivars (Rangelander and Rambler) were arranged on plots in a randomized complete block design with five replications and were subjected to four irrigation treatments. For the optimal irrigation treatment (W_1), soil water content was maintained between 60 - 90% of available water in the designated root zone. Other irrigation treatments received 75% (W_2), 50% (W_3) and 25% (W_4) of the volume of water applied to the optimal treatment. Mean total forage yields were higher at Lethbridge (10.15 Mg ha^{-1}) compared to Picture Butte (6.21 Mg ha^{-1}). The mean DM yields of irrigated alfalfa cultivars were higher than dryland cultivars in both locations. The Cut 1and Cut 2 yields and plant heights were greater than that of Cut 3 for both locations and years. Generally, mean total DM yield for Blue J, Longview and Rambler for W_2 and W_3 at Lethbridge were higher than those of W_1, although the differences were not always significant. The DM yields obtained from this study indicated that alfalfa cultivars developed for irrigated areas of western Canada can be irrigated at 75% of the volume applied to the optimal irrigation treatment, with 40% depletion of available water at the root zone without incurring drastic yield loss.

3.1. Introduction

Alfalfa, also known as the “Queen of forages”, is an ancient forage legume grown extensively across the world due to its high feed value and wide adaptation to different climatic conditions and soil types (Soroka and Otani, 2011). It is cultivated on over 30 million hectares worldwide (Michaud et al., 1988). In Canada, alfalfa is considered the most important forage legume and it is cultivated on over 4.5 million hectares (Statistics Canada, 2002). Several studies to determine the effect of different irrigation treatments on the consumptive water use and yield across different regions have been documented (Daigger et al., 1970; Bauder et al., 1978; Retta and Hanks, 1980; Sammis, 1981; Guitjens, 1982; Carter and Sheaffer, 1983; Undersander, 1987; Smeal et al., 1991). Lindenmayer et al. (2011) reported an annual biomass yield of 16.6, 11.1 and 6.0 Mg ha^{-1} under full irrigation, deficit irrigation treatments and dryland conditions respectively. Lindenmayer et al. (2008) again reported a total season yield of 18.3, 13.7, 13.3 and 8.8 Mg ha^{-1} for full irrigation, stop irrigation after 2nd Cutting, spring and fall irrigation and stop irrigation after 1st Cutting treatments respectively in northern Colorado. Saeed et al. (1997) also presented a maximum yield of six cuttings; 15.3, 12.9 and 11.2 Mg ha^{-1} for frequent, less frequent and in-frequent irrigation treatments in Sudan. Another study conducted by Ismail and Almarshadi (2013) in Saudi Arabia showed that the highest fresh yield was obtained under field capacity (FC) level, followed by 85% and 70% FC respectively. Campbell et al. (1960) also observed a slight increase of 0.4 Mg ha^{-1} per year in alfalfa trial with irrigation up to FC compared to non-irrigated treatments. Yield reduction due to over-irrigation (Stanberry, 1955; Peterschmidt et al., 1979) and deficit irrigation (Lucey and Tesar, 1965; Stewart and Hagan, 1969; Saeed and El-Nadi, 1997; Al-Naeem, 2008; Ismail and Almarshadi, 2013) have also been reported.

Alfalfa is a high water-use crop (Stanberry, 1955; Schneekloth and Andales, 2009). In southern Alberta, alfalfa is considered as the major single forage legume grown under irrigation with approximately 907,000 tonnes produced annually (Dill et al., 2007). Notwithstanding these facts, erratic rainfall patterns in Alberta coupled with the increase in demand for water for irrigation, livestock production, industrial and other domestic purposes pose a threat to alfalfa cultivation in the foreseeable future. These competing demands and the large volume of irrigated agricultural water extraction are approaching their critical limit in some locations (Corkal and Adkins, 2007). Hence, the provincial government has placed a moratorium on new licence applications for the use of irrigation water within the Bow, Oldman River and South Saskatchewan River Basin (SSRB). It is therefore imperative to explore and adopt management strategies that can lead to the optimization of the limited water available for irrigation for forages such as alfalfa. The objective of this study was to determine the effect of different irrigation treatments on the yield of both irrigated and dryland type alfalfa cultivars grown in southern Alberta.

3.2. Materials and Methods

3.2.1. Plot Location and Experimental Design

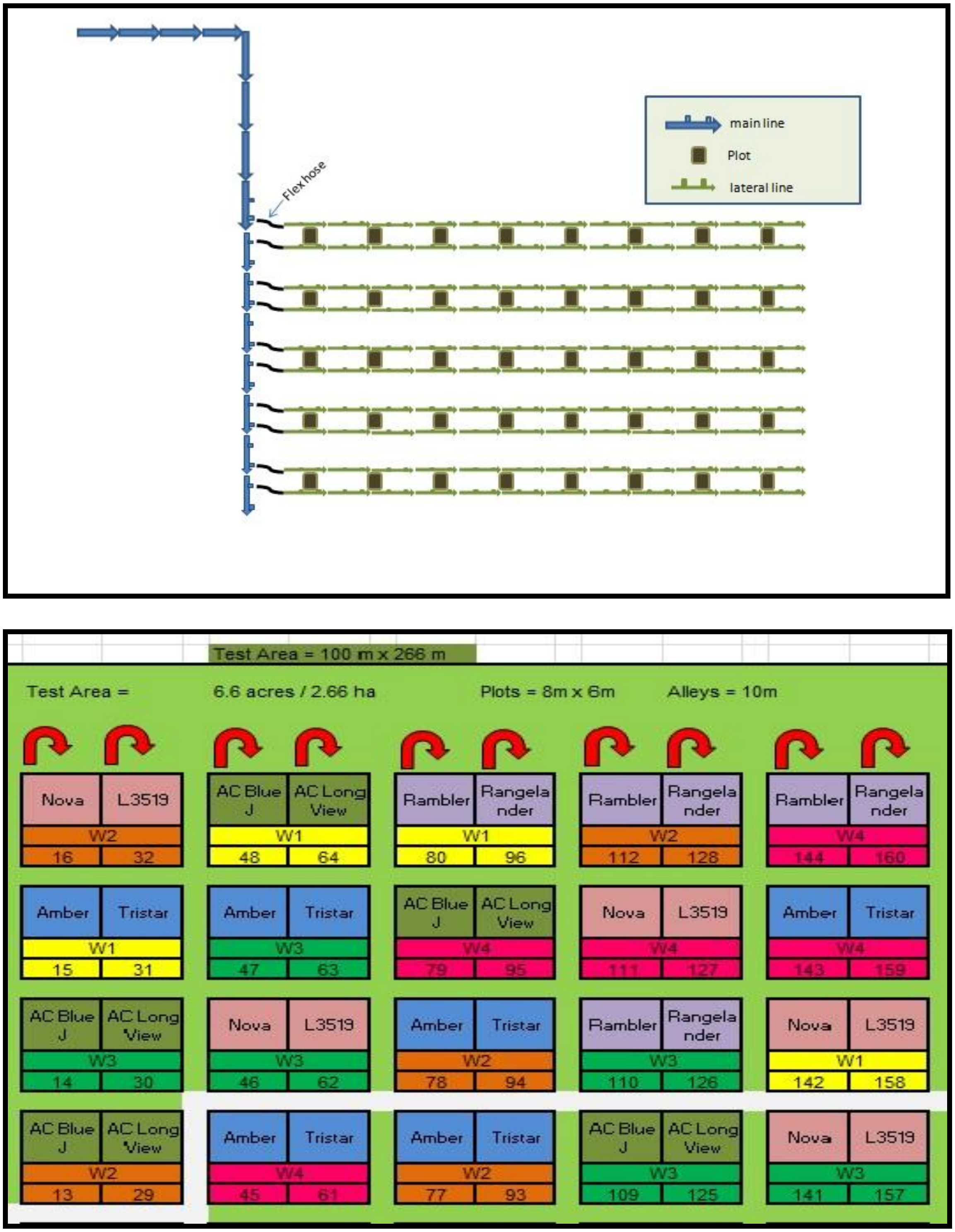
Two field experiments were conducted at two different locations in southern Alberta. The first experiment was located at Lethbridge Alberta Agriculture and Rural Development (ARD), Alberta Irrigation Technology Centre (AITC) (Lat. 49^o 45' N and Long. 112^o 45' W, 900 m elevation) and the second at Picture Butte (Lat. 49^o 55' N, Long. 112^o 48' W, 950 m elevation) on a farmer's field. Both sites were located on Orthic Dark Brown Chernozemic soil. Alfalfa cultivars used in this study were grown on plots arranged in a randomized complete block design (RCBD), with five replications and four irrigation water treatments. The experimental site at Lethbridge ARD AITC and Picture Butte were divided into 80 and 40 individual plots, respectively. The site at Lethbridge occupied a total area of 2.67 hectares, while that at Picture Butte had a total size of 1.21 hectares. Each plot had a dimension of 6 m by 6 m with a sprinkler in each of the four corners. A buffer zone of 10 m was maintained between each plot to minimize the effect of irrigation water drift from adjacent sprinklers.

3.2.2. Crop Agronomics

High-yielding alfalfa cultivars for dryland (Rangelander and Rambler; Heinrichs et al., 1958; Heinrichs et al., 1979) and irrigation (Blue J and Longview; Acharya et al., 1995; Acharya and Huang, 2000) were seeded in 2010 on both experimental sites. These alfalfa cultivars were selected based on their adaptation to different moisture conditions and root features. The crops were seeded with a custom built 10 row small plot forage seeder, at a rate of 10 kg ha^{-1}, with 0.2 m row spacing and at a depth of about 0.019 m. Though the focus of this study was on alfalfa, two sainfoin (Nova, L3519) and two fenugreek (Amber, Tristar) cultivars were also grown in addition to the alfalfa cultivars on the Lethbridge experimental site. Information from these sainfoin and fenugreek cultivars are not presented. The two varieties of each alfalfa cultivar type were grown on the same 6 m by 6 m plot, with each variety grown 3 m on both sides of a neutron probe access tube inserted in the middle of the plots (Figure 3.1).

3.2.3. Irrigation Water System and Treatments

The plots were irrigated using a solid set sprinkler irrigation system with the following pipe dimensions; 0.15 m x 12.19 m main lines and 0.08 m x 12.19 m lateral lines, with a 0.019 m x 0.61 m riser above the soil surface at the four corners of each plot, Nelson R2000 ROTATORS® and Nelson Low-Angle (7 degrees) sprinkler heads were used at the Lethbridge and Picture Butte sites respectively. The main lines at the Lethbridge site were connected to a lateral line through a 0.25 m diameter flex hose (Figure 3.1). The irrigation water at the Picture Butte site was delivered to each plot via a system of underground pipes, which were installed several years prior to this study. The plots were subjected to the four irrigation treatments. For the optimal irrigation treatment (W_1), soil water content was maintained between 60% and 90% of available water in the top 75 cm root zone (Chapter 4, Figure 4.1). Other irrigation treatments received 75% (W_2), 50% (W_3) and 25% (W_4) of the volume of water applied to the optimal treatment. The optimal irrigation treatment (W_1) was managed to maintain soil water content between 60% and 90% of available water in the top 75 cm root zone as shown in Figure 4.1 (Chapter 4) for the first year.



Test Area = 100 m x 266 m

Test Area = 6.6 acres / 2.66 ha Plots = 8m x 6m Alleys = 10m

Nova	L3519	AC Blue J	AC Long View	Rambler	Rangelander	Rambler	Rangelander	Rambler	Rangelander
W2		W1		W1		W2		W4	
16	32	48	64	80	96	112	128	144	160
Amber	Tristar	Amber	Tristar	AC Blue J	AC Long View	Nova	L3519	Amber	Tristar
W1		W3		W4		W4		W4	
15	31	47	63	79	95	111	127	143	159
AC Blue J	AC Long View	Nova	L3519	Amber	Tristar	Rambler	Rangelander	Nova	L3519
W3		W3		W2		W3		W1	
14	30	46	62	78	94	110	126	142	158
AC Blue J	AC Long View	Amber	Tristar	Amber	Tristar	AC Blue J	AC Long View	Nova	L3519
W2		W4		W2		W3		W3	
13	29	45	61	77	93	109	125	141	157

Figure 3.1. The design of the experimental field at Lethbridge. W_1, W_2, W_3 and W_4 represents the irrigation treatments whereas the number represent plot ID.

This approach was similar to what Woods and McKenzie, (2011) used in their water use efficiency studies for cereals and oilseeds. In the second year the root zone for irrigation management at Lethbridge was changed to 100 cm due to alfalfa root extension (Chapter 4, Figure 4.2). The project was terminated at the Picture Butte site in the second year due to manpower limitations.

3.2.4. Soil Moisture Monitoring

In order to schedule irrigation, soil moisture readings were taken two times per week (Mondays and Thursdays) using a neutron probe (a Boart Long Year, CNP® 503DR Hydro probe) at 25 cm increments, to a 100 cm depth of root zone, from a 2 m aluminium tube fixed close to the center of each plot. In order to reduce exposure to the radioactive element in the probe, on the individual taking the moisture readings, neutron probe readings were taken on all plots on Mondays whereas on Thursdays readings were taken in the trigger plots only (plots that received irrigation treatment W_1).

3.2.5. Harvest

A Hege 212™ Forage Harvester was used to remove 1.55 m by 6 m strips from each plot on both sides of the access tube located at the center of all plots leaving stubble of about 12 cm above the ground. A total of three harvests (Cuts) were made on each experimental site. Harvesting was done on July 10, August 28 and October 16, 2012 at the Picture Butte site, while crops at Lethbridge were harvested on July 12, August 29 and October 17, 2012. In 2013 harvesting was only done at Lethbridge on July 3, August 22 and October 15. The samples were dried at 60°C for 48 hours to determine the dry matter content which was in turn used to calculate the total yield produced on a dry matter basis.

3.2.7. Statistical Analyses

All data collected were analysed using the mixed model procedure for repeated measure (SAS Institute Inc., 2011) with cut as the repeated factor. The cultivar, irrigation treatment and cut were modeled as fixed effects while the replication and its interactions with the fixed effects were random effects. The output measures analyzed included plant height, and yield. The LSD test ($P< 0.05$) was used for mean separation.

3.3. Results and Discussion

3.3.1. Forage height

There was a significant water x cut ($P<0.05$) interaction for height at both the Lethbridge and Picture Butte locations in 2012 (Table 3.1). The cultivar x cut interaction was also significant ($P<0.05$) for height at Picture Butte in the same year (Table 3.1). The main effect for cut was used in indicating the range for forage height at the Lethbridge location in 2013 since the interactions were not statistically significant ($P<0.05$). The mean forage height for all three harvests (i.e., Cut 1, 2 and 3) in relation to the water treatments ranged from 22.8 to 86.3 cm in 2012 at Lethbridge (Table 3.2), whereas that of Picture Butte in the same year ranged between 13.0 and 71.0 cm (Table 3.4). The mean forage height recorded at Lethbridge alone in 2013 ranged between 40 and 78 cm (± 1.35, standard error). Al-Naeem (2008) reported that alfalfa height ranged from 22.9 to 46.8 cm for different irrigation treatments in Saudi Arabia. Goplen et al. (1980) also indicated that alfalfa grows to a height of 60 to 100 cm in Canada. Forages were harvested in a 10 - 20% flowering stage for Cut 1 and Cut 2 and in a vegetative to early bud stage for Cut 3 at both locations and years. The mean forage height values for cuts in relation to all the water treatments at Lethbridge in 2012 was Cut 1 > Cut 2 > Cut 3 (Table 3.2), whereas that of Picture Butte in the same year was Cut 2 > Cut 1 > Cut 3 (Table 3.4).

Table 3.1. Degrees of freedom (df) and probability (Pr) of F values for forage height among irrigation treatments, cultivars and cuts as determined by a mixed model repeated measure ANOVA at the Lethbridge and Picture Butte locations in 2012.

	Lethbridge		Picture Butte	
	2012		2012	
Effect	**df**	**Pr of F**	**df**	**Pr of F**
cultivar	3	<0.001	3	0.178
water	3	0.649	3	0.001
cut	2	<0.001	2	<0.001
cultivar x water	9	0.705	9	0.472
cultivar x cut	6	0.154	6	0.042
water x cut	6	0.044	6	0.001
cultivar x water x cut	18	0.798	18	0.619

Table 3.2. [†]Mean forage height among four irrigation treatments in relation to three cuts at the Lethbridge location in 2012.

Cuts	**W_1 (cm)**	**W_2 (cm)**	**W_3 (cm)**	**W_4 (cm)**
Cut 1	80.0a B	83.8a AB	82.5a AB	86.3a A
Cut 2	72.5b A	75.5b A	75.5b A	72.0b A
Cut 3	26.9c A	24.6c AB	25.4c AB	22.8c B

Mean values within each row followed by the same uppercase letter are not significantly different (P<0.05). Mean values within each column followed by the same lowercase letter are not significantly different (P<0.05).

[†] Means calculated from five replications.

Table 3.3. [†]**Mean forage height among three cuts in relation to four alfalfa cultivars at the Picture Butte location in 2012.**

Cultivars	Cut 1 (cm)	Cut 2 (cm)	Cut 3 (cm)
Blue J	44.4a B	69.3a A	22.8ab C
Longview	44.4a B	67.9a A	23.5a C
Rambler	44.3a B	62.1ab A	23.5a C
Rangelander	44.3a B	55.9b A	18.3b C

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each column followed by the same lowercase letter are not significantly different ($P<0.05$).

[†] Means calculated from five replications.

Table 3.4. [†]**Mean forage height among four irrigation treatments in relation to three cuts at the Picture Butte location in 2012.**

Cuts	W_1 (cm)	W_2 (cm)	W_3 (cm)	W_4 (cm)
Cut 1	45.0b A	46.3b A	45.0b A	41.3b A
Cut 2	71.0a A	67.4a A	68.9a A	47.9a B
Cut 3	27.9c A	22.8c A	24.4c A	13.0c B

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each column followed by the same lowercase letter are not significantly different ($P<0.05$).

[†] Means calculated from five replications.

Similarly, the mean forage height values for the three cuts in relation to all of the cultivar types at this same location followed Cut 2 > Cut 1 > Cut 3 (Table 3.3). The mean forage height for Blue J and Longview Cut 2 in 2012 at Picture Butte was not significantly different from that of Rambler but were significantly ($P<0.05$) greater than that of

Rangelander. Similarly, the mean forage height for Longview Cut 3 was not different from those of Blue J and Rambler, but was significantly ($P<0.05$) greater than that of Rangelander (Table 3.3).

The relatively taller plants for Cut 1 and 2 corroborates the higher yields for both Cut 1 and 2 that was recorded at both locations and years in this study. Orloff et al. (2005) argued that spring and early summer harvests are typically higher in yield than late summer or fall harvest, and that the reduction in yield during fall could be due to the decline in temperature and day length and the resulting decline in potential evapotranspiration (ET_o). Shortened day length and temperature decline during late summer and early fall resulted in greater amounts of photosynthate partitioning into root reserves rather than being utilised for plant growth. This stored photosynthate is subsequently used for growth in spring resulting in a lower biomass yield in early fall (Hanson et al., 1988). This could partly account for the relatively shorter plant heights observed for Cut 3 at both locations and years in this study.

Table 3.5. Degrees of freedom (df) and probability (Pr) of F values for dry matter yield among irrigation treatments, cultivars and cuts as determined by a mixed model repeated measure ANOVA at the Lethbridge in 2012, 2013 and at the Picture Butte location in 2012 respectively.

	Lethbridge				Picture Butte	
	2012		2013		2012	
Effect	**df**	**Pr of F**	**df**	**Pr of F**	**df**	**Pr of F**
cultivar	3	<0.001	3	<0.001	3	0.011
water	3	<0.001	3	0.021	3	<0.001
cut	3	<0.001	3	<0.001	3	<0.001
cultivar x water	9	0.002	9	0.008	9	0.001
cultivar x cut	9	<0.001	9	<0.001	9	<0.001
water x cut	9	<0.001	9	0.271	9	<0.001
cultivar x water x cut	27	0.001	27	0.001	27	0.001

Table 3.6. [†]Mean dry matter yield among four irrigation treatments for four alfalfa cultivars in relation to three cuts at the Lethbridge location in 2012.

Cuts	**Cultivars**	**W_1 (Mg ha^{-1})**	**W_2 (Mg ha^{-1})**	**W_3 (Mg ha^{-1})**	**W_4 (Mg ha^{-1})**
1	Blue J	5.57 b AB	6.29b A	5.33b B	5.18b B
	Longview	6.81.4a B	7.77a A	6.88a B	5.67ab C
	Rambler	6.19ab A	5.77b A	5.99ab A	5.73ab A
	Rangelander	7.03a A	5.45b B	6.15ab AB	6.13a B
2	Blue J	4.25a A	4.15a A	4.18ab A	2.45a B
	Longview	3.95ab AB	3.88ab AB	4.32a A	3.12a B
	Rambler	3.68ab AB	4.07ab A	3.39bc AB	3.16a B
	Rangelander	3.21b A	3.23b A	3.16c A	2.66a A
3	Blue J	0.65a A	0.87a A	0.45a A	0.13a A
	Longview	0.78a A	0.73a A	0.66a A	0.17a A
	Rambler	0.47a A	0.15a A	0.31a A	0.16a A
	Rangelander	0.09a A	0.05a A	0.11a A	-
Total	Blue J	10.48b AB	11.31a A	9.96b B	7.26b C
	Longview	11.53a A	11.711a A	12.42a A	9.52a B
	Rambler	10.35b A	9.99.1b A	9.69b A	9.66a A
	Rangelander	10.33b A	8.72c B	9.42b B	8.79a B

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different ($P<0.05$).

[†] Means calculated from five replications. - No harvesting due to slow regrowth.

Table 3.7. [†]**Mean dry matter yield among four irrigation treatments for four alfalfa cultivars in relation to three cuts at the Picture Butte location in 2012.**

Cuts	Cultivars	W_1 (Mg ha^{-1})	W_2 (Mg ha^{-1})	W_3 (Mg ha^{-1})	W_4 (Mg ha^{-1})
1	Blue J	3.96a A	2.93a AB	2.60b B	3.76a B
	Longview	3.76ab A	2.38a B	2.11ab B	2.51a B
	Rambler	2.56b A	3.22a A	2.71ab A	2.10a A
	Rangelander	2.75b A	3.45a A	3.30a A	2.41a A
2	Blue J	4.59a A	3.74ab AB	2.85ab BC	2.12ab C
	Longview	2.63bc A	2.55bc A	2.15b A	2.85a A
	Rambler	3.80ab A	3.89a A	3.54a A	1.72ab B
	Rangelander	2.32c A	2.36c A	2.22b A	1.41b A
3	Blue J	1.61a A	1.02a AB	0.42a AB	0.33a B
	Longview	1.04a A	0.73a A	0.48a A	0.41a A
	Rambler	0.67a A	0.96a A	0.52a A	0.19a A
	Rangelander	0.49a A	0.73a A	0.36a A	0.16a A
Total	Blue J	10.16a A	7.69ab B	5.04b C	5.06ab C
	Longview	7.43b A	5.66c B	4.74b B	5.76a B
	Rambler	7.04b AB	8.07a A	6.78a B	4.01b C
	Rangelander	5.56c A	6.54bc A	5.88ab A	3.99b B

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different ($P<0.05$).

[†] Means calculated from five replications.

Table 3.8. [†]Mean dry matter yield among four irrigation treatments for four alfalfa cultivars in relation to three cuts at the Lethbridge location in 2013.

Cuts	Cultivars	W_1 (Mg ha^{-1})	W_2 (Mg ha^{-1})	W_3 (Mg ha^{-1})	W_4 (Mg ha^{-1})
1	Blue J	4.74a AB	4.16b B	4.29ab B	5.14a A
	Longview	4.38a AB	4.75ab A	4.25ab AB	3.85bc B
	Rambler	4.97a AB	5.53a A	4.49a B	4.29b B
	Rangelander	2.86b A	3.15c A	3.64b A	3.24c A
2	Blue J	3.97ab A	4.08ab A	4.46a A	4.55a A
	Longview	4.26ab A	4.45a A	4.69a A	4.28a A
	Rambler	4.32a A	4.26ab A	4.88a A	4.52a A
	Rangelander	3.57b A	3.71b A	3.55b A	3.57b A
3	Blue J	1.72b B	2.22a A	2.17b A	1.63bc B
	Longview	2.16a BC	2.42a AB	2.578a A	2.03a C
	Rambler	1.75b AB	1.57b B	1.97b A	1.87ab AB
	Rangelander	1.22c A	1.15c A	1.23c A	1.43c A
Total	Blue J	9.93b B	10.47b B	10.92a AB	11.77a A
	Longview	10.80ab AB	11.62a A	11.53a A	10.15b B
	Rambler	11.05a A	11.36ab A	11.35a A	10.68ab A
	Rangelander	7.64c A	8.01c A	8.42b A	8.24c A

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different ($P<0.05$).

[†] Means calculated from five replications.

3.3.2. Forage dry matter (DM) yield

The total forage DM yield recorded at Lethbridge for all the cultivar types in relation to the irrigation treatments ranged from 7.26 to 12.42 Mg ha^{-1} and 7.64 to 11.77 Mg ha^{-1} for the years 2012 and 2013 respectively (Table 3.6 and 3.8) whereas that of Picture Butte in 2012 ranged between 3.99 and 10.16 Mg ha^{-1} (Table 3.7). Dill et al. (2007) reported a total yield of 8.4 to15.6 Mg ha^{-1} for different irrigation treatments in southern Alberta. Al-Naeem (2008) also reported a total yield between 2.21 and 5.33 Mg ha^{-1} for four irrigation treatments under Saudi Arabia conditions. Additionally, Lindenmayer et al. (2008) presented an average total season yield between 8.8 and 18.3 Mg ha^{-1} for different irrigation treatments in northern Colorado. Total DM yield ranging from 7.2 to 12.5 Mg ha^{-1} and 3.0 to 15.1 Mg ha^{-1} in an irrigation trial was also reported by Retta and Hanks (1980) in Utah and Smeal et al. (1991) in New Mexico, respectively. The total DM yield for all of the alfalfa cultivar types in both years at Lethbridge were greater than those recorded at Picture Butte in 2012 (Table 3.6, 3.7 and 3.8). This difference in total DM yield between locations could be due to the relatively high rainfall amount that was recorded from May to June and October (Chapter 4, Table 4.1) which could have also contributed to the relatively high ET values (Chapter 4, Table 4.4, 4.5, 4.6 and 4.7) recorded in both years at Lethbridge compared to that of Picture Butte in 2012. Irmak et al. (2007) indicated that, although alfalfa is regarded to be relatively drought tolerant, it produces yields almost proportional to the amount of water available to the crop. However, the difference in soil texture and structure at these locations could have also contributed to the high yields observed at Lethbridge in both years. The soil texture and structure typically determines the soil water holding capacity, fertility and nutrient availability, aeration and drainage. These factors can also influence plant productivity. Orloff (2007) indicated that the restrictive subsurface layers such as hardpans, claypans, sand and layered soils serve as a barrier which restricts root penetration, reduces rate of water infiltration and diminishes aeration within the soil thereby reducing alfalfa yield. This could possibly help explain the yield difference observed between locations in this study. Since soil physical and chemical properties were not determined in this study, this preposition requires further testing for confirmation. Generally, the mean DM yield values for Cut 1 and Cut 2 in most instances were similar and greater than that of Cut 3 in both years and locations, but there were few occasions where either DM yields of one cut were greater than the other and at the same time greater than Cut 3 (Table 3.6, 3.7 and 3.8). The greater DM yields for Cut 1 and 2 in both years and locations could be attributed in part to the relatively high ET associated with these cuts (Chapter 4; Table 4.3, 4.5 and 4.7). Lindenmayer et al. (2011) indicated that alfalfa biomass yield responds in a positive linear relationship to increasing ET. The DM yield trend observed among cuts in this study are comparable to that of Dill et al. (2007) who reported that alfalfa yield was highest for the first cut and lowest for the third cut, regardless of the water treatment. As discussed in the crop height section, Orloff et al. (2005) indicated that a spring and early summer harvest are typically higher in yield and forage quality than a late summer or fall harvest, and that a reduction in yield during fall could be due to a decline in temperature and day length. Shortened day length and temperature decline during late summer and early fall results in greater amounts of photosynthate partitioning into root reserves, which is used for growth in spring, resulting in a lower biomass yield in early fall (Hanson et al., 1988).

3.3.2.1. Comparison of yield among the cultivar types and irrigation treatments

The cultivar x water x cut interaction for forage DM yield was significant ($P<0.05$) across irrigation treatments and among cultivar types in relation to cuts at both locations and years (Tables 3.5). A comparison of total forage DM yield among cultivar types in relation to irrigation treatments and cuts at Lethbridge in 2012 indicated that the total forage DM yield for Longview was significantly ($P<0.05$) greater than those of Blue J, Rambler and Rangelander for the optimal (W_1) and 50% irrigation treatment (W_3) respectively. Again, the total DM yield for Blue J and Longview were not significantly different but were significantly ($P<0.05$) greater than those of Rambler and Rangelander for the 75% irrigation treatment (W_2) (Table 3.6). At the Picture Butte location in the same year, the total DM yield for Blue J was significantly ($P<0.05$) greater than for Longview, Rambler and Rangelander with the optimal irrigation treatment (W_1). The yield of Rambler W_2 was also not significantly different from Blue J but was significantly ($P<0.05$) greater than those of Longview and Rangelander (Table 3.7). The total DM yield for Rambler was not significantly different from that of Rangelander on the W_3 treatment but was significantly ($P<0.05$) greater than those of Blue J and Longview (Table 3.7). In 2013 at Lethbridge, the total forage DM yield for Rambler was not significantly different from that of Longview but was significantly ($P<0.05$) greater than those of Blue J and Rangelander on the W_1 treatment. Similarly, total DM yield for Longview was not significantly different from that of Rambler but was significantly ($P<0.05$) greater than those of Blue J and Rangelander on the W_2 treatment (Table 3.8). There was no significant difference in yield among Blue J, Longview and Rambler on the W_3 treatment although yields for these cultivars were significantly ($P<0.05$) greater than that of Ranglander. Again, the total DM yield for Blue J was not significantly different from that of Rambler, but was significantly ($P<0.05$) greater than those of Longview and Rangelander on the W_4 treatments. Generally, there was a trend towards relatively high yields for the irrigated types compared to dryland types although the difference among them in relation to the irrigation treatments in some instances were not significant and stable across locations and years. These results do not agree with the findings of Retta and Hanks (1980) and Hattendorf et al. (1990) who conducted line-source irrigation study to evaluate the WUE of different alfalfa varieties in New Mexico and Washington, respectively, and indicated no difference in biomass yield and water use for these varieties.

The observed difference in DM yield among the cultivar types could be attributed to the difference in their root morphology. Carter et al. (1982) and McIntosh and Miller (1981) attributed differences in yield response to soil moisture among alfalfa cultivars to their root characteristics and the rate of transpiration (Cole et al., 1970). Creeping root type alfalfa (e.g. Rangelander and Rambler) typically tends to yield less than tap root types (e.g. Blue J and Longview) in wet areas and more in drier areas (Saskatchewan Forage Council, 2007). A trend of relatively lesser DM yield mean values for Ranglander was also observed across cuts, especially for Cut 3 when compared to the other cultivars in both years and locations. Due to slow regrowth, no harvesting was done for Ranglander W_4 Cut 3 at Lethbridge in 2012 (Table 3.6, 3.7 and 3.8). Rangelander alfalfa has a creeping root system and is also drought tolerant but has slow regrowth (North Peace Applied Research Association, 2006). Heinrichs et al. (1979) also indicated that Rangelander alfalfa had a lower yield when compared to Beaver on irrigated land.

Analysis of the total forage DM yield across the irrigation treatments in 2012 at Lethbridge indicated that the total forage DM yield for Blue J W_2 was not significantly different from that of W_1 but was significantly ($P<0.05$) greater than those of W_3 and W_4. Total DM yield for Longview W_2 was not significantly different from those of W_1 and W_3 but was significantly ($P<0.05$) greater than that of W_4 (Table 3.6). In the same year at Picture Butte, total forage DM yield for Blue J and Longview (W_1) was statistically significantly ($P<0.05$) greater than those of W_2, W_3 and W_4, whereas that of Rambler W_2 was not significantly different from that of W_1 but was significantly ($P<0.05$) greater than those of W_3 and W_4 (Table 3.7). Additionally, in 2013 at Lethbridge total forage DM yield for Blue J W_2 was not significantly different from those of W_1 and W_3 but the total DM yields for Blue J W_1 and W_2 were significantly ($P<0.05$) lesser than that of W_4. The total DM yield for Longview W_2 was also not different from those of W_1 and W_3 but the total DM yields for Longview W_2 and W_3 were significantly ($P<0.05$) greater than W_4 (Table 3.8). The yield trend observed among the irrigation treatments in this study did not conform to the results of Kuslu et al. (2010). These researchers indicated that water stress treatments decreased dry yield compared to the field capacity (FC) treatment. Another study conducted by Ismail and Almarshadi (2013) also showed that the highest fresh yield was obtained under field capacity level, followed by 85% FC and 70% FC respectively.

The observed similarities in total DM yield between the W_1 and the lower irrigation treatments (W_3 and W_4) in relation to the irrigated alfalfa cultivars at Lethbridge in both years could be due to plant growth resulting from crop water use from the water table. Benz et al. (1983) reported that water table makes a sizable contribution to the actual alfalfa evapotranspiration when irrigation level decreases. Dardanelli and Collino (2002) indicated that water table also affected dry matter production and its annual variability. Although water table influence was generally absent within the 100 cm root zone depth at which neutron probe readings were taken across the field, high rainfall in spring and summer of 2010 and in 2013 could have elevated the water table. It is possible that the rains may have brought the water table close to the root zone. The deep rooting system of the irrigated alfalfa could have made it possible for it to access water from a deeper soil profile. Bauder et al. (2011) argued that the deep root system of alfalfa allows it to extract water from the soil moisture reserves when irrigation is limited.

Generally, the total forage DM yield mean values for Blue J, Longview and Rambler W_2 and W_3 at Lethbridge in both years were higher than those of W_1, although the differences in some instances were not significant (except Lethbridge 2012 Blue J $W_1 > W_2$). This is interesting because the difference in total irrigation water applied to W_1 in 2012 at Lethbridge was 147 and 284 mm greater than those of W_2 and W_3 respectively. In 2013 at this same location W_1 received 179 and 360 mm more irrigation water than those of W_2 and W_3 respectively but the yields recorded for the W_2 and W_3 were comparable and in some instances greater than that of W_1. The total DM yield for Blue J and Longview W_1 at Picture Butte in 2012 was statistically significantly ($P<0.05$) greater than all other treatments including W_2. Although W_1 used 165 mm irrigation water more than W_2, the yield reduction between W_1 and W_2 for these cultivars was not drastic (24%).

3.4. Conclusion

The findings of this study are important to farmers who produce alfalfa on a large scale in southern Alberta and other water challenged regions of the world. Generally, the lower water treatments produced yields that were comparable to that obtained at the optimal treatment for all the cultivars in both years. Irrigation treatments W_2 and W_3 appeared to have produced yields which were comparable to that of W_1 although these treatments used less water (i.e., on an average W_2 (148 mm) < W_1 and W_3 (278 mm) < W_1 in both years at Lethbridge; W_2 (80 mm) < W_1 at Picture Butte in 2012. It is well known that alfalfa is a relatively high water user and produces yield in response to the amount of water available to it, so even the types that are known to do well under dryland conditions also in some cases indicated the same linear yield trend as that observed for irrigated types.

These results seem to suggest the possibility of irrigating alfalfa at 75% (W_2) of the amount of water applied at the optimal treatment (W_1), with 40% depletion of available water at the top 60 - 90 % of the 75 cm - 100 cm root zone and still produce yields which will be comparable to that produced at the optimal irrigation treatment. This will be beneficial to producers in that less water could be used for production of the same amount of forage thereby reducing the cost of irrigation. Again, producers can use the amount of water saved (i.e., on an average, 186 mm for 1.21 ha) for irrigating more land or could allocate it to other crops. Based on the fact that on an annual basis total yield for at least one of the irrigated types outperformed the dryland types, producers will be better off using irrigated alfalfa if high biomass yield production is important. Again, since Rambler in some instances had yields which were comparable to the irrigated types, further work needs to be done to confirm its suitability and performance under irrigated conditions. Perhaps this could lead to breeding of alfalfa cultivars that are drought tolerant and at the same time can produce relatively higher yields when grown under deficit irrigation conditions.

Chapter Four: Water use efficiency of irrigated and dryland type alfalfa cultivars under southern Alberta conditions

Abstract

In semiarid southern Alberta, irrigation water is at a premium making the water use efficiency (WUE) of crops an important goal. To determine the effect of irrigation treatments on the WUE of alfalfa cultivars developed for irrigated and dryland areas of western Canada, a field study was conducted in 2012 and 2013 at Lethbridge and 2012 at Picture Butte. The irrigated cultivars (Longview and Blue J) and dryland cultivars (Rangelander and Rambler) were grown on plots arranged in a randomized complete block design with five replications. The plots were subjected to four irrigation treatments. For the optimal irrigation treatment (W_1), soil water content was maintained between 60 - 90% of available water in the designated root zone. Other irrigation treatments received 75% (W_2), 50% (W_3) and 25% (W_4) of the volume of water applied to the optimal treatment. Mean WUE calculated using total forage yield ranged from 7.44 to 20.25 kg ha^{-1} mm^{-1} between individual years and locations. The total WUE was higher for W_4 compared to other treatments in 2013 but, in 2012 total WUE for W_2,W_3 and W_4 were similar and different from W_1 for the irrigated cultivars. The total WUE for W_1 and W_2 for the dryland cultivars were also similar in 2012 at Lethbridge. The WUE mean was higher for irrigated cultivars compared to the dryland types although in some cases the differences were not significant. For Picture Butte no clear trend was noticed. A linear relationship between total dry matter yield and total water use (ET) for each cultivar type in relation to the irrigation treatments was established at both locations in 2012. Considering the WUE trend, it was concluded that alfalfa cultivars developed for both

irrigated and dryland areas could be irrigated at 75% of the volume of water applied to the optimal treatment, with 40% depletion of available water within 60 - 90% of the root zone and still optimize WUE.

4.1. Introduction

Canada is considered as one of the world leaders in the production of many agricultural crops. Most of these crops, which include cereals, oilseeds, alfalfa, sugar beets and potatoes, are predominately grown under irrigation (CANCID, 1997). As the largest single sector of water consumption in Canada, agriculture utilizes about 4.5 billion m^3 of water annually (Corkal and Adkins, 2007). In western Canada about 85% of agricultural water withdrawals in this part of the country are used for irrigation purposes while 15% is utilised in livestock production (Environment Canada; 2003, 2004). Again in the province of Alberta, irrigated agriculture is practiced on approximately 500,000 ha of land, accounting for about 64% of the irrigated cropland in Canada (Statistics Canada, 2001). Alfalfa is the major single forage legume grown under irrigation in southern Alberta, with approximately 907,000 tonnes produced annually (Dill et al., 2007). It is considered as the most important forage legume in Canada and it is cultivated on over 4.5 million hectares (Statistics Canada, 2002). In 2013 in Alberta, approximately 60,000 ha of alfalfa were grown under irrigation, within the province's irrigation districts (ARD, 2014). Along with domestic use for cattle feed, Canada exports 350,000 tonnes of alfalfa pellets annually, making it the leading exporter in the world and the second largest exporter of alfalfa cubes (225,000 tonnes; Agriculture and Agri-Food Canada, 2003).

In spite of its significance to the economy of Canada, alfalfa is known as a high water-use crop (Stanberry, 1955; Schneekloth and Andales, 2009). This can be attributed to the fact that it has a deep root system and a longer growing season. Alfalfa grown under ideal conditions in southern Alberta can use between 540 and 680 mm of water per growing season. Available estimates also indicate that alfalfa grown under irrigation uses approximately 100 to 125 mm of water for every tonne of hay produced (Efetha, 2011).

Erratic rainfall patterns and increase in demand for water for irrigation, livestock production, industrial and other domestic purposes in southern Alberta pose a threat to alfalfa cultivation in the foreseeable future. These competing demands and the large volume of irrigated agricultural water extraction is approaching its critical limit in some locations (Corkal and Adkins, 2007). Hence, the provincial government has placed a moratorium on new licence applications for the use of irrigation water within the Bow, Oldman River and South Saskatchewan River Basin (SSRB). It is therefore imperative to explore and adopt strategies that can optimize irrigation efficiency within this province.

Water use efficiency (WUE) has been used in most irrigation management studies as a criterion for measuring the efficient use of irrigation water and crop productivity, under limited water conditions. WUE is considered as a significant factor for determining the productivity of alfalfa and other crops because it serves as the basis for evaluating the yield a crop produces, relative to the use of total water applied. Sheaffer et al. (1988) defined WUE as the biomass (Yield, Y) produced per unit area for a unit crop water used (ET). Several studies on alfalfa WUE have been reported with mean annual values ranging between 10.0 and 25.9 kg ha^{-1} mm^{-1} (Abdul-Jabbar et al., 1983; Grimes et al., 1992; and Hirth et al., 2001).

Saeed and El-Nadi (1997) reported that alfalfa grown under semiarid conditions should be watered lightly and frequently to attain high yield and high WUE. Carter and Sheaffer (1983) recommended that on coarse-textured soils, moderate water application to alfalfa at 50% depletion of available water could be efficient. A linear relationship between alfalfa yield (Y) and evapotranspiration (ET) with WUE as the slope has also been established in most irrigation management studies (Carter and Sheaffer 1983; Undersander, 1987; Smeal et al., 1991). Jodari-Karimi et al. (1983) reported that WUE of alfalfa was higher in deep irrigated treatments than in shallow irrigated treatments. This study also indicated that the rate of root growth increased in non-irrigated alfalfa as a result of limited water stress. Lazaridou and Koutroubas (2004) studied the effect of drought on plants water use efficiency at various phenological stages of berseem clover and alfalfa (Lazaridou et al., 2003). Their results indicated a reduction of above ground biomass to one third of irrigated plants (2.3 vs. 6.8 g plant^{-1}). Recently, Al-Naeem (2008) studied the performance of alfalfa under stress conditions and determined WUE for optimal forage production under arid conditions in Saudi Arabia with its limited irrigation water supply. This study showed high WUE at field capacity and a reduction in dry matter yield for irrigation stress treatments. In another study conducted to evaluate the potential water saving strategies on the front range of Colorado (Lindenmayer et al., 2008) the effect of four irrigation strategies were evaluated for ET, WUE, stand density and forage quality. Their results indicated that, on average, up to 282 mm, of water were saved in the stress treatments, but a reduction in ET also resulted in a yield reduction of up to 6.5 Mg ha^{-1}.

Considerable variability in WUE within and among cultivars has also been reported in the past (Cole et al., 1970). Carter et al. (1982) and McIntosh and Miller (1981) attributed differences in yield response to soil moisture among alfalfa cultivars to their root characteristics and the rate of transpiration (Cole et al., 1970). Additionally, a study conducted by Grimes et al. (1992) to evaluate WUE of three alfalfa varieties indicated that semi dormant WL318 had a relatively higher WUE than two other varieties tested during a cool spring season, whereas CUF101 and Moapa 69 varieties had higher WUE in hot summer conditions. Conversely, studies conducted by Hattendorf et al. (1990) and Wilson et al. (1983) to determine water use and yield characteristics of cultivars of different dormancy types, indicated inconsistent results. A two year study conducted by Retta and Hanks (1980) showed no significant difference in biomass yield or water use among the varieties Ladak, Washoe and Mesilla. Similarly, Undersander (1987) evaluated WUE of alfalfa varieties Vangard, Cody, Zia and Dawson. Results obtained from this study showed no significant difference in WUE among the alfalfa varieties for any level of irrigation. Sheaffer et al. (1988) indicated that determination of WUE for different alfalfa cultivars should be done under specific local climatic and soil conditions since these factors influence cultivar ET.

Notwithstanding the fact that there is a tremendous stock of knowledge on WUE for many crops in Canada, the greater part of this knowledge base was built on outmoded assumptions and irrigation technologies (Environment Canada, 2004). Therefore, it is essential that studies on WUE of crops under current conditions using current technologies are undertaken to optimize use of this important natural resource. The objective of this study was to determine the water use (ET) and water use efficiency (WUE) of both irrigated and dryland type alfalfa cultivars under different irrigation regimes.

4.2. Materials and Methods

4.2.1. Plot Location and Experimental Design

Two field experiments were conducted at two different locations in southern Alberta. The first experiment was located at Lethbridge Alberta Agriculture and Rural Development (ARD), Alberta Irrigation Technology Centre (AITC) (Lat. 49^o 45' N and Long. 112^o 45' W, 900 m elevation) and the second at Picture Butte (Lat. 49^o 55' N, Long. 112^o 48' W, 950 m elevation) on a farmer's field. Both sites were located on Orthic Dark Brown Chernozemic soil. Alfalfa cultivars used in this study were grown on plots arranged in a randomized complete block design (RCBD), with five replications and four irrigation water treatments. The experimental site at Lethbridge ARD AITC and Picture Butte were divided into 80 and 40 individual plots respectively. The site at Lethbridge occupied a total area of 2.67 hectares, while that at Picture Butte had a total size of 1.21 hectares. Each plot had a dimension of 6 m by 6 m with a sprinkler in each of the four corners. A buffer zone of 10 m was maintained between each plot to minimize the effect of irrigation water drift from adjacent sprinklers.

4.2.2. Crop Agronomics

High-yielding alfalfa cultivars for dryland (Rangelander and Rambler; Heinrichs et al., 1958; Heinrichs et al., 1979) and irrigation (Blue J and Longview; Acharya et al., 1995; Acharya and Huang, 2000) alfalfa were seeded in 2010 on both experimental sites. These alfalfa cultivars were selected based on their adaptation to different moisture conditions and root features. The crops were seeded with a custom built 10 row small plot forage seeder, at a rate of 10 kg ha^{-1}, with 0.2 m row spacing and at a depth of about 0.019 m. Though the focus of this study was on alfalfa, two sainfoins (Nova, L3519) and two fenugreek (Amber, Tristar) cultivars were also grown in addition to the alfalfa cultivars on the Lethbridge experimental site. Information from these sainfoin and fenugreek cultivars are not presented. The two varieties of each alfalfa cultivar type were grown on the same 6 m by 6 m plot, with each variety grown 3 m on both sides of a neutron probe access tube inserted in the middle of the plots.

4.2.3. Irrigation Water System and Treatments

The plots were irrigated using a solid set sprinkler irrigation system with the following pipe dimensions; 0.15 m x 12.19 m main lines and 0.08 m x 12.19 m lateral lines, with a 0.019 m x 0.61 m riser above the soil surface at the four corners of each plot, Nelson R2000 ROTATORS® and Nelson Low-Angle (7 degrees) sprinkler heads were used at the Lethbridge and Picture Butte sites respectively. The main lines at the Lethbridge site were connected to a lateral line through a 0.25 m diameter flex hose (Chapter 3, Figure 3.1). The irrigation water at the Picture Butte site was delivered to each plot via a system of underground pipes, which were installed at the time the plots were established. The plots were subjected to the four irrigation treatments. For the optimal irrigation treatment (W_1), soil water content was maintained between 60 - 90% of available water in the designated root zone. Other irrigation treatments received 75% (W_2), 50% (W_3) and 25% (W_4) of the volume of water applied to the optimal treatment. The optimal irrigation treatment (W_1) was managed to maintain soil water content between 60% and 90% of available water in the top 75 cm root zone as shown in Figure 4.1 for the first year.

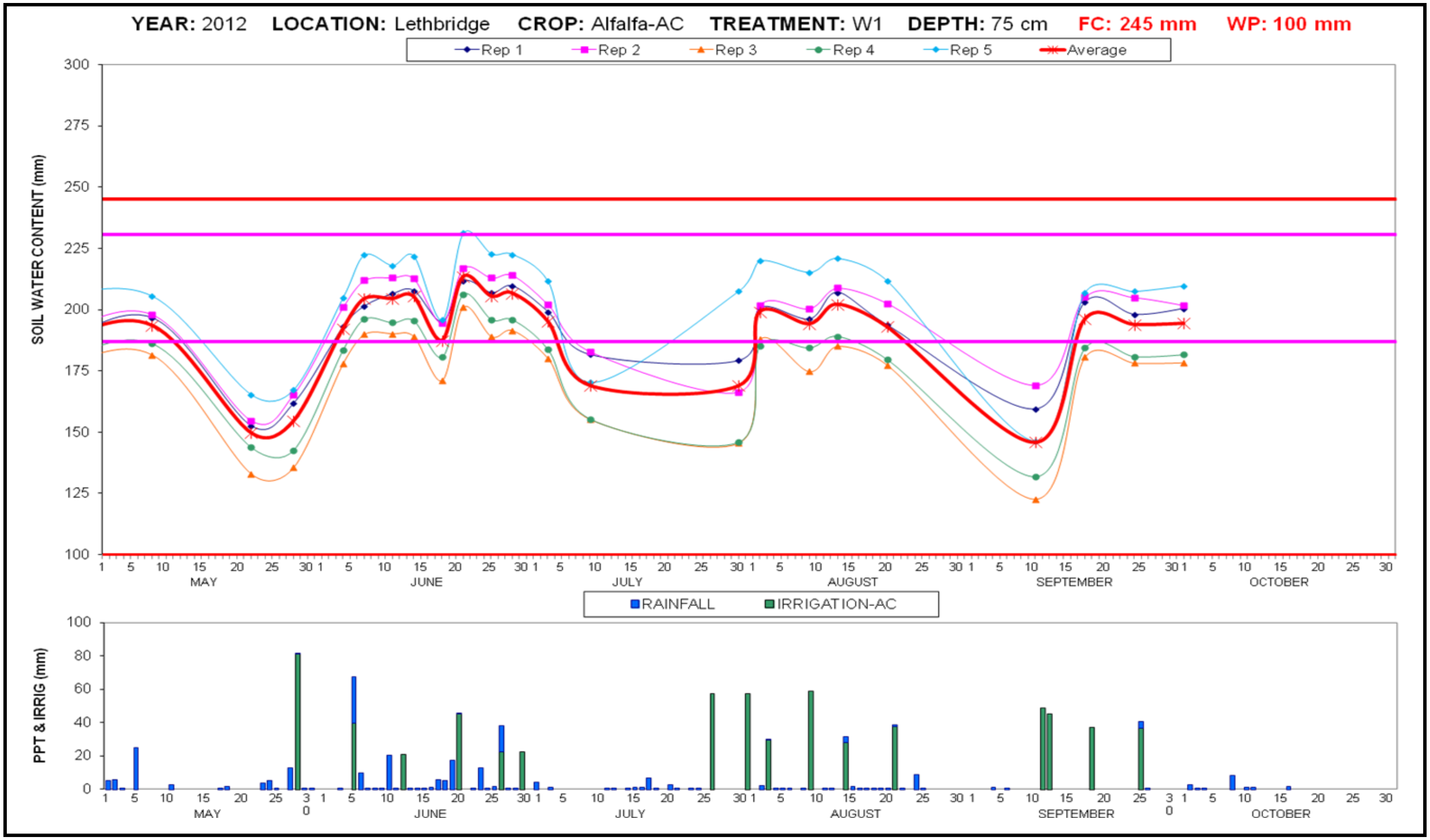


Figure 4.1. Soil water content in the top 0-75 cm depth with measured precipitation and irrigation applied to treatment W_1 (bottom) for the alfalfa water use efficiency experiment in Lethbridge, 2012. The horizontal pink lines represent 60% and 90% of available water, while the two red lines indicate field capacity and wilting point.

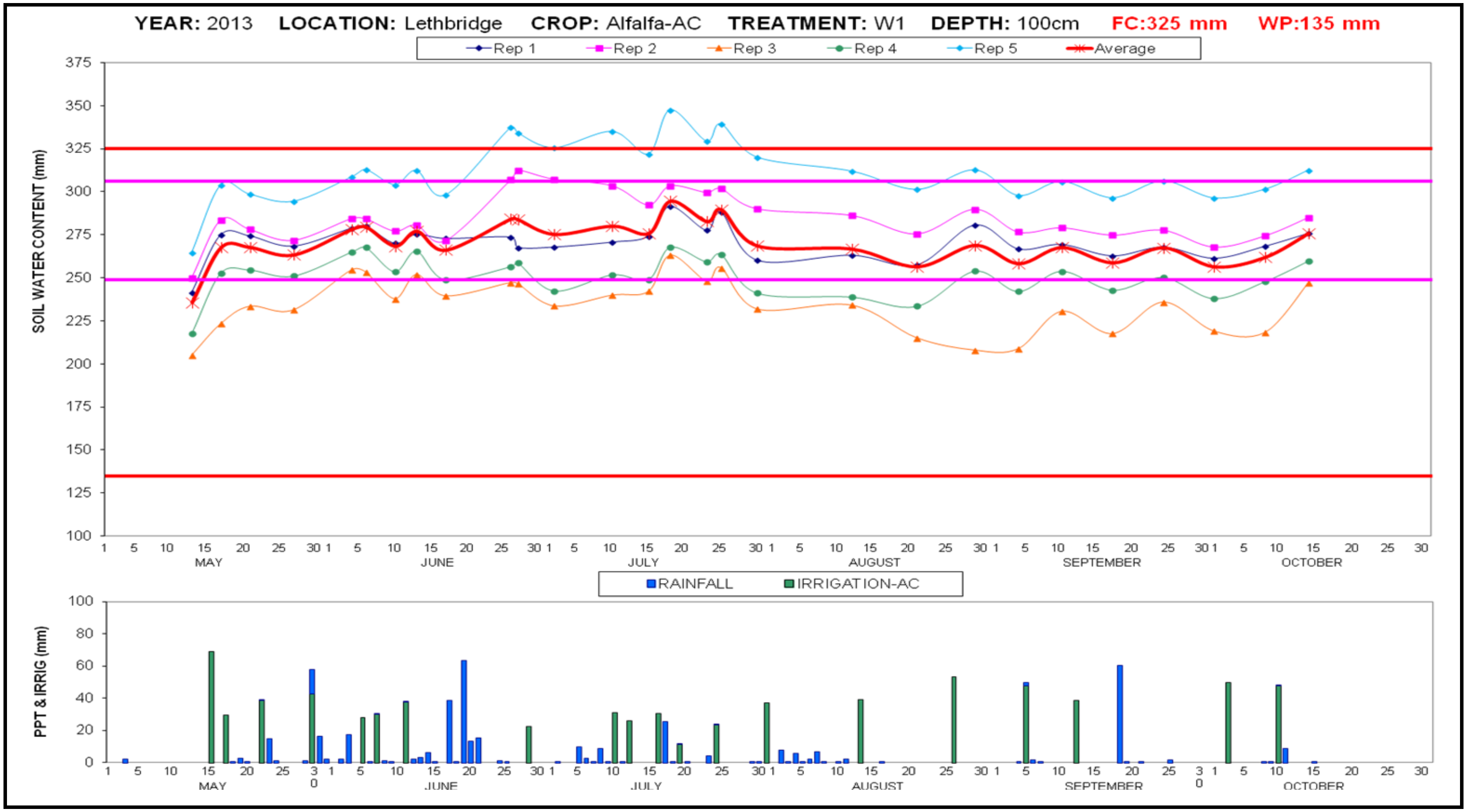


Figure 4.2. Soil water content in the top 0-100 cm depth with measured precipitation and irrigation applied to treatment W$_1$ (bottom) for the alfalfa water use efficiency experiment in Lethbridge, 2013. The horizontal pink lines represent 60% and 90% of available water, while the two red lines indicate field capacity and wilting point.

This approach was similar to what Woods and McKenzie, (2011) used in their water use efficiency studies for cereals and oilseeds. In the second year the root zone for irrigation management at Lethbridge was changed to 100 cm due to alfalfa root extension (Figure 4.2). The project was terminated at the Picture Butte site in the second year due to manpower limitations.

4.2.4. Soil Moisture Monitoring

In order to schedule irrigation, soil moisture readings were taken two times per week (i.e., on Mondays and Thursdays) using a neutron probe (i.e., a Boart Long Year, CNP® 503DR Hydro probe) at 25 cm increments, to a 100 cm depth of root zone, from a 2 m aluminium tube fixed close to the center of each plot. In order to reduce exposure to the radioactive element in the probe, on the individual taking the moisture readings, neutron probe readings were taken on all plots on Mondays whereas on Thursdays readings were taken in the trigger plots only (plots that received irrigation treatment W_1).

4.2.5. Precipitation and Water Use (ET)

Daily precipitation values were obtained from a weather station located near the Lethbridge site, Iron Spring climate station near Picture Butte and from the IMCIN website (Alberta Agriculture and Rural Development, 2014). ET was computed using a water balance model equation:

$$ET = \Delta S_w + P + I + R_{on} - R_{off} - D$$

Where:

ET = Total water use
ΔS_w = Soil water used (mm); calculated as
= Soil water at planting (first probe reading) - Soil water at harvest (use full root zone)
P = Precipitation

I = Irrigation
R_{on} = Run on (assumed to be zero)
R_{off} = Runoff (assumed to be zero)
D = Drainage; was calculated as;
D = ($PZMC_2$ - $PZMC_1$)
$PZMC_1$ = Percolation zone (75 - 100cm) moisture content expressed in mm at the start of the time period (1) as measured with neutron probe.
$PZMC_2$ = Percolation zone (75 - 100cm) moisture content expressed in mm at the end of the time period (2) as measured with neutron probe.
If $PZMC_2 < PZMC_{1,}$ ($PZMC_2$ - $PZMC_1$) was set to zero.

The formula for the drainage calculation is similar to that was used by Dill et al. (2007).

4.2.6. Spatial Uniformity of Irrigation

Rain gauge experiments were conducted to measure the spatial uniformity of the irrigation application within individual plots at the two experimental sites. Twenty five collection cans were placed in an equally-spaced grid (5 by 5 m) within the plots and irrigation water was collected and measured after a given period of time (minimum 2 hours). Measurements were taken on two different plots at each experimental site. Some variability in irrigation applications were observed with overall averages being 8.9 mm and 8.4 mm for Lethbridge and Picture Butte respectively (Figure 4.3 a and b). There were a couple of spots in the corners of the plots that received less water but yield samples were not collected there. Hence this did not affect the dry matter yield computation.

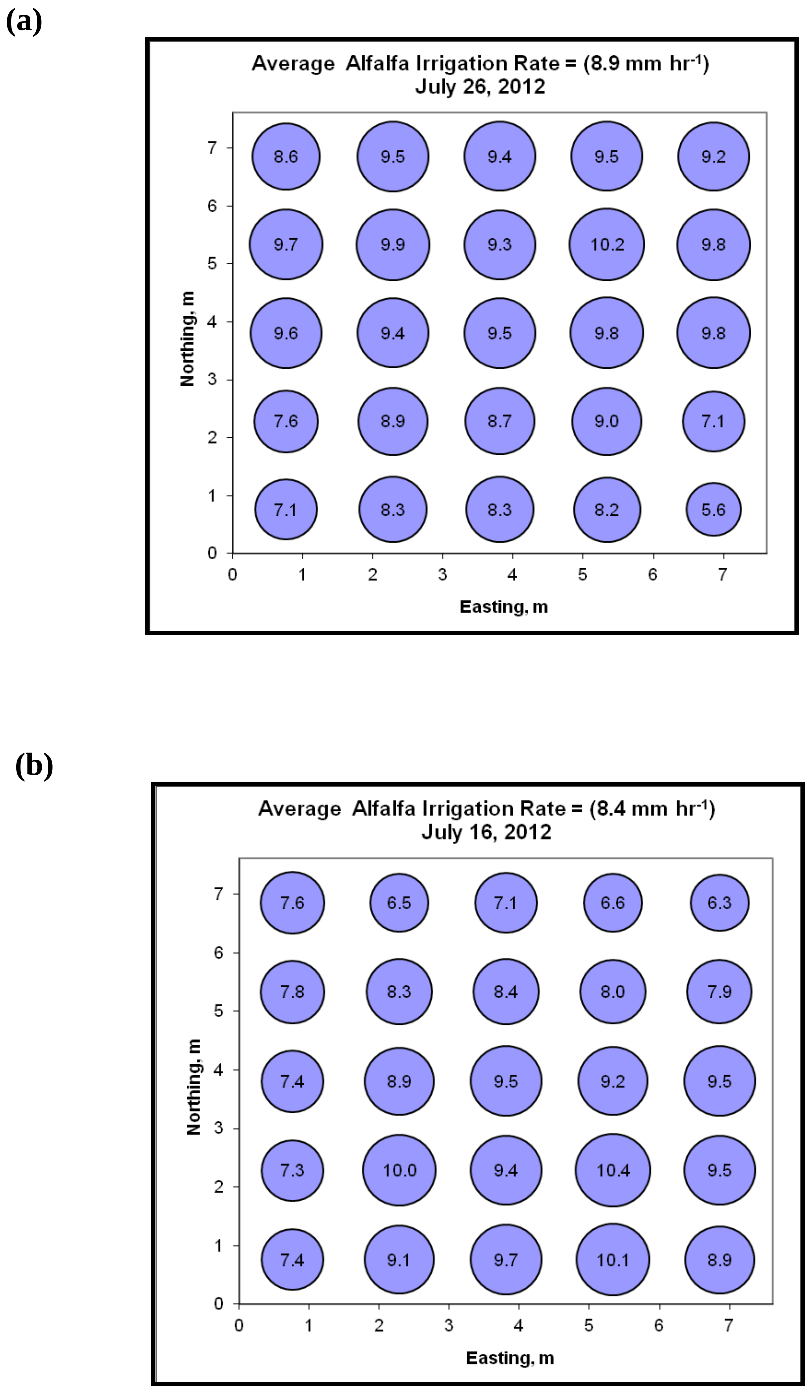


Figure 4.3. Average irrigation rate (mm hr^{-1}) and uniformity for the (a) Lethbridge and (b) Picture Butte water use efficiency experiment for two irrigated and two dryland cultivars, 2012. The size of the circle is proportionate to the amount of water applied.

4.2.7. Harvest

A Hege 212^{TM} Forage Harvester was used to remove 1.55 m by 6 m strips from each plot on both sides of the access tube located at the center of all plots leaving stubble of about 12 cm above the ground. A total of three harvests (Cuts) were made on each experimental site. Harvesting was done on July 10, August 28 and October 16, 2012 at the Picture Butte site while crops at Lethbridge were harvested on July 12, August 29 and October 17, 2012. In 2013 harvesting was only done at Lethbridge on July 3, August 22 and October 15. The samples were dried at 60^{o}C for 48 hours to determine the dry matter content which was in turn used to calculate the total yield produced on a dry matter basis.

4.2.8. Statistical Analyses

All data collected were analysed using the mixed model procedure for repeated measure (SAS Institute Inc., 2011) with cut as the repeated factor. The cultivar, irrigation treatment and cut were modeled as fixed effects while the replication and its interactions with the fixed effects were random effects. The output measures analyzed included water use and water use efficiency. The LSD test ($P< 0.05$) was used for mean separation.

4.3. Results and Discussion

4.3.1. Water Use (ET) and Rainfall

Climate conditions recorded at the two experimental sites during the period of the study were different with the exception of temperature which was similar and close to the long-term average (Table 4.1). There was a significant cultivar x water x cut ($P< 0.05$) interaction for ET at Lethbridge in 2012, whereas in 2013 at Lethbridge and 2012 at Picture Butte respectively only cultivar x cut and water x cut interactions were significant ($P<0.05$) (Tables 4.2). The total ET computed for all the water treatments from May to October ranged from 518 to 887 mm and 548 to 1038 mm at Lethbridge in 2012 and 2013, respectively (Table 4.3 and 4.4), whereas that of Picture Butte in 2012 ranged between 541 and 889 mm (Table 4.6). Dill et al. (2007) reported a total consumptive use of alfalfa (Blue J) between 352 and 862 mm in a five year study conducted at Picture Butte to determine the impact of different irrigation management practices on yield, quality and consumptive use of alfalfa. Sonmor (1963) reported a consumptive use of 660 mm for alfalfa in southern Alberta. Krogman and Hobbs (1965) reported a total evapotranspiration of 680 mm in Vauxhall southern Alberta. Another study conducted by Wright (1988) to determine the daily and seasonal ET of well-irrigated alfalfa in an irrigated region of southern Idaho indicated a seasonal ET average of 1022 mm. Other ET values reported in the literature across different countries and climatic conditions, range between 546 and 1516 mm (Daigger et al., 1970; Bauder et al., 1978; Retta and Hanks, 1980; Sammis, 1981; Undersander, 1987; Smeal, 1991; Li and Zhang, 2004; Hanson et al., 2008; Kuslu et al., 2010).

Table 4.1. Temperature and precipitation at the Lethbridge and Picture Butte locations, in 2012 and 2013.

	Lethbridge						Picture Butte			
	Temperature (^oC)			Rainfall (mm)			Temperature (^oC)		Rainfall (mm)	
	1980-2007	2012	2013	1980-2007	2012	2013	2004-2007	2012	2004-2007	2012
May	11.16	10.96	10.96	48.18	61.7	55.3	8.83	11.09	36.4	47.4
June	15.18	15.18	15.21	80.35	119.7	164.6	14.65	15.28	108.15	110.0
July	18.21	18.11	18.12	40.56	18.0	51.6	14.73	18.08	12.67	41.4
August	17.62	17.53	17.50	37.02	18.8	25.5	16.78	17.44	36.25	30.9
September	12.13	12.58	12.43	37.80	5.6	66.1	11.93	12.29	53.75	9.1
October	6.41	6.85	6.94	10.08	36.9	24.1	6.18	6.80	11.13	36.1
Total	80.71	81.21	81.16	253.9	260.7	387.2	73.1	80.98	258.3	274.9

Table 4.2. Degrees of freedom (df) and probability (Pr) of F values for water use (ET) among irrigation treatments, cultivars and cuts as determined by a mixed model repeated measure ANOVA at Lethbridge in 2012, 2013 and at the Picture Butte location in 2012 respectively.

	Lethbridge				Picture Butte	
	2012		2013		2012	
Effect	**df**	**Pr of F**	**df**	**Pr of F**	**df**	**Pr of F**
cultivar	3	0.324	3	<0.001	3	0.006
water	3	<0.001	3	<0.001	3	<0.001
cut	3	<0.001	3	<0.001	9	0.447
cultivar x water	9	0.099	9	0.065	3	<0.001
cultivar x cut	9	0.001	9	<0.001	9	0.003
water x cut	9	<0.001	9	<0.001	9	<0.001
cultivar x water x cut	27	0.023	27	0.381	27	0.999

Table 4.3. [†]Mean water use (ET) among the irrigation treatments and four alfalfa cultivars, in relation to three cuts at the Lethbridge location in 2012.

Cuts	**Cultivars**	**W_1 (mm)**	**W_2 (mm)**	**W_3 (mm)**	**W_4 (mm)**
1	Blue J	430a A	381b B	386a B	319a C
	Longview	430a A	381b B	386a B	319a C
	Rambler	431a A	407a B	372a C	321a D
	Rangelander	431a A	407a B	372a C	321a D
2	Blue J	271a A	198a B	130a C	135a C
	Longview	271a A	198a B	130a C	135a C
	Rambler	268a A	191a B	122a C	93b D
	Rangelander	268a A	191a B	122a C	93b D
3	Blue J	184a A	158a B	115a C	82b D
	Longview	184a A	158a B	115a C	82b D
	Rambler	182a A	156a B	123a C	102a D
	Rangelander	182a A	156a B	123a C	102a D
Total	Blue J	886a A	738a B	645a C	537a D
	Longview	886a A	738a B	645a C	537a D
	Rambler	882a A	755a B	618b C	517a D
	Rangelander	882a A	755a B	618b C	517a D

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different ($P<0.05$). [†]Means calculated from five replications.

Table 4.4. †Mean water use (ET) among four irrigation treatments in relation to cuts at the Lethbridge location in 2013.

Cuts	W_1 (mm)	W_2 (mm)	W_3 (mm)	W_4 (mm)
Cut 1	460b A	384b B	310b C	258b D
Cut 2	302c A	259c B	215c C	174c D
Cut 3	274d A	246d B	189d C	119d D
Total	1038a A	889a B	714a C	548a D

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each column followed by the same lowercase letter are not significantly different ($P<0.05$).

†Means calculated from five replications.

Table 4.5. †Mean water use (ET) among four cultivars in relation to three cuts at the Lethbridge location in 2013.

Cuts	Blue J (mm)	Longview (mm)	Rambler (mm)	Rangelander (mm)
Cut 1	362b A	362b A	344b B	344b B
Cut 2	241c A	241c A	237c A	237c A
Cut 3	215d A	215d A	199d B	199d B
Total	813a A	813a A	781a B	781a B

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each column followed by the same lowercase letter are not significantly different ($P<0.05$).

†Means calculated from five replications.

Table 4.6. †Mean water use (ET) among four irrigation treatments in relation to cuts at the Picture Butte location in 2012.

Cuts	W_1 (mm)	W_2 (mm)	W_3 (mm)	W_4 (mm)
Cut 1	367b A	293b B	230b C	195b D
Cut 2	325c A	297b B	234b C	179c D
Cut 3	195d C	226c A	210c B	165d D
Total	889a A	809a B	675a C	540a D

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each column followed by the same lowercase letter are not significantly different ($P<0.05$).

†Means calculated from five replications.

Table 4.7. †Mean water use (ET) among four cultivars in relation to three cuts at the Picture Butte location in 2012.

Cuts	Blue J (mm)	Longview (mm)	Rambler (mm)	Rangelander (mm)
Cut 1	261b B	261b B	286b A	286b A
Cut 2	261b A	261b A	256c A	256c A
Cut 3	199c A	199c A	199d A	199d A
Total	707a B	715a B	749a A	749a A

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each column followed by the same lowercase letter are not significantly different ($P<0.05$).

†Means calculated from five replications.

The high ET values that were observed in 2013 in this study could be attributed in part to the high amount of rainfall that was recorded in the months of June and September (Table 4.1 and Figure 4.2). The ET mean values in relation to cuts for both the irrigated (Blue J and Longview) and dryland (Rambler and Rangelander) followed Cut 1 > Cut 2 > Cut 3 in both years and at both locations with the exceptions of Blue J and Longview which exhibited a different trend at Picture Butte in 2012 (Table 4.3, 4.5 and 4.7). Total ET among irrigation treatments generally followed W_1>W_2>W_3>W_4 at both locations and years (Table 4.3, 4.4 and 4.6). This trend was expected because the W_1 treatment received adequate soil water supply during the growing season whereas the other treatments underwent water deficits. A similar trend was reported by Kuslu et al. (2010) under semiarid conditions. Although there was a significant difference in total ET between the irrigated and dryland alfalfa cultivar types and the irrigation treatments, this difference was not consistent at both locations and years (Table 4.3, 4.4, 4.5, 4.6 and 4.7).

Total rainfall recorded from May to early October in 2012 was 239 mm and 252 mm for Lethbridge and Picture Butte, respectively. In 2013, 372 mm of rainfall was recorded at the Lethbridge experimental site. The total amount of rainfall recorded at Lethbridge in June, 2013 was 165 mm. This rainfall amount was double the 27 year average for Lethbridge and was also greater than the value recorded in June, 2012 for the same location and that of Picture Butte in both years (Table 4.1). A similar rainfall pattern was also observed in July for both years and experimental locations.

4.3.2. Irrigation management

The alfalfa cultivars were managed using four irrigation treatments. There was an optimal treatment W_1 which was managed to maintain soil water content between 60 and 90% of available water in the designated root zone (Figure 4.1 and 4.2). The remaining three treatment received 75% (W_2), 50% (W_3) and 25% (W_4) of the volume of water applied to the optimal treatment. The focus was to maintain the average of the five replicates of the W_1 soil moisture between 60 and 90% of available water (two pink horizontal lines in Figures 4.1 and 4.2) in the surface 0-75 cm of the soil, with an allowable depletion of 40% of available soil moisture as shown in Figure 4.1 and 4.2. This approach to irrigation management was similar to what Woods and McKenzie (2011) used in their WUE studies for cereals and oilseed. The 60 - 90% range of the available water was used for irrigation management because, studies have shown that about 80 to 90% of water extraction by alfalfa takes place in the upper 80 to 90 cm section of the 120 cm root zone (Alberta Agriculture and Rural Development, 2013). Due to root extension in the second year, the root zone for irrigation management was changed to 100 cm (Figure 4.2).

At the bottom of Figures 4.1 and 4.2 are the amount of rainfall (blue bars) and the amount of irrigation (green bars) applied to treatment W_1. The oscillation of the average soil moisture of the optimal (W_1) treatment line typically represented soil moisture readings on Mondays and Thursdays and the corresponding moisture addition (i.e., irrigation) on Tuesdays and Fridays. Some sections of the average soil moisture of treatment W_1 oscillation also resulted from moisture additions due to rainfall (Figure 4.1 and 4.2). The graph representing soil moisture oscillation of treatment W_1 for Picture Butte in 2012 is not shown. The average soil moisture for treatment W_1 for this location in most cases dropped below the 60% line because of large gaps in (July 4 to15 and August 23 to September 12) when the crops was not irrigated due to the breakdown of irrigation pumps and also drying of the plots prior to harvesting.

The highest amount of rainfall at Lethbridge in 2012 was recorded on June 5 (28 mm) and June 10 (20 mm) (Figure 4.1). A total of 81 mm was applied on May 28, 2012 at Lethbridge to bring the average soil moisture content of the W_1 treatment up to the 60 - 90% available water zone (Figure 4.1). The soil moisture content for replications 3 and 4 dropped below 60% line on June 15 and 16, 2012, respectively. Subsequent rainfall from June 17 to 19 and irrigation on June 20 brought the soil moisture content of these replications above the 60% line (Figure 4.1). Again, the soil moisture contents of all the replications including the average dropped below the 60% line after the first cut on July 12, until July 26, 2012 when irrigation was resumed. It took about 12 days to remove all the pipes from the field so the entire experimental site could be mowed; and reconnect the pipes to their original positions. Irrigations on July 26 and 31, 2012 were sufficient to bring the soil moisture content of the various replicates of treatment W_1 up to the 60 - 90% range (Figure 4.1). A similar situation as observed after the first cut occurred after the second cut on August 29. The soil moisture content of replicates 3 and 4 dropped below the 60% line until the last cut was carried out on October 17, 2012.

In 2013, 69 mm of irrigation was applied at the Lethbridge experimental site in order to raise the soil moisture content of all the five replications of the treatment W_1 to the 60 - 90% moisture level within the 100 cm root zone (Figure 4.2). The highest amount of rainfall was recorded on June 19 (64 mm) and September 18 (60 mm); rainfall amounts which were higher than the long term average (Figure 4.2 and Table 4.1). Continuous rainfall from June 17 to 21, 2013 increased the soil moisture content of replication 5 to greater than field capacity (top red line) and led to flooding on some of the plots. The average of the five replications was kept within the 60 - 90% range until the last cut on October 15, 2013. Replication 3 in most cases fell below the 60% line. This could be due to different soil texture, rocks or gopher holes near that particular neutron probe access tube.

4.3.3. Relationship of yield and crop water use (ET)

The total DM yield versus their respective total ET for all cultivars and irrigation treatments are shown in Figure 4.4. The total DM yield for each cultivar type in relation to their respective irrigation treatments increased typically linearly with total ET at both locations, except for 2013 at Lethbridge, where a different trend was observed. The slope, intercept and regression coefficient for all cultivars in each year were presented in Table 4.8. The slope of each line represents the WUE (kg ha^{-1} mm^{-1}). The yield and ET relationship that was observed at both locations in 2012 agrees with those reported by Bauder et al. (1978), Sheafer et al. (1988), Guitjens (1990), Smeal et al. (1991), Grimes et al. (1992), Saeed and El-Nadi (1997) and for Bai and Li (2003). On the other hand, the regression coefficients obtained in this study were lower than those reported by Brown and Tanner (1983), Saeed and El-Nadi (1997) and Kuslu et al. (2010) (Table 4.8).

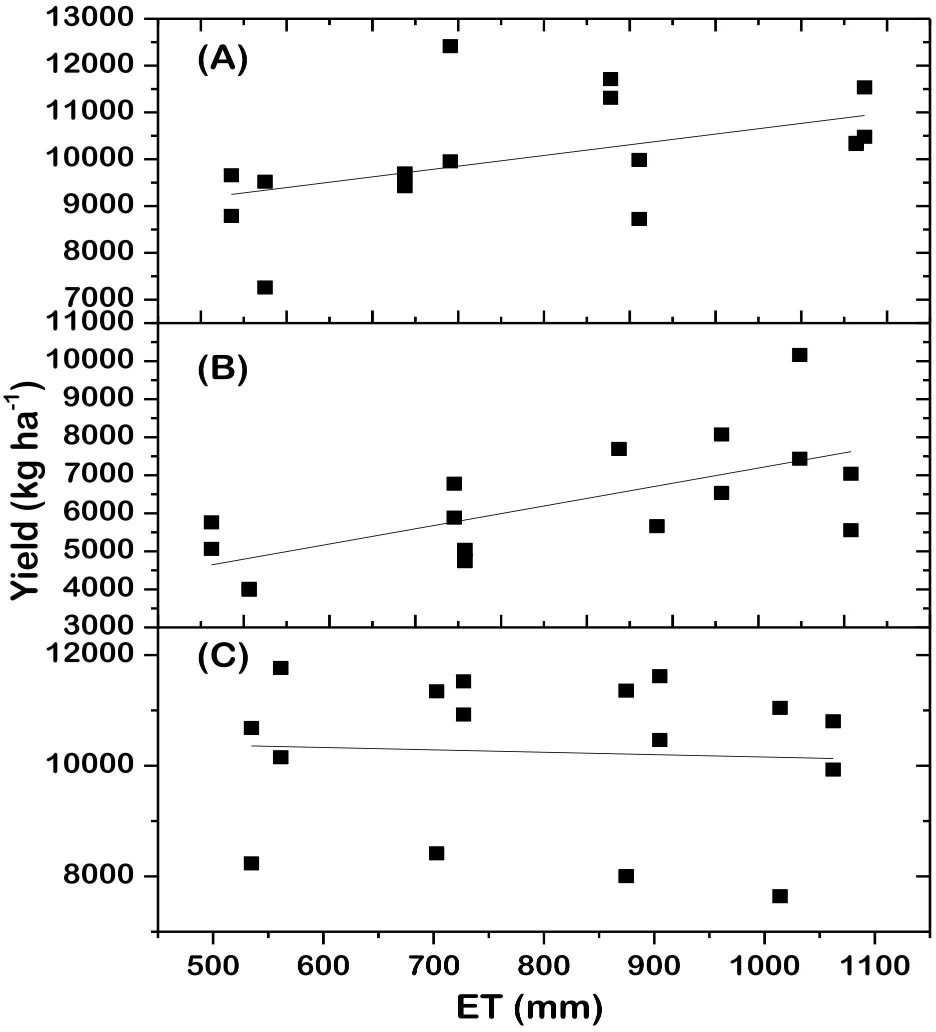


Figure 4.4. Relationship between alfalfa biomass yield and water use (ET) for all cultivar types and irrigation treatments at (a) Lethbridge in 2012 (b) Picture Butte in 2012 (c) Lethbridge in 2013. Each value represents an average of five replications.

Table 4.8. Regression coefficients for alfalfa biomass yield and water use (ET) for the four irrigation treatments. General equation is yield=a +b x *ET*.

	Experimental Site		
	Lethbridge		Picture Butte
	2012	2013	2012
Regression Coefficients			
a (SE[†]) (kg ha^{-1})	6682(1541)	10588(1598)	401(1739)
b (SE) (kg ha^{-1} mm^{-1})	4.57 (2.17)	-0.43(1.95)	7.99(2.35)
R^2	0.19	-0.07	0.41
No. of Replications	5	5	5

[†] Standard Error

The different total yield and ET relationship that was observed at Lethbridge in 2013 could be partly due to alfalfa water extraction deep from the water table. This could have resulted in plant water use which was not accounted for because the water table contribution to these parameters was not quantified in this study. Although water table influence was generally absent within the 100 cm root zone depth at which neutron probe readings were taken across the field, high rainfall in spring and summer of 2010 and in 2013 could have affected the water table and may have brought it closer to the root zone (i.e., ~ 150 to 300 cm depth). The deep rooting system of alfalfa could have made it possible for it to access water within this depth. Borg and Grimes (1986) reported an expected maximum rooting depth in alfalfa between 3 m and 6 m after the second growing year. A study conducted by Dardanelli and Collino (2002) to determine the water table contribution to alfalfa water use in Argentine Pampas indicated that the water table contribution varied among locations between 15 and 25% of the crop water use at different water table depths. These authors also indicated that water table also affected dry matter production and its annual variability.

4.3.4. Water Use Efficiency (WUE)

There was a significant cultivar x water x cut ($P< 0.05$) interaction for WUE at Lethbridge in both years (Tables 4.9). Again, cultivar x water, cultivar x cut and water x cut interactions were also significant ($P< 0.05$) for WUE at Picture Butte in 2012 (Table 4.9). The total WUE for all of the three harvests (i.e., Cut 1, 2 and 3) in relation to the water treatments ranged from 11.56 to 18.39 kg ha^{-1} mm^{-1} and 7.54 to 20.25 kg ha^{-1} mm^{-1} at Lethbridge in 2012 and 2013, respectively; whereas that of Picture Butte in 2012 ranged between 5.77 and 11.29 kg ha^{-1} mm^{-1} (Table 4.10, 4.11 and 4.13). The WUE values obtained in this study were comparable to those reported by Abdul-Jabbar (1983), Grimes et al. (1992), Saeed and El-Nadi (1997), Hirth et al. (2001) and Kuslu et al. (2010). Generally, the WUEs for Lethbridge in both years were greater than those obtained at Picture Butte in 2012 (Table 4.10, 4.11 and 4.13). The high WUE values observed at Lethbridge may perhaps be due to the relatively high rainfall amount that was recorded in May to June and September (Table 4.1) in both years which could have contributed to the relatively high yield (Chapter 3; Table 3.6, 3.7 and 3.8) values recorded in both years at this location compared to that of Picture Butte in 2012. Irmak et al. (2007) indicated that although alfalfa is regarded to be relatively drought tolerant, it produces yields almost proportional to the amount of water available to the crop. WUE is a ratio of yield per unit water used (ET) hence, lower values for yield or greater values for ET could lead to lower computed WUE values. Additionally, the WUE mean values for Cut 1and Cut 2 in relation to the irrigation treatments and cultivar types were greater than that of Cut 3 in both years and locations (Table 4.10, 4.12 and 4.13). This trend of high WUE observed for Cut 1 and 2 in both years and locations is comparable to those reported by Daigger et al. (1970), Undersander (1987), Wright (1988) and Smeal et al. (1991).These authors indicated that WUE was highest with the first cutting and then decreased among subsequent harvests later in the growing season. Results from a study conducted by Smeal et al. (1991) to compare biomass yield per unit of transpiration with levels of solar irradiance over harvest interval helps to explain the observed decrease in WUE among subsequent harvest. Their study indicated that biomass yield increased with increasing average daily solar irradiance: a result which corroborates the work of Holt et al. (1975), who also indicated that increase in biomass per unit transpiration was due to increased light penetration into the canopy rather than an increase in heat energy. Typically, solar irradiance is greater in spring than in fall hence; high light intensity coupled with low temperature facilitates high levels of photosynthesis and low evaporation thereby increasing yield in spring (Bauder et al., 2011). Light intensity levels in fall are low compared to that in spring. Thus, harvest intervals corresponding to the greatest WUE occurs when solar irradiance is high enough to induce high levels of photosynthesis, with associated low temperature being enough to maintain evapotranspiration at a minimum, such as first harvest in spring (Delaney et al., 1974 and Leavitt et al., 1979).

Table 4.9. Degrees of freedom (df) and probability (Pr) of F water use efficiency (WUE) irrigation treatments, cultivars and cuts as determined by a mixed model repeated measure ANOVA at Lethbridge in 2012, 2013 and at the Picture Butte location in 2012 respectively.

	Lethbridge				Picture Butte	
	2012		2013		2012	
Effect	**df**	**Pr of F**	**df**	**Pr of F**	**df**	**Pr of F**
cultivar	3	0.001	3	<0.001	3	<0.001
water	3	<0.001	3	<0.001	3	0.877
cut	3	<0.001	3	<0.001	3	<0.001
cultivar x water	9	0.001	9	0.599	9	<0.001
cultivar x cut	9	<0.001	9	0.031	9	0.001
water x cut	9	<0.001	9	<0.001	9	<0.001
cultivar x water x cut	27	0.001	27	0.006	27	0.082

Table 4.10. [†]Mean water use efficiency (WUE) among four irrigation treatments for four alfalfa cultivars in relation to three cuts at the Lethbridge location in 2012.

Cuts	**Cultivars**	**W_1 (kg ha^{-1} mm^{-1})**	**W_2 (kg ha^{-1} mm^{-1})**	**W_3 (kg ha^{-1} mm^{-1})**	**W_4 (kg ha^{-1} mm^{-1})**
1	Blue J	12.98b B	16.48b A	13.79b AB	16.22a A
	Longview	15.92ab B	20.37a A	17.75a AB	17.75a AB
	Rambler	14.32ab B	14.16bc B	16.06ab AB	17.86a A
	Rangelander	16.34a AB	13.37c B	16.49ab A	19.09a A
2	Blue J	15.66a C	20.87a B	32.13ab A	15.45c BC
	Longview	14.53a C	19.56a B	35.59a A	25.24b B
	Rambler	13.76a C	21.29a B	29.78bc A	27.36a A
	Rangelander	12.09a C	16.87a B	25.87c A	28.57ab A
3	Blue J	3.52ab B	5.44a A	3.69ab B	1.66ab C
	Longview	4.241a A	4.58a A	5.23a A	2.14a B
	Rambler	2.56b A	0.97b A	2.57b A	1.59ab A
	Rangelander	0.48c A	0.306b A	0.91c A	-
Total	Blue J	11.82a B	15.33ab A	15.47b A	14.45b A
	Longview	13.03a B	16.71a A	18.39a A	16.68ab A
	Rambler	11.73a C	13.22bc BC	15.66b AB	17.01a A
	Rangelander	11.71a B	11.56c B	15.22b A	16.59ab A

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different ($P<0.05$). [†]Means calculated from five replications.

Table 4.11. [†]Mean water use efficiency (WUE) among four irrigation treatments and four alfalfa cultivars at the Picture Butte location in 2012.

Cultivars	**W_1 (kg ha^{-1} mm^{-1})**	**W_2 (kg ha^{-1} mm^{-1})**	**W_3 (kg ha^{-1} mm^{-1})**	**W_4 (kg ha^{-1} mm^{-1})**
Blue J	11.29a A	9.16ab B	7.32bc C	8.63a BC
Longview	8.17b B	6.78c B	6.84c B	9.86a A
Rambler	7.44b B	9.45a A	10.08a A	6.40b B
Rangelander	5.77c C	7.67bc AB	8.48b A	6.66b BC

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each column followed by the same lowercase letter are not significantly different ($P<0.05$).

[†]Means calculated from five replications.

Table 4.12. [†]Mean water use efficiency (WUE) among three cuts for four alfalfa cultivars at the Picture Butte location in 2012.

Cuts	**Blue J (kg ha^{-1} mm^{-1})**	**Longview (kg ha^{-1} mm^{-1})**	**Rambler (kg ha^{-1} mm^{-1})**	**Rangelander (kg ha^{-1} mm^{-1})**
Cut 1	10.03b A	10.51a A	9.22b A	10.83a A
Cut 2	12.61a A	9.46ab B	12.92a A	8.18b B
Cut 3	4.29c A	3.34c B	2.85c BC	2.14c C
Total	9.53b A	8.31b AB	8.66bAB	7.44b B

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each column followed by the same lowercase letter are not significantly different ($P<0.05$).

[†]Means calculated from five replications.

Table 4.13. [†]**Mean water use efficiency (WUE) among four irrigation treatments for four alfalfa cultivars in relation to three cuts at the Lethbridge location in 2013.**

Cuts	Cultivars	W_1 (kg ha^{-1} mm^{-1})	W_2 (kg ha^{-1} mm^{-1})	W_3 (kg ha^{-1} mm^{-1})	W_4 (kg ha^{-1} mm^{-1})
1	Blue J	9.97a C	10.62bc C	13.63ab B	19.42a A
	Longview	9.19a B	12.10b A	13.54ab A	14.58b A
	Rambler	11.24a B	14.83a A	14.76a A	17.19a A
	Rangelander	6.46b B	8.38c B	11.98b A	12.99b A
2	Blue J	13.48a C	15.88a C	18.82ab B	22.11a A
	Longview	14.53a B	17.29a B	21.45a A	23.41ab A
	Rambler	13.85a B	16.40a B	23.13a A	25.07a A
	Rangelander	11.45a C	14.25a BC	16.84b B	21.52b A
3	Blue J	5.86ab C	8.78a B	11.35b A	13.17b A
	Longview	7.39a D	9.55a C	13.51a B	16.23a A
	Rambler	6.83a C	6.56b C	10.62b B	16.29a A
	Rangelander	4.74b B	4.80b B	6.57c B	12.46b A
Total	Blue J	9.82a C	11.56a C	15.02a B	20.25a A
	Longview	10.17a D	12.84a C	15.85a B	18.10b A
	Rambler	10.89a D	12.99a C	16.15a B	19.97a A
	Rangelander	7.54b C	9.15b C	11.98b B	15.44c A

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different ($P<0.05$). [†]Means calculated from five replications.

Carbohydrates reserve flux in alfalfa plants during spring also explains why this cool season plant has a higher WUE at first harvest compared to subsequent harvests. Smith (1962) and Robison and Massengale (1968) argued that alfalfa growth early in the growing season is dependent on carbohydrate reserves accumulated during the previous fall season and that after the first harvest, photosynthesis in new leaves act to accelerate growth and restoration of carbohydrates in the root system. Declining temperature and shorter day-length in late summer and early fall result in greater amounts of photosynthate partitioning into root reserves resulting in lower above-ground biomass yield and WUE than in spring (Hanson et al., 1988).

Perhaps, the high WUEs observed for Cut 1 and Cut 2 at both locations and years in this study could also be due to relatively high levels of solar radiation in early summer which could have induced a relatively high rate of photosynthesis resulting in taller alfalfa plants for Cut 1 and Cut 2 (Chapter 3, Table 3.2, 3.3 and 3.4) hence the relative increase in yield when compared to Cut 3. Noble (1970) argued that an increase in solar radiation resulted in an increase in the ratio of carbon fixed per unit of water transpired through a more efficient photosynthesis process. Holt et al. (1975) also indicated that increases in yield with increasing solar radiation are probably due to increased light penetration into the canopy rather than heat energy. This could account for the yield trend that was observed in this study in both years and locations which also influenced the WUE trends. Since solar radiation was not directly measured in this study, this supposition requires further research to be confirmed.

4.3.4.1. Comparing WUE among irrigation treatments and cultivar types

There was a significant cultivar x water x cut ($P<0.05$) interaction for WUE in relation to irrigation treatments and cultivar types in both years at Lethbridge (Table 4.9), whereas cultivar x water, cultivar x cut and water x cut interactions were significant ($P<0.05$) at Picture Butte in 2012 (Table 4.9). A comparison of WUE among irrigation treatments generally indicated a trend of higher WUE for the lower water treatments (W_2, W_3 and W_4) at Lethbridge in both years, whereas that of Picture Butte in 2012 was inconsistent (Table 4.10, 4.11 and 4.13). In 2012 at Lethbridge, the total WUEs for Blue J (W_2, W_3 and W_4) were not significantly different but were significantly ($P<0.05$) greater than that of W_1. A similar trend was also observed for Longview (Table 4.10). Again, the total WUEs for Rambler (W_2 and W_3) were not significantly different but those of W_3

and W_4 were significantly ($P<0.05$) greater than W_1 (Table 4.10). Similarly, the total WUEs for Rangelander W_3 and W_4 were not significantly different but were significantly ($P<0.05$) greater than those of W_1 and W_2. Although the same trend of higher WUE for the lower irrigation treatments was observed at Lethbridge in 2013, the total WUE for W_4 in all cases was statistically significantly ($P<0.05$) greater than those of W_1, W_2 and W_3 (Table 4.13). The total WUEs for Blue J and Rangelander (W_1 and W_2) were not significantly different but were significantly ($P<0.05$) lesser than those of W_3 and W_4. Again total WUEs for Longview and Rambler (W_2, W_3 and W_4) were significantly ($P<0.05$) greater than that of W_1 (Table 4.13).

The WUE results obtained at Lethbridge in both years were comparable to those reported by Ismail and Almarshadi (2013) who indicated that the highest WUE was obtained for 70% FC followed by 85% FC, with field capacity (FC) recording the least WUE. Lindenmayer et al. (2008) also reported an increase in WUE as irrigation decreased with an average WUE of 25.1, 32.7, 31.1 and 35.1 kg ha^{-1} mm^{-1} for the full irrigation, stop irrigation after 2nd Cutting, spring and fall irrigation and stop irrigation after 1st Cutting treatments respectively. Ritchie (1974) and Guitjens (1982) also showed that limited irrigation as opposed to full irrigation improved the WUE of alfalfa. They postulated that the efficient use of water could be due to less water loss through evaporation from the soil surface or by deep percolation. These authors also suggested that the stomata of water stressed plants had constricted, thus increasing resistance to water loss. Another study conducted by Collino et al. (2005) indicated no modification in WUE for alfalfa for the 1st and 2nd drought period, although there was a significant increase in WUE for the 3rd drought period. Collino et al. (2005) also argued that stomata control became more manifested during the 3rd drought period resulting in a reduction in water loss rather than photosynthesis. Sinclair et al. (1984) also postulated that stomata control could act to prevent high transpiration rates thereby significantly improving WUE. Additionally, Ismail and Almarshadi (2013) reported that an increase in WUE under water stress conditions could also be due to a relative increase in yield with minimal water application; and the ability of alfalfa to use water more effectively from the soil profile due to its extensive root system when under water stress (Lindenmayer et al., 2008). Increase in WUE under soil moisture stress has also been reported for other crops: e.g., tomatoes (Sammis and Wu, 1986); onion (Al-Jamal et al., 2001) and pepper (Dorji et al., 2005; Ismail and Ozawa, 2007).

The high total WUE means values observed for the lower irrigation treatments W_3 and W_4 compared to W_1 and W_2 in relation to the alfalfa cultivars at Lethbridge in both years could be partly due to alfalfa water extraction deep from the water table. This could have resulted in plant water use which was not accounted for because the water table contribution to ET was not quantified in this study. Although water table influence was generally absent within the 100 cm root zone depth at which neutron probe readings were taken across the field, high rainfall in spring and summer of 2010 and in 2013 could have elevated the water table closer to the root zone of the crop (~150 to 300 cm). The deep rooting system of alfalfa could have made it possible for it to access water within this depth. Bauder et al. (2011) argued that the deep root system of alfalfa allows it to extract water from the soil moisture reserves when irrigation is limited.

A comparison of total WUE among cultivar types at Lethbridge in 2012 indicated that the total WUE for Longview W_2 was not significantly different from that of Blue J but was significantly ($P<0.05$) greater than those of Rambler and Rangelander (W_2). Again, the total WUE for Longview W_3 was significantly ($P<0.05$) greater than those of Blue J, Rambler and Rangelander (W_3) (Table 4.10). At the same location in 2013, the total WUEs for Blue J, Longview and Rambler (W_1, W_2 and W_3) were not significantly different but were significantly ($P<0.05$) greater than those of Rangelander (W_1, W_2 and W_3) (Table 4.13). Additionally, the total WUE for Blue J and Rambler (W_4) were not significantly different but were significantly ($P<0.05$) greater than those of Longview and Rangelander. At Picture Butte in 2012, the WUE for Blue J W_1 was significantly greater ($P<0.05$) than those of Longview, Rambler and Rangelander. The WUE for Rambler W_2 was also not significantly different than that of Blue J but was significantly ($P<0.05$) greater than those of Longview and Rangelander (Table 4.11). Again, the WUE for Rambler W_3 was significantly ($P<0.05$) greater than those of Blue J, Longview and Rangelander. The WUEs for Blue J and Longview (W_4) at this same location and year were not significantly different but were significantly ($P<0.05$) greater than those of Rambler and Rangelander (Table 4.11).

Although there were significant differences among cultivar type in relation to irrigation treatments and cuts, no particular cultivar showed a distinct and consistent trend in WUE in both years and locations across cuts and among irrigation treatments. Generally, the irrigated types appeared to have had a higher WUE although there were a few instances where the WUE of either of them was comparable to the dryland type Rambler. These results were not in agreement with the findings of Undersander (1987) who indicated no significant difference in WUE among the alfalfa varieties for any level of irrigation. However, it is comparable to the findings of Grimes et al. (1992) who evaluated the WUE of three alfalfa varieties and indicated that the semi-dormant WL318 had a relatively higher WUE than the other two varieties during the cool spring season, whereas CUF101 and Moapa 69 varieties had higher WUE under hot summer conditions.

4.4. Conclusion

Generally, the lower irrigation treatments (W_2, W_3 and W_4) produced the highest WUEs. However, the total WUE for irrigation treatment W_2 in both years at the Lethbridge location was greater than that of W_1 but was statistically not different from W_3 and W_4, whereas at Picture Butte in 2012 the trend was inconsistent. These results seem to suggest the possibility of irrigating both the irrigated and dryland alfalfa cultivar types used in this study at less of the volume of water applied to the optimal treatment (W_1), with 40% depletion of available water maintained between 60 and 90% of the 75 cm to 100 cm root zone. There is a greater prospect of optimizing water use efficiencies of these cultivars under southern Alberta climatic conditions. This will be beneficial to producers in that less water could be used for production thereby reducing the energy cost associated with irrigation. Again, producers can use the amount of water saved for irrigating more land or allocate it to other crops. Finally, since these cultivars were selected only for yield, this finding offers plant breeders the opportunity to explore the possibility of selecting cultivars for high water use efficiency.

Chapter Five: Determination of forage quality for dryland and irrigated type alfalfa cultivars as influenced by different irrigation treatments in southern Alberta

Abstract

Field studies were conducted at Lethbridge in 2012 and 2013 and at Picture Butte in 2012 to determine the effects of different irrigation treatments on the forage quality of both irrigated and dryland type alfalfa cultivars. The irrigated cultivars (Longview and Blue J) and dryland cultivars (Rangelander and Rambler) were arranged on plots in a randomized complete block design with five replications. These cultivars were subjected to four irrigation treatments. For optimal irrigation treatment (W_1), soil water content was maintained between 60 - 90% of available water in the designated root zone. Other irrigation treatments received 75% (W_2), 50% (W_3) and 25% (W_4) of the volume of water applied to the optimal treatment. The acid detergent fiber (ADF) and neutral detergent fiber (NDF) mean values for both locations and years ranged from 14.68 to 38.16% and 23.79 to 48.73% (whole-plant); 13.58 to 29% and 22.14 to 36.78% (leaf); 20.67 to 52.44% and 26.22 to 61.19% (stem) respectively. The stem ADF and NDF mean values obtained at both locations and years were greater than those of the whole-plant and leaf respectively. The whole-plant ADF and NDF for Cut 1 and Cut 2 at Lethbridge in both years were greater than that of Cut 3 with some exceptions. However, in 2012 at Picture Butte the trend among cuts were inconsistent. Similarly, the leaf and stem ADF and NDF for Cut 1 and Cut 2 at Lethbridge in 2013 were in most instances greater than Cut 3. The mean relative feed value (RFV) and leaf-to-stem ratio (LSR) ranged from 121 to 277 and 0.43 to 2.68 at both locations and years respectively. Although there were significant differences among cultivar types and irrigation treatments in relation to cuts, no particular

cultivar type or irrigation treatment showed a consistent and stable trend when whole-plant, leaf and stem ADF, NDF, crude protein (CP), RFV and LSR were compared for both locations and years. However, the Leaf CP in both years and locations was greater than that of the whole-plant and stem, with stem recording the lowest CP. Again the RFV for Cut 3 in relation to all the cultivars and irrigation treatments at Lethbridge in both years were greater than those of Cut 1 and Cut 2 with few exceptions. It was concluded that the height and stage of maturity at the time of harvest affects alfalfa nutritional quality.

5.1. Introduction

Appropriate management of alfalfa enhances the yield produced at the end of the growing season while maintaining a high nutritive value of the forage (Kephart et al., 1989). High quality forages are crucial to the livestock industry: they furnish essential energy, proteins, vitamins, minerals and fiber to livestock when used as feed. Typically, the diet of most domestic and commercial livestock consist predominantly (if not exclusively) of forages (Caddel and Allen, 2000). Alfalfa (*Medicago sativa* L.) is used extensively in the production of most highly productive livestock. It is considered as superior to other forage crops because of its high crude protein and energy content. Notably, alfalfa produces the greatest amount of forage protein per unit area compared to other legumes (Huyghe, 2003). The crude protein content of alfalfa can be as high as 20% at the bud stage (Marten et al., 1988). Alfalfa forage quality is typically, determined on the basis of leaf-to-stem ratio, degree of lignification, its palatability, digestibility (fiber) and crude protein content (Elliott et al., 1972).

Alfalfa yield and quality can be influenced by both biotic and abiotic factors which include growing conditions, soil fertility, temperature, solar radiation, presence of disease and insect pests, water stress, effect of harvesting frequency and stage of maturity (Buxton, 1996; Hill et al., 1988). The stage of maturity and time of harvesting are considered the most critical factors that influence alfalfa yield and quality. As the alfalfa plant matures, its fiber and lignin content increases whereas there is a decrease in crude protein, digestibility and metabolizable energy (Kalu and Fick, 1983; Stallcup et al.,1987; Fick and Janson, 1990). According to Buxton (1996), a week delay in harvesting decreases digestibility and crude protein concentration by about 20 g kg^{-1} and an increased cell-wall concentration by approximately 30 g kg^{-1}. This negative relationship between alfalfa advancing maturity and declining forage quality is well established (Hintz and Albrecht, 1991; Sanderson, 1992; Sulc et al., 1997). Stallcup et al. (1987) and Griffin et al. (1994) also found that first-cut alfalfa had lower quality than later cutting at both pre-bloom and later maturity. Their results were in agreement with work by Sheaffer et al. (1998) who found that third-cut crude protein was higher than that of first-cut, with third-cut ADF and NDF also being lower than first-cut. Although little quality changes occur in forage leaves, greater portion of the decline in forage quality can be mostly attributed to a marked decrease in the quality of the stem (Albrecht et al., 1987; Barnes and Gordon, 1972; Buxton and Hornstein, 1986).

Water stress on the other hand has also been shown to affect alfalfa yield and quality. Alfalfa forage quality increases with water stress compared to those under well watered conditions (Wilson, 1982, 1983a, 1983b). Water stress slows down maturation (Halim et al., 1989) thus, slowing growth (Brown and Tanner, 1983) which results in an increase in the leaf-to-stem ratio (Halim et al., 1989; Bolger, 1988). Another study by Peterson et al. (1992) indicated a reduction in whole herbage ADF, NDF and acid detergent lignin (ADL) concentration when drought occurred throughout the growth period. Halim et al. (1989) also indicated an increase in LSR from 0.60 in an adequately watered treatment to 0.72 in a most severely stressed treatment. However, if water stress is so severe as to reduce leaf mass through senescence, forage quality can decrease (Ottman, 1999). Water stress has also been reported to have decreased cell wall concentration (Halim et al., 1989; Deetz et al., 1996) but not necessarily the wall degradability (Deetz et al., 1996). Again, Kidambi et al. (1990) and Buscaglia et al.

(1994) indicated an increase in mineral concentration (Ca,Mg, Zn,K, and P) in whole plants due to water stress: but the effect of water stress on crude protein in some studies has been inconsistent (Vough and Marten, 1971; Snaydon, 1972; Carter and Sheaffer, 1983). On the other hand, a study conducted by Convertini et al. (2001) indicated that no improvement in alfalfa forage quality would be observed in response to water deficit stress, instead all qualitative parameters were almost similar at both optimal and stressed water levels. Jensen et al. (1967) stated that fiber and lignin percentages increased significantly with an increase in water. This result was not in agreement with that of Vough et al. (1971) who reported a lower percentage of ADF and ADL at a higher soil moisture.

Although there is a substantial volume of literature on the effect of water stress on alfalfa, very little information is available on the effect of different levels of irrigation water regimes on the quality of alfalfa under southern Alberta conditions. The objective of the study was to determine how different alfalfa cultivar types and levels of irrigation treatments affect forage quality in southern Alberta.

5.2. Materials and Methods

5.2.1. Plot Location and Experimental Design

Two field experiments were conducted at two different locations in southern Alberta. The first experiment was located at Lethbridge Alberta Agriculture and Rural Development (ARD), Alberta Irrigation Technology Centre (AITC) (Lat. 49^{o} 45' N and Long. 112^{o} 45' W, 900 m elevation) and the second at Picture Butte (Lat. 49^{o} 55' N, Long. 112^{o} 48' W, 950 m elevation) on a farmer's field. Both sites were located on Orthic Dark Brown Chernozemic soil. Alfalfa cultivars used in this study were grown on plots arranged in a randomized complete block design (RCBD), with five replications and four irrigation water treatments. The experimental site at Lethbridge ARD AITC and Picture Butte were divided into 80 and 40 individual plots respectively. The site at Lethbridge occupied a total area of 2.67 hectares, while that at Picture Butte had a total size of 1.21 hectares. Each plot had a dimension of 6 m by 6 m with a sprinkler in each of the four corners. A buffer zone of 10 m was maintained between each plot to minimize the effect of irrigation water drift from adjacent sprinklers.

5.2.2. Crop Agronomics

High-yielding alfalfa cultivars for dryland (Rangelander and Rambler; Heinrichs et al., 1958; Heinrichs et al., 1979) and irrigation (Blue J and Longview; Acharya et al., 1995; Acharya and Huang, 2000) alfalfa were seeded in 2010 on both experimental sites. These alfalfa cultivars were selected based on their adaptation to different moisture conditions and root features. The crops were seeded with a custom built 10 row small plot forage seeder, at a rate of 10 kg ha^{-1}, with 0.2 m row spacing, at a depth of about 0.019 m. Though the focus of this study was on alfalfa, two cultivars of sainfoin (Nova, L3519) and two of fenugreek (Amber, Tristar) were also grown in addition to the alfalfa cultivars on the Lethbridge experimental site. Information from these sainfoin and fenugreek cultivars are not presented. The two varieties of each alfalfa cultivar type were grown on the same 6 m by 6 m plot; with each variety grown 3 m on both sides of a neutron probe access tube inserted in the middle of the plots.

5.2.3. Irrigation Water System and Treatments

The plots were irrigated using a solid set sprinkler irrigation system with the following pipe dimensions; 0.15 m x 12.19 m main lines and 0.08 m x 12.19 m lateral lines, with a 0.019 m x 0.61 m riser above the soil surface at the four corners of each plot, Nelson R2000 ROTATORS® and Nelson Low-Angle (7 degrees) sprinkler heads were used at the Lethbridge and Picture Butte sites respectively. The main lines at the Lethbridge site were connected to a lateral line through a 0.25 m diameter flex hose (Chapter 3, Figure 3.1). The irrigation water at the Picture Butte site was delivered to each plot via a system of underground pipes, which were installed at the time the plots were established. The plots were subjected to the four irrigation treatments. For the optimal irrigation treatment (W_1), soil water content was maintained between 60 - 90% of available water in the designated root zone. Other irrigation treatments received 75% (W_2), 50% (W_3) and 25% (W_4) of the volume of water applied to the optimal treatment. The optimal irrigation treatment (W_1) was managed to maintain soil water content between 60% and 90% of available water in the top 75 cm root zone as shown in Figure 4.1 (Chapter 4) for the first year. This approach was similar to what Woods and McKenzie, (2011) used in their water use efficiency studies for cereals and oilseeds. In the second year the root zone for irrigation management at Lethbridge was changed to

100 cm due to alfalfa root extension (Chapter 4, Figure 4.2). The project was terminated at the Picture Butte site in the second year due to manpower limitations.

5.2.4. Soil Moisture Monitoring

In order to schedule irrigation, soil moisture readings were taken two times per week (i.e., on Mondays and Thursdays) using a neutron probe (i.e., a Boart Long Year, CNP® 503DR Hydro probe) at 25 cm increments, to a 100 cm depth of root zone, from a 2 m aluminium tube fixed close to the center of each plot. In order to reduce exposure to the radioactive element in the probe, on the individual taking the moisture readings, neutron probe readings were taken on all plots on Mondays whereas on Thursdays readings were taken in the trigger plots only (plots that received irrigation treatment W_1).

5.2.5. Harvest

A Hege 212™ Forage Harvester was used to remove 1.55 m by 6 m strips from each plot on both sides of the access tube located at the center of all plots leaving stubble of about 12 cm above the ground. A total of three harvests (Cuts) were made on each experimental site. Harvesting was done on July 10, August 28 and October 16, 2012 at the Picture Butte site, while crops at Lethbridge were harvested on July 12, August 29 and October 17, 2012. In 2013 harvesting was only done at Lethbridge on July 3, August 22 and October 15. The samples were dried at 60°C for 48 hours to determine the dry matter content which was in turn used to calculate the total yield produced on a dry matter basis.

5.2.6. Forage Quality analyses

Forage quality analyses were conducted on sub samples (250 g) collected from the harvested material. Two-thirds (2/3) of a sub sample was separated into leaves and stems after being dried at 60°C for 48 hours, and then used to determine the leaf-to-stem ratio (LSR). The other one third (1/3) was used in whole-plant quality analysis. All samples were ground through a 1-mm screen with a whilly mill. ADF and NDF content were determined using an ANKOM ^{200} fiber analyzer. The total nitrogen (N) in plant samples were determined by the Dumas combustion technique using a Combustion Analyzer (Carlo Erba NA1500, Carlo Erba, Milan, Italy) interfaced with an Optima Mass Spectrometer (V.G. Isotech, Middlewich, Cheshire, UK) at the Agriculture and Agri-Food Canada research facility at Lethbridge, AB (Olatuyi et al., 2012). The crude protein content was determined indirectly by measuring the amount of N in the forage and multiplying that value by 6.25 (i.e., N X 6.25).

5.2.7. Relative feed value

Relative feed value (RFV) of alfalfa sample was calculated from the estimate of Digestible Dry Matter (DDM) and Dry Matter Intake (DMI) using the following equations:

$$DDM(\%) = 88.9 - \left(0.779 \cdot ADF(\%)\right)$$

$$DMI(\%) = 120/NDF(\%)$$

$$RFV = \left(DDM(\%) \cdot DMI(\%)\right)/1.29$$

where: DDM, ADF, NDF, DMI and RFV were as previously defined. The RFV was developed by the Hay Marketing Task Force of American Forage and Grassland Council (Rohweder et al.,1978) as a forage quality index in the marketing of hay. Quality standards of legume hays are represented in Table 5.1.

Table 5.1 Market hay grades for legumes, legume-grass mixture quality standards.

Quality standard [†]	CP (%)	ADF (% of DM)	NDF (% of DM)	RFV [*]
Prime	>19	<31	<40	>151
1	17-19	31-40	40-46	151-125
2	14-16	36-40	47-53	124-103
3	11-13	41-42	54-60	102-87
4	8-10	43-45	61-65	86-75
5	<8	>45	>65	<75

[†] Standard assigned by Hay Market Task Force of America Forage and Grassland Council; [*]Relative Feed Value (RFV).

- Reference hay of 100 RFV contains 41% ADF and 53% NDF.

5.2.8. Statistical Analyses

All data collected were analysed using the mixed model procedure for repeated measure (SAS Institute Inc., 2011) with cut as the repeated factor. The cultivar, irrigation treatment and cut were modeled as fixed effects while the replication and its interactions with the fixed effects were random effects. The output measures analyzed included ADF, NDF, CP, LSR and RFV. The LSD test ($P < 0.05$) was used for mean separation.

5.3. Results and Discussion

5.3.1. Mean Acid Detergent Fiber (ADF) and Neutral Detergent Fiber (NDF)

The ADF mean values for all the cultivar types in relation to the water treatments and cuts ranged from 14.68 to 37.78% and 17.96 to 38.16% (whole-plant), 13.58 to 29.82% and 15.97 to 28.89% (leaf), 20.67 to 52.44% and 28.62 to 51.74% (stem) at Lethbridge in 2012 and 2013 respectively (Table A.2, A.9 and A.16), whereas those at Picture Butte in 2012 were 21.39 to 35.03% (whole-plant), 14.39 to 23.65% (leaf), 34.89 to 49.46% (stem) (Table A.3, A.10, and A.17). Additionally, the NDF mean values for all the cultivars in relation to the water treatments and cuts ranged from 23.79 to 48.73% and 24.75 to 45.79% (whole-plant), 22.14 to 28.04% and 22.95 to 32.30% (leaf), 26.22 to 56.03% and 34.25 to 61.19% (stem) at Lethbridge in 2012 and 2013 respectively (Table A.5, A.12, A.13, A.14 and A.19), whereas those at Picture Butte in 2012 ranged from 28.34 to 40.59% (whole-plant), 22.67 to 36.78% (leaf), 44.93 to 60.53% (stem) (Table A.6, A.14 and A.20).

Generally, the whole-plant mean NDF values in 2012 and 2013 as well as locations were greater than those of ADF. This was expected because the ADF fraction was a subset of NDF and also insoluble in neutral detergent (Cash and Bowman, 1993). The mean stem ADF and NDF values obtained at both locations and years were also greater than those of the whole-plant and leaf respectively. Typically, alfalfa leaf tissues do not accumulate fiber and lignin to the same extent as stem tissues. This implies that leaves (12 - 16%) are lower in fiber than the stems (28 - 45%) and thus, are much more digestible (Putnam et al., 2007).

The whole-plant ADF and NDF mean values for Cut 1 and Cut 2 at Lethbridge in both years were generally greater than that of Cut 3 with few exceptions (Table A.2 and A.5). At Picture Butte in 2012, the trend among cuts was inconsistent (Table A.3, A.6 and A.7). Similarly, the leaf and stem ADF and NDF mean values for Cut 1 and Cut 2 at Lethbridge in 2013 were in most instances greater than Cut 3 (Table A.9, A.14, A.16 and A.19). The leaf NDF mean values among cuts were inconsistent at both locations in 2012 (Table A.13 and A.14). Although the ADF and NDF stem mean values for Cut 2 were greater than Cut 3 at Lethbridge in 2012 (Table A.16 and A.19), those for Picture Butte in the same year were inconsistent (Table A.17 and A.20). Alfalfa quality typically decreases as it grows and develops. This decrease in quality as it matures could be attributed to the decline in leaf percentage as against the increase in stem height which in turn decreases the leaf-to-stem ratio (LSR). Stem growth initiates the lignification of the secondary cell wall as a support to the primary cell wall which causes a corresponding increase in the ADF and NDF percentage and a decline in crude protein (CP) content thereby reducing the forage quality (Putnam et al., 2007). Since the height of alfalfa for Cut 1and Cut 2 for all the cultivars were significantly ($P<0.05$) greater than Cut 3 (Chapter 3, Table 3.2 and 3.4), the LSR for Cut 3 was expected to be higher resulting in lower ADF and NDF values for Cut 3. Fick and Onstad (1988) indicated a slow decline in leaf NDF concentration and an increase in stem ADF and NDF concentration with increasing maturity. Other studies by Buxto et al. (1985); Sanderson et al. (1989) also indicated the decline in forage quality (i.e., increase in fiber content) with increasing maturity. Stallcup et al. (1987) and Griffin et al. (1994) also found that first-cut alfalfa had lower quality than subsequent cuts taken at a later date. Their results were in agreement with work by Onstad and Fick (1983) who found that the first spring growth of alfalfa had a lower LSR than subsequent regrowth. Sheaffer et al. (1998) also indicated that the third-cut had a higher CP and lower ADF and NDF than the first-cut. Griffin et al. (1994) attributed this difference in forage quality among cuts to the different maturity rate for alfalfa from spring to summer.

5.3.2. Analysis of whole-plant ADF and NDF among cultivar types and irrigation treatments

There was a significant ($P<0.05$) cultivar x water x cut interaction for whole-plant ADF and NDF at Lethbridge in 2012 and 2013 respectively (Table A.1 and A.4). The cultivar x water x cut interaction for whole-plant ADF was also significant ($P<0.05$) at Picture Butte in 2012, whereas only the cultivar x cut and water x cut interactions for whole-plant NDF were significant ($P<0.05$) at this location in 2012 (Table A.1 and A.4). A comparison of whole-plant ADF and NDF among the irrigation treatments in relation to the cultivar types and cuts did not show any distinct pattern although there were few instances where ADF and NDF means for the lower irrigation treatments appeared to be significantly ($P<0.05$) greater. For instance, in 2012 at Lethbridge, the whole-plant ADF for Blue J (W_2 and W_3), Longview W_2, Rambler W_3 and Rangelander W_4 Cut 1; Longview (W_2 and W_3) Cut 2 were significantly ($P<0.05$) greater than the other treatments and their associated cultivar types (Table A.2). Similarly, the whole-plant NDF for Blue J (W_3 and W_4) Cut 2 were not significantly different from that of W_2 but were significantly ($P<0.05$) greater than that of W_1 (Table A.5). At Lethbridge in 2013, the whole-plant ADF for Rangelander W_3 Cut 1 was significantly ($P<0.05$) greater than those of W_1,W_2 and W_4. In contrast, whole-plant ADF of Blue J (W_2 and W_4) Cut 2 was not significantly different from W_3 but was significantly ($P<0.05$) greater than that of W_1

(Table A.2). The whole-plant NDF for Blue J (W_2 and W_3) Cut 2 at this same location was not significantly different but was significantly ($P<0.05$) greater than that of (W_1 and W_4) (Table A.5). This trend observed among the irrigation treatments with less water in relation to some of the cultivar types did not conform to the results of Wilson (1982, 1983a, 1983b), who indicated an increase in forage quality with water stress. Water stress slows down maturation (Halim et al., 1989) thus, slowing growth (Brown and Tanner, 1983), which results in an increase in the LSR (Halim et al., 1989; Bolger, 1988). However, Mueller and Orloff (1994) and Ottman (1999) argued that severe water stress could reduce leaf mass through senescence and thus lower the LSR, which in turn decreases the forage quality. This could partly explain why the lower irrigation treatments in some instances had statistically significantly greater ADF and NDF mean values.

Although no particular cultivar type consistently showed better whole-plant ADF and NDF in relation to the irrigation treatments in both years and locations, the whole-plant ADF and NDF mean values for the irrigated types appeared to be greater. In some cases the values were similar to Rambler.

5.3.3. Analysis of leaf ADF and NDF among cultivar types and irrigation treatments

The cultivar x water x cut interaction for leaf ADF was significant ($P<0.05$) at Lethbridge in both years, whereas only cultivar x cut interaction was significant ($P<0.05$) at Picture Butte in 2012 (Table A.8). Again, the cultivar x water, cultivar x cut and water x cut interactions for leaf NDF were significant ($P<0.05$) at Lethbridge in 2012 (Table A.11), whereas the cultivar x water x cut interaction for leaf NDF was significant ($P<0.05$) at both Lethbridge (2013) and Picture Butte (2012) (Table A.11). The leaf ADF and NDF for Cut 1 at both locations in 2012 were not measured. Although no particular cultivar type showed any distinct and consistent trend when leaf ADF and NDF were compared among cultivar types, there were few instances where the leaf ADF and NDF for the irrigated types appeared to be significantly greater than the dryland types. For instance at Lethbridge in 2012, the leaf ADF mean values for Blue J and Longview (W_1, W_2 and W_3) Cut 2 were significantly ($P<0.05$) greater than those of Rambler and Rangelander (Table A.9). In contrast the leaf ADF for Rambler and Rangelander Cut 2 at Picture Butte in 2012 was significantly ($P<0.05$) greater than those of Blue J and Longview (Table A.10). The leaf NDF for Longview W_1 Cut 2 at the same location was not significantly different from that of Blue J but was significantly ($P<0.05$) greater than those of Rambler and Rangelander (Table A.14). Again, the leaf NDF for Rangelander and Longview W_2 Cut 3 was also not significantly different but was significantly ($P<0.05$) greater than that of Blue J and Rambler (Table A.14).

5.3.4. Comparing stem ADF and NDF among cultivar types and water treatments

The cultivar x water x cut interaction for stem ADF and NDF was significant ($P<0.05$) at both locations and years (Table A.15 and A.18). Although no particular cultivar showed a distinct and consistent trend across the irrigation treatments in relation to cuts, there were few instances where at least one of the cultivar types exhibited significant differences when compared among the others. For instance in 2012 at Lethbridge, stem ADF for Blue J W_2 Cut 2 was significantly ($P<0.05$) greater than those of Longview, Rambler and Ranglander (Table A.16). The stem ADF for Rambler W_2 Cut 3 was also significantly ($P<0.05$) greater than those of Longview, Blue J and Rangelander (Table A.16). Additionally, the stem NDF for Longview W_3 Cut 2 at this same location in

2012 was not significantly different from that of Rambler but was significantly ($P<0.05$) greater than those of Rangelander and Blue J (Table A.19). The stem NDF for Blue J and Longview (W_4) Cut 3 was also significantly ($P< 0.05$) greater than those of Rambler and Rangelander. In 2013 at this same location, stem ADF for Longview W_1 Cut 1 was not significantly different from that of Blue J but was significantly ($P<0.05$) greater than those of Rambler and Rangelander (Table A.16). Again, stem ADF for Rambler W_1 Cut 2 was not significantly different from that of Longview but was significantly ($P<0.05$) greater than those of the Blue J and Rangelander. The stem ADF for Blue J W_2 Cut 3 was also not significantly different from that of Longview but was significantly ($P<0.05$) greater than those of Rambler and Rangelander (Table A.16). Additionally, the stem NDF for Longview W_1 Cut 1 in the same year and at the same location was not significantly different from that of Blue J but was significantly ($P<0.05$) greater than those of Rambler and Rangelander (Table A.19). The stem ADF for Longview and Rangelander (W_1) Cut 3 was also significantly ($P<0.05$) greater than those of Blue J and Rambler at Picture Butte in 2012 (Table A.17). A similar trend was also observed for stem NDF for Longview and Rangelander (W_2 and W_3) Cut 3 at this same location and year (Table A.20).

The stem ADF and NDF trend in both years at the Lethbridge among the irrigation treatments was inconsistent, although there were few instances where the stem ADF and NDF for treatment W_2 appeared to be greater. At Lethbridge in 2012, the stem ADF for Blue J W_2 Cut 2; and stem ADF and NDF for Rambler W_2 Cut 3 were significantly ($P<0.05$) greater than those of W_1, W_3 and W_4 (Table A.16 and A.19). In 2013 at the same location, stem ADF for Blue J W_2 Cut 2 was not significantly different from that of W_4 but was significantly ($P<0.05$) greater than those of W_1 and W_3. The stem ADF for

Rangelander W_2 Cut 2 was significantly ($P<0.05$) greater than those of W_1, W_3 and W_4 (Table A.16). Additionally, stem NDF for Blue J W_2 Cut 2 was also significantly ($P<0.05$) greater than those of W_1, W_3 and W_4 (Table A.19). On the other hand in 2012 at Picture Butte, the stem ADF and NDF for all the cultivar types for W_1, W_2, and W_3 Cut 2 were not significantly different but were significantly ($P<0.05$) greater than those of W_4 (Table A.17 and A.20).

5.3.5. Mean Crude Protein (CP)

The mean CP range for all the cultivars in relation to the water treatments and cuts at Lethbridge was; 18.1 to 32.2% and 17.4 to 31.8% (whole-plant), 26.6 to 33.2% and 27.1 to 30.7% (leaf), 12.10 to 29.4% and 10.8 to 17.2% (stem) for year 2012 and 2013 respectively (Table A.22, A.25, A.26 and A.29). At Picture Butte in 2012, CP for all the cultivars in relation to the water treatments and cuts ranged from 15.6 to 33.0% (whole-plant), 22.2 to 32.3% (leaf) and 10.4 to 16.0% (stem) (Table A.23, A.25 and A.30). Michaud et al. (2001) reported whole-plant, leaf and stem CP; 19.7, 28.4 and 10.7% of dry matter respectively in Canada. Another study conducted by Gray et al. (1996) indicated a CP range of 18.3 to 20.4% (whole-plant), 23.6 to 25.4% (leaves) and 14.5 to 17.2% (stem) for irrigated alfalfa. Brown et al. (2005) also presented a substantially higher CP for leaf fraction than stem for lucerne (29%), red clover (25%) and chicory (17%) under different irrigation treatments. Interestingly, the leaf CP in both years and locations was greater than that of the whole-plant and stem, with stem recording the lowest CP. Higher CP for alfalfa leaves compared to stem were observed earlier by Mowat, 1965; Putnam et al., 2007; Hintz and Albrecht (1991) and Bourquin and Fahey (1994). Huyghe (2003) and Marten et al. (1988) reported that alfalfa produces the greatest amount of forage protein per unit area compared to other legumes and that CP content of alfalfa can be as high as 20% at the bud stage.

The whole-plant, leaf and stem CP among cuts in relation to cultivar types and irrigation treatments in this present study did not indicate any consistent trend (Table A.22, A.23, A.25, A.27, A.29, A.30 and A.31).This result is comparable to those of Brown et al. (2005) who indicated no systematic change in CP and metabolisable energy (ME) concentration within seasons or between irrigation treatments. Vough et al. (1971) also showed that the effect of increasing moisture stress on CP was inconsistent.

5.3.6. Comparing CP in whole-plant among cultivar types and irrigation treatments

The cultivar x water x cut interaction for whole-plant CP was significant ($P<0.05$) at both locations and years (Table A.21). The whole-plant CP across the irrigation treatments in relation to all the cultivar types and cuts indicated an inconsistent trend at both locations and years (Table A.22 and A.23). For example, there was no significant difference in whole-plant CP for all cultivar types under W_1 and W_2 irrigation treatment for Cut 1 and 2 at Lethbridge in 2012, however those of Blue J and Rambler (W_1) Cut 3 were not significantly different but were significantly ($P<0.05$) greater than those of Longview and Rangelander. The whole-plant CP for Blue J W_2 Cut 3 was also significantly ($P<0.05$) greater than those of Longview, Rambler and Rangelander (Table A.22). In 2013 at this same location, the whole-plant CP for Rangelander W_2 Cut 1 was not significantly different from that of Blue J but was significantly ($P<0.05$) greater than those of Longview and Rambler. There was no significant difference in whole-plant CP among all the cultivar types in relation to all the irrigation treatments at this location for Cut 3 (Table A.22). Although there were significant differences among cultivar types at

Picture Butte in 2012, no particular cultivar type exhibited a unique and consistent pattern across water treatments and cuts (Table A.23).

5.3.7. Comparing CP in leaf and stem among cultivar types and treatments

There was a significant ($P<0.05$) cultivar x water x cut interaction for leaf CP at both locations in 2012, whereas in 2013 at Lethbridge, the cultivar x water and cultivar x cut interactions were significant ($P<0.05$) (Table A.24). Again, the cultivar x water x cut interactions for stem CP were significant ($P<0.05$) at Lethbridge in both years, whereas at Picture Butte in 2012 only cultivar x cut and water x cut interactions were significant ($P<0.05$) (Table A.28). Although there were statistically significant differences among cultivar types and irrigation treatments in relation to cuts, no particular cultivar type or irrigation treatment showed a consistently better leaf and stem CP in both locations and years (Tables A.25, A.26, A.29 and A.30).

5.3.8. Relative Feed Value (RFV) and Leaf-to-Stem Ratio (LSR)

The mean RFV ranged from 122 to 277 and 121 to 276 at Lethbridge in 2012 and 2013 respectively, whereas that of Picture Butte in 2012 ranged between 166 and 205 (Table A.33 and A.34). The RFV mean values obtained in this study were comparable to those reported by Canbolat et al. (2006) (i.e., 106 to 225). Kiraz (2011) also reported a RFV range of 138.81 to 155.07 for different hay legumes in Turkey. Another study by Gray et al. (1996) also indicated a RFV range of 158 to 212 for whole plant irrigated alfalfa. The mean LSR ranged from 1.12 to 2.68 and 1.02 to 2.48 at Lethbridge in 2012 and 2013 respectively, whereas that of Picture Butte in 2012 ranged between 0.43 and 2.57 (Tables A.37 and A.38). Halim et al. (1989) presented a LSR range of 0.52 to 0.77 in a study conducted to determine the effect of water stress on alfalfa forage quality.

Generally, the RFV mean values for Cut 3 for all the cultivars and irrigation treatments at Lethbridge in both years was greater than those of Cut 1 and Cut 2 with few exceptions (Table A.33). A similar trend was also observed at Picture Butte in 2012 except for Longview and Rangelander Cut 3 which had lesser RFV mean values (Table A.35). The RFV trend observed at Lethbridge in both years was in accordance with what was reported by Gray et al. (1996). Additionally, the LSR mean values for Cut 3 for all the cultivars were also generally greater than those of Cut 1 and Cut 2 in both years at Lethbridge with few exceptions (Table A.37). The LSR among cuts were inconsistent at Picture Butte in 2012, except for Blue J and Rambler (W_2) which exhibited similar trends to what was observed at Lethbridge in both years (Table A.38).

This trend of higher RFV and LSR mean values for Cut 3 that was observed at Lethbridge in both years was expected because the height of all the alfalfa cultivars for Cut 3 at both locations in relation to the irrigation treatments was lower than those of Cut 1and Cut 2 (Chapter 3, Table 3.2 and 3.4). Stem elongation associated with plant maturity decreases the LSR (Hides et al., 1983) and thereby increasing the NDF and ADF contents hence resulting in a decrease in forage quality (Terry and Tilley, 1964). This explains why the Cut 3 which had shorter plants exhibited a higher RFV than the other cuts. These results corroborate the idea that the height of alfalfa and stage of maturity at the time of harvest (Kalu and Fick, 1981) does affect the quality of alfalfa produced.

5.3.9. Comparison of Relative Feed Value (RFV) and Leaf-to-Stem Ratio (LSR) among cultivar types and irrigation treatments

The cultivar x water x cut interaction for RFV was significant ($P<0.05$) at Lethbridge in both years, whereas in 2012 at Picture Butte, only cultivar x water, cultivar x cut and water x cut interactions were significant ($P<0.05$) (Table A.32). Only the cultivar x cut interaction for LSR was significant ($P<0.05$) at Lethbridge in both years (Table A.36). However, the cultivar x water x cut interaction for LSR was significant ($P<0.05$) at Picture Butte in 2012 (Table A.36). Although significant differences in RFV were observed among the cultivar types and across the irrigation treatments, no particular cultivar and irrigation treatment showed a consistent and stable trend at both locations and years (Table A.33, A.34 and A.35).On the other hand, the LSR for Blue J and Longview in some instances appeared to be significantly ($P<0.05$) lesser and similar to Rambler when cultivars were compared in relation to cuts in both years and locations (Table A.37 and A.38).

5.4. Conclusion

Although there were significant differences among cultivar types and irrigation treatments in relation to cuts, no particular cultivar type or irrigation treatment showed a consistent and stable trend when whole-plant, leaf and stem ADF, NDF, CP, LSR and RFV were compared for both locations and years. However, the stem ADF and NDF mean values obtained at both locations and years were greater than those of the whole-plant and leaf respectively. The leaf CP in both years and locations were also greater than those of the whole-plant and stem, with stem recording the lowest CP. Additionally the ADF, NDF, LSR and RFV for the later harvest in relation to all the cultivars and irrigation treatments at one of the locations in both years were greater than the earlier harvest with few exceptions. These results indicated that the height of alfalfa and stage of maturity at the time of harvest does affect the quality of alfalfa produced. Hence, stage of maturity at the time of harvest should be of prime consideration if high quality alfalfa production is the goal.

Chapter Six: General synthesis

Alfalfa is considered the most important forage legume in Canada and it is cultivated on over 4.5 million hectares (Statistics Canada, 2002). In southern Alberta, approximately 907,000 tonnes of alfalfa is produced annually under irrigation (Dill et al., 2007). In 2013 in Alberta, about 60,000 ha of alfalfa were grown under irrigation, within the province's irrigation districts (ARD, 2014). However, the increase in demand for water for irrigation, livestock production, industrial and other domestic purposes coupled with the erratic rainfall patterns in southern Alberta pose a threat to alfalfa cultivation in the foreseeable future. These competing demands and the large volume of irrigated agricultural water extraction are approaching a critical limit in some locations (Corkal and Adkins, 2007). Hence, the provincial government has placed a moratorium on new licence applications for the use of irrigation water within the Bow, Oldman and South Saskatchewan River Basin (SSRB). It is therefore imperative to explore and adopt management strategies that can lead to the optimization of the limited water available for irrigation for forages such as alfalfa which has a high water requirement.

To determine the effect of different irrigation treatments on yield, water use efficiency (WUE) and forage quality of alfalfa cultivars developed for irrigated and dryland areas of western Canada, field studies were conducted in 2012 and 2013 at Lethbridge and Picture Butte . The mean total forage DM yields were higher at Lethbridge compared to Picture Butte. The mean DM yields for Cut 1 and Cut 2 in most instances were similar, and greater than that of Cut 3 at both locations and years. The mean forage height for cuts in relation to all the water treatments at Lethbridge and Picture Butte in 2012 followed this trend: Cut 1 > Cut 2 > Cut 3 and Cut 2 > Cut 1> Cut

3, respectively. The irrigated alfalfa cultivars out-yielded the dryland types in both locations, although among irrigated types the performance was not consistent. A comparison of the DM yield among the irrigation treatments indicated that total forage DM yield for Blue J, Longview and Rambler (W_2 and W_3) at Lethbridge in both years were higher than those of W_1 although the differences in some cases were not significant. Considering the forage yield, it was concluded that alfalfa cultivars developed for irrigated areas could be irrigated at 75% of the volume applied to the optimal irrigation treatment (W_1), with 40% depletion of available water at the root zone without incurring drastic yield loss. If water was limited, applying less water over more area would provide greater total biomass yield.

A comparison of total WUE among the irrigation treatments indicated that the total WUE was higher for W_4 compared to other treatments in 2013 but, in 2012 total WUE for W_2, W_3 and W_4 were similar and higher than W_1 for the irrigated cultivars. Again, the total WUE for W_1 and W_2 for the dryland cultivars were also similar in 2012 at Lethbridge. The WUE was generally higher for irrigated cultivars compared to the dryland types, although in some cases the differences were not significant. For Picture Butte no clear trend was noticed. A linear relationship between total dry matter yield and total water use (ET) for each cultivar type in relation to the irrigation treatments was established at both locations in 2012. The WUE results suggest the possibility of irrigating both the irrigated and dryland alfalfa cultivar types used in this study at 75% of the volume of water applied to the optimal treatment (W_1), with 40% depletion of available water within 60 - 90% of the root zone with a greater prospect of optimizing water use efficiencies of these cultivars under southern Alberta climatic conditions.

The stem ADF and NDF mean values obtained at both locations and years were greater than those of the whole-plant and leaf respectively. Again, the whole-plant ADF and NDF for Cut 1 and Cut 2 at Lethbridge in both years were greater than that of Cut 3 with some few exceptions. However, in 2012 at Picture Butte the trend among cuts was inconsistent. Similarly, the leaf and stem ADF and NDF for Cut 1 and Cut 2 at Lethbridge in 2013 were in most instances greater than Cut 3. Although there were significant differences among cultivar types and irrigation treatments in relation to cuts, no particular cultivar type or irrigation treatment showed a consistent and stable trend when whole-plant, leaf or stem ADF, NDF, CP, RFV and LSR were compared for both locations and years. However, the leaf CP in both years and locations was greater than that of the whole-plant and stem, with stem recording the lowest CP. The RFV for Cut 3 in relation to all the cultivars and irrigation treatments at Lethbridge in both years were greater than those of Cut 1 and Cut 2 with some few exceptions. These results indicated that the height of alfalfa and stage of maturity at the time of harvest does affect the quality of alfalfa produced. Hence consideration needs to be given to the stage of maturity and the time at which harvesting is conducted during the growing season if high quality alfalfa forage is desired.

Overall there was limited evidence generated by the present study to support the suggestions by earlier studies (by other authors) that optimal irrigation or irrigation at field capacity (Jodari-Karimi et al.,1983; Al-Naeem, 2008) does improve water use efficiency, whereas deficit irrigation also improve alfalfa forage quality (Wilson, 1982, 1983a, 1983b). Again yields produced by treatments with less irrigation water applied in the present study were comparable to those obtained using the optimal irrigation treatment. This result was at variance with those reported by Saeed and El-Nadi (1997) and Al-Naeem (2008). The forage quality results in the present study do agree with studies that indicated the stage of maturity and time of harvest affect alfalfa quality and yield produced in a growing season (Buxto et al., 1985; Fick and Onstad, 1988; Sanderson et al., 1989).

The findings of the present study are important to farmers who produce alfalfa on a large scale in southern Alberta and other water challenged regions of the world in that, less water could be used for production of the same amount of forage with a greater prospect of optimizing WUE of the cultivars used in this study, and also reducing the energy cost associated with irrigation. Producers can use the amount of water saved to irrigate more land or could allocate it to other crops. Based on the fact that on an annual basis total yield for at least one of the irrigated types outperformed the dryland types, producers will be better off using irrigated alfalfa cultivars if high biomass yield production is important. Additionally, alfalfa producers need to pay attention to the stage of maturity and time at which harvesting is conducted during the growing season if alfalfa forage of high quality needs to be produced.

There is need for further work to be done with Rambler to confirm its suitability and performance under irrigated conditions since its yields in some instances were comparable to the irrigated types. Perhaps this could lead to breeding of alfalfa cultivars that are more drought tolerant and at the same time can produce relatively high yields when grown under deficit irrigation conditions. Again because all the cultivars types used in this present study were selected only for yield, this offers plant breeders the opportunity to explore the possibility of selecting cultivars for high water use efficiency.

Finally, there will be the need to conduct studies to quantify water table contribution to ET and yield under deficit irrigation conditions, since water tables can influence crop water use, dry matter production and its annual variability.

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Appendices

Table A.1. Degrees of freedom (df) and probability (Pr) of F values for whole-plant ADF among irrigation treatments, cultivars and cuts as determined by a mixed model repeated measure ANOVA at Lethbridge in 2012, 2013 and at the Picture Butte location in 2012 respectively.

	Lethbridge				Picture Butte	
	2012		2013		2012	
Effect	**df**	**Pr of F**	**df**	**Pr of F**	**df**	**Pr of F**
cultivar	3	<0.001	3	<0.001	3	<0.001
water	3	0.001	3	0.005	3	0.004
cut	2	<0.001	2	<0.001	2	<0.001
cultivar x water	9	<0.001	9	<0.001	9	0.001
cultivar x cut	6	<0.001	6	0.258	6	<0.001
water x cut	6	0.004	6	0.006	6	<0.001
cultivar x water x cut	18	<0.001	18	0.001	18	0.003

Table A.2. [†]Mean (%) whole-plant ADF among four irrigation treatments for four alfalfa cultivars in relation to three cuts at the Lethbridge location in 2012 and 2013 respectively.

		2012				2013			
Cuts	**Cultivars**	W_1	W_2	W_3	W_4	W_1	W_2	W_3	W_4
1	Blue J	30.67a B	33.61b A	33.56a A	30.06b B	32.55a A	29.58ab A	31.53ab A	30.42a A
	Longview	31.86a B	37.78a A	29.59b B	30.01b B	31.50a A	33.37a A	31.74a A	29.99a A
	Rambler	30.05a B	27.01c C	33.47a A	25.98c C	34.02a A	30.35ab AB	27.45b B	26.039b B
	Rangelander	31.94a B	29.18c C	17.49b C	36.32a A	22.91b B	26.14b B	36.08a A	25.15b B
2	Blue J	30.39b A	29.81ab A	29.89b A	25.13b B	32.46bc B	38.16a A	36.72a AB	37.43a A
	Longview	26.78c B	31.98a A	34.39a A	28.36a B	31.43c B	38.09a A	35.66ab AB	32.69b B
	Rambler	33.90a A	27.41bc BC	29.57b B	25.40b C	36.47ab A	33.53b AB	33.37ab AB	30.923b B
	Rangelander	23.59d B	26.03c A	24.03c AB	24.73b AB	37.08a A	34.88ab AB	31.38b B	31.41b B
3	Blue J	16.68ab A	18.62ab A	18.39ab A	18.34a A	20.77a AB	20.54a AB	19.81a B	21.76a A
	Longview	18.54a A	20.61a A	19.84a A	15.64b B	19.77ab A	20.19ab A	19.48a A	20.79ab A
	Rambler	14.68b B	17.68b A	15.30c AB	17.55ab B	19.51ab AB	20.71a A	17.96a B	18.37c B
	Rangelander	17.49a A	16.46b A	16.92bc A	18.26a A	18.37b A	18.57b A	18.93a A	19.46bc A

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different ($P<0.05$). [†]Means calculated from three replications.

Table A.3. [†]Mean (%) whole-plant ADF among four irrigation treatments for four alfalfa cultivars in relation to three cuts at the Picture Butte in 2012.

Cuts	Cultivars	W_1	W_2	W_3	W_4
1	Blue J	27.10a B	28.77a B	32.55a A	34.59a A
	Longview	30.16a B	32.01a AB	29.65a B	34.84a A
	Rambler	28.92a B	29.79a B	29.09a B	35.03a A
	Rangelander	29.83a A	30.56a A	31.58a A	30.301b A
2	Blue J	34.09a A	28.16a B	32.99a A	23.93a C
	Longview	29.99b A	27.36a AB	26.29b B	21.06ab C
	Rambler	23.79c B	27.73a A	29.27b A	20.46b B
	Rangelander	23.19c A	21.31b AB	21.74c AB	19.54b B
3	Blue J	26.28c B	26.90a B	30.44a A	29.18a AB
	Longview	35.31a A	27.33a B	28.039a B	26.23a B
	Rambler	23.94c A	21.60b A	21.93b A	21.39b A
	Rangelander	31.27b A	29.45a A	28.13a A	28.08a A

Mean values within each row followed by the same uppercase letter are not significantly different (P<0.05). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different (P<0.05).

[†] Means calculated from three replications.

Table A.4. Degrees of freedom (df) and probability (Pr) of F values for forage whole-plant NDF among irrigation treatments, cultivars and cuts as determined by a mixed model repeated measure ANOVA at Lethbridge in 2012, 2013 and at the Picture Butte location in 2012 respectively.

	Lethbridge				Picture Butte	
	2012		2013		2012	
Effect	**df**	**Pr of F**	**df**	**Pr of F**	**df**	**Pr of F**
cultivar	3	0.176	3	0.006	3	0.005
water	3	0.325	3	0.012	3	0.004
cut	2	<0.001	2	<0.001	2	<0.001
cultivar x water	9	0.013	9	0.129	9	0.839
cultivar x cut	6	<0.001	6	<0.001	6	<0.001
water x cut	6	0.029	6	0.003	6	0.005
cultivar x water x cut	18	0.025	18	<0.001	18	0.499

Table A.5. †Mean (%) whole-plant NDF among four irrigation treatments for four alfalfa cultivars in relation to three cuts at the Lethbridge location in 2012 and 2013 respectively.

		2012				2013			
Cuts	**Cultivars**	**W_1**	**W_2**	**W_3**	**W_4**	**W_1**	**W_2**	**W_3**	**W_4**
1	Blue J	47.02ab A	46.51a A	47.75a A	39.49a B	45.79a A	38.52b B	38.50a B	36.37ab B
	Longview	44.66a AB	48.73a A	42.81b B	40.89a B	36.68b A	38.60b A	39.01ab A	37.14a A
	Rambler	40.58b A	37.66b A	40.73b A	39.59a A	40.15b A	43.29a A	42.79a A	33.97ab B
	Rangelander	43.44ab A	40.518b A	40.26b A	42.86a A	28.58c C	33.75c B	41.36ab A	32.67b BC
2	Blue J	34.66c B	38.17a AB	40.85ab A	39.55a A	38.88b B	45.19a A	43.63a A	38.89a B
	Longview	40.40ab AB	40.28a AB	43.25a A	38.09a B	36.87b B	44.80a A	42.96a A	40.63a AB
	Rambler	43.93a A	40.92a AB	41.75ab AB	38.64a B	43.86a A	38.39b AB	40.37a AB	39.43a B
	Rangelander	39.19b A	39.40a A	38.47b A	39.54a A	43.80a A	42.63ab AB	40.69a AB	38.38a B
3	Blue J	23.79b A	24.49a A	25.96a A	26.53bc A	28.07a A	27.87a A	27.04a A	30.92a A
	Longview	30.37a A	25.32a BC	29.58a AB	25.08c C	26.47a A	28.69a A	29.22a A	28.13ab A
	Rambler	27.72ab B	28.19a B	30.22a AB	33.31a A	26.35a A	24.75a A	25.79a A	24.97b A
	Rangelander	25.59b B	27.47a AB	27.29a AB	32.80ab A	25.45a A	27.23a A	25.39a A	27.29ab A

Mean values within each row followed by the same uppercase letter are not significantly different (P<0.05). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different (P<0.05).† Means calculated from three replications.

Table A.6. [†]Mean (%) whole-plant NDF among four alfalfa cultivars in relation to two cuts at the Picture Butte location in 2012.

Cultivars	Cut 1	Cut 2	Cut 3
Blue J	36.65a A	38.05a A	28.34d B
Longview	37.64a A	34.13b B	37.11b A
Rambler	37.34a A	33.93b B	31.95c B
Rangelander	38.38a A	31.44b B	40.59aA

Mean values within each row followed by the same uppercase letter are not significantly different (P<0.05). Mean values within each column followed by the same lowercase letter are not significantly different (P<0.05).

[†]Means calculated from three replications.

Table A.7. [†]Mean (%) whole-plant NDF among three cuts and four irrigation treatments at the Picture Butte location in 2012.

Cuts	W_1	W_2	W_3	W_4
Cut 1	37.63a A	37.09a A	37.53a A	37.86a A
Cut 2	35.77ab A	36.32a A	36.70a A	28.76c B
Cut 3	34.68b A	34.38a A	34.86a A	34.07b A

Mean values within each row followed by the same uppercase letter are not significantly different (P<0.05). Mean values within each column followed by the same lowercase letter are not significantly different (P<0.05).

[†] Means calculated from five replications.

Table A.8. Degrees of freedom (df) and probability (Pr) of F values for leaf ADF among irrigation treatments, cultivars and cuts as determined by a mixed model repeated measure ANOVA at Lethbridge in 2012, 2013 and at the Picture Butte location in 2012 respectively.

		Lethbridge			Picture Butte	
		2012		2013		2012
Effect	df	Pr of F	df	Pr of F	df	Pr of F
cultivar	3	<0.001	3	0.044	3	0.001
water	3	<0.001	3	0.083	3	0.005
cut	1	<0.001	2	<0.001	1	<0.001
cultivar x water	9	0.003	9	0.251	9	0.139
cultivar x cut	3	<0.001	6	<0.001	3	0.021
water x cut	3	0.053	6	<0.001	3	0.994
cultivar x water x cut	9	0.004	18	<0.001	9	0.414

Table A.9. †Mean (%) leaf ADF among four irrigation treatments for four alfalfa cultivars in relation to two cuts at the Lethbridge location in 2012 and 2013 respectively.

		2012				2013			
Cuts	**Cultivars**	**W_1**	**W_2**	**W_3**	**W_4**	**W_1**	**W_2**	**W_3**	**W_4**
1	Blue J	-	-	-	-	22.46 ab A	20.38a A	19.84c A	19.92a A
	Longview	-	-	-	-	19.86b B	19.59a B	22.54b A	20.64a AB
	Rambler	-	-	-	-	22.22a A	20.99a A	21.11bc A	21.27a A
	Rangelander	-	-	-	-	21.30ab B	21.23a B	26.77a A	21.68a B
2	Blue J	28.51a A	29.66a A	27.29a A	27.74a A	20.55a A	21.08c A	21.22a A	21.68ab A
	Longview	26.40a B	29.82a A	28.93a AB	20.88b C	22.32a A	20.96c AB	21.70a A	18.95c B
	Rambler	21.38b AB	22.35c A	18.90b B	22.81b A	22.30a B	28.89a A	23.32a B	22.65a B
	Rangelander	21.74b B	26.35b A	21.20b B	23.15b B	22.59a AB	24.99b A	21.39a BC	19.80bc C
3	Blue J	16.64a AB	18.75a A	13.58b B	16.83a AB	16.88ab A	17.49ab A	18.146a A	18.03a A
	Longview	17.29a A	14.91b A	17.03a A	16.93a A	18.89a A	18.69a A	18.01a A	19.13a A
	Rambler	17.15a A	16.97ab A	15.12ab AB	13.68b B	15.97b B	16.11b AB	18.40a A	16.80a AB
	Rangelander	15.42a A	14.34b A	14.82ab A	15.21b A	15.98b A	16.06b A	16.75a A	17.85a A

Mean values within each row followed by the same uppercase letter are not significantly different (P<0.05). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different (P<0.05). † Means calculated from three replications.

Table A.10. †Mean (%) leaf ADF among two cuts for four alfalfa cultivars at the Picture Butte location in 2012.

Cultivars	**Cut 2**	**Cut 3**
Blue J	14.76c B	22.68a A
Longview	14.39c B	22.28a A
Rambler	18.76a B	22.96a A
Rangelander	17.66b B	23.65a A

Mean values within each row followed by the same uppercase letter are not significantly different (P<0.05). Mean values within each column followed by the same lowercase letter are not significantly different (P<0.05). †Means calculated from three replications.

Table A.11. Degrees of freedom (df) and probability (Pr) of F values leaf NDF among irrigation treatments, cultivars and cuts as determined by a mixed model repeated measure ANOVA at Lethbridge in 2012, 2013 and at the Picture Butte location in 2012.

	Lethbridge				**Picture Butte**	
	2012		**2013**		**2012**	
Effect	**df**	**Pr of F**	**df**	**Pr of F**	**df**	**Pr of F**
cultivar	3	<0.001	3	0.661	3	<0.001
water	3	0.348	3	0.738	3	0.246
cut	1	0.117	2	<0.001	1	0.371
cultivar x water	9	0.019	9	0.877	9	0.252
cultivar x cut	3	<0.001	6	0.030	3	<0.001
water x cut	3	0.011	6	0.734	3	0.677
cultivar x water x cut	9	0.326	18	0.001	9	0.003

Table A.12. †Mean (%) leaf NDF four irrigation treatments and four alfalfa cultivars at the Lethbridge location in 2012.

Cultivars	W_1	W_2	W_3	W_4
Blue J	25.83a A	27.74a A	26.56a A	25.56a A
Longview	24.91a B	27.82a A	28.04a A	25.43a B
Rambler	24.33a AB	22.93c B	22.14b B	25.32a A
Rangelander	24.79a A	25.40b A	24.17b A	25.69a A

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each column followed by the same lowercase letter are not significantly different ($P<0.05$).†Means calculated from three replications.

Table A.13. †Mean (%) leaf NDF among two cuts for four alfalfa cultivars at the Lethbridge location in 2012.

Cultivars	Cut 2	Cut 3
Blue J	28.30a A	24.54b B
Longview	27.81a A	25.68ab A
Rambler	21.36c B	26.00ab A
Rangelander	23.11b B	26.92a A

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each column followed by the same lowercase letter are not significantly different ($P<0.05$).
†Means calculated from three replications.

Table A.14. [†]Mean (%) leaf NDF among four irrigation treatments for four alfalfa cultivars in relation to three cuts at the Lethbridge and Picture Butte location in 2013 and 2012 respectively.

		Lethbridge				Picture Butte			
		2013				2012			
Cuts	**Cultivars**	**W_1**	**W_2**	**W_3**	**W_4**	**W_1**	**W_2**	**W_3**	**W_4**
1	Blue J	28.59a A	29.37b A	31.04a A	28.76b A	-	-	-	-
	Longview	30.41a AB	32.11a A	28.91a B	29.40ab AB	-	-	-	-
	Rambler	30.99a A	27.10b B	30.47a A	32.17a A	-	-	-	-
	Rangelander	29.18a A	28.61b A	30.45a A	27.88b A	-	-	-	-
2	Blue J	32.30a A	28.99a B	30.32a AB	31.23a AB	31.20ab B	36.37a A	34.54a AB	31.29b B
	Longview	30.33ab AB	28.00a B	31.45a A	30.47a AB	34.54a A	33.68ab A	34.17a A	35.08a A
	Rambler	27.89b A	30.73a A	30.20a A	29.44ab A	28.77b AB	31.14b A	27.59b B	27.52c B
	Rangelander	30.10ab A	29.31a AB	28.60a AB	26.49b B	24.96c A	22.67c A	23.87c A	25.08c A
3	Blue J	24.88a A	24.21a A	24.21ab A	23.35b A	27.16c A	28.07b A	27.92c A	28.073a A
	Longview	24.97a A	24.47a A	23.63b A	24.84ab A	32.03b A	32.37a A	31.81ab A	29.36a A
	Rambler	24.42a A	25.75a A	24.81ab A	24.27ab A	27.28c B	28.65b AB	29.69bc AB	30.80a A
	Rangelander	22.95a B	24.93a AB	26.65a A	27.05a A	36.78a A	34.89a A	35.32a A	29.81a B

Mean values within each row followed by the same uppercase letter are not significantly different (P<0.05). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different (P<0.05). [†] Means calculated from three replications.

Table A.15. Degrees of freedom (df) and probability (Pr) of F values for stem ADF among irrigation treatments, cultivars and cuts as determined by a mixed model repeated measure ANOVA at Lethbridge in 2012, 2013 and at the Picture Butte location in 2012 respectively.

	Lethbridge				Picture Butte	
	2012		2013		2012	
Effect	**df**	**Pr of F**	**df**	**Pr of F**	**df**	**Pr of F**
cultivar	3	0.021	3	0.037	3	0.004
water	3	<0.001	3	0.084	3	<0.001
cut	1	<0.001	2	<0.001	1	0.304
cultivar x water	9	0.001	9	0.090	9	0.972
cultivar x cut	3	0.001	6	0.074	3	<0.001
water x cut	3	0.171	6	0.359	3	0.001
cultivar x water x cut	9	<0.001	18	0.001	9	0.026

Table A.16. [†]Mean (%) stem ADF among four irrigation treatments for four alfalfa cultivars in relation to cuts at the Lethbridge location in 2012 and 2013 respectively.

		2012				2013			
Cuts	**Cultivars**	**W_1**	**W_2**	**W_3**	**W_4**	**W_1**	**W_2**	**W_3**	**W_4**
1	Blue J	-	-	-	-	44.49ab A	43.51a A	44.12a A	45.07a A
	Longview	-	-	-	-	44.91a A	43.53a AB	44.33a A	38.63b B
	Rambler	-	-	-	-	40.52bc A	44.62a A	43.63a A	43.82a A
	Rangelander	-	-	-	-	40.53c B	42.71a AB	45.36a A	45.30a A
2	Blue J	44.43a BC	52.44a A	47.97a B	42.74b C	46.42b C	51.21a A	48.59b BC	49.49a AB
	Longview	46.72a A	46.64b A	48.00a A	45.29ab A	48.29ab A	49.52ab A	48.31bc A	48.32ab A
	Rambler	45.35a A	47.83b A	46.15ab A	48.19a A	50.85a AB	47.46bC	51.74a A	48.66a BC
	Rangelander	46.13a AB	46.93b A	42.85b B	45.85ab AB	47.46b B	49.97a A	46.08c B	46.16b B
3	Blue J	22.45a A	23.38b A	23.35b A	22.16ab A	31.18ab AB	32.84a A	30.22a B	30.09a B
	Longview	24.58a A	24.03b AB	20.67b B	25.75a A	32.07a A	31.15ab AB	30.71a AB	29.56a B
	Rambler	23.43a B	39.61a A	23.79ab B	21.11b B	29.38b A	30.20bc A	30.12a A	29.59a A
	Rangelander	25.01a AB	27.42b A	27.19a A	21.87b B	30.59ab A	28.89c A	30.50a A	28.62a A

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different ($P<0.05$). [†] Means calculated from three replications.

Table A.17. †Mean (%) stem ADF among four irrigation treatments for four alfalfa cultivars in relation to two cuts at the Picture Butte location in 2012.

Cuts	Cultivars	W_1	W_2	W_3	W_4
2	Blue J	45.77ab A	44.56a A	45.36a A	37.02a B
	Longview	46.56ab A	46.12a A	44.15a A	38.30a B
	Rambler	49.26a A	46.24a A	45.98a A	34.89a B
	Rangelander	44.65b A	45.52a A	43.76a A	35.58a B
3	Blue J	37.22b A	40.41b A	37.91b A	35.41b A
	Longview	49.46a A	46.29ab A	46.53a A	43.29a A
	Rambler	38.19b A	40.93ab A	42.65ab A	41.87ab A
	Rangelander	48.84a A	47.67a A	45.08a A	42.18ab A

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different ($P<0.05$). †Means calculated from three replications.

Table A.18. Degrees of freedom (df) and probability (Pr) of F values for stem NDF among irrigation treatments, cultivars and cuts as determined by a mixed model repeated measure ANOVA at Lethbridge in 2012, 2013 and at the Picture location in 2012 respectively.

	Lethbridge				Picture Butte	
	2012		2013		2012	
Effect	**df**	**Pr of F**	**df**	**Pr of F**	**df**	**Pr of F**
cultivar	3	0.002	3	0.141	3	<0.001
water	3	0.058	3	0.035	3	<0.001
cut	1	<0.001	2	<0.001	1	0.505
cultivar x water	9	<0.001	9	0.097	9	0.324
cultivar x cut	3	0.129	6	0.008	3	<0.001
water x cut	3	0.045	6	0.214	3	0.002
cultivar x water x cut	9	0.001	18	0.018	9	0.001

Table A.19. [†]Mean (%) stem NDF four irrigation treatments for four alfalfa cultivars in relation to cuts at the Lethbridge location in 2012 and 2013 respectively.

		2012				2013			
Cuts	**Cultivars**	**W_1**	**W_2**	**W_3**	**W_4**	**W_1**	**W_2**	**W_3**	**W_4**
1	Blue J	-	-	-	-	52.80ab A	50.74b A	53.57a A	53.00b A
	Longview	-	-	-	-	55.18a A	53.59ab A	53.37a A	53.18b A
	Rambler	-	-	-	-	50.97b B	55.89a A	52.02a AB	52.19b AB
	Rangelander	-	-	-	-	49.16b B	55.19a A	55.62a A	59.58a A
2	Blue J	53.99ab A	49.01b B	48.47b B	51.11b AB	56.28a B	61.19a A	58.14a B	57.67a B
	Longview	54.97ab A	53.19a A	56.03a A	55.24a A	58.51a A	58.55ab A	58.26a A	58.38a A
	Rambler	51.83b B	55.91a A	55.58a AB	54.39ab AB	57.83a A	57.53b A	59.06a A	58.49a A
	Rangelander	55.81a A	53.26a AB	50.59b B	52.98ab AB	56.21a B	59.40ab AB	56.67a AB	56.17a B
3	Blue J	30.38a A	30.91b A	30.87ab A	30.57a A	38.91a AB	40.12a A	37.99a AB	37.10a B
	Longview	32.86a A	32.45b AB	28.67b B	32.72a A	37.87ab A	37.23b A	37.23a A	37.32a A
	Rambler	30.99a B	45.38a A	31.76ab B	26.34b C	35.63b A	36.57b A	36.73a A	36.29ab A
	Rangelander	33.51a A	26.22c B	32.58a A	30.86b A	36.22ab A	34.84b A	36.60a A	34.25b A

Mean values within each row followed by the same uppercase letter are not significantly different (P<0.05). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different (P<0.05). [†] Means calculated from three replications.

Table A.20. †Mean (%) stem NDF four irrigation treatments for four alfalfa cultivars in relation to two cuts at the Picture Butte location in 2012.

Cuts	Cultivars	W_1	W_2	W_3	W_4
2	Blue J	54.55ab A	54.35a A	54.89a A	48.19ab B
	Longview	56.10ab A	54.34a A	53.62a A	49.15a B
	Rambler	57.14a A	55.15a A	54.06a A	44.93b B
	Rangelander	52.61b A	53.53a A	51.67a A	46.69ab B
3	Blue J	47.61c A	45.69c A	47.73c A	47.47b A
	Longview	54.77abc A	57.33a A	58.13a A	56.38a A
	Rambler	51.98b A	51.47b A	51.95b A	50.77b A
	Rangelander	60.53a A	56.91a AB	56.53a B	48.38b C

Mean values within each row followed by the same uppercase letter are not significantly different (P<0.05). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different (P<0.05).

†Means calculated from three replications.

Table A.21. Degrees of freedom (df) and probability (Pr) of F values for whole-plant CP among irrigation treatments, cultivars and cuts as determined by a mixed model repeated measure ANOVA at Lethbridge in 2012, 2013 and at the Picture Butte location respectively.

	Lethbridge				Picture Butte	
	2012		2013		2012	
Effect	df	Pr of F	df	Pr of F	df	Pr of F
cultivar	3	0.001	3	0.002	3	0.005
water	3	<0.001	3	0.007	3	0.006
cut	2	<0.001	2	<0.001	2	<0.001
cultivar x water	9	0.043	9	0.098	9	0.006
cultivar x cut	6	0.001	6	0.001	6	<0.001
water x cut	6	0.623	6	0.022	6	0.007
cultivar x water x cut	18	<0.001	18	0.007	18	<0.001

Table A.22. †Mean (%) whole-plant CP among four irrigation treatments for four alfalfa cultivars in relation to three cuts at the Lethbridge location in 2012 and 2013 respectively.

		2012				2013			
Cuts	**Cultivars**	**W_1**	**W_2**	**W_3**	**W_4**	**W_1**	**W_2**	**W_3**	**W_4**
1	Blue J	23.2a AB	26.9a A	22.1b B	24.3a AB	25.5a A	22.4ab AB	20.6ab B	22.2a AB
	Longview	22.7a A	24.3a A	18.1c B	21.7a AB	20.2b B	20.9b AB	18.6b B	23.8a A
	Rambler	24.6a A	24.9a A	23.8ab A	24.7a A	19.0b B	17.4c B	23.2a A	24.1a A
	Rangelander	25.9a A	26.2a A	26.1a A	24.8a A	28.5a A	24.6a BC	21.4ab C	24.9a B
2	Blue J	21.5a A	20.7a A	21.5ab A	22.5a A	23.6b AB	23.5a AB	21.1b B	26.1b A
	Longview	22.8a A	21.1a A	20.6ab A	21.8a A	27.3a A	23.1a BC	21.6b C	25.5b AB
	Rambler	22.1a AB	22.4a AB	19.4b B	23.3a A	23.8b B	26.3a AB	26.8a AB	29.6a A
	Rangelander	22.4a AB	23.6a A	22.6a AB	20.4a B	26.8ab B	26.2a B	27.4a B	31.8a A
3	Blue J	31.6a A	31.9a A	28.0b B	27.5b B	25.7a A	25.6a A	25.9a A	26.8a A
	Longview	28.9b AB	27.2b BC	25.3c C	29.9a A	27.2a A	26.1a A	27.1a A	26.9a A
	Rambler	32.2a A	29.3b BC	30.8a AB	28.2ab C	26.8a A	26.5a A	27.3a A	26.9a A
	Rangelander	26.4c C	29.1b AB	27.0bc BC	29.9a A	25.6a A	26.7a A	27.1a A	26.7a A

Mean values within each row followed by the same uppercase letter are not significantly different (P<0.05). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different (P<0.05). † Means calculated from three replications.

Table A.23. [†]Mean (%) whole-plant CP among four irrigation treatments for four alfalfa cultivars in relation to three cuts at the Picture Butte location in 2012.

Cuts	Cultivars	W_1	W_2	W_3	W_4
1	Blue J	21.1a AB	22.8a A	19.4c B	19.5bc B
	Longview	22.1a A	21.3ab A	21.3b A	18.1c B
	Rambler	21.9a A	22.2ab A	21.5b A	21.8a A
	Rangelander	20.3a B	20.5b B	23.4a A	20.2ab B
2	Blue J	19.5a AB	21.9b A	16.4c B	21.4a A
	Longview	21.6a A	21.4b A	22.7ab A	21.8a A
	Rambler	22.0a A	21.8b A	20.4b A	20.7a A
	Rangelander	23.4a B	33.0a A	24.9a B	22.3a B
3	Blue J	28.4a A	28.6a A	28.0a A	27.5a A
	Longview	25.4a AB	23.6b B	26.2a AB	29.1a A
	Rambler	26.5a A	26.9a A	25.9a A	21.5b B
	Rangelander	15.6b B	16.8c AB	18.7b AB	19.4b A

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different ($P<0.05$).

[†] Means calculated from three replications.

Table A.24. Degrees of freedom (df) and probability (Pr) of F values for leaf CP among irrigation treatments, cultivars and cuts as determined by a mixed model repeated measure ANOVA at Lethbridge in 2012, 2013 and at the Picture Butte location in 2012 respectively.

	Lethbridge				Picture Butte	
	2012		2013		2012	
Effect	**df**	**Pr of F**	**df**	**Pr of F**	**df**	**Pr of F**
cultivar	3	0.038	3	0.004	3	<0.001
water	3	0.281	3	0.015	3	0.001
cut	1	0.003	2	<0.001	1	<0.001
cultivar x water	9	0.225	9	0.006	9	0.014
cultivar x cut	3	0.006	6	0.024	3	<0.001
water x cut	3	0.173	6	0.552	3	<0.001
cultivar x water x cut	9	0.047	18	0.157	9	0.001

Table A.25. †Mean (%) leaf CP among four irrigation treatments for four alfalfa cultivars in relation to two cuts at the Lethbridge and Picture Butte location in 2012 respectively.

		Lethbridge				Picture Butte			
Cuts	**Cultivars**	**W_1**	**W_2**	**W_3**	**W_4**	**W_1**	**W_2**	**W_3**	**W_4**
2	Blue J	30.9ab AB	32.6a A	30.9a AB	28.4b B	27.3ab A	27.1b A	25.9c AB	24.5b B
	Longview	29.1b AB	31.2a A	26.6b B	27.2b B	29.1a A	27.8b A	29.4ab A	27.5a A
	Rambler	33.2a A	29.9a BC	29.2ab C	32.7a AB	25.2b BC	26.0b B	27.9b A	24.1b C
	Rangelander	32.4a A	30.3a A	31.2a A	32.5a A	28.4a A	29.7a A	29.9a A	24.9b B
3	Blue J	31.7a A	32.0a A	32.1a A	32.7a A	31.2a A	31.5a A	30.9ab A	31.0a A
	Longview	30.9a A	32.2a A	31.8a A	31.4a A	27.6b C	28.5b BC	29.7a AB	30.4ab A
	Rambler	32.3a A	31.2a A	31.8a A	31.9a A	29.7a B	31.2a AB	32.3a A	31.7a A
	Rangelander	32.2a A	31.7a A	30.5a A	31.5a A	22.2c C	23.1c C	26.5c B	29.2b A

Mean values within each row followed by the same uppercase letter are not significantly different (P<0.05). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different (P<0.05). † Means calculated from three replications.

Table A.26. [†]Mean (%) leaf CP among four irrigation treatments for four alfalfa cultivars at the Lethbridge location in 2013.

Cultivars	W_1	W_2	W_3	W_4
Blue J	27.1b A	28.9a A	28.4ab A	28.9a A
Longview	27.4b AB	27.7a AB	26.5c B	28.4a A
Rambler	28.9b A	27.6a A	28.9a A	28.7a A
Rangelander	30.7a A	28.4a BC	27.2bc C	29.6a AB

Mean values within each row followed by the same uppercase letter are not significantly different (P<0.05). Mean values within each column followed by the same lowercase letter are not significantly different (P<0.05).[†]Means calculated from three replications.

Table A.27. [†]Mean (%) leaf CP among three cuts for four alfalfa cultivars at the Lethbridge location in 2013.

Cultivars	Cut 1	Cut 2	Cut 3
Blue J	24.6b C	31.5a A	29.1a B
Longview	24.1b B	29.3b A	29.4a A
Rambler	24.6b B	30.9a A	29.9a A
Rangelander	26.5a B	30.5ab A	29.8a A

Mean values within each row followed by the same uppercase letter are not significantly different (P<0.05). Mean values within each column followed by the same lowercase letter are not significantly different (P<0.05).

[†] Means calculated from three replications.

Table A.28. Degrees of freedom (df) and probability (Pr) of F values for stem CP among irrigation treatments, cultivars and cuts as determined by a mixed model repeated measure ANOVA at Lethbridge in 2012, 2013 and at Picture Butte location in 2012 respectively.

		Lethbridge			Picture Butte	
		2012	2013		2012	
Effect	df	Pr of F	df	Pr of F	df	Pr of F
cultivar	3	0.003	3	0.443	3	<0.001
water	3	0.039	3	0.349	3	0.028
cut	1	<0.001	2	<0.001	1	0.001
cultivar x water	9	0.001	9	0.001	9	0.221
cultivar x cut	3	0.289	6	0.024	3	<0.001
water x cut	3	0.854	6	0.187	3	0.048
cultivar x water x cut	9	<0.001	18	0.014	9	0.144

Table A.29. [†]**Mean (%) stem CP among four irrigation treatments for four alfalfa cultivars in relation to cuts at the Lethbridge location in 2012 and 2013 respectively.**

		2012				2013			
Cuts	**Cultivars**	**W_1**	**W_2**	**W_3**	**W_4**	**W_1**	**W_2**	**W_3**	**W_4**
1	Blue J	-	-	-	-	12.5c B	14.3ab AB	15.6a A	11.8a B
	Longview	-	-	-	-	12.6bc B	15.8a A	13.2ab AB	13.5a AB
	Rambler	-	-	-	-	15.2ab A	12.2b B	13.0ab AB	14.2a AB
	Rangelander	-	-	-	-	16.4a A	14.9ab AB	11.9b C	12.9a BC
2	Blue J	13.8a A	14.9a A	13.3ab A	14.3a A	13.2a A	13.3a A	14.2a A	13.4ab A
	Longview	14.3a A	13.9a A	12.3b A	12.4a A	13.5a A	12.4a A	12.1ab A	11.9b A
	Rambler	15.3a A	14.4a A	14.8a A	12.1a B	12.2a AB	14.1a A	10.8b B	14.1a A
	Rangelander	14.1a A	14.2a A	13.8ab A	13.4a A	12.8a A	12.2a A	12.5ab A	12.5ab A
3	Blue J	24.8a A	23.2b A	23.9a A	23.1ab A	15.8ab A	12.5b B	15.3ab A	15.5a A
	Longview	21.6c A	21.4bc A	21.9a A	21.2a A	14.5b A	14.9a A	16.4a A	15.6a A
	Rambler	24.2ab A	19.7c B	22.9a A	25.0a A	16.6ab A	15.5a AB	14.2b B	16.6a A
	Rangelander	21.9bc B	29.4a A	22.2a B	20.9b B	17.2a A	16.8a A	15.8ab A	16.5a A

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different ($P<0.05$). [†] Means calculated from three replication.

Table A.30. †Mean (%) stem CP among two cuts for four alfalfa cultivars at the Picture Butte location in 2012.

Cultivars	Cut 2	Cut 3
Blue J	12.9b B	16.0a A
Longview	13.8a A	10.7c B
Rambler	13.8a A	14.4b A
Rangelander	14.7a A	10.4c B

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each column cut followed by the same lowercase letter are not significantly different ($P<0.05$). † Means calculated from three replications.

Table A.31. †Mean (%) stem CP among four irrigation treatments in relation to two cuts at the Picture Butte location in 2012.

Cuts	W_1	W_2	W_3	W_4
Cut 2	13.3a B	13.4a B	13.6a B	14.8a A
Cut 3	12.2b B	13.2a AB	13.3a A	12.8b AB

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each column followed by the same lowercase letter are not significantly different ($P<0.05$)
† Means calculated from three replications.

Table A.32. Degrees of freedom (df) and probability (Pr) of F values for RFV among irrigation treatments, cultivars and cuts as determined by a mixed model repeated measure ANOVA at Lethbridge in 2012, 2013 and the Picture Butte location in 2012 respectively.

		Lethbridge				Picture Butte
		2012		2013		2012
Effect	**df**	**Pr of F**	**df**	**Pr of F**	**df**	**Pr of F**
cultivar	3	0.001	3	0.001	3	0.011
water	3	0.003	3	0.097	3	<0.001
cut	2	<0.001	2	<0.001	2	<0.001
cultivar x water	9	0.001	9	0.085	9	0.021
cultivar x cut	6	<0.001	6	<0.001	6	<0.001
water x cut	6	0.024	6	0.045	6	<0.001
cultivar x water x cut	18	<0.001	18	0.001	18	0.307

Table A.33. [†]**Mean (%) RFV among four irrigation treatments for four alfalfa cultivars in relation to three cuts at the Lethbridge location in 2012 and 2013 respectively.**

		2012				2013			
Cuts	**Cultivars**	**W_1**	**W_2**	**W_3**	**W_4**	**W_1**	**W_2**	**W_3**	**W_4**
1	Blue J	129 a AB	125bc B	122b B	154a A	129c B	159ab A	164aA	167b A
	Longview	133a AB	117c B	143ab AB	149a A	163bc A	151b A	154a A	165b A
	Rambler	150a A	168a A	143ab A	158a A	144bc B	136b B	147a AB	175ab A
	Rangelander	137a A	152ab A	153a A	137a A	232a A	189a B	142a C	199a B
2	Blue J	175a A	160a A	149ab A	163a A	153ab A	121a B	128a AB	149b AB
	Longview	152ab A	148a A	133b A	162a A	162a A	122a B	132a B	145b AB
	Rambler	138b B	154a AB	148ab AB	166a A	128b A	142a A	145a A	153ab A
	Rangelander	167a A	163a A	171a A	164a A	128b A	135a A	148a A	144a A
3	Blue J	218a B	212b B	213ab B	253a A	241b AB	243b AB	253ab A	216c B
	Longview	197a B	201b B	236a A	195b B	259ab A	237b A	237b A	241bc A
	Rambler	195a B	118c C	206b B	257a A	261ab A	276a A	270a A	279a A
	Rangelander	213a B	277a A	234a B	232a B	273a A	255ab A	271a A	255ab A

Mean values within each row followed by the same uppercase letter are not significantly different (P<0.05). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different (P<0.05).

[†] Means calculated from three replications.

Table A.34. †Mean (%) RFV among four irrigation treatments for four alfalfa cultivars at the Picture Butte location in 2012.

Cultivars	W_1	W_2	W_3	W_4
Blue J	181 ab A	191a A	178a A	192b A
Longview	166b C	172b BC	185aAB	197ab A
Rambler	192a B	192a B	179a B	205a A
Rangelander	173a B	168b B	176a B	198a A

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each column by the same lowercase letter are not significantly different ($P<0.05$). † Means calculated from two replications.

Table A.35. †Mean (%) RFV among three cuts for four alfalfa cultivars at the Picture Butte location in 2012.

Cultivars	Cut 1	Cut 2	Cut 3
Blue J	160ab B	168c B	228a A
Longview	172a B	196b A	170b B
Rambler	162ab B	199b A	215a A
Rangelander	158b B	225a A	156b B

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each column followed by the same lowercase letter are not significantly different ($P<0.05$). †Means calculated from two replications.

Table A.36. Degrees of freedom (df) and probability (Pr) of F values for leaf-to-stem ratio among irrigation treatments, cultivars and cuts as determined by a mixed model repeated measure ANOVA at Lethbridge in 2012, 2013 and the Picture Butte location in 2012 respectively.

	Lethbridge				Picture Butte	
	2012		2013		2012	
Effect	**df**	**Pr of F**	**df**	**Pr of F**	**df**	**Pr of F**
cultivar	3	0.083	3	<0.001	3	0.002
water	3	0.435	3	0.088	3	<0.001
cut	1	<0.001	2	<0.001	1	0.006
cultivar x water	9	0.124	9	0.615	9	0.029
cultivar x cut	3	0.001	6	0.004	3	<0.001
water x cut	3	0.643	6	0.675	3	0.003
cultivar x water x cut	9	0.445	18	0.765	9	0.001

Table A.37. [†]**Mean (%) leaf-to-stem ratio among cuts for four alfalfa cultivars at the Lethbridge location in 2012 and 2013 respectively.**

	2012		2013		
Cultivars	**Cut 2**	**Cut 3**	**Cut 1**	**Cut 2**	**Cut 3**
Blue J	1.12b B	2.20b A	1.19b B	1.02b B	1.80b A
Longview	1.14ab B	2.68a A	1.17b B	1.03b B	1.77b A
Rambler	1.17ab B	2.15b A	1.12b B	2.04a A	2.08a A
Rangelander	1.32a B	2.01b A	1.59a C	2.03a B	2.48a A

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different ($P<0.05$). [†] Means calculated from two replications.

Table A.38. [†]**Mean (%) leaf-to-stem ratio among four irrigation treatments for four alfalfa cultivars in relation to two cuts at the Picture Butte in 2012.**

Cuts	Cultivars	W_1	W_2	W_3	W_4
2	Blue J	0.96 b B	0.94c B	1.18bc B	1.64b A
	Longview	1.67a A	1.36b A	1.44b A	1.57b A
	Rambler	1.11b B	1.27bc B	0.93c B	2.25a A
	Rangelander	1.61a C	1.91a BC	2.05a B	2.48a A
3	Blue J	1.93a AB	2.07b A	1.18ab C	1.64a B
	Longview	0.89b B	1.01c B	0.96b B	1.57a A
	Rambler	1.63a B	2.53a A	1.39a B	1.64a B
	Rangelander	0.58b AB	0.65a AB	0.43c B	0.93b A

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different ($P<0.05$). [†] Means calculated from two replications.

Summary of net returns from alfalfa production

The net returns from alfalfa production were determined for the three site-years. The net returns were the revenue from alfalfa production (yield x price) less the cost of harvesting the alfalfa (cutting, raking, baling and hauling from the field). Yields of less than 1.0 t ha^{-1} were not harvested because harvesting costs were at least as high as the value of the forage. The price of alfalfa used in the analysis was \$180 t^{-1}, based on 2013 prices for alfalfa hay dairy quality, first cut and stored in a shed. Costs did not include the cost of establishing or removing the alfalfa because the stand was in for fewer years than a commercial grower would have an alfalfa stand. Establishment costs were about \$400 ha^{-1} at both sites.

Production costs included in the analysis were the cost of mowing (\$25.15 ha^{-1}), raking (\$11.70 ha^{-1}) and hauling (\$5.89 t^{-1}). The cost of baling was based on yield because costs are higher for smaller yielding crops. Baling costs were as follows: if the alfalfa yield was greater than 3.99 t ha^{-1} then the cost of baling was \$11.34 t^{-1}; if the yield is greater than 3 but less than 4 t ha^{-1}, the cost was \$13.96 t^{-1} minus \$1.23 t^{-1} multiplied by (yield minus 3); if the yield was greater than 2 but less than 3 t ha^{-1}, the cost was \$19.35 t^{-1} minus \$5.39 t^{-1}multiplied by (yield minus 2); if the alfalfa hay yield was greater than 1 and less than 2 t ha^{-1}, the baling cost was \$35.78 t^{-1} minus \$16.43 t^{-1} multiplied by (yield minus 1); and if the yield was less than 1.0 t ha^{-1}, costs were zero because the alfalfa was not harvested. The net returns were computed for each plot and then analyzed by analysis of variance, by site-year. The main effects of cultivar and irrigation treatment were the fixed effects in the model, while replication and its interactions with the fixed effects were random effects. Means and statistical differences were computed for the significant effects. The data were analyzed using PROC MIXED (SAS Institute Inc. 2012. SAS OnlineDoc® 9.3**.** Cary, NC: SAS Institute Inc.) with cultivar, irrigation treatment as fixed effects while replications and its interaction with the fixed effects were set as random effects.

Results and Discussion

The ANOVA determined the interaction of cultivar and irrigation treatment (water). The cultivar x water interaction was significant at Picture Butte in 2012 and high enough at Lethbridge in 2012 to be considered (Table A.39). The interaction was not significant at Lethbridge in 2013, but the two main effects were significant.

Table A.39. ANOVA results for net returns, three location-years.

	Picture Butte		Lethbridge			
	2012		2012		2013	
Effect	**F Value**	**Pr > F**	**F Value**	**Pr > F**	**F Value**	**Pr > F**
cultivar	12.57	<0.0001	5.17	0.0031	58.22	<0.0001
water	25.91	<0.0001	4.36	0.0077	7.84	0.0002
cultivar x water	7.29	<0.0001	2.00	0.0554	1.29	0.2615

At Picture Butte in 2012, the net return was highest for Blue J with full water application (W_1), but was not significantly different from the 75% irrigation treatment (W_2) (Table A.40). This is interesting because a significant difference ($P<0.05$) in DM yield was observed for Blue J W_1 and W_2 although the yield difference between these treatments was not drastic (24%). Restricting water for the forage alfalfas (Blue J and Longview) had more of an impact on net returns, than for the range-type alfalfas (Rambler and Rangelander).

Table A.40. Net returns means and standard errors from alfalfa production, Picture Butte, 2012.

Cultivar	Water Treatments W_1	W_2	W_3	W_4	Average
Blue J	1066 (190) Aa	855 (88) Aa	393 (58) Bb	252 (103) Ba	619
Longview	635 (111) Ab	446 (136) Bb	393 (49) Bb	257 (131) Ba	432
Rambler	566 (48) Ab	671 (149) Aa	728 (64) Aa	218 (96) Ba	546
Rangelander	299 (99) ABc	412 (100) ABb	488 (97) Ab	250 (97) Ba	362
Average	619 (81)	604 (69)	500 (44)	244 (49)	489 (35)

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different ($P<0.05$).
The averages were presented without indicating statistical differences because the cultivar x water interaction was significant.

The net return for Lethbridge in 2012 was similar across the cultivars and irrigation treatments (Table A.41). The low water rate had an impact on net returns from Blue J and Longview. This was expected because the total forage DM yield mean values for Blue J and Longview W_2 and W_3 at Lethbridge in both years were higher than those of W_1 although the differences in some instances were not significant (except Lethbridge 2012 Blue J $W_1>W_2$).There was not a consistent pattern of net returns across the alfalfa cultivars. Restricting water had less impact at this site because the growing season precipitation was generally high, and spring soil moisture was high.

Table A.41. Net returns means and standard errors from alfalfa production, Lethbridge, 2012.

	Water Treatments				
Cultivar	**W_1**	**W_2**	**W_3**	**W_4**	**Average**
Blue J	1166 (113) Aa	1293 (57) Aa	1157 (46) Ab	892 (94) Ba	1127
Longview	1269 (82) ABa	1363 (89) Aa	1433 (84) Aa	1086 (123) Ba	1284
Rambler	1124 (70) Aa	1166 (36) Aab	1132 (122) Ab	1101 (138) Aa	1131
Rangelander	1179 (62) Aa	972 (22) Ab	1118 (128) Ab	1084 (49) Aa	1088
Average	1184 (40)	1190 (42)	1210 (55)	1041 (53)	1156 (24)

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different ($P<0.05$). The averages were presented without indicating statistical differences because the cultivar x water interaction was significant.

The cultivar x water interaction for Lethbridge in 2013 was not significant, so the significant differences were reported for the main effects (Table A.42). Rangelander had lower net returns than the other three cultivars. This was expected because a trend of relatively lesser DM yield mean values for Rangelander was observed across cuts when compared to the other cultivars in both years and locations. The net returns were similar across irrigation treatments, when Rangelander was not considered, but tended to be a bit lower for the full irrigation treatment.

Table A.42. Net returns means and standard errors from alfalfa production, Lethbridge, 2013.

	Water Treatments				
Cultivar	**W_1**	**W_2**	**W_3**	**W_4**	**Average**
Blue J	1159 (103)	1227 (73)	1357 (74)	1479 (101)	1305 (49) a
Longview	1225 (49)	1418 (58)	1462 (36)	1287 (66)	1348 (33) a
Rambler	1276 (35)	1376 (60)	1434 (75)	1376 (85)	1365 (33) a
Rangelander	684 (45)	803 (34)	900 (49)	961 (61)	837 (32) b
Average	1086 (61) B	1206 (62) A	1288 (59) A	1276 (57) A	1214 (30)

Mean values within each row followed by the same uppercase letter are not significantly different ($P<0.05$). Mean values within each cut and each irrigation treatment followed by the same lowercase letter are not significantly different ($P<0.05$).
Significant differences were not reported for the cultivar x water interaction because it was not significant.