AN ABSTRACT OF THE THESIS OF

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Title: Annual Forages Differ in Response to Partial-Season Irrigation Deficit in Both Spring Seeded and Summer Seeded Cropping Systems.

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Water scarcity during summer becomes a serious problem in the Pacific Northwest, threatening forage production provided to livestock. Annual forages show great potential in handling drought because of their flexibility in seeding date and short growing season, and can shift the production to periods of feed shortage and fill the forage gap. This project focused on determining the annual forage species best suited to different irrigation regimes in both spring and summer seeded cropping systems. The study was conducted for two years and determined the yield, quality, water use efficiency (WUE)and phenology of twenty annual forages under full season irrigation (W1), early season cutoff (W2), late season cutoff (W3), and no irrigation (W4) at Union, OR, on a La Grande silt loam (fine-silty, mixed, superactive, mesic Pachic Haploxeroll). Results showed that DM yield decreased while forage quality increased (higher CP%, lower ADF% and NDF%) when water stress occurred. W2, rather than W1, could be applied to allow good production and better quality and conserve water as well. In addition, summer seeding of annual forage as a cover crop after winter triticale is not recommended in a Mediterranean climate with inadequate irrigation water (W3 and W4). Annual warm season grasses (AC4) generally had the highest yield while annual legumes (AL) had the best quality. In a spring seeded cropping system, there was a 2.6-fold range in forage yield between species under W1, a 2.4-fold range under W2, a 4.1-fold range under W3 and a 5.0-fold range. Within AC3, a 1.5-fold, 1.6-fold, 1.6-fold and 3.2-fold range existed between forage under W1, W2, W3 and W4, respectively. Within AL, the yield range was 1.5, 2.2, 4.3 and 4.6 fold between forages under W1, W2, W3 and W4, respectively. Radish

(*Raphanus sativus* L. var.*longipinnatus*) outyielded others (10.9 Mg/ha on average) irrespective of irrigation treatments within annual brassica (AB). In a summer seeded cropping system, oat (*Avena sativa* L.) had the highest production (6.7, 5.2 and 1.8 for W1, W2 and W3, respectively) under irrigation. Within AL, no difference existed among species across irrigation. Radish (*Raphanus sativus* L. var.*longipinnatus*) (5.9 Mg/ha) outyielded other brassicas irrespective of irrigation treatments within AB. Sorghum-sudan [*Sorghum bicolor* (L.) Moench] had the highest production across irrigation treatments in both 2017 (6.0 Mg/ha) and 2018 (10.2 Mg/ha). On average, teff [*Eragrostis tef* (Zuccagni) Trotter] (14.7% for spring seeded; 10.5% for summer seeded), annual ryegrass [*Lolium multiflorum* L.] (14.1% for spring seeded; 16.2% for summer seeded) and chickling vetch [*Lathyrus sativus* L.] (20.8% for spring seeded; 19.7% for summer seeded) had the highest CP% within AC4, AC3 and AL, respectively. In summary, annual forages have potential to augment the perennial forage shortage in the PNW with flexible planting dates and short growing seasons and matching species selection and/or cropping systems with available water will give annual forages more opportunity.

Annual Forages Differ in Response to Partial-Season Irrigation Deficit in Both Spring Seeded and Summer Seeded Cropping Systems

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APPROVED:

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Qianqian Fan, Author

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General Introduction

Qianqian Fan

Forage Importance and Water Scarcity in the Pacific Northwest

Agriculture is one of the most important industries in the Pacific Northwest (PNW). Among different agricultural products sold, *Cattle and Calves* is ranked 2nd, 1st, and 5th in Idaho, Oregon, and Washington, respectively, based on market value (USDA, 2018a). A range of forage species is produced in PNW to provide livestock grazing as well as hay production. Specifically, the hay acreages in Idaho, Oregon, and Washington totals 1.49, 1.04, and 0.77 million acres, respectively (USDA, 2018b).

With a Mediterranean-type climate, almost two-thirds of the precipitation in the PNW falls between October and March (USFWS, 2011). From May to September, rainfall declines and is both sporadic and undependable. Therefore, irrigation during this period is necessary for most traditional forage production systems. In the PNW, snow usually accumulates in winter and melts in spring and summer allowing the snowpack to serve as a natural reservoir to supply water in the dry season (Vano et al., 2015). However, climate change in the PNW is predicted to lead to wetter winters and drier summers (Snover et al., 2003). In the future, due to higher winter temperatures, snow-covered areas in the mountains will be reduced and snowpack will diminish, reducing dry season water supply, especially reducing the summer water supply (Snover et al., 2003; USFWS, 2011). In addition, spring peak flow will occur earlier and the time between snowmelt and fall rains will be increased since global warming is predicted to cause a greater proportion of snow melting earlier in the season, resulting in less summer streamflow and higher frequency of significant low-flow events (Snover et al., 2003). This presents potential problems for forage irrigation in summer. Moreover, water deficits for irrigated forages can also originate from other high water-use sectors like fisheries, industrial use, and water use priority for certain species (Orloff et al., 2016). Thus, water scarcity for forage production during the dry season is becoming increasingly serious.

Regulated Deficit Irrigation Research

Regulated Deficit Irrigation (RDI) is an irrigation practice that is commonly used when water is insufficient. Using RDI, crops are irrigated with less water than the full irrigation requirement for optimal plant growth, producing reasonable yield while reducing irrigation amount and increasing water use efficiency (WUE) (Chai et al., 2016). Four main irrigation methods for RDI in crop production are summarized as follows.

Different irrigation cutoff seasons

Irrigation was terminated at variable dates during the crop growing season, coping with different water right levels that exist in certain states. For example, water right in Oregon follows the principle of first come, first served (OWRD, 2018). Irrigation will be shut off earlier for junior users while senior users can keep irrigating without regard for the needs of other users when water is inadequate to satisfy the requirements of all water users. Generally, irrigation treatments include the full-season irrigation, and different-cutoff-date irrigation treatments. Irrigation was applied to fully satisfy crop evapotranspiration (ET) every time. The research on forages response under variable irrigation cutoff seasons has been limited so far but one study conducted by Orloff et al. (2016) evaluated the tolerance of cool season perennial grasses (tall fescue, orchardgrass, bromegrass and wheatgrass) under partial-season irrigation deficits in the northern California and concluded that the average annual yield of perennial forages across three years was 11.3 Mg/ha for the full-season irrigation, 9.8 Mg/ha for mid-season cutoff (mid-July; before second cutting) and 6.9 Mg/ha for early-season cutoff (late May; before first harvest). He pointed out that tall fescue had the highest yield under full-season irrigation while tall wheatgrass, immediate wheatgrass and smooth bromegrass were the most drought tolerant when an early-season irrigation cutoff was applied.

Different irrigation amount during each irrigation

One treatment would be optimal irrigation which could fully water the soil to field capacity (FC) or fully satisfy crop ET while other irrigation treatments applied water at less amount than the optimal irrigation. To compare the response of hybrid corn under water stress and no water stress, Montgomery (2009) arranged two irrigation treatments: irrigation to compensate 50% ET and irrigation to satisfying 100% ET. He found that drought induced 50% grain yield loss but no significant difference in forage yield was observed. For nutritive value, both ADF and NDF contents were higher under moisture stress while CP% had no change statistically. Yield and water use efficiency (WUE) of seventeen annual forages were evaluated under optimal irrigation and deficit irrigation (irrigating at 66% and 33% of optimal irrigation) in Australia (Neal et al., 2010; Neal et al., 2011). Based on these study, WUE was mainly determined by yield so maize produced the highest yield (29.0 t DM/ha) and also the highest WUE (42.9 kg ha^{-1} mm^{-1}) under optimal irrigation, and the reductions in yield and WUE were both smaller for cool season forages compare to warm season forages when deficit irrigation was applied. In another study conducted in Ethiopia by Yihun et al. (2013), yield and crop water productivity (CWP) of teff was evaluated under four levels of irrigation: full crop water requirement, 75%, 50% and 25% of full crop water requirements. The same author concluded that the greatest grain yield (3.3 t/ha) was obtained under no water stress and there was no significant difference in yield and CWP between full irrigation and 75% of full irrigation.

Stage-based deficit irrigation

The irrigation method that applies water to meet crop ET at the critical growth stage while less water at the non-critical growth stage is called stage-based deficit irrigation (Chai et al., 2016). The main principle behind this approach is that crops are especially sensitive to water stress during certain phenological stages while at less sensitive stages, crop productivity may not significantly decrease when irrigation does not meet ET requirements (Chai et al., 2016). Therefore, determining the critical growth stage of crops is very important when using this method. Katuwal et al. (2018) investigated yield and biomass partitioning of spring canola (*Brassica napus* L.) under irrigation treatments of full season irrigation, no irrigation at the vegetative stage, no irrigation at the reproductive stage and dryland control and concluded that skipping irrigation during the vegetative growth stage would be an option when water was limited since it didn’t have significant negative impact on most of measured parameters, especially seed yield. One stage-based irrigation research on turnip in arid region of Iran indicated that turnip had the maximum forage yield (2709.8 kg/ha) under no water stress condition and it was very sensitive to water stress at germination and establishment stages (Afshar et al., 2012). For forage quality, the same author reported that with increasing water stress, metabolizable energy, protein, and *in vitro* dry matter digestibility of turnip decreased while CP, ADF, ash, and water soluble carbohydrate tended to increase. Furthermore, another research by Rowe and Neilsen (2010) concluded that the yield of forage turnip increased lineally with irrigation water input irrespective of different irrigation periods of vegetative growth, thus providing flexibility of irrigation scheduling for producers.

Partial root-zone irrigation

Partial root-zone irrigation is a system which irrigates half of a crop's root mass while the other half of the root mass receives no irrigation (Chai et al., 2016). Partial root-zone irrigation can be subdivided into two types: alternate partial root-zone irrigation and fixed partial root-zone irrigation. Using alternate partial root-zone irrigation, half of the crop roots are fully irrigated then allowed to dry down while the remaining non-irrigated half root zone receives full irrigation. In a fixed partial root-zone irrigation system, half of a crop's root system is consistently irrigated while the other half is never irrigated. Research on forages under partial root-zone irrigation is limited now but studies on other crop species is available. The effect of partial root zone irrigation was on major crops in Mediterranean region has been investigated by Kirda et al. (2007). This author pointed out that the fruit yield reduction for tomato and seed yield loss for cotton were both not significant under partial zoot zone irrigation (50% deficit) compared to full irrigation but significant increase of irrigation water use efficiency (IWUE) existed for tomato while not for pepper under partial zoot zone irrigation. Another research conducted in Italy by Consoli et al. (2017) also concluded partial zoot-zone irrigation (50% ET) was an effective water saving strategy with increasing fruit yield of orange tress by 15% across two years and improving WUE compared to full irrigation.

Annual Forage Adaptation Mechanisms under Drought

Plants have developed different mechanisms to adapt to drought, namely, drought escape, drought avoidance, and drought tolerance (Basu et al., 2016).

Drought escape occurs when plants complete their life cycle before the onset of drought. They can form rapid phenological development involving producing a minimal number of seeds before soil water scarcity happens. Desclaux and Roumet (1996) reported that when water stress occurred, soybean reduced days it needed to reach 50% flowering by accelerating the switch from vegetative to reproductive development. A shortened flowering duration was also observed for cowpea under drought (Selvaraju, 1999). Inducing developmental plasticity is another way annuals use to escape drought. Plants reduce their growth when water is scarce while they can have indeterminate growth during wet seasons. For example, pearl millet is not affected a lot by mid-season drought since as long as moisture is available later, it can produce secondary tillers to compensate for main and primary tillers which are lost during mid-season drought (Vadez et al., 2012).

Drought avoidance is defined as the ability of plants to maintain higher tissue water content when soil water content is reduced. This is achieved by minimizing water loss and maximizing water uptake. Drought avoidance is the main mechanism that sorghum-sudan adopt to resist drought. Sorghum-sudan has the ability of deep rooting and produces high proportion of roots in the subsoil contribute, thus presenting greater drought resistance than other warm season grasses when water stress occurred (Schittenhelm and Schroetter, 2014). Besides, high water sue efficiency also leads to its good performance under drought (Lenssen and Cash, 2011). Cowpea is capable of maintain leaf water status and photosynthesis under extended drought conditions (Rivas et al., 2016). It can increase both rooting and root dry matter per leaf area to improve water uptake (Matsui and Singh, 2003). Besides, when water supply is inadequate to satisfy ET, decreasing stomatal conductance to reduce water loss through transpiration is another important adaptive trait for some species, like barley (Hasanuzzaman et al., 2019).

Drought tolerance is when plants are able to endure low tissue water content through adaptive traits like adjusting osmotic potential to maintain cell turgor. Hasanuzzaman et al. (2019) pointed out that barley can maintain a low content of organic osmolytes (Na^+, K^+ and Cl^-) for osmotic adjustment to endure low tissue water content.

Annual Forage Potential under Drought and Different Cropping Systems

Since the early 1900s, annual forage has been used as a supplement to deal with drought and perennial pasture shortage to avoid buying more expensive feed grain, thereby reducing cost (McCartney et al., 2009). Annuals offer an alternate forage option that shifts production to periods of feed shortage, like summer and autumn, and extend the grazing season beyond the normal perennial grazing season, thus grazing year-round can be achieved and profitability can be improved (Neal et al., 2010). Based on a study conducted in the Loess Plateau, a typical semi-arid region of China, annual forage-based systems had higher water use efficiency compared to alfalfa (*Medicago sativa* L.) (Jia et al., 2009).

When used as a cover crop, annual forages can increase soil aggregate stability (Steele et al., 2012), reduce nitrate leaching (Liebig et al., 2015), and provide greater soil microbial biomass and particulate organic carbon (Faé et al., 2009). In addition, annual cover crops can add economic value since forage produced from cover crops can be fed to livestock to reduce purchased feed cost (Faé et al., 2009). Another advantage annual forages have is that they show great potential in suppressing weeds (Lawley et al., 2011; Fisk et al., 2001). Compared to perennials, annual forages have more flexible planting dates (McCartney et al., 2008), enabling them to be used in variable cropping systems: spring seeding as a long season cover crop, late summer seeding after harvesting an annual crop or interseeding into a standing crop (Brummer et al., 2005). Based on one study conducted by Sanderson et al. (2008) in a semi-arid environment of the northern Great Plains (NGP), annuals could provide early summer forage in a grazing and cropping system that includes perennial grassland when spring seeded while it could defer grazing from perennial grasslands and augment perennial pasture shortfall in a short-season environment when summer seeded. An average biomass of 1169 kg/ha in 2008, 95 kg/ha in 2009 and 682 kg/ha in 2010 for annual forage monoculture in the NGP was reported by Liebig et al. (2015), providing both agronomic and environmental benefits. There are quite a few researches about annual grasses interseeded into bermudagrass sod. Moyer and Coffey (2000) concluded that interseeding small grains into bermudagrass in fall showed potential of extending the grazing season in the central USA and rye was the best species to achieve year-round grazing among wheat, barley and rye since it could provide early-season forage. Another study by Beck et al. (2007) also pointed out that annual cool season grasses could be fall-interseeded to bermudagrss to graze calves in fall and winter and rye and wheat were preferred due to better animal performance and greater profitability, comparted to oat and triticale.

Group and Species Characteristics of Annual Forages

Annual cool season grasses

From late fall to early spring, cool season grasses provide actively growing forage and serve as the primary forage for ruminant animals in temperate regions of the world (Moser and Hoveland, 1996). Cool season grasses provide winter-spring grazing when most warm-season forages are dormant, reducing stored feed needs for cattle (Demers and Clausen, 2002; Bambo et al., 2009). In addition, incorporating cool season grasses into perennial pasture can improve both the seasonal dry matter production and nutritive value of the pasture, thus improving animal performance (Botha et al., 2008; Yang et al., 2010; DeRouen et al., 1991). Moreover, they provide spring weed control (Evers, 1983).

Common species of annual cool season grasses for forage production are wheat, barley, triticale, oats, and annual ryegrass. Besides ryegrass, these annual cool season grasses are generally called small grains, popular in production in grain.

In general, wheat is able to provide high quality feed for livestock (Hossain et al., 2003) but it has lower yield compared to oat and barley (Walton, 1975). Barley is a versatile feed used throughout the world for a wide variety of livestock species, especially for dairy animals, like young calves and lactating and non-lactating dairy cows (Anderson and Schroeder, 1999). As a hybrid of wheat and rye (*Secale cereal* L.), triticale inherits the high yielding potential and wide adaptability of wheat together with the disease resistance, stress tolerance, and superior nutritional quality of rye (Ö Zkan et al., 1999). In addition, spring triticale showed tolerance to post anthesis high temperatures and having reasonable productivity even when the maximum temperature was above optimal (Munjonji et al., 2017). It is the most popular cool season forage in the Northern Great Plains (Fraser and McCartney, 2004). Oat produces high-quality as well as high-yield forage (Kim et al., 2006). Oat has poor drought and cold tolerance and is susceptible to various leaf and crown disease (Kim et al., 2014). Late-maturing varieties have better forage quality compared to early-maturing varieties (Kim et al., 2006).

Annual ryegrass (*Lolium multiflorum* L.) is easily established even without seedbed preparation, tolerates intense and frequent grazing, and adapts to a wide range of soil types (Evers et al., 1997). In addition, from late fall through late spring, it produces high quality forage with high CP content and low levels of NDF and ADF (Kallenbach et al., 2003). Italian and Westerwolds ryegrasses are collectively called annual ryegrasses (Narasimhalu et al., 1992). Italian ryegrass is a biennial originating from northern Italy while Westerwolds is an annual developed from Italian ryegrass (McCartney et al., 2008). While Italian ryegrass remains vegetative, Westerwolds ryegrass can mature to the reproductive stage in the seeding year and produce seeds, which could cause volunteer seed problems the next year (Narasimhalu et al., 1992; McCartney et al., 2008). Moreover, Italian ryegrass is superior to Westerwolds ryegrass in terms of composition, voluntary intake, and digestibility while Westerwolds cultivars mature faster and yield more than Italian type cultivars (Narasimhalu et al., 1992).

Annual brassicas

There has been growing interest in the utilization of forage brassicas in the USA. Several attributes make them useful as forage for cattle and sheep. First, they have high frost tolerance, enabling them to grow during cooler periods, accounting for wide use in the high-desert region of the southwestern USA where there is a large diurnal temperature change (Guldan et al., 1997). Second, brassicas can provide high quality forage with high CP content, high DM digestibility, and high metabolisable energy (Barry, 2013; Wiedenhoeft and Barton, 1994). This makes the quality of brassica forages comparable to a concentrate (Wiedenhoeft and Barton, 1994). Third, in contrast to most grasses and legumes, brassica forage quality doesn't decline significantly with advancing maturity (Barnes et al., 2003). In addition, rapid germination generally leads to easy establishment from seed as long as the temperature is suitable and competition from weeds is controlled (Barnes et al., 2003). Brassicas have very high water content (Guldan et al., 1997), making them suitable only for grazing. Some brassica have regrowth potential. Generally, compared to the initial growth, the regrowth has a lower fiber and a higher protein concentration (Wiedenhoeft and Barton, 1994).

Brassicas can be classified into short growing season and long growing season types (Barnes et al., 2003). For example, turnip (*Brassica rapa* L. var. *rapa*), rape (*Brassica napus* L. var. *oleifera*), and radish (*Raphanus sativus* L. var. *longipinnatus*) belong to the short season brassicas while kale (*Brassica oleracea* var. *acephala* L.) is a long growing season type.

Turnip requires 60 to 90 days of growth to reach maximum DM yield (Barnes et al., 2003). Turnip has regrowth potential and both the root and top are harvestable (Barnes et al., 2003). After root expansion, turnip can maintain high growth rate for up to ten weeks because of a high leaf area index (Neilsen et al., 2008). In addition to providing feed for livestock, turnip is able to help prepare weed-free seedbeds for reseeding pasture under non-irrigated conditions (Eckard et al., 2001). In comparing kale and rape, turnip was found to be the most suitable as a summer fodder crop, in both dryland and irrigated systems (Eckard et al., 2001).

Radish is sensitive to frost and winter-kill when exposed to temperatures below -3.9°C (Weil et al., 2009). Radish is grown as a forage crop and has been widely grown in humid North America as cover crop (Wang et al., 2017). Several characteristics make radish competitive compared to other cover crops. Forage radish emerges quickly and grows rapidly in the fall, which enables weed suppression (Weil et al., 2009). In addition, it decomposes rapidly in winter and spring, leaving a low residue seedbed for planting (Lawley et al., 2011). Moreover, radish has high tissue P concentration and shows potential for mitigating soil C depletion (Wang et al., 2017; White and Weil, 2011).

Rape requires 60 to 90 growing days before harvesting. Only the top is harvestable (Barnes et al., 2003), with regrowth potential. With high DM digestibility and high CP content, rape is one of the best crops available for fattening lambs and flushing ewes (Jung et al., 1988). When fed to lambs, forage rape is the most preferred forage over kale or radish, based on lamb performance and forage production (Fitzgerald and Black, 1984). There are two kinds of rape, the giant type and the dwarf type (Barne et al., 2003). Giant types produce tall, upright growth with multiple stems while the dwarf types are shorter and more highly branched.

As the most cold-tolerant brassica, kale is capable of surviving temperature as low as -12.2°C (Barnes et al., 2003). There are two different types of kale, Marrow stem kale and stemless kale (Barnes et al., 2003). The former type has coarse, fleshy stems, comprising more than 60% of the total forage while the latter type is a short-statured plant composed mostly of leaves. Marrow stem kale is a long growing season crop without regrowth potential while the stemless type is a short season type capable of regrowth. Only the tops are harvestable for both types.

In addition to the brassica species mentioned above, several brassica hybrids have been developed in the last couple of decades. For example, hybrid turnip, is a cross between turnip and rutabaga (*Brassica napus* var *napobrassica*). It combines the faster growth and maturity of turnip, with the cold tolerance and greater DM yield of rutabaga (Miles et al., 2013).

Annual legumes

In addition to being used to extend the grazing season, annual legumes can also improve forage quality and reduce the cost of nitrogen fertilizer due to their ability of fixing nitrogen (McCartney and Fraser, 2010). Annual legumes are often used in crop rotations as both forage and green manure crops to improve the organic matter and N content of soils and provide soil cover to prevent erosion and suppress weeds (McCartney and Fraser, 2010). When used as green manure, incorporating the crop into the soil during early to mid-bloom stage is recommended since the N content in annual legumes is greatest at that time (McCartney and Fraser, 2010). In addition to the higher seed cost compared to perennials, other challenges of annual legume production include shortage of commercially available strains of *Rhizobium (a soil bacteria that fixes nitrogen)* suited to specific crops, and weed control during establishment (McCartney and Fraser, 2010).

Crimson clover, originally from Europe, is now the most important annual clover in US agriculture. Crimson clover has excellent seedling vigor and early maturity (Butler et al., 2002). It can tolerate soil acidity well (Evers, 2003) and has good freeze tolerance (Brandsaeter et al., 2002). However, the use of crimson clover is limited by its poor reseeding ability due to the initial low hard seed production as well as the decrease of hard seed percentage during summer (Evers and Smith, 2006).

Field peas are generally divided into forage and grain types. The forage type includes leafed and semi-leafless cultivars (Koivisto et al., 2003). Positive impacts were shown for finishing efficiency, average daily gain, and hot carcass weights, when forage pea was fed to steers compared to a traditional grass forage (Anderson and Ilse, 2011). Semi-leafless cultivars show a potential for reduced lodging because their tendrils support the crop in a more erect manner, (Koivisto et al., 2003). Semi-leafless field pea cultivars are more susceptible to drought than leafed types (Knott, 1999).). Lodging is a big problem for field pea, making mechanical harvesting without soil contamination more difficult (Koivisto et al., 2003).

Chickling vetch, also called grass pea, has gained interest in the past as a plant adapted to arid areas. Chickling vetch is highly drought tolerant with abundant nodulation (Biederbeck et al., 1993). It can survive on a wide range of soil types, even heavy clays, due to its strong and penetrating root system (Campbell, 1997). Chickling vetch has shown potential for use as a fallow replacement in semiarid environments due to its high water use efficiency, high rate of N fixation and biomass production, fast emergence to provide an early ground cover, and resistance to insects and diseases (Biederbeck et al., 1993).

Native to sub-Saharan Africa, cowpea [*Vigna unguiculata* (L.) Walp] is both heat and drought tolerant, well adapted to low fertility soil, and able to withstand acid and alkaline soil conditions (Ehlers and Hall, 1997). Cowpea cultivars have various growth habits, namely, erect, semi-erect, and prostrate. Generally, cultivars that are erect and determinate are more suitable for mechanical harvesting while indeterminate and prostrate types are preferred as forage or cover crop due to greater ground cover (Hill et al., 2017). 'Iron Clay', a cowpea cultivar with regrowth potential, is suitable for hay, grazing, and silage (Vendramini et al., 2012). Its erect growth habit, rapid early growth plus vigorous climbing vines, work together to suppress weeds (Harrison et al., 2006). However, cowpea has a high percentage of hard seeds, which could create a weed problem in subsequent crops (Harrison et al., 2006).

Soybean plant nutritive value is comparable to early-bloom alfalfa (Kökten et al., 2014). In general, it has a CP content of 12~14% for stems, 19~20% for leaves, and 12~27% for pods (Asekova et al., 2014). To obtain forage with the highest production and quality, soybean should be harvested at 90% pod filling (Kökten et al., 2014). However, since soybean is able to maintain good forage quality over a long period, harvesting date can be quite flexible (Kökten et al., 2014). When harvested at the optimal recommended stage, compared with cowpea, soybean produces greater herbage mass and higher N yield (Foster et al., 2009). Soybean has no regrowth potential.

Annual warm season grasses

Annual warm season grasses have the highest growth rate in summer, and due to their C4 photosynthetic system, they generally have greater drought tolerance than annual cool season grasses (Brown, 1999). Therefore, they can be used to supplement forage shortfall during the driest and warmest times of the grazing season when annual cool season grasses are unproductive. However, compared to annual cool season grasses, warm season annual grasses usually have lower forage quality due to a higher proportion of highly lignified and less digestible tissue (Barnes et al., 2003). This is because warm season forages grow in a higher temperature environment during which greater lignin and fiber are produced (Barnes et al., 2003). In addition to being grazed by cattle and sheep, annual warm season grasses also show potential for use as horse pasture forages (Tracy et al., 2010; Kiesling and Swartz, 1997; DeBoer et al., 2017).

Proso millet (*Panicum miliaceum* L.) is well adapted to the semi-arid Central Great Plains of the United States with excellent water use efficiency; 122.5 kg of water is needed by proso millet to produce 0.5 kg of DM while it takes 240.4 kg of water for wheat to produce 0.5 kg of DM (Baltensperger et al., 1995). Proso millet tolerates drought mainly through two mechanisms: (1) it has rapid phenological development and reaches maturity quickly, and (2) it stops vegetative growth when temperature is above 30 ºC, ceasing to flower and maintaining its primary stem at a shorter height (Habiyaremye et al., 2017). Proso millet generally completes its life cycle within 60-90 days after seeding (Baltensperger et al., 1995). It's less leafy than foxtail millet (*Setaria italic* L. Beauv.), thus less palatable to livestock (McCartney et al., 2009).

Foxtail millet is the second most important millet after pearl millet [*Pennisetum glaucum* (L.) R. Br.]. Foxtail millet tolerates drought conditions quite well with rapid growth rate and high protein concentration (Arbabi and Ghoorchi, 2008). It can produce as much tonnage as corn while using only 60% of the water that corn requires (Arbabi Ghoorchi, 2008). When compared with proso millet, foxtail millet is generally taller, later maturing, and better suited to forage production (McCartney et al., 2009). Foxtail millet is able to regrow after cutting or grazing. However, foxtail millet has low seedling vigor, poor competitiveness, and there are few weed control options (McCartney et al., 2009).

Native to Ethiopia, teff [*Eragrostis tef* (Zuccagni) Trotter] is well adapted to arid regions with good drought tolerance (Davison et al., 2011). Teff has a short growing season and can produce nutritious, fine stemmed, and palatable hay 40 to 60 days after seeding during summer (Davison et al., 2011). However, teff is sensitive to frost and will not survive temperatures below 2.2°C (Davison et al., 2011). It will regrow after cutting or grazing.

Pearl millet is very drought tolerant due to its ability to match growth with precipitation by compensating main tiller with lateral young tillers when water is available after a drought period (Winkel eta l., 1997). In addition, high water use efficiency also contributes to high drought tolerance (Zegada-Lizarazu and Iijima, 2005). Compared to foxtail millet and sorghum-sudangrass [*Sorghum bicolor* (L.) Moench], pearl millet has a significantly higher leaf-to-stem ratio (Cuerrier et al., 2010). Pearl millet has regrowth potential but has a slow initial growth rate, which could result in weed infestation in the early stage of establishment (Cuerrier et al., 2010).

Forage sorghum-sudangrass is an important livestock feed in the USA, usually used as hay, silage and pasture in summer when water is too scarce to produce other crops (Beyaert and Roy, 2005). Sorghums-sudangrass is well known for their drought tolerance. They are more efficient in water absorption than corn because they have twice as many secondary roots per unit of primary root as corn and have only half as much leaf area as corn for evaporation (McKinlay and Wheeler, 1998). They have the ability to become dormant during extended drought periods (McKinlay and Wheeler, 1998). Besides, sorghum-sudangrass is characterized by fast establishment and rapid vegetative growth, low soil fertility demand, superior forage yield, and ability to suppress weeds (Parlak et al., 2016; Lenssen and Cash, 2011).

Summary

Annual forages can augment forage availability in livestock operations. They can be used to provide feed during a seeding year when perennial crops have not yet established or when pasture production is insufficient to meet livestock demands. During periods of water scarcity, annual forages have the potential to combine annual forage selection with regulated deficit irrigation (RDI) to conserve water while obtaining a sustainable forage production system. However, annual forages are more costly to produce than perennial forages. Therefore, when comparing the response of annual forage species under limited water conditions, it is important to select annual forages with high productivity, high quality, and with the greatest profit potential while also using less water. This requires that we evaluate a much wider range of annual forage species and cultivars within species than are currently being used.

Experiments reported in this thesis were designed to provide information about annual forage species that performed best under different irrigation regimes in both spring seeded and summer seeded cropping systems. Twenty annual forage species were selected from four functional groups, namely, five warm season grasses, five cool season grasses, five legumes, and five brassicas, to test their response under full and deficit irrigation. Yield, water use efficiency, quality, and phenology were compared. Research results will allow conclusions regarding which annual species have superior forage quality and higher yield while using less water and which species are more susceptible to drought stress when different irrigation regimes are applied. This information will allow livestock producers in the PNW to more effectively use annual forages in their production systems.

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Annual Forages Differ in Response to Partial-Season Irrigation Deficits in a Spring Seeded Cropping System

Qianqian Fan and Guojie Wang

Abstract

Forage production during summer is primarily limited by the water scarcity in the Pacific Northwest, United States. Annual forages present flexibility in planting date due to the short growing season and thus can shift production to periods of forage shortage. Therefore, this study was conducted to screen annual forage species for suitability to variable irrigation regimes. The production, quality, water use efficiency (WUE) and phenology of twenty annual forage species were investigated under four irrigation treatments; full-season irrigation (W1), early-season cutoff (W2), late-season cutoff (W3), and no irrigation (W4), over two years at Union, OR, on a La Grande silt loam. WUE and forage quality increased with increasing water stress while yield decreased. No significant difference in forage response was observed between W1 and W2. Thus, the W2 approach could be used to repalce W1 when water was limited. Annual warm season grass (AC4) group had highest yield (8.2 Mg/ha) but annual legume (AL) group had better quality (17.2% CP, 33.0% ADF and 38.7% NDF) than AC4 or annual cool season grass (AC3) group. Species performance under partial season irrigation deficit is species-specific. Within AC4, there was a 2.6-fold range in forage yield between species under W1, a 2.4-fold range under W2, a 4.1-fold range under W3 and a 5.0-fold range under W4. Teff [*Eragrostis tef* (Zuccagni) Trotter] (14.7% CP; 32.7% ADF; 53.4% NDF) and proso millet (*Panicum miliaceum* L.) (13.7% CP; 33.2% ADF; 56.0% NDF) had higher quality than others within AC4. Within AC3, a 1.5-fold, 1.6-fold, 1.6-fold and 3.2-fold range existed between forage under W1, W2, W3 and W4, respectively. Annual ryegrass (*Lolium multiflorum* L.) had the best forage quality (14.1 CP%; 33.1% ADF; 51.2% NDF) within AC3. Within AL, the yield range was 1.5, 2.2, 4.3 and 4.6 fold between forages under W1, W2, W3 and W4, respectively and chickling vetch (*Lathyrus sativus* L.) had superior forage quality (20.8% CP; 30.2% ADF; 37.2% NDF) over others. Radish (*Raphanus sativus* L. var.*longipinnatus*) outyielded others (10.9 Mg/ha on average) irrespective of irrigation treatments within annual brassica (AB). All in all, compared to find the best species suited under all irrigation regimes, matching annual forage species to water availability is more practical and achievable.

Introduction

Agriculture is one of the most important industries in the Pacific Northwest (PNW). Cattle and calves are a key economic product of this region, ranking 2nd, 1st, and 5th in agricultural commodity value in Idaho, Oregon, and Washington, respectively (USDA, 2018a). To provide grazing as well as feed to livestock, hay acreage alone consists of 1.49 million acres in Idaho, 1.04 million acres in Oregon, and 0.77 million acres in Washington (USDA, 2018b).

To produce enough forage for these livestock, irrigating during summer is necessary. However, irrigation water availability is a serious challenge in the PNW. Three main factors are responsible for this water deficit. First, it is rainfall distribution. The PNW has a Mediterranean climate with two thirds of the precipitation occurring between October and April (USFWS, 2011). Rainfall during the majority of growing season from May to September is sporadic and undependable. Second, snowpack serves as a natural reservoir to supply water during dry seasons but due to climate change, snow melting occurs earlier and snow melting speed is faster, thus causing less summer streamflow (Snover et al., 2003). In addition, Snover et al. (2003) also reported that because spring peak flow comes earlier, the time between the snowmelt and fall rain is increased, which means a longer dry season before the fall rain arrives. Third, there are competing demands for water, including industrial use and fisheries (Orloff et al., 2016).

Annual forages have been used during periods of drought since the 1900s to mitigate perennial pasture shortage (McCartney et al., 2009). As a short season crop, annual forages have great flexibility in both planting dates and crop rotation. They can shift production schedules to summer and autumn when there is a lack of feed, thus extending the grazing season beyond the normal perennial species grazing season (Neal et al., 2010). Therefore, annual forages can play an important role coping with irrigation water shortages in the PNW.

Species level variability exists among annual forages in response to differences in water availability. In one study conducted at Camden, Australia, there was more than a 4-fold range in yield among annual forages when they were grown with optimal irrigation; maize (*Zea mays* L.) produced the highest yield [29.0 Mg/ha dry matter (DM)] and subterranean clover (*Trifolium subterraneum* L.) had the lowest yield (6.5 Mg/ha DM) (Neal et al., 2010). Another study reported that there was a 3-fold difference in water use efficiency among annual forage species when optimal irrigation was applied (Neal et al., 2011).

Different types or functional groups of annual forages also differ in response to irrigation regimes. Cool season annual forages showed a smaller decline in yield than warm season annual forages under deficit irrigation because cool season species have higher growth rates during periods of relatively low temperature and a lower water requirement in the main growing season (Neal et al., 2010). The decline of water use efficiency (WUE) in response to deficit irrigation was largest for warm season annuals while WUE of most cool season annuals was unaffected (Neal et al., 2011).

Irrigation water supplies for forage production during dry seasons in the PNW are highly variable and uncertain due to water scarcity. Research is needed to identify forage species that can perform well under full season irrigation in years when water is sufficient, yet yield reasonably well during drought periods with late or early season irrigation termination or no irrigation. Thus, the objective of this project was to quantify and compare the response of numerous spring seeded annual forage species representing several functional groups under different irrigation regimes. A two-year experiment was conducted to test three hypotheses. First, four functional groups differ in annual forage response under partial season irrigation deficits. Second, annual forage response within each functional group is species-specific and variable under partial season irrigation deficits. Third, ranking of twenty annual forage performance, including production, quality and WUE, is different under partial season irrigation deficits.

Materials and Methods

Field Site

This study was conducted during 2017 and 2018 at the Eastern Oregon Agricultural Research Center located in Union, Oregon (45°12’N, 117°52’W). The soil type at this site is a La Grande silt loam (fine-silty, mixed, superactive, mesic Pachic Haploxerolls).

The location has a Mediterranean type climate with dry, warm summers and cool, wet winters. Precipitation and temperature patterns were typical of those throughout the PNW (Fig. 2.1). The total rainfall during the irrigation treatment period in 2017 and 2018 was 27.9 and 71.6

mm, respectively. During growing season, the precipitation in July and August in 2017 was 0.3 and 2.5 mm, respectively, while the precipitation in July, August and September of 2018 was 0.5, 1.8 and 2.8 mm, respectively. These values are much lower than the average precipitation in the past 30 years.

The average maximum and minimum temperature during the 2017 growing season was 25.0 and 7.9 °C in June, 32.8 and 9.9 °C in July, 32.2 and 9.0 °C in August, and 25.9 and 6.1 °C in September. In 2018, maximum and minimum temperatures were 21.7 and 6.7 °C in May, 23.7 and 6.8 °C in June, 32.0 and 9.1 °C in July, 30.4 and 8.8 °C in August, and 24.2 and 2.8 °C in September. The 30-year average temperature showed a similar seasonal pattern. The first killing frost (0 °C) at the site occurs no later than September 20th at the 50% probability level (NOAA, 2019).

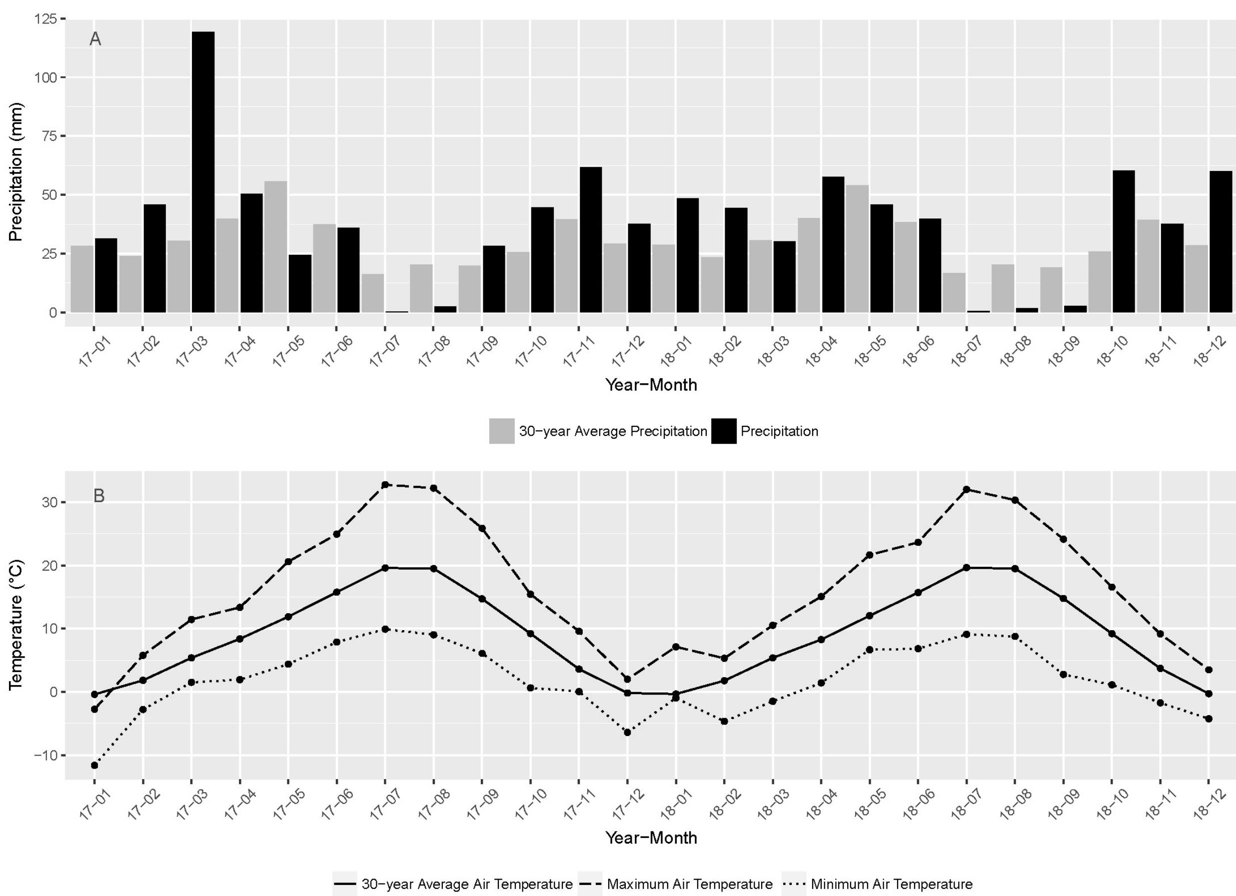

Fig. 2.1. Monthly precipitation (A) and mean monthly air temperature (B) for Union, OR, during 2017 and 2018 and the past 30 years.

Experimental Design

A randomized complete block split-plot design with four replications was used for this study. Main plots were four irrigation treatments: full-season irrigation (W1), late-season irrigation cutoff (W2), early-season irrigation cutoff (W3), and no irrigation (W4). Subplots contained twenty annual forage species representing four functional groups: annual cool season grasses (AC3), annual warm season grasses (AC4), annual legumes (AL), and annual brassicas (AB) (Table 2.1). Each subplot was 133 cm by 457 cm and contained 9 rows spaced 15.2 cm apart. All species were drill-seeded at an appropriate seeding rate (Table 2.1) using a small plot seeder (Kincaid Equip. Manufacturing, Haven, KS).

Table 2.1. Common name, scientific name, cultivar and seeding rate for annual forage species evaluated in a spring seeded cropping system for yield, phenology, water use efficiency, and quality under different irrigation cutoff seasons in Union, OR.

Common name	Scientific name	Cultivar	Seeding rate
			kg/ha
Annual cool season grass			
Wheat	Triticum aestivum L.	Louise	135
Barley	Hordeum vulgare L.	Haybet	112
Triticale	Triticosecale rimpaui Wittm.	1010	135
Oat	Avena sativa L.	Monida	135
Annual ryegrass	Lolium multiflorum L	Tetraploid	45
Annual warm season grass			
Proso millet	Panicum miliaceum L.	White	34
Foxtail millet	Setaria italica L.	Golden German	22
Teff	Eragrostis tef (Zuccagni) Trotter	Tiffany	11
Pearl millet	Pennisetum glaucum (L.) R. Br.	MS2500	22
Sorghum-sudangrass	Sorghum bicolor (L.) Moench	CC BMR	45
Annual legume			
Crimson clover	Trifolium incarnatum L.	Dixie	34
Field pea	Pisum sativum L.	Journey	168
Chickling vetch	Lathyrus sativus L.	AC Greenfix	112
Cowpea	Vigna unguiculata (L.) Walp.	Iron&Clay	67
Soybean	Glycine max (L.) Merr	Bobwhite Trailing	112
Annual brassica			
Turnip	Brassica rapa L. var. rapa	Purple Top	8
Radish	Raphanus sativus L. var. longipinnatus	Ripper	13
Rape	Brassica napus L. var. oleifera	Dwarf Essex	7
Kale	Brassica oleracea var. acephala L.	Hunter	9
Brassica hybrid	B. campestris sensulato L. * Brassica napus L. var. oleifera	Winfred	9

A solid set irrigation system was used to irrigate weekly. Irrigation began on June 9th in 2017 and on May 15th in 2018 (Table 2.2). Sufficient water was applied at each irrigation to fully satisfy potential crop evapotranspiration. Potential crop evapotranspiration was determined based on alfalfa (*Medicago sativa* L.) evapotranspiration, and monitored using an on-site Imbler AgriMet Weather Station, which was 37.0 kilometers away from Union (https://www.usbr.gov/pn/agrimet/agrimetmap/imboda. html).

Field Management

Soil sampling to a depth of 30.5 cm was conducted on 15 April and 12 April in 2017 and 2018, respectively. In 2017, the soil had a pH of 6.6, 4.55% organic matter, 85 kg/ha N, 286.75 ppm K, and 39.5 ppm P. Since P and K levels were sufficient from 2016 fall fertilization, only urea was applied, at a rate of 146 kg/ha N, to grass and brassica plots before seeding. In 2018, the soil analysis indicated a pH of 7.375, 4.375% organic matter, 178 kg/ha N, 431.75 ppm K and 40 ppm P. Due to sufficient levels of nutrients, no fertilizer was applied before seeding.

The seeding date for twenty annual forages was shown in Table 2.3. Before seeding, 7.0 L/ha MAKAZE® Glyphosate (Loveland Products) was applied to all plots. After seeding, 1.2 L/ha of CLEAN AMINE® 2,4-D (Loveland Products) was applied to annual cool season grasses and annual warm season grasses to control broadleaf weeds while 365.0 mL/ha Raptor® {2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1h-imidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid; BASF Corporation}was applied to annual legumes to control broadleaf and grass weeds. For annual brassicas, 292.0 mL/ha of Mustang® Maxx [3-phenoxyphenylmethyl (+) cis/trans 3-(2,2-dichloro-ethenyl)-2,2 dimethylcyclopropane carboxylate; FMC Corporation] was applied twice to control flea beetles. Plots were also hand-weeded as needed.

All the necessary field management followed the best management practices (BMPs) whenever we can.

Table 2.2. The starting date, ending date, irrigation events, irrigation amount, and rainfall amount of each irrigation treatment in Union, OR in 2017 and 2018.

Irrigation treatments	2017 Starting date	2017 Ending date	2017 Irrigation events	2017 Irrigation amount	2017 Rainfall amount	2018 Starting date	2018 Ending date	2018 Irrigation events	2018 Irrigation amount	2018 Rainfall amount
			——mm——					——mm——		
Full-season irrigation	June 9th	Sep. 15th	14	643.2		May 15th	Sep. 7th	18	694.4	
Late-season cutoff	June 9th	Aug. 3rd	8	380.4	27.9	May 15th	Aug. 1st	13	385.6	71.6
Early-season cutoff	June 9th	June 15th	3	115.8		May 15th	June 15th	6	127.0	
No irrigation	\	\	0	0		\	\	0	0	

Table 2.3. Seeding date, 1st cut harvesting date, harvesting stage, and multiple cuts of twenty annual forage species in Union, OR in 2017 and 2018.

Species	2017				2018			
	Seeding date	1st cut harvesting date	Harvesting stage	Multiple cuts	Seeding date	1st cut harvesting date	Harvesting stage	Multiple cuts
Wheat	May 5th	July 18th	Soft-dough	\		July 16th	Soft-dough	\
Barley	May 5th	July 18th	Soft-dough	\		July 16th	Soft-dough	\
Triticale	May 5th	July 18th	Milking	\		July 16th	Soft-dough	\
Oat	May 5th	July 18th	Milking	2		July 16th	Milking	2
Annual ryegrass	May 5th	July 18th	Soft-dough	3		July 16th	Late anthesis	2
Proso millet	June 14th	Aug. 17th	Milking	\		July 25th	Anthesis	2
Foxtail millet	June 14th	Sep. 6th	Hard-dough	\		Aug. 9th	Anthesis	\
Teff	June 14th	Aug. 17th	Early heading	2		Aug. 9th	Anthesis	2
Pearl millet	June 14th	Sep. 6th	Late heading	\		Aug. 20th	Anthesis	\
Sorghum-sudangrass	June 14th	Sep. 6th	Anthesis	\		Aug. 20th	Anthesis	\
Crimson clover	June 14th	Sep. 13th	50% flowering	\		Aug. 2nd	Podding	\
Field pea	June 14th	Aug. 21st	50% flowering	\	May 1st†	July 24th	Late pod formation	\
Chickling vetch	June 14th	Aug. 21st	Pod formation	\		July 24th	Late pod formation	\
Cowpea	June 14th	Sep. 13th	Vegetative	\		Sep. 11th	Vegetative	\
Soybean	June 14th	Sep. 13th	Pod formation	\		Aug. 23rd	Pod formation	\
Turnip	May 5th	\	\	\		July 19th		2
Radish	May 5th	\	\	\		July 19th	60-90 days after	\
Rape	May 5th	\	\	\		July 19th	seeding‡	2
Kale	May 5th	\	\	\		July 19th		2
Brassica hybrid	May 5th	\	\	\		July 19th		2

† May 1st was seeding date for all annual forages in 2018

‡ 60-90 days after seeding was the harvesting stage for all annual brassicas in 2018

Note: annual brassicas didn't survive in 2017

Measurements

DM

A 91-cm wide strip containing 5 rows in the center of each subplot was harvested and weighed using a John Deer harvester and an Ohaus balance (Ohaus Corporation. USA), respectively. Stubble height was 5.1 cm. Dry matter (DM) yield of each plot was measured from a ~1.0 kg grab sample which was dried in the oven at 60°C for 120 h for brassicas and for 72 h for other annual forages, using a laboratory balance (Ohaus Corporation. PineBrook, NJ, USA). In addition to measuring harvest length and forage height, weed components were visually estimated by the same observer before every harvesting. Regrowth potential of each plot was evaluated visually as well at the end of growing season in both years.

Phenology

Phenological development was monitored every three days for annual grasses and annual legumes in 2018. Each plot was separated into four sections. For each section, the phenological data were recorded on days to 50% heading and days to 50% flowering for annual grasses while it was days to 50% flowering and days to 50% pod formation for annual legumes. The average of the dates of the four sections was used to assess species' phenology stage in each plot.

Water Use Efficiency

The water use efficiency (WUE) was defined as the ratio of annual forage DM yield (Kg/ha) to evapotranspiration (ET) (mm). ET was determined for each subplot from seeding to the time when all the irrigation treatments were terminated. The following equation was used to calculate ET (Garrity et al., 1982):

$$\mathrm{ET} = \Delta S + P + I - D - R \qquad [1]$$

Where ΔS is soil water content change (mm), P is precipitation (mm), I is irrigation amount (mm), D is drainage and R is runoff. D and R were negligible since the slope of all plots was close to zero and plots were only irrigated to field capacity (FC) every time. Then ET calculation equation was:

$$\mathrm{ET} = \Delta S + P + I \qquad [2]$$

It was assumed all plots soil profile was at FC before irrigation treatments were conducted. Soil water content was assumed at the FC for W1 treatment plots and at permanent wilting point (PWP) for W2, W3, and W4 treatment plots after all irrigation treatments were shut off. Estimated soil water for loamy soil was 96.52 mm (3.8 inches) every 304.8 mm (1 foot) of soil for FC while 45.72 mm (1.8 inches) every 304.8 mm (1 foot) of soil for PWP (PASSEL, 2019). Therefore, ΔS was 50.8 mm (2 inches) every 304.8 mm (1 foot) of soil for W2, W3, and W4. We assumed the average rooting depth was 914.4 mm (3 feet) so ΔS was 152.4 mm (6 inches) for W2, W3 and W4. ΔS was 0 for W1.

Quality

Dry samples were ground into coarse powder first with a Wiley Mill (Arthur H. Thomas Co. Philadelphia, USA). Then they were ground again into fine powder through Cyclone Sample Mill (UDY Corporation. Fort Collins, Colorado, USA). Near-infrared reflectance spectroscopy (NIRS) was used to analyze crude protein (CP), acid detergent fiber (ADF), and neutral detergent fiber (NDF) of the first cut of annual legumes and annual grasses in 2018. Reference methods used for NIR calibrations were as follows: CP using the Kjeldahl method; ADF and NDF by the method of Van Soest (1967).

Statistical Analysis

Forage DM yield, quality, WUE and phenology data were the response parameters. Original data were organized and summarized using Excel. ANOVA analysis was conducted using the PROC GLM procedure of the SAS ® University Edition statistical software package (SAS Institute, 2008) with year, block and block × irrigation assigned as random effects. Multiple comparisons were evaluated using Tukey's HSD test. For unequal sample sizes, Tukey-Kramer Method was used. Statistical significance of results was assessed at the 5% probability level unless otherwise indicated. All the line plots and bar plots were developed in R 3.5.0 using the package ggplot (RStudio, Inc., 2018).

Results

Yield

The group level analysis of variance for yield of annual forages grown in a spring seeded cropping system is shown in Table 2.4. Main effects of year, irrigation, and group and their interactions were all significant ($p < 0.05$). Average yield over all the functional groups in 2017 was 5.5 Mg/ha while in 2018, it was 7.7 Mg/ha, a difference of 2.2 Mg/ha.

Table 2.4. Analysis of variance of year, irrigation, forage functional group, and their interactions for yield of annual forages in a spring seeded cropping system.

Source	DF	Type III SS	Mean Square	F value	Significance
Year	1	668.7	668.7	102.6	**
Irrigation	3	1747.7	582.6	89.4	**
Group	3	1149.2	383.1	58.8	**
Irrigation × Group	9	178.8	19.9	3.1	**
Irrigation × Year	3	72.7	24.2	3.7	*
Year × Group	2	168.3	84.2	12.9	**
Irrigation × Group × Year	6	107.8	18.0	2.8	*

* and ** indicate significance at the 0.05 and 0.01 probability levels, respectively.

Yield generally decreased as water stress increased. In 2017, the forage yield averaged over four functional groups was 7.8, 7.4, 4.3, and 2.5 Mg/ha under W1, W2, W3, and W4, respectively. In 2018, the forage yield was 8.9, 9.2, 7.2, and 5.5 Mg/ha under W1, W2, W3, and W4, respectively. However, no significant difference was observed between W1 and W2 treatments in both years.

AL had the lowest ($p < 0.05$) yield among groups in both years under all irrigation treatments (Fig. 2.2). In 2017, the forage yield averaged over four irrigation treatments was 7.8, 5.9, and 2.8 Mg/ha for AC4, AC3, and AL, respectively. In 2018, the forage yield was 8.7, 8.5, 7.2, and 6.4 Mg/ha for AC3, AC4, AB, and AL, respectively.

Highly significant interaction ($p < 0.01$) was found between forage functional groups and irrigation treatments in 2017 but not in 2018. AC4 had a higher ($p < 0.05$) yield in 2017 and numerically higher yield in 2018 than other functional groups under both W1 and W2 treatments (Fig. 2.2). A sharp yield decrease, 5.2 Mg/ha in 2017 and 4.0 Mg/ha in 2018, existed for AC4 from W2 to W3 treatments, while the decrease was consistently 2.0 Mg/ha in both years for AL from W2 to W3 treatments (Fig. 2.2). AC3 showed an insignificant decrease of 2.0 Mg/ha and 3.9 Mg/ha in 2017 and 2018, respectively between W3 and W4 treatments, while AB decreased by 2.0 Mg/ha.

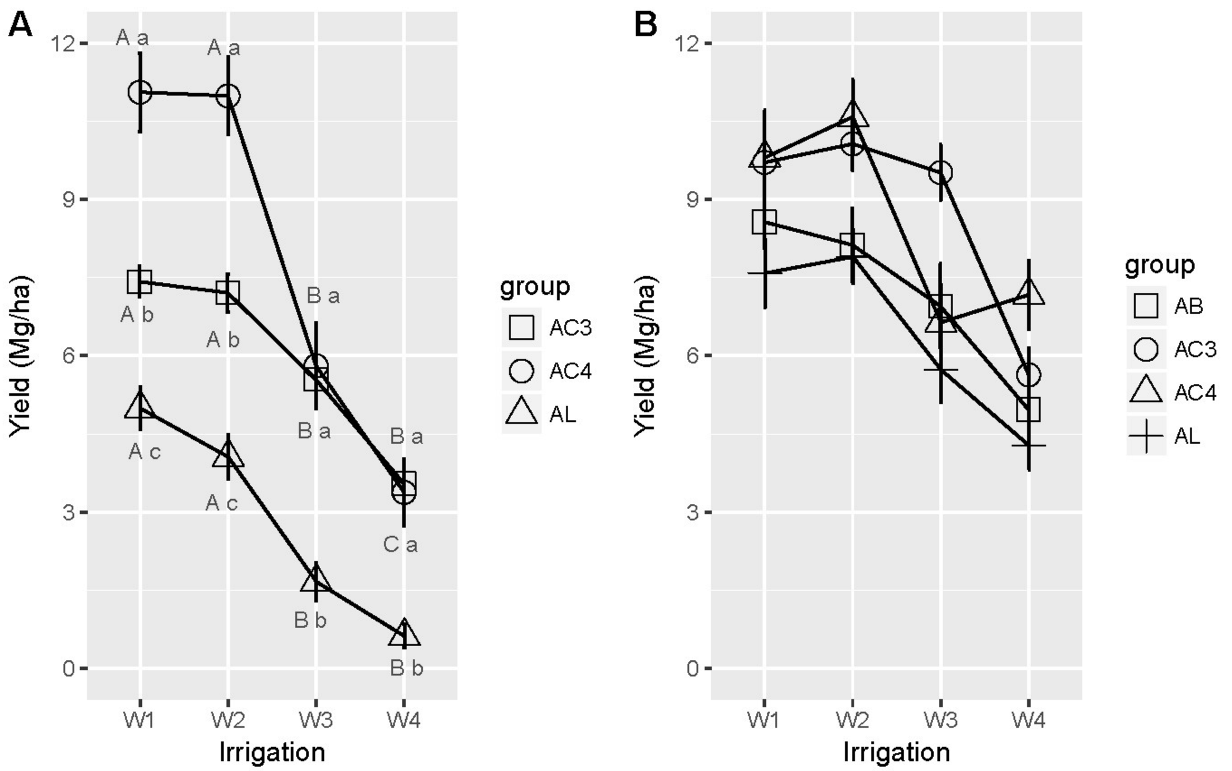

Fig. 2.2. Yields of annual forage functional groups grown in a spring seeded cropping system in 2017 (A) and in 2018 (B) in Union, OR.
Note: Means followed by the same capital letters are not significantly different at the 0.05 confidence level within each functional group under four irrigation treatments while means followed by the same lowercase letters are not significantly different at the 0.05 confidence level within each irrigation treatment for four forage functional groups. W1, full season irrigation; W2, late season cutoff; W3, early season cutoff; W4, no irrigation; AB, AC3, AC4, and AL indicate annual brassicas, annual cool season grasses, annual warm season grasses, and annual legumes, respectively. Error bars represent the standard error.

Within AC4, the species level variance analysis was shown in Table 2.5. Pearl millet had an average yield of 14.0 Mg/ha under both W1 and W2 treatments across two years, similar to foxtail millet but significantly higher than others (Fig. 2.3). Annual warm season grasses, except teff, had comparable yield to each other under W3. Under W4, sorghum-sudangrass was the highest yielding species (7.2 Mg/ha) in 2017 and its yield (8.8 Mg/ha) was similar to other millets in 2018. Teff consistently had the lowest ($p < 0.05$) production under all irrigation treatments in both years except for W3 in 2018.

Table 2.5. Species level analysis of variance of year, irrigation, species and their interactions for annual forage yield within the annual warm season grass group in a spring seeded cropping system.

Source	DF	Type III SS	Mean Square	F value	Significance
Year	1	22.0	22.0	5.2	*
Irrigation	3	965.2	321.7	75.5	**
Species	4	911.9	228.0	53.5	**
Irrigation × Species	12	150.5	12.5	2.9	**
Irrigation × Year	3	146.3	48.8	11.4	**
Year × Species	4	34.2	8.6	2.0	NS
Irrigation × Species × Year	12	56.2	4.7	1.1	NS

* and ** indicate significance at the 0.05 and 0.01 probability levels, respectively; NS, not significant at the 0.05 level.

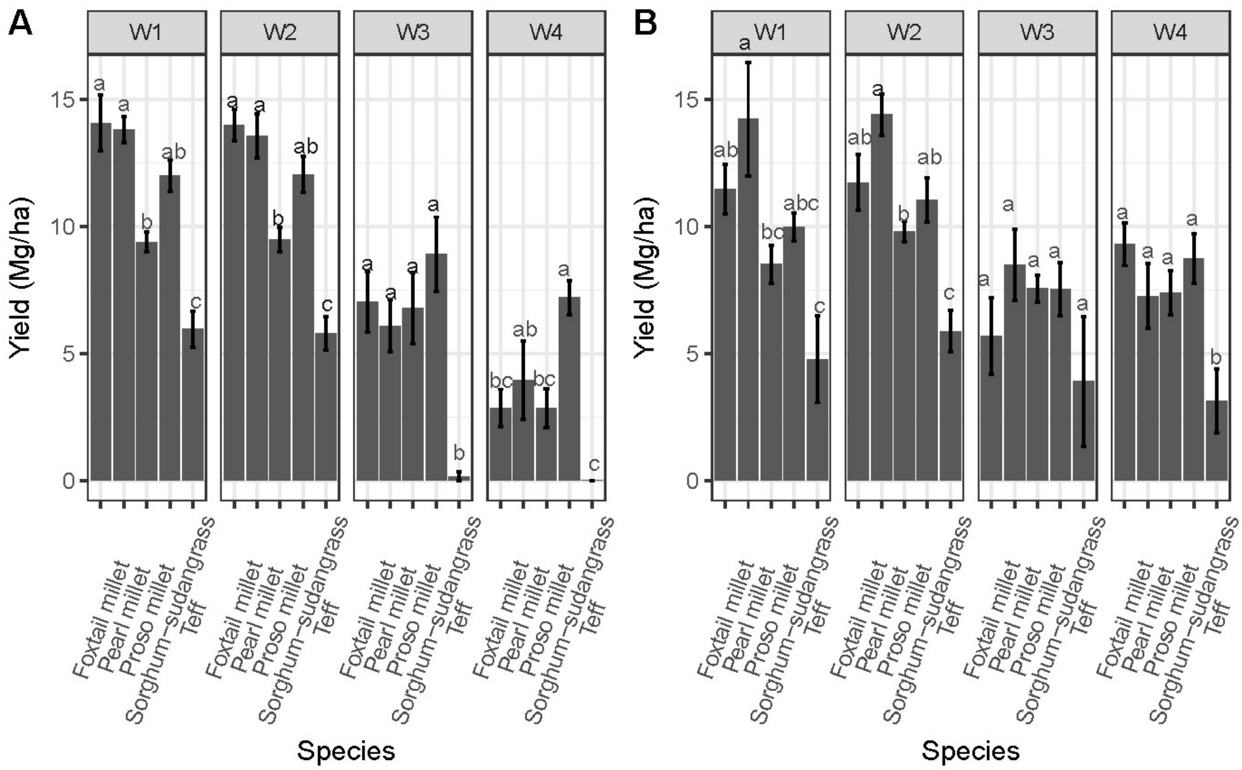

Fig. 2.3. The yield of annual forage species within the annual warm season grass group under variable irrigation treatments in a spring seeded cropping system in (A) 2017 and (B) 2018 in Union, OR.
Note: Means followed by the same letters are not significantly different at the 0.05 confidence level within each irrigation treatment. W1, full season irrigation; W2, late season cutoff; W3, early season cutoff; W4, no irrigation; Error bars represent the standard error.

Within AC3, the species level variance analysis was shown in Table 2.6. With 10.7, 11.6 under W1 and W2, respectively, oat had the highest average ($p < 0.001$) across two years. Under W3 and W4, oat, barley and wheat produced comparable yield to each other in 2017 while no significance was observed among species under W3 or among species except annual ryegrass under W4 in 2018 (Fig. 2.4). Annual ryegrass produced significantly lower yield than other annual cool season grasses under W4 in both years.

Table 2.6. Species level analysis of variance of year, irrigation, species, and their interactions for annual forage yield within the annual cool season grass group in a spring seeded cropping system.

Source	DF	Type III SS	Mean Square	F value	Significance
Year	1	313.8	313.8	185.0	**
Irrigation	3	431.6	143.9	84.8	**
Species	4	226.6	56.6	33.4	**
Irrigation × Species	12	80.7	6.7	4.0	**
Irrigation × Year	3	21.4	7.1	4.2	**
Year × Species	4	17.2	4.3	2.5	*
Irrigation × Species × Year	12	7.9	0.7	0.4	NS

* and ** indicate significance at the 0.05 and 0.01 probability levels, respectively; NS, not significant at the 0.05 level.

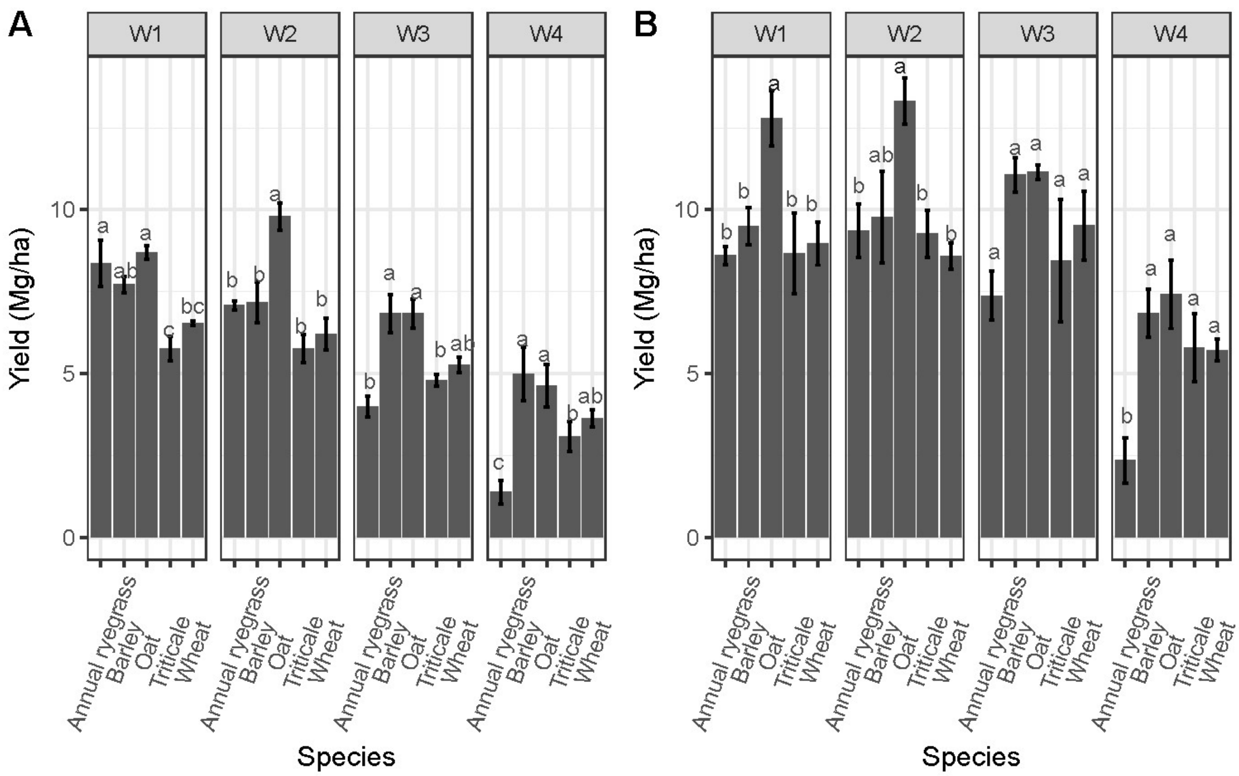

Fig. 2.4. The yield of annual forage species within the annual cool season grass group under variable irrigation treatments in a spring seeded cropping system in (A) 2017 and (B) 2018 in Union, OR.
Note: Means followed by the same letters are not significantly different at the 0.05 confidence level within each irrigation treatment. W1, full season irrigation; W2, late season cutoff; W3, early season cutoff; W4, no irrigation; Error bars represent the standard error.

Within the AL group, the species level variance analysis was shown in Table 2.7. No significance existed among five legumes under W1 (Fig. 2.5). There was no significant difference in yield among field pea, soybean, cowpea and chickling vetch when W2 or W3 was applied. Under W4, cowpea was the highest yielding species (2.3 Mg/ha) in 2017 while it produced comparable yield (5.2 Mg/ha) to other legumes except crimson clover in 2018. Crimson clover consistently produced a much lower yield than other legumes under W2, W3 and W4 in both years.

Table 2.7. Species level analysis of variance of year, irrigation, species, and their interactions for annual forage yield within the annual legume group in a spring seeded cropping system.

Source	DF	Type III SS	Mean Square	F value	Significance
Year	1	501.3	501.3	210.6	**
Irrigation	3	408.1	136.0	57.1	**
Species	4	159.5	39.9	16.8	**
Irrigation × Species	12	61.5	5.1	2.2	*
Irrigation × Year	3	12.8	4.3	1.8	NS
Year × Species	4	55.1	13.8	5.8	**
Irrigation × Species × Year	12	19.0	1.6	0.7	NS

* and ** indicate significance at the 0.05 and 0.01 probability levels, respectively; NS, not significant at the 0.05 level.

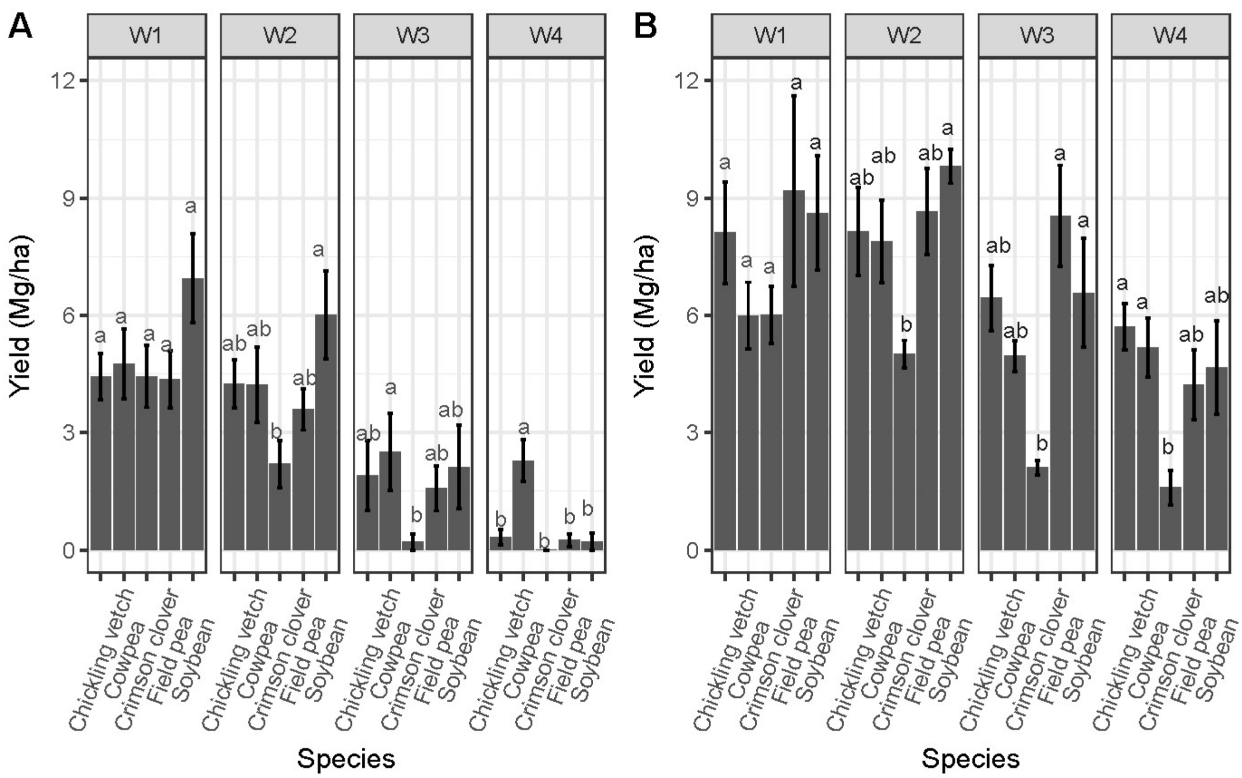

Fig. 2.5. The yield of annual forage species within the annual legume group under variable irrigation treatments in a spring seeded cropping system in (A) 2017 and (B) 2018 in Union, OR.
Note: Means followed by the same letters are not significantly different at the 0.05 confidence level within each irrigation treatment. W1, full season irrigation; W2, late season cutoff; W3, early season cutoff; W4, no irrigation; Error bars represent the standard error.

Within AB, the species level variance analysis was shown in Table 2.8. Radish consistently had the highest yield under all the irrigation treatments with 11.9 Mg/ha for W1, 13.0 Mg/ha for W2, 11.7 Mg/ha for W3 and 7.2 Mg/ha for W4 (Fig 2.6).

Table 2.8. Species level analysis of variance of irrigation, species, and their interaction for annual forage yield within the annual brassica group in a spring seeded cropping system

Source	DF	Type III SS	Mean Square	F value	Significance
Irrigation	3	155.4	51.8	26.6	**
Species	4	342.4	85.6	43.9	**
Irrigation × Species	12	61.7	5.1	2.6	**

** indicates significance at the 0.01 probability levels.

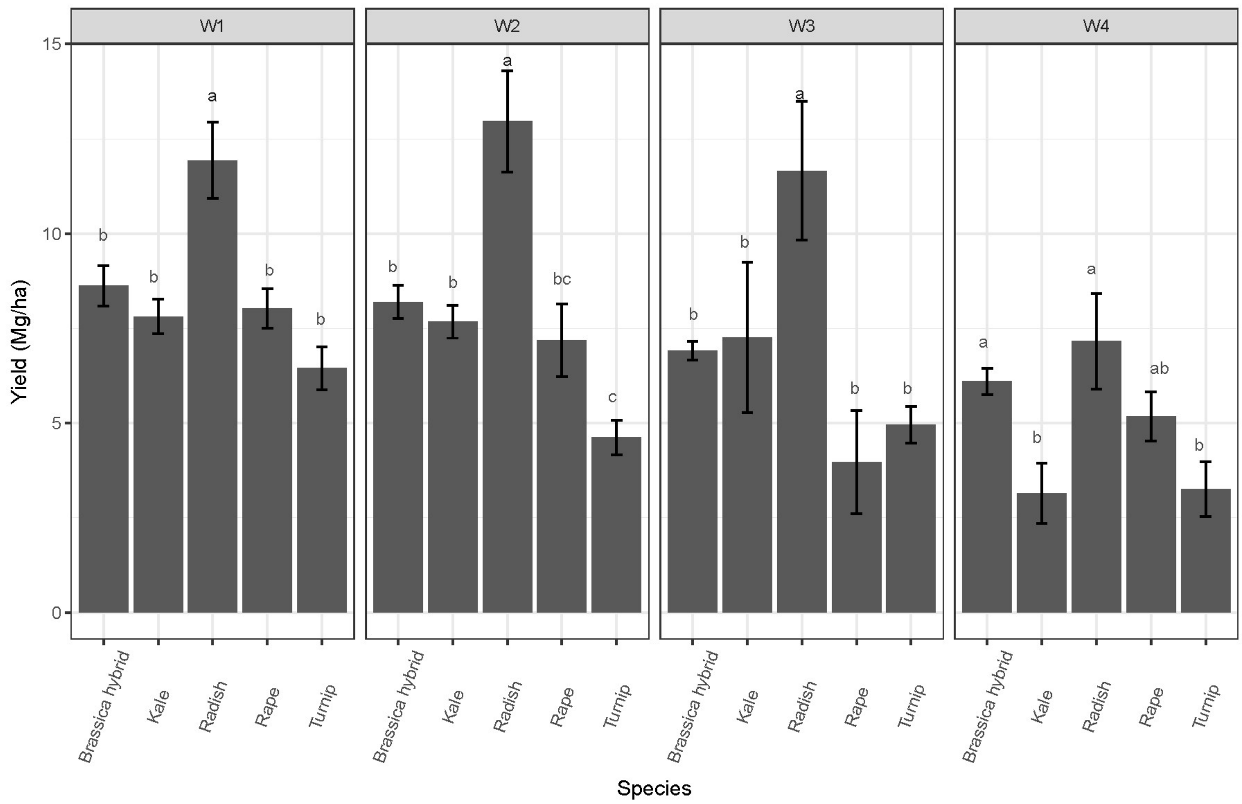

Fig. 2.6. The yield of annual forage species within the annual brassica group under variable irrigation treatments in a spring seeded cropping system in 2018 in Union, OR.
Note: Means followed by the same letters are not significantly different at the 0.05 confidence level within each irrigation treatment. W1, full season irrigation; W2, late season cutoff; W3, early season cutoff; W4, no irrigation; Error bars represent the standard error.

All main effects (year, irrigation, and species) and interaction effects were significant (Table 2.9) when the twenty annual forage species were compared together. Pearl millet had the highest average yield under W1 and W2 while radish outcompeted all other species under W3 across two years (Table 2.10). When no irrigation was applied, sorghum-sudangrass had the highest average yield. Plus, no significant difference was observed between W1 and W2 for each species.

Table 2.9. Species level analysis of variance of year, irrigation, group, and their interactions for yield of annual forages in a spring seeded cropping system.

Source	DF	Type III SS	Mean Square	F value	Significance
Year	1	668.7	668.7	226.4	**
Irrigation	3	1754.4	584.8	198.0	**
Species	19	2789.6	146.8	49.7	**
Irrigation × Species	57	533.2	9.4	3.2	**
Irrigation × Year	3	72.7	24.2	8.2	**
Year × Species	14	274.8	19.6	6.64	**
Irrigation × Species × Year	42	190.8	4.5	1.5	*

* and ** indicate significance at the 0.05 and 0.01 probability levels, respectively.

Table 2.10. The average yield of annual forage species under variable irrigation treatments in a spring seeded cropping system across 2017 and 2018 in Union, OR.

Species	Irrigation treatment				MSD ($p \leq 0.05$) among irrigation treatments
	W1	W2	W3	W4	
	Mg/ha				
Pearl millet	14.0 a†	14.0 a	7.3 abc	5.6 abc	3.4
Foxtail millet	12.8 a	12.9 ab	6.4 abcd	6.1 abc	2.5
Radish	11.9 ab	13.0 ab	11.7 a	7.2 ab	6.3
Sorghum-sudangrass	11.0 ab	11.6 abc	8.2 abc	8.0 a	3.0
Oat	10.7 abc	11.6 abc	9.0 ab	6.0 abc	1.5
Proso millet	9.0 bcd	9.7 bcd	7.2 abcd	5.1 abcd	2.2
Brassica hybrid	8.6 bcde	8.2 cde	6.9 abcd	6.1 abc	1.5
Barley	8.6 bcde	8.5 bcde	8.9 ab	5.9 abc	1.8
Annual ryegrass	8.5 bcde	8.2 cde	5.7 abcd	1.9 cd	1.5
Rape	8.0 bcde	7.2 def	4.0 bcd	5.2 abcd	4.2
Wheat	7.8 bcde	7.4 def	7.4 abc	4.7 abcd	1.6
Soybean	7.8 bcde	7.9 cde	4.4 bcd	2.4 bcd	1.8
Kale	7.8 bcde	7.7 cdef	7.3 abcd	3.1 bcd	3.9
Triticale	7.2 cde	7.5 def	6.6 abcd	4.4 abcd	2.7
Field pea	6.8 de	6.1 def	5.1 bcd	2.2 cd	3.0
Turnip	6.4 de	4.6 ef	4.9 bcd	3.3 bcd	1.9
Chickling vetch	6.3 de	6.2 def	4.2 bcd	3.0 bcd	1.8
Teff	5.4 de	5.9 ef	2.0 d	1.6 cd	3.5
Cowpea	5.4 de	6.1 def	3.7 cd	3.7 bcd	1.1
Crimson clover	5.2 e	3.6 f	1.2 d	0.8 d	1.3

† Means followed by the same letter within a column are not significantly different at the 0.05 confidence level. MSD, minimum significant difference. W1, full season irrigation; W2, late season cutoff; W3, early season cutoff; W4, no irrigation

Phenological Development

Phenological development was monitored for grasses and legumes in 2018. The variance analysis result is shown in Table 2.11.

Within annual legumes, average days to 50% flowering were 75.6, 75.6, 74, 72.5 under W1, W2, W3 and W4 treatments, respectively, while days to 50% pod formation over species were 88.8, 87.0, 84.3 and 83.4 under W1, W2, W3 and W4 treatments, respectively. No significant difference existed between W1 and W2 or between W3 and W4. Significant interaction was observed. Soybean took ~7 days and ~15 days less ($p < 0.05$) under W4 than W1 for days to 50% flowering and to 50% pod formation, respectively (Table 2.12). For other legumes, decreasing trends in days to 50% flowering (chickling vetch: $p = 0.3$; crimson lover; $p = 0.2$; field pea: $p = 0.9$) and 50% heading were also observed as water stress increased. Generally, the ranking in the days annual legumes needed to reach flowering or pod formation was soybean > crimson clover > field pea > chickling vetch. The average days for the AL group to reach flowering and pod formation was 74.4 and 85.9, respectively.

Table 2.11. Species level analysis of variance of main effects and their interactions for days to various phenological stages for grasses and legumes grown in a spring seeded cropping system in 2018 in Union, OR.

Source	Days to 50% flowering (legume)		Days to 50% pod formation (legume)		Days to 50% heading (grass)		Days to 50% flowering (grass)	
	df	Significance	df	Significance	df	Significance	df	Significance
Irrigation	3	**	3	**	3	**	3	**
Species	3	**	3	**	9	**	9	**
Irrigation × Species	9	*	9	**	26	**	25	NS

* and ** indicate significance at the 0.05 and 0.01 probability levels, respectively; NS, not significant at the 0.05 level.

Table 2.12. Days to 50% flowering and to 50% pod formation for annual legumes grown in a spring seeded cropping system in 2018 in Union, OR.

Species	Days to 50% flowering				MSD ($p \leq 0.05$) among irrigation treatments	Days to 50% pod formation				MSD ($p \leq 0.05$) among irrigation treatments
	W1	W2	W3	W4		W1	W2	W3	W4	
Chickling vetch	60.5 d†	58.6 d	59.1 c	56.8 d	NS	74.8 c	73.8 c	71.0 c	72.5 c	NS
Crimson clover	80.9 b	83.1 b	82.4 b	78.9 b	NS	92.0 b	92.0 b	92.0 b	92.0 b	NS
Field pea	63.9 c	64.4 c	63.0 c	64.6 c	NS	75.5 c	74.5 c	72.5 c	71.1 c	2.3
Soybean	97.1 a	96.3 a	91.5 a	89.8 a	6.7	113.1 a	107.8 a	101.6 a	98.0 a	6.9

† Means followed by the same letter within a column are not significantly different at the 0.05 confidence level. MSD, minimum significant difference. NS, not significant. W1, full season irrigation; W2, late season cutoff; W3, early season cutoff; W4, no irrigation.

Within annual grasses, average days to 50% heading were 75.1, 75.3, 73.8, 71.2 under W1, W2, W3 and W4 treatments, respectively, while days to 50% flowering over species were 82.3, 82.9, 78.8 and 75.6 under W1, W2, W3 and W4 treatments, respectively. There was no significant difference between W1 and W2. Interaction had significant effect on days to 50% heading but not days to 50% flowering. Pearl millet took 6 days longer to head out under W3 than W1 (Table 2.13). Species effect was significant for both phenological stages ($P < 0.01$). AC3 group took 58.2

and 66.0 days to reach 50% heading and 50% flowering, respectively while it took AC4 group 92.5 days to head out and 98.7 days to flower on average.

Table 2.13. Days to 50% heading and 50% flowering for annual grasses grown in a spring seeded cropping system in 2018 in Union, OR.

Species	Days to 50% heading				MSD ($p \leq 0.05$) among irrigation treatments	Days to 50% flowering
	W1	W2	W3	W4		
Teff	89.5 b†	90.9 b	94.4 b	92.8 b	NS	101.0 c
Foxtail millet	90.6 b	91.4 b	96.7 b	NA	3.2	96.7 d
Sorghum-sudangrass	99.2 a	98.7 a	105.2 a	99.8 ab	NS	104.7 b
Pearl millet	100.7 a	100.2 a	101.9 ab	104.9 a	NS	109.8 a
Proso millet	77.0 c	77.6 c	78.8 c	80.8 c	NS	85.3 e
Annual ryegrass	59.8 d	59.2 d	59.2 d	60.3 d	NS	69.1 f
Barley	57.5 d	58.3 d	57.7 d	55.3 d	NS	62.6 g
Oat	60.8 d	60.9 d	59.9 d	56.6 d	2.0	67.0 f
Triticale	58.6 d	58.4 d	59.0 d	55.6 d	3.3	67.6 f
Wheat	57.7 d	57.5 d	57.9 d	54.5 d	2.0	63.6 g

† Means followed by the same letter within a column are not significantly different at the 0.05 confidence level. NA, not applicable; NS, not significant. MSD, minimum significant difference. NS, not significant. W1, full season irrigation; W2, late season cutoff; W3, early season cutoff; W4, no irrigation.

Water Use efficiency

The group level analysis of variance for water use efficiency (WUE) of annual forages is shown in Table 2.14. Generally, WUE increased as water stress increased (Fig. 2.7). No significant WUE difference was observed between W1 and W2 for AC4, AC3 and AB but they were lower than WUE under W4. Irrigation didn't produce difference in WUE in the AL group. In addition, AL had the least WUE irrespective of irrigation treatments while AC4 had the greatest WUE under W1, W2.

Table 2.14. Group level analysis of variance of year, irrigation, forage functional group, and their interactions for water use efficiency (WUE) of annual forages in a spring seeded cropping system.

Source	DF	Type III SS	Mean Square	F value	Significance
Year	1	2072.8	2072.8	42.0	**
Irrigation	3	4268.7	1422.9	28.8	**
Group	3	7760.9	2587.0	52.4	**
Irrigation × Group	9	1651.7	183.5	3.7	**
Irrigation × Year	3	2253.0	751.0	15.2	*
Year × Group	2	1018.5	509.2	10.3	**
Irrigation × Group × Year	6	836.1	139.4	2.8	*

* and ** indicate significance at the 0.05 and 0.01 probability levels, respectively.

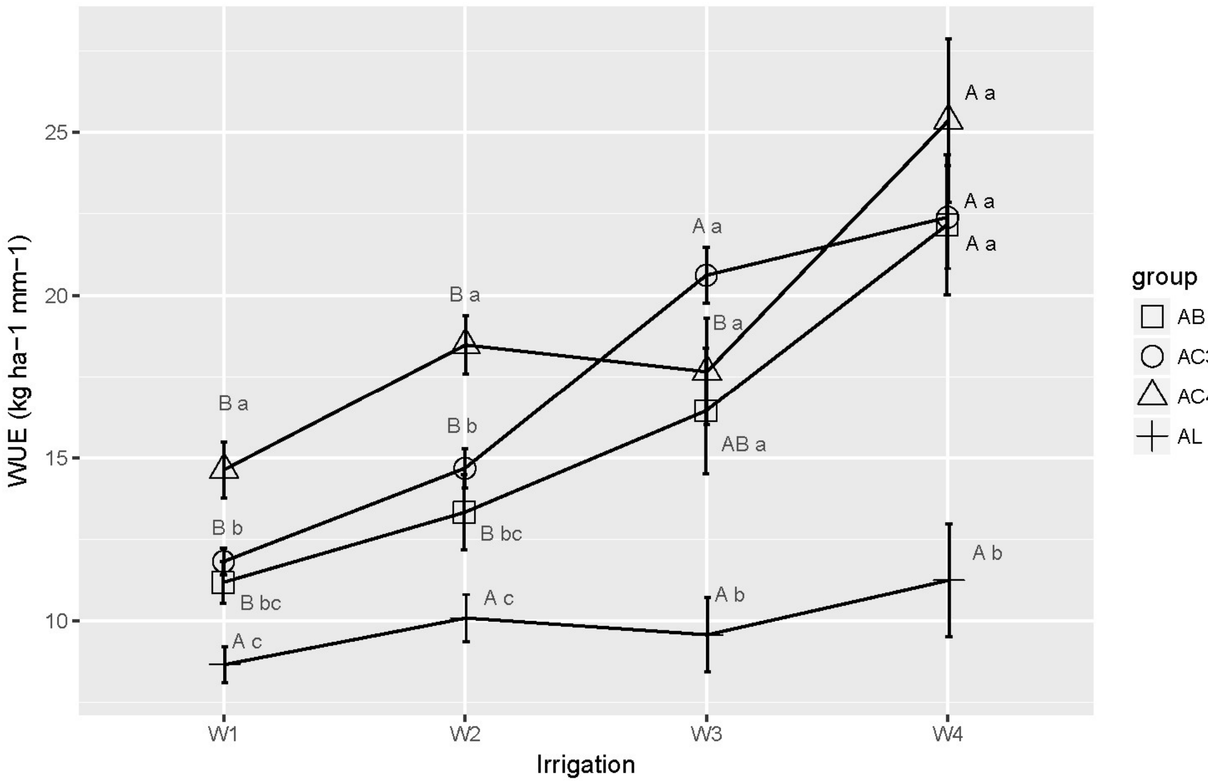

Fig. 2.7. The average water use efficiency (WUE) of annual forage functional groups grown in a spring seeded cropping system across 2017 and 2018 in Union, OR.
Note: Means followed by the same capital letters are not significantly different at the 0.05 confidence level within each functional group while means followed by the same lowercase letters are not significantly different at the 0.05 confidence level within each irrigation treatment. W1, full season irrigation; W2, late season cutoff; W3, early season cutoff; W4, no irrigation; AB, AC3, AC4 and AL indicate annual brassica, annual cool season grass, annual warm season grass, and annual legume group, respectively. Error bars represent the standard error.

The species level analysis of variance for WUE of annual forages was shown in Table 2.15. WUE increased from W1 to W4 but there was no significant WUE difference between W1 and W2 for all annual forage species (Table 2.16). Pearl millet showed the greatest WUE under W1 and W2; 19.6 kg/ha-mm under W1 and 23.9 kg/ha-mm under W2. Radish had the greatest WUE under W3 with 27.6 kg/ha-mm while WUE of sorghum-sudangrass was greatest, 39.5 kg/ha-mm, without irrigation.

Table 2.15. Species level analysis of variance of year, irrigation, species, and their interactions for water use efficiency (WUE) of annual forages in a spring seeded cropping system.

Source	DF	Type III SS	Mean Square	F value	Significance
Year	1	2072.8	2072.8	97.1	**
Irrigation	3	4015.7	1338.6	62.7	**
Species	19	18393.2	968.1	45.3	**
Irrigation × Species	57	5907.4	103.6	4.9	**
Irrigation × Year	3	2253.0	751.0	35.2	**
Year × Species	14	1863.3	133.1	6.2	**
Irrigation × Species × Year	42	2053.2	48.9	2.3	**

** indicate significance at the 0.01 probability levels.

Table 2.16. The average water use efficiency (WUE) of annual forage species under variable irrigation treatments in a spring seeded cropping system across 2017 and 2018 in Union, OR.

Species	Irrigation treatment				MSD ($p \leq 0.05$) among irrigation treatments
	W1	W2	W3	W4	
	Kg ha^{-1} mm^{-1}				
Pearl millet	19.6	23.9	20.3	27.2	NS
Foxtail millet	18.0	22.1	18.6	28.7	NS
Radish	15.6	21.3	27.6	31.9	NS
Sorghum-sudangrass	15.5	19.8	24.0	39.5	9.4
Oat	14.8	20.0	24.7	29.4	6.5
Proso millet	12.6	16.5	20.4	24.4	9.6
Barley	12.0	14.4	24.6	29.1	5.5
Annual ryegrass	11.9	14.0	15.5	9.1	4.4
Brassica hybrid	11.3	13.4	16.3	27.2	4.1
Soybean	10.8	13.4	11.4	11.0	NS
Rape	10.5	11.8	9.4	23.1	10.9
Wheat	10.5	12.6	20.1	22.9	4.6
Kale	10.2	12.6	17.2	14.0	NS
Triticale	10.0	12.7	18.1	21.5	7.8
Field pea	9.2	10.3	12.8	10.1	NS
Chickling vetch	8.6	10.5	10.8	13.7	NS
Turnip	8.4	7.6	11.7	14.5	6.7
Teff	7.6	10.0	4.9	7.0	NS
Cowpea	7.5	10.2	10.1	17.9	7.1
Crimson clover	7.2	6.1	2.8	3.6	4.2
MSD† ($p \leq 0.05$) among species	4.6	5.4	11.9	12.7	-

MSD, minimum significant difference; NS, not significant; W1, full season irrigation; W2, late season cutoff; W3, early season cutoff; W4, no irrigation.

Quality

The effect of forage functional group, irrigation, and their interaction on CP, ADF and NDF were all significant at group level except the interaction effect on NDF (Table 2.17). In general, CP content increased with increasing water stress; 12.4% for W1, 12.6% for W2, 14.4 for W3 and 14.5% for W4 (Fig. 2.8A). The CP of AC4 ranged from 14.2% under W4 to 9.3% under W1 with a significant difference of 4.9%. There was no significant difference between W1 and W2 or between W3 and W4 in CP, ADF or NDF content for all groups. AL had consistent significantly higher CP than other groups irrespective of irrigation treatments. The average CP content was 17.2%, 11.6% and 11.6% for AL, AC3 and AC4, respectively. In general, both ADF and NDF decreased as water stress increased; 36.9% under W1, 35.8% under W2, 32.2% under W3 and 32.1% under W4 for ADF (Fig. 2.8B); 53.0% under W1, 52.0% under W2, 48.2% under W3 and 47.9% under W4 for NDF (Fig. 2.8C). The average ADF content was 33.0% for AL, 35.4% for AC4 and 34.4% for AC3 while average NDF was 38.7% for AL, 56.8% for AC4 and 55.4% for AC3.

Table 2.17. Group level analysis of variance of main effect and their interactions for crude protein (CP), acid detergent fiber (ADF) and neutral detergent fiber (NDF) in a spring seeded cropping system.

Source	df	CP	ADF	NDF
Group	2	**	**	**
Irrigation	3	**	**	**
Group × Irrigation	6	**	**	NS

** indicate significance at the 0.01 probability level; NS, not significant at the 0.05 level.

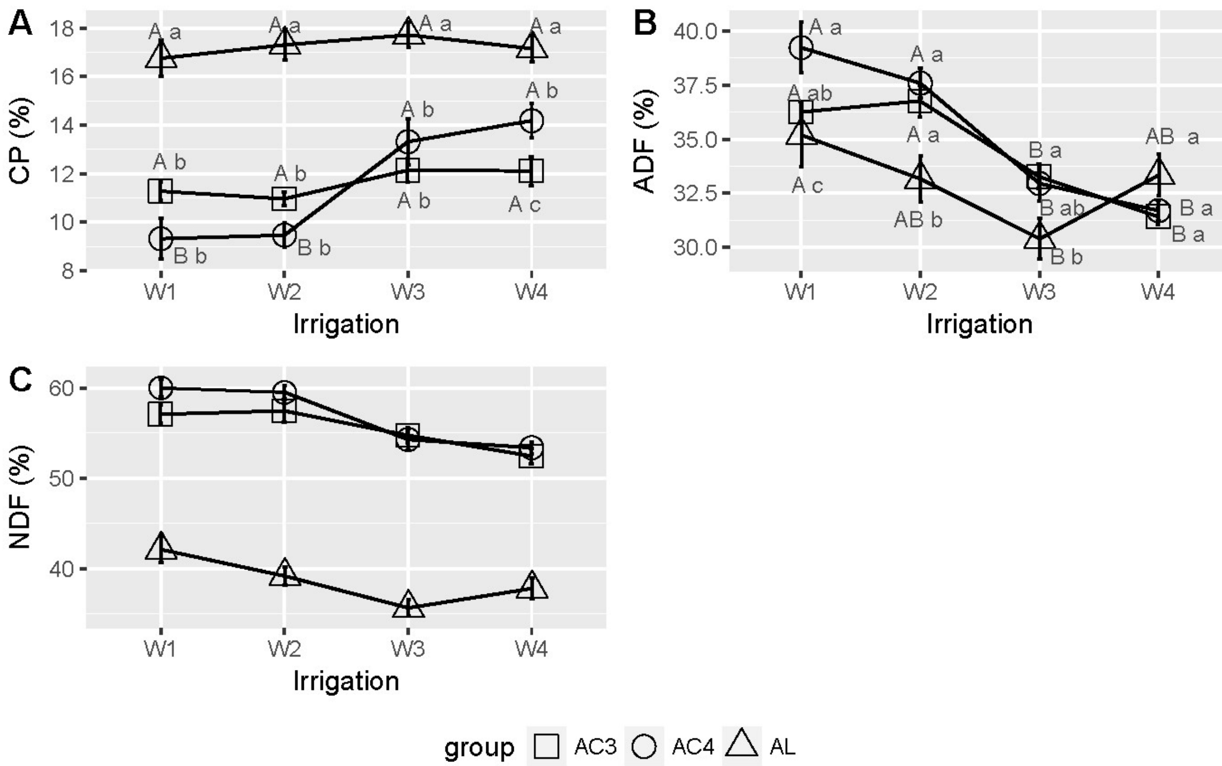

Fig. 2.8. The content of (A) crude protein (CP), (B) acid detergent fiber (ADF) and (C) neutral detergent fiber (NDF) of annual forage functional groups grown in a spring seeded cropping system in 2018 in Union, OR.
Note: Means followed by the same capital letters are not significantly different at the 0.05 confidence level within each functional group while means followed by the same lowercase letters are not significantly different at the 0.05 confidence level within each irrigation treatment. W1, full season irrigation; W2, late season cutoff; W3, early season cutoff; W4, no irrigation; AC3, AC4 and AL indicate annual cool season grass, annual warm season grass, and annual legume group, respectively. Error bars represent the standard error.

ANOVA analysis of species, irrigation and their interaction for CP, ADF and NDF within each functional group was shown in Table 2.18. No significant interaction existed for ADF and NDF of AC4, or for CP and ADF of AL.

Table 2.18. Species level analysis of variance of main effects and their interactions for crude protein (CP), acid detergent fiber (ADF), and neutral detergent fiber (NDF) within annual warm season grass (AC4), annual cool season grass (AC3) and annual legume (AL) groups in a spring seeded cropping system.

Source	df	AC4			AC3			AL		
		CP	ADF	NDF	CP	ADF	NDF	CP	ADF	NDF
Species	4	**	**	**	**	**	**	**	**	**
Irrigation	3	**	**	**	**	**	**	NS	**	**
Species × Irrigation	12	*	NS	NS	**	**	**	NS	NS	**

* and ** indicate significance at the 0.05 and 0.01 probability levels, respectively; NS, not significant at the 0.05 level.

Within AC3, annual ryegrass had the highest CP content under W1 and W4 and its CP% was similar to triticale and wheat under W3 (Fig. 2.18A). The CP% of annual cool season grasses was comparable to each other under W2. Oat and triticale had comparable ADF content under W1 and W2 and comparable NDF content irrespective of irrigation treatments (Fig. 2.18B; Fig. 2.18C). There was no difference in ADF% among cool season grasses under W3 and W4.

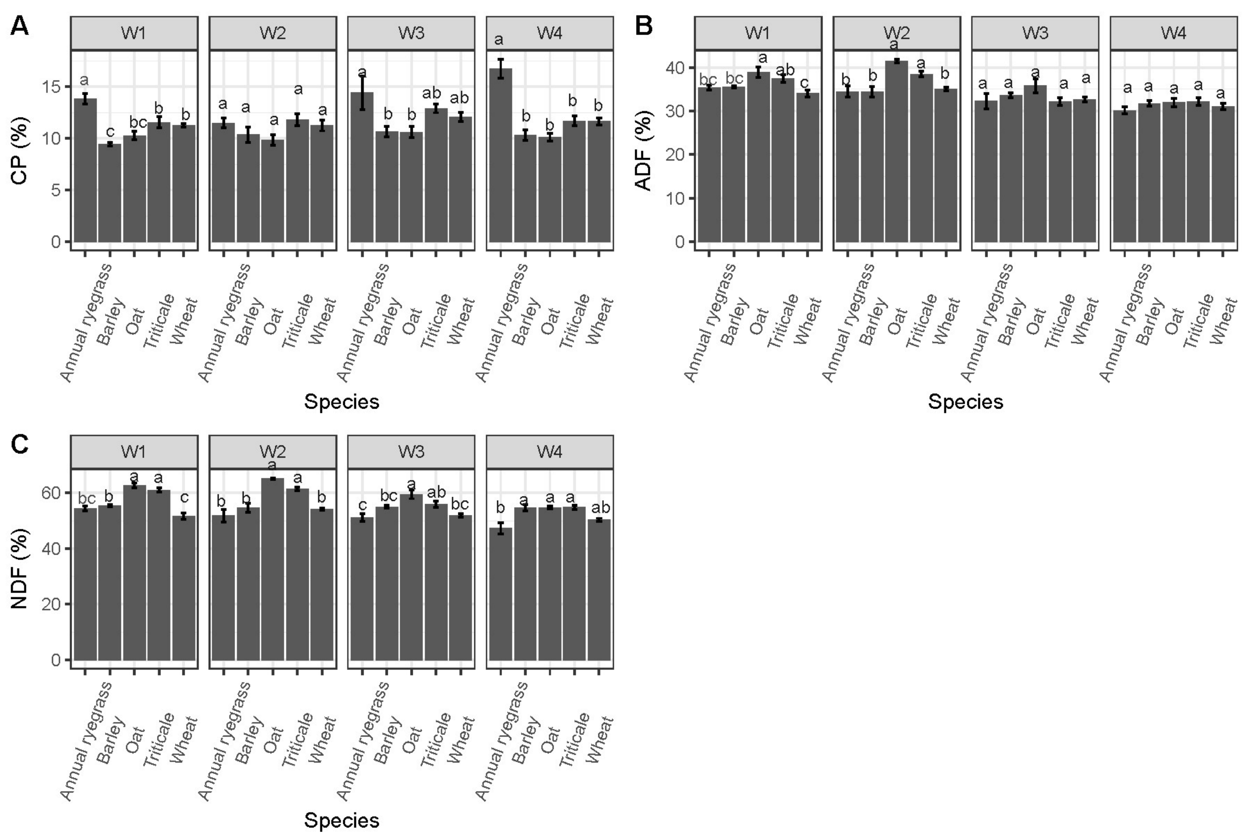

Fig. 2.9. The content of (A) crude protein (CP), (B) acid detergent fiber (ADF), and (C) neutral detergent fiber (NDF) of annual forages within the annual cool season grass (AC3) group in a spring seeded cropping system in 2018 in Union, OR.

Note: Means followed by the same letters are not significantly different at the 0.05 confidence level within each irrigation treatment. W1, full season irrigation; W2, late season cutoff; W3, early season cutoff; W4, no irrigation; Error bars represent the standard error.

Within AC4, the CP content ranged from 13.0% for teff to 5.8% for pearl millet under W1, from 11.4% for proso millet to 7.1% for pearl millet under W2, from 17.4% for teff to 10.7% for sorghum-sudangrass under W3 and from 17.2% for teff to 9.8% for sorghum-sudangrass under W4 (Fig. 2.10A). ADF% ranged from 38.0% for pearl millet to 32.7% for teff (Fig. 2.10B) while NDF% ranged from 58.9% for pearl millet to 53.4% for teff (Fig. 2.10C).

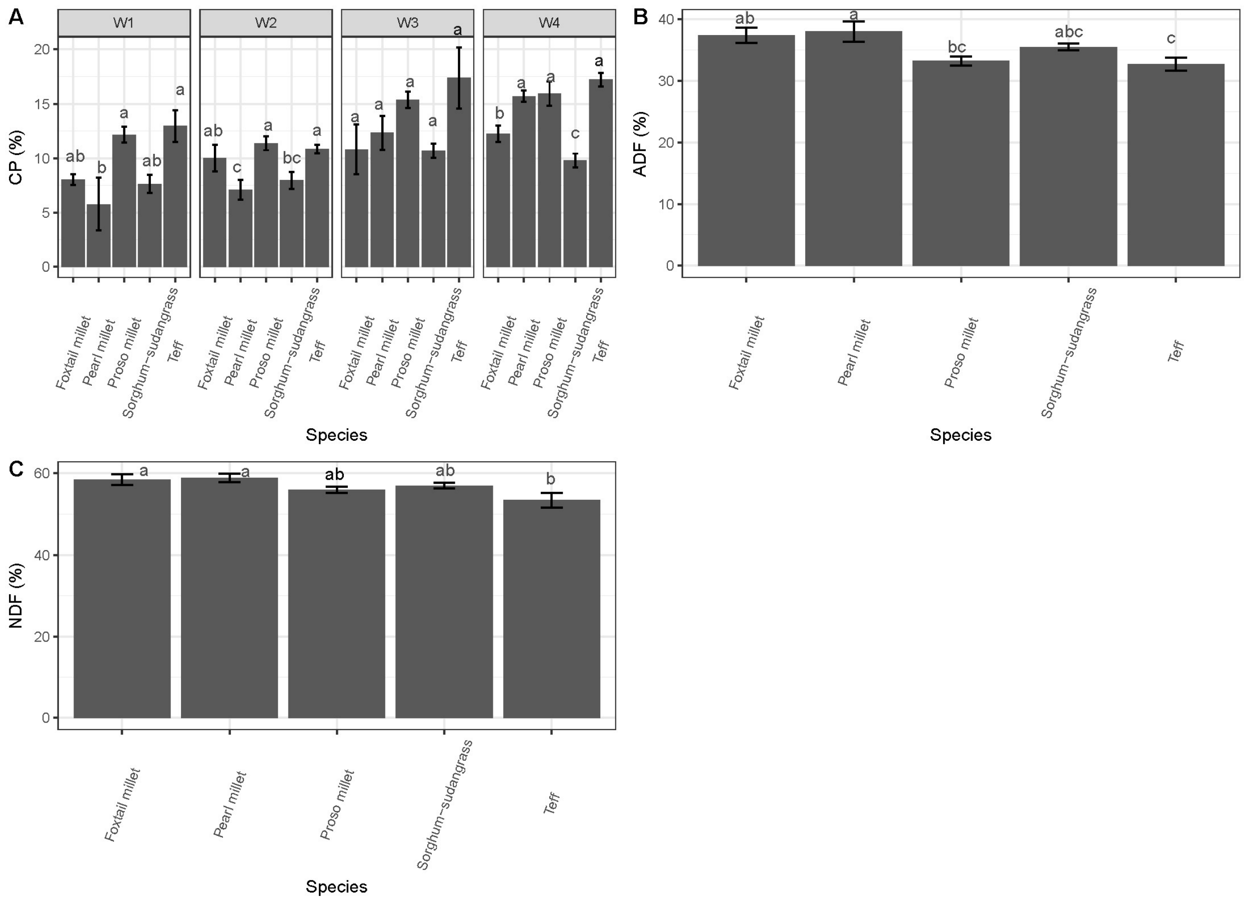

Fig. 2.10. The content of (A) crude protein (CP), (B) acid detergent fiber (ADF), and (C) neutral detergent fiber (NDF) of annual forages within the annual warm season grass (AC4) group in a spring seeded cropping system in 2018 in Union, OR.
Note: Means followed by the same letters are not significantly different at the 0.05 confidence level within each irrigation treatment. W1, full season irrigation; W2, late season cutoff; W3, early season cutoff; W4, no irrigation; Error bars represent the standard error.

Within AL, the average CP content ranged from 20.8% for chickling vetch to 15.8% for soybean (Fig. 2.11A). Cowpea and crimson clover had greater ADF content than others (Fig. 2.11B). Cowpea had greater NDF content (49.0%) than others except crimson clover under W1 while crimson clover had greater NDF% (45.5%) than others except cowpea (Fig. 2.11C). There was no difference in NDF content among annual legumes when W3 or W4 was applied.

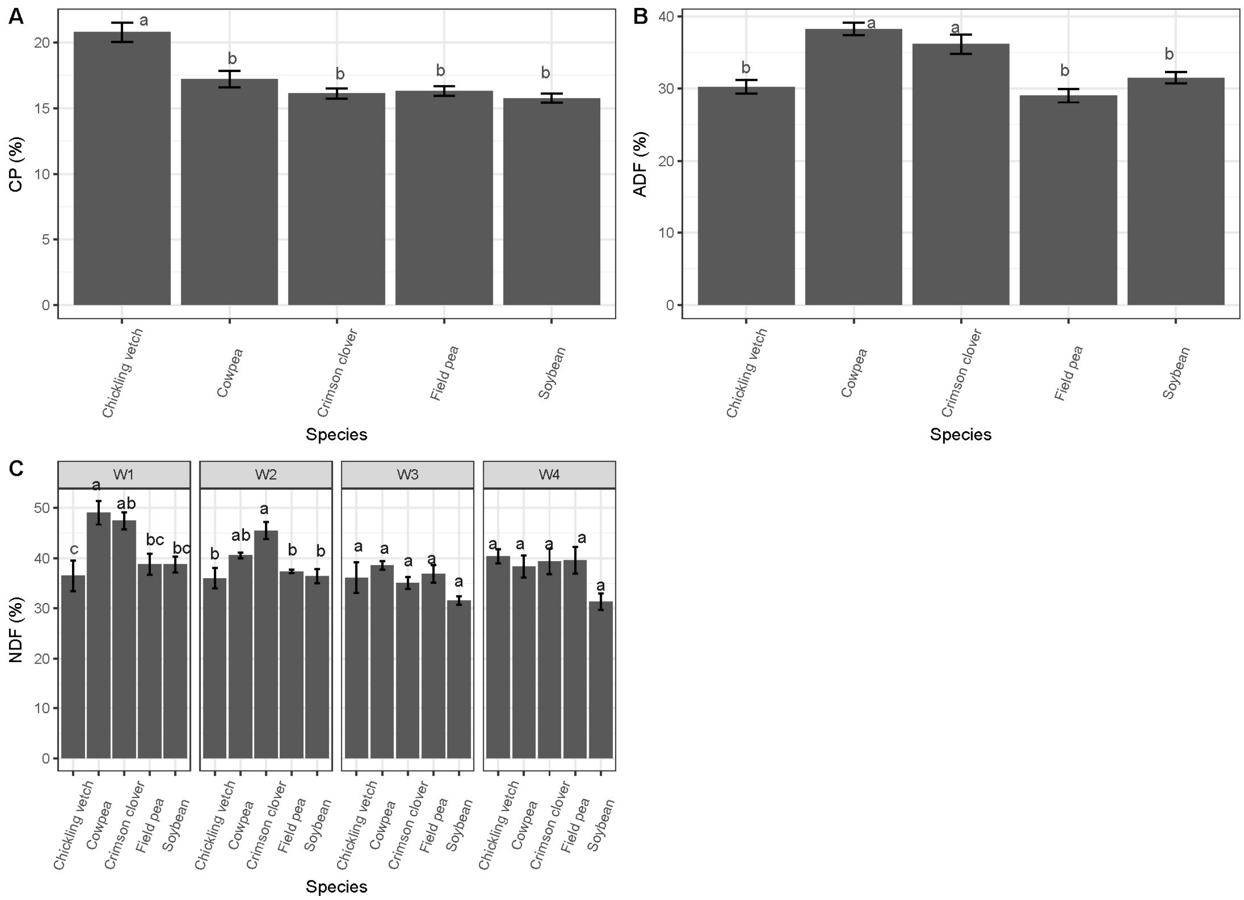

Fig. 2.11. The content of (A) crude protein (CP), (B) acid detergent fiber (ADF), and (C) neutral detergent fiber (NDF) of annual forages within the annual legume (AL) group in a spring seeded cropping system in 2018 in Union, OR. Note: Means followed by the same letters are not significantly different at the 0.05 confidence level within each irrigation treatment. W1, full season irrigation; W2, late season cutoff; W3, early season cutoff; W4, no irrigation; Error bars represent the standard error.

ANOVA analysis of twenty species for quality is shown in Table 2.19. For CP, pearl millet had the greatest CP% under W1 (21.7%) and W2 (21.9%) treatments (Table 2.20). Under W3, CP concentration ranged from 20.0% for chickling vetch to 10.6% for both barley and oat while under W4, it ranged from 19.5% for chickling vetch to 9.8% for sorghum-sudangrass. ADF content ranged from 45.2% for pearl millet to 29.1% for field pea under W1, from 41.5% for oat to 28.1% for field pea under W2, from 36.6% for cowpea to 27.4% for field pea under W3 and from 36.4% for cowpea to 29.5% for teff under W4. For NDF, it was from 64.0% for foxtail millet to 36.5% for chickling vetch under W1, from 65.1% for oat to 36.0% for chickling vetch under W2, from 59.5% for oat to 31.6% for soybean under W3 and from 55.1% for pearl millet to 31.3% for soybean under no irrigation.

Table 2.19. Species level analysis of variance of main effect and their interactions for crude protein (CP), acid detergent fiber (ADF), and neutral detergent fiber (NDF) of annual forages in a spring seeded cropping system.

Source	df	CP	ADF	NDF
Species	14	**	**	**
Irrigation	3	**	**	**
Species × Irrigation	42	**	**	**

** indicate significance at the 0.01 probability level

Table 2.20. The average content of crude protein (CP), acid detergent fiber (ADF), and neutral detergent fiber (NDF) of twenty annual forage species under variable irrigation treatments in a spring seeded cropping system in 2018 in Union, OR.

Species	CP				MSD (p ≤ 0.05) among irrigation treatments	ADF				MSD (p ≤ 0.05) among irrigation treatments	NDF				MSD (p ≤ 0.05) among irrigation treatments
	W1	W2	W3	W4		W1	W2	W3	W4		W1	W2	W3	W4	
	%														
Chickling vetch	21.7	21.9	20.0	19.5	NS	29.6	29.7	28.8	32.8	NS	36.5	36.0	36.1	40.4	NS
Field pea	16.6	16.1	16.6	16.0	NS	29.1	28.1	27.4	31.4	NS	38.8	37.4	36.9	39.6	NS
Soybean	16.4	15.4	15.7	15.5	NS	34.3	32.2	28.9	30.5	NS	38.7	36.4	31.6	31.3	5.6
Cowpea	14.6	17.4	18.3	18.5	NS	42.7	37.2	36.6	36.4	4.1	49.0	40.5	38.6	38.4	5.9
Crimson clover	14.5	15.7	17.9	16.4	2.5	40.2	38.6	30.1	35.5	8.7	47.5	45.5	35.1	39.4	7.6
Annual ryegrass	13.8	11.5	14.4	16.8	3.9	35.4	34.5	32.2	30.1	NS	54.4	51.8	51.2	47.4	NS
Teff	13.0	10.8	17.4	17.2	NS	35.7	36.6	29.0	29.5	5.4	55.5	58.6	48.4	51.2	NS
Proso millet	12.2	11.4	15.4	15.9	4.2	34.9	36.2	31.4	30.3	3.4	57.8	59.5	53.9	52.6	3.5
Triticale	11.6	11.8	12.9	11.7	NS	37.4	38.5	32.1	32.2	4.0	60.9	61.5	55.9	54.9	3.9
Wheat	11.2	11.2	12.1	11.7	NS	34.0	35.0	32.6	31.0	2.6	51.7	54.1	51.9	50.4	3.2
Oat	10.3	9.9	10.6	10.1	NS	38.9	41.5	35.8	32.0	5.4	62.7	65.1	59.5	54.8	4.6
Barley	9.5	10.4	10.6	10.3	NS	35.5	34.4	33.6	31.7	3.0	55.4	54.6	55.0	54.7	NS
Foxtail millet	8.0	10.0	10.8	12.2	NS	42.4	38.6	35.5	33.0	8.6	64.0	60.1	55.9	54.0	8.7
Sorghum-sudangrass	7.6	8.0	10.7	9.8	NS	37.9	36.2	34.6	33.3	3.8	59.8	58.4	56.1	53.8	3.5
Pearl millet	5.8	7.1	12.3	15.7	7.7	45.2	40.3	34.1	32.4	9.8	62.8	60.7	56.9	55.1	7.0
MSD (p ≤ 0.05) among species	4.9	3.5	6.4	3.4	-	7.7	6.5	7.2	6.8	-	8.3	7.7	9.8	8.1	-

MSD, minimum significant difference; NS, not significant. W1, full season irrigation; W2, late season cutoff; W3, early season cutoff; W4, no irrigation.

Discussion

Yield

Year effect

The average yield over four irrigation treatments and all species was 2.2 Mg/ha significantly higher in 2018 than in 2017. The main reason is because plants received an average amount of 67.6 mm more irrigation water over irrigation treatments and 43.7 mm more rainfall water in 2018 compared to 2017. More available water helped with establishment and improved emergence, resulting in higher yield. In addition, there were two seeding dates (May 5th and June 14th) in 2017 and irrigation started on June 9th after all the seeding was done. Therefore, for annul forages planted on May when the rainfall was less than 25 mm, they experienced water stress to some extent unavoidably before irrigation began. Yield decreased with increasing water stress, since moisture availability is a major determinant of forage production across species and environments (Neal et al., 2010; Afshar et al., 2012). In 2018, all the forages were seeded at the same date (May 1st) and irrigation was applied on May 15th, thus less probability of drought condition and greater yield.

Irrigation

Irrigation treatments were determined based on the water right in Oregon. The first person to obtain a water right on a stream is the last to be shut off in times of low streamflow (OWRD, 2018). Therefore, full-season irrigation (W1), late-season cutoff (W2), early-season cutoff (W3) and no irrigation (W4) were for very senior, senior, junior, very junior users, respectively.

Applying moderate water stress won't reduce crop production significantly since no significant yield difference was found between full irrigation (W1) and the late season cutoff (W2) irrigation treatments in our results regardless of functional groups or species. Similar conclusions were found by Yihun et al. (2013) who tested teff grain yield under different irrigation treatments and found no significant difference between a full irrigation and 25% deficit irrigation, regardless of seeding rates. In addition, Munjonji et al. (2017) reported that for triticale (*Triticosecale rimpaui* Wittm.), there was no significant difference of grain yield or biomass at different development stages between well-watered and moderately well-watered treatments. Similar results were also reported for non-forage species (Yuan et al., 2003). However, in another study conducted in a Mediterranean environment by Karrou and Oweis (2012), a significant average yield increase was found for wheat, faba bean, chickpea and lentil when comparing full supplemental irrigation with two-thirds full supplemental irrigation.

Functional Groups

AC4 had comparable yield to AC3 in 2018 while in 2017, AC4 produced significantly higher yield than AC3 in our study. This is probably because AC4 was seeded in mid-June in 2017 while it was planted in early May in 2018. Temperature in June was higher than May. Unlike AC3, AC4 possess a C4 photosynthesis system (Tracy et al., 2010; Brown, 1999). They have highest growth rate when planted during summer. When water was insufficient, AC4 was able to close stomata, reducing the water loss from the leaves and reduce photorespiration, leading to great water use efficiency (Tadele, 2016), thus yielding more when planted in early summer. Besides, both AC4 and AL had a sharp decrease in yield from W2 to W3 while AC3 decreased sharply from W3 to W4 in 2017 and 2018. This was because AC4 and AL matured late and needed a much longer irrigation season than the W3 application to produce an adequate yield. However, AC3's early-maturity enabled them to grow reasonably well even with a shorter irrigation season like W3. Therefore, AC3 production decreased greatly under W4 relative to W3 treatment.

Grasses

Within AC4, pearl millet produced 14.0 Mg/ha under both W1 and W2 across two years. A similar yield of 13.5 Mg/ha was obtained by harvesting pearl millet at the dough stage in a Brazilian semi-arid region (Dos Santos et al., 2016). DM yield of ~ 11.0 Mg/ha under optimal irrigation was also achieved in a warm temperate climate in Australia (Neal et al., 2010) and under rain-fed conditions in an arid-to-semiarid environment in Iran (Rostamza et al., 2011). The high production of pearl millet under optimal irrigation mainly attributes to its high growth rate which relates to its large leaf area index and high radiation-use efficiency (Vadez et al., 2012). Moreover, pearl millet is able to match its rooting to water availability, depending on the intensity of water scarcity (Squire et al., 1987), which could partially explain its high yield under W2. A greater biomass for sorghum-sudangrass than proso and foxtail millets under rain-fed conditions in

Montana has been reported, and attributed to significantly higher water use efficiency of sorghum-sudangrass (Lenssen and Cash, 2011). The deep-rooting potential and high proportion of roots in the subsoil may also contribute to the greater drought resistance of sorghum-sudangrass than other warm season grasses (Schittenhelm and Schroetter, 2014). Teff consistently had the lowest yield under all irrigation treatments in both years. It has shallow rooting system which could partly explain its much lower yield under drought compared to other warm season grasses. Plus, Mengistu (2009) pointed out that low yielding nature of teff might result from its low light use efficiency and this was probably due to its leaf size and orientation which reduce amount of photons intercepted for CO^2 fixation. Teff had extremely poor production, close to 0 under W3 and W4 in 2017 Teff receive little water from rainfall or irrigation for W3 and W4 treatments. Takele (1997) reported that early stress occurring after emergence could cause a 69~77% yield loss in teff. In addition, teff was harvested early, at the late heading stage. The shallow root, great yield loss due to early stress and early harvesting can explain the negligible production of teff under W3 and W4 in 2017.

Within AC3, oat's yield under W1 and W2 was similar to the 11.6 Mg/ha reported by Lithourgidis et al. (2006) in the Mediterranean region of Greece. Oat had two harvestings in both years and its high regrowth characteristic contributed to the consistently high yield. Barley, wheat produced comparable yield to oat when more serious water stress occurred (W3 and W4). Hasanuzzaman et al. (2019) pointed out that barley had the ability of enduring low tissue water content and they could decrease stomatal conductance to enable more efficient water conservation under drought. Plus, osmotic adjustment was another important mechanism that barley adopted when drought occurred (Hasanuzzaman et al., 2019; Blum 1989). Annual ryegrass was the lowest yielding AC3 group grass. When irrigation was applied, the yield of annual ryegrass was comparable to some of the grasses in AC3. However, its yield was significantly lower than the other four cool season grasses under W4. This was probably because annual ryegrass growth potential was limited greatly under no irrigation. In 2017, the W4 treatment had two harvestings while it had three under other treatments. Without the 3rd cut regrowth, it yielded significantly less than other cool season grasses. In 2018, annual ryegrass had only two cuts in all irrigation treatments but the 2nd cut regrowth under W4 was much less compared to other irrigation treatments. Therefore, irrigation is needed for annual ryegrass to have good yield.

Legumes

Within AL, soybean produced 7.8 Mg DM/ha under W1 and 7.9 Mg DM/ha under W2. These yields are comparable to those reported by Sheaffer et al. (2001). Soybean yields ranging from 8.7 to 10.1 Mg/ha DM were reported in the Central Great Plains with optimal irrigation when harvested at the full seed stage (Nielsen, 2011). The yield was greater in their study because they harvested soybean later than the soft dough stage we used for harvest timing. Soybean matured more slowly than most annual legumes. Thus, it had superior yield when longer irrigation season (W1 and W2) was applied. Cowpea showed consistently good production under severely limited soil moisture (W3, W4). In 2017, when other legumes performed poorly under drought due to late seeding, cowpea still achieved a reasonable yield. The greater drought tolerance of cowpea compared to other legumes was also reported by Foster et al. (2009) and Mia et al. (1996). Under water stress, cowpea, as a warm season legume, was capable of increasing root dry matter per leaf area and develop deep roots capable of extracting soil moisture from deep soil layers (Matsui and Singh, 2003). Furthermore, cowpea's ability to maintain leaf water status and photosynthesis under extended drought conditions has been suggested as the main mechanisms for overcoming water stress and recovering quickly after rehydration (Rivas et al., 2016). Crimson clover had comparable yield to other legumes under W1 but much lower yield than most legumes under drought condition (W2, W3 and W4) in both years. This indicated that crimson clover appeared to have lower drought resistance than the other annual legumes. Besides insufficient soil water, crimson clover is a cool season forage, thus planting it in mid-summer in 2017 when temperature was high, resulted in negligible production under W3 and W4.

Brassicas

Flea beetle (*Psylliodes chrysocephala*) was a big problem in both years. Pesticide was applied too late to control the flea beetle in 2017 so brassicas were greatly damaged by the pest. In addition, serious weed problems led to brassicas not surviving in 2017. Field visual observation in 2018 determined that rape and the brassica hybrid could resist flea beetle damage much better than the other three brassicas. The brassica hybrid used in this project is a cross between rape and Chinese cabbage. Therefore, rape's higher insect resistance contributed to the improved hybrid's resistance to flea beetle.

Shattering loss was unavoidable for all forages during harvesting. Another yield loss, especially for annual brassicas resulted from the turning over of brassica samples during the drying process. The high water content of brassicas required turning for drying. When the brassicas were turned over, however, there was unavoidable leaf loss.

Radish outcompeted the other four brassicas in yield under all irrigation treatments. Radish was the only species that bolted before harvesting while other brassicas were still at vegetative stage. The reproductive production of radish could partly explain its higher yield compared to other brassicas. In addition, radish matured fastest within AB. Its early-maturity enabled radish to escape late season drought and we had decent rainfall amount in May and June of 2018 after brassicas were seeded, which could explain its high production under W3 and W4 in 2018.

Phenological Development

One of the strategies plants use to resist drought is “drought escape”. This involves two mechanisms: rapid phenological development and developmental plasticity. “Drought escape” means that plants can modify their vegetative and reproductive growth based on water availability, thus completing their life cycle before drought begins (Basu et al., 2016).

Annual legumes probably use the mechanism of rapid phenological development with rapid plant growth (Desclaux and Roumet, 1996; Selvaraju, 1999). In this study, soybean reached the 50% flowering and 50% pod formation stages significantly earlier as water stress increased. A decreasing trend of DAS to reach 50% flowering and 50% pod formation was also observed in other annual legumes as water stress increased. Drought stress probably accelerates the switch from vegetative to reproductive development, thus fewer days are needed to reach 50% flowering (Desclaux and Roumet, 1996). Both Desclaux and Roumet (1996) and Sionit and Kramer (1977) reported that flowering duration was shortened for soybean when drought stress was applied during the flowering period due to earlier flower appearance and earlier cessation of flower progression. In this study, irrigation cut off for W3 was initiated on June 15^{th} and legumes usually began flowering in July, so water stress had begun prior to the flowering period for W4 and W3 treatments. Therefore, the fewer days to reach pod formation for soybean could be explained by both a shorter flowering period and fewer days in transition from vegetative to reproductive stage.

The fewer flowers and pods observed in legume plots with W4 and W3 probably resulted from a shortened flowering period and abortion of some flowers (Selvaraju, 1999).

Annual grasses probably use the mechanism of developmental plasticity to escape drought (Winkel et al., 1997). Based on the field observation, annual grasses showed little growth during the dry season with very few flowers, but following irrigation or a precipitation event, AC4 and AC3 headed out or flowered quickly. Therefore, annual grasses mostly escape drought by matching its phenology to rainfall distribution (Winkel et al., 1997; Fischer and Maurer, 1978). Other researchers also reported that flowering was delayed or totally inhibited under drought for AC4 (Winkel et al., 1997; Singh Brar et al., 2016). Phenology being delayed before flowering under water stress has also been reported in other plants, including rice (Wopereis et al., 1996).

Water Use Efficiency

In general, increased soil moisture stress caused higher WUE (Jacobs et al., 2004; Rostamza et al., 2011). Several reasons attribute to the higher WUE under drought. First, water loss through evaporation decreased (Geerts et al., 2009). Second, Water loss through transpiration was reduced because of enhanced guard cell signal transduction network (Schroeder et al., 2001). Third, the ration of photosynthesis to transpiration was improved (Cui et al., 2009). Annual legumes usually had lower WUE compared to annual grasses and annual brassicas, which was confirmed by Neal et al. (2011). Pearl millet had 19.6 and 23.9 Kg ha^{-1} mm^{-1} of WUE under W1 and W2, respectively. Similar WUE was reported by Neal et al. (2011) after applying optimal irrigation to pearl millet in a clay loam in Australia. Radish showed the greatest WUE under W3 with a value of 27.6 Kg ha^{-1} mm^{-1} which was higher than what Neal et al. (2011) found under drought. The much higher WUE of sorghum-sudangrass over other annual warm season grasses and similar WUE among millets without irrigation were also confirmed by Lessen and Cash (2011) while the values in our study were much greater.

WUE in this study was calculated based on assumptions with a few limitations. We assumed all species had the same root length and W2, W3, and W4 plots consumed the same amount of soil water; at FC before seeding and at PWP when all irrigation was terminated. The root depth of different species and soil water content change at each plot should be measured to obtain more accurate values of WUE. However, Neal et al. (2011) suggested that yield difference among annual forage species, instead of ET, was the main determinant of WUE. Therefore, WUE data in this work could still provide producers a general idea of how efficiently different annual forages used water under variable irrigation regimes.

Quality

The percentage of CP increased as a result of increasing water stress, which is in agreement with Rostamza et al. (2011) and Mustafa Tahir et al. (2014). Increased CP content could be due to a higher N level and availability in the dry soil (Buxton et al., 1996) and dilution effect of higher crop yield under W1 compared to other irrigation treatments. ADF% and NDF% had a reverse trend relative to CP%. Their percentages both decreased as water stress increased, which was in contrast to Montgomery (2009) who reported that ADF was 20.7% for corn hybrids subjected to well water treatment (100ET) and was 24.3% under drought stress (50ET) while NDF was 36.8% irrigated at 100ET and was 42.3% under 50ET.

AL group outcompeted AC4 and AC3 groups in forage quality because of its higher CP%, lower NDF% and ADF%. Annual ryegrass had the greatest CP content within AC3 group. The potential of annual ryegrass to produce high quality forage with high CP content and low ADF and NDF level was also reported by Kallenbach et al. (2003). Teff was the best quality species within AC4, which was indicated by the highest CP and lowest ADF and NDF level in our study. However, the value of CP% was much lower than what Saylor (2017) reported for greenhouse-grown teff. Different harvesting times may have caused this big CP% difference. Teff was harvested at anthesis in our research while Saylor (2017) harvested it before seed head development. CP decreased with advanced maturity (Contreras-Govea, and Albrecht, 2006). Therefore, CP% in our result was much lower. Chickling vetch had the highest average CP content, 20.8%, among AL species, which was close to what Karadag and Buyukburc (2004) reported.

The NRC (2001) suggested that forages with a CP content of 15% or more maintain high-producing dairy cows on grazed pastures. Based on our findings, CP% was 20.8% for chickling vetch, 16.3% for field pea, 16.1% for crimson clover, 15.8% for soybean and 17.2% for cowpea. Thus, all five annual legumes could satisfy the CP requirement of high-producing dairy cows.

We selected five species for each annual forage functional group in our current study based on species popularity, adaptation, maturity, between species differences, and yield potential. The results we found here will be different if we have different species selection. However, the general trend between function groups and major species should be applicable to a broader species. The ranking of each species could be different with different locations within the intermountain region due to specific site characteristics. We have limited available cultivars within each species with current annual forage breeding program. There are differences in performance if an annual forage species contains several cultivars, especially different cultivars with different maturity timing. Broader species screening and evaluation with different cultivars will be next step to continue our current study. By doing so, the livestock and forage producers can have the information to fine-tune their species selection for their annual forage production systems.

Conclusions

Moisture supply is a major determinant of annual forage response. DM yield decreased while both WUE and forage quality (CP, ADF and NDF) were improved with increasing water stress. Full season irrigation (W1) and late season cutoff (W2) produced no significant difference in forage yield. Thus, when irrigation water is limited, W2, rather than W1, could be applied to allow reasonably good production and good quality.

Functional groups differed in response to partial season irrigation deficit. Annual warm season grass (AC4) produced higher yields than other groups under W1 and W2. Annual legume (AL) group had the lowest production consistently over two years but it produced forage with better quality than AC4 or annual cool season grass (AC3) group. Species performance under partial season irrigation deficit is species-specific within each group or when twenty species were compared together. Thus, there was no single "super" species and matching annual forage species with water availability would be more applicable and achievable.

All in all, we can use functional groups to narrow down the species selection for each production scenario and further determine specific species for the best match under different water levels. Besides, forage that had the greatest yield generally didn't have the best quality. Producers should consider which factor is more important and make a compromise between yield and quality during annual forage selection. And more collaboration with breeders could be done in the future to improve quality characteristic for these high yielding annual forage species under drought.

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Annual Forages Differ in Response to Partial-Season Irrigation Deficits in a Summer Seeded Cropping System

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Abstract

Water scarcity during summer is severe in the Pacific Northwest, United States, threatening forage production in this area. With their flexibility of seeding date annual forages have potential as a late-season cover crop and provide supplemental forage to extend grazing season in the late fall and early winter. This study was conducted to evaluate annual forage species for their suitability as cover crops following winter triticale (*X. Triticosecale*) under different irrigation regimes in a Mediterranean climate. Phenological development, yield, water use efficiency (WUE) and quality of twenty annual forage species were evaluated in four irrigation treatments: full-season irrigation (W1), late-season cutoff (W2), early-season cutoff (W3), and no irrigation (W4), over two years at Union, OR, on a La Grande silt loam. Results showed that yield decreased while forage quality increased (lower ADF% and NDF%) when water stress occurred. Summer seeding annual forage after winter triticale with inadequate irrigation (W3 and W4) is not recommended in a Mediterranean climate and W2 is preferred to produce a reasonable yield and better quality than W1 when water was limited. Annual warm season grass (AC4) had the greatest average yield in both 2017 (3.7 Mg/ha) and 2018 (6.1 Mg/ha) while annual legume (AL) had the best forage quality (14.5% CP; 35.0% ADF; 42.6% NDF) irrespective of irrigation treatments. Oat (*Avena sativa* L.) had the highest production (6.7, 5.2 and 1.8 for W1, W2 and W3, respectively) under irrigation while annual ryegrass [*Lolium multiflorum* L.] had the greatest CP% (16.2%) within AC3. Within AL, no difference existed among species across irrigation and years but chickling vetch [*Lathyrus sativus* L.] had the greatest CP% (19.7%). Radish (*Raphanus sativus* L. var.*longipinnatus*) (5.9 Mg/ha) outyielded other brassicas irrespective of irrigation treatments. Sorghum-sudangrass [*Sorghum bicolor* (L.) Moench] had the highest production across irrigation treatments in both 2017 (6.0 Mg/ha) and 2018 (10.2 Mg/ha) while teff (*Eragrostis Tef*) had the greatest CP% (10.5%) within AC4. In conclusion, there is no single super species that suited well under variable water situation but sorghum-sudangrass is closest to the best species among twenty species considering its yield performance under all irrigation regimes and as long as protein supplement is provided, summer seeded annuals after winter triticale could be viable option to produce forage and provide late season grazing in PNW.

Introduction

Grazing resources and hay production provide the foundation for livestock production in the Pacific Northwest (PNW), which is the leading commodity in the region. Cattle and calves are the first, second, and fifth most important agricultural product in Oregon, Idaho, and Washington, respectively. The 2012 Agricultural Census showed the livestock commodity was valued at $8.94 billion, 18.09 billion, and 9.95 billion for these three states, respectively (USDA, 2018).

In the PNW, with a Mediterranean-type climate, nearly two-thirds of the annual precipitation occurs between October and March and precipitation from May to September is scarce (USFWS, 2011). Mountain snowpack serves as a natural reservoir to provide water when rainfall is insufficient during summer (Vano et al., 2015). However, changes in climate patterns have resulted in earlier snow melt and faster snow melting speed thus less water supply in summer (Snover et al., 2003). Moreover, spring peak flow comes earlier and this extends the time between snowmelt and fall rain, further prolonging dry seasons before fall rain begins (Snover et al., 2003). Therefore, the need for dry season irrigation to maintain forage production is increased greatly. However, other water-demanding sectors, including water transfer from agriculture to cities and water use priority on other more lucrative crops, present great competition for water, increasing the challenge for providing adequate irrigation water for forage production in the region (Orloff et al., 2016).

Water right in Oregon follows the principle of first come, first served. The first person to obtain a water right on a stream is the last to be shut off in times of low streamflow (OWRD, 2018). This means when water is insufficient to irrigation all crop lands, irrigation will be shut off earlier for junior users while senior users can keep irrigating without regard for the needs of other users.

Annuals have shown potential for producing forage under drought conditions. Unlike perennials, annual forages have a short growing season. This provides flexibility for seeding date and crop rotation. Although they have a shorter growing season, annual forages can yield more annually than perennials (Neal et al., 2007). In addition, their seasonal production profiles can provide advantages over perennial forages, with increased production in summer (Neal et al., 2007), fall, and winter (Stockdale, 1983). Thus, annual forages provide flexibility to shift production to periods of feed shortages, especially summer and autumn, extending the grazing season beyond the normal grazing season. Combined, these attributes can reduce annual feed costs (Chapman et al., 2008a, 2008b). Furthermore, annual forages can serve well as cover crops in a short-season environment (Sanderson et al., 2018). Cover crops bring multiple benefits, including increasing diversification in the cropping system, providing supplemental forage (Thiessen Martens and Entz, 2011), effectively suppressing weeds (Lawley et al., 2011; Fisk et al., 2001), and improving soil quality like enhancing N conservation and aggregate stability (Steele et al., 2012; Liebig et al., 2015).

Annual forages have shown great potential as cover crops in a short-season environment, especially when irrigation water is insufficient. However, very few studies have evaluated the effect of different irrigation cutoff seasons on the summer seeded cropping system with annual forage as cover crops in the PNW from both the species level and functional group level. The objective of this project was to quantify and compare the response of a range of summer-seeded annual forage species after winter triticale (*X. triticosecale*) over a two-year period, under different irrigation cutoff seasons. Three hypotheses were tested. First, that functional groups differ in response to variable irrigation cutoff seasons. Second, that within each functional group, annual forages differ in response to variable irrigation cutoff seasons. Third, ranking of twenty annual forage species is different under variable irrigation cutoff seasons.

Materials and Methods

Study Site

This study was conducted during 2017 and 2018 at the Eastern Oregon Agricultural Research Center located in Union, Oregon (45°12’N, 117°52’W). The soil type at this site is a La Grande silt loam (fine-silty, mixed, superactive, mesic Pachic Haploxerolls).

The location has a Mediterranean type climate with dry, warm summers and cool, wet winters. Precipitation and temperature patterns were typical of those throughout the PNW (Fig. 2.1). The total rainfall during the irrigation treatment period in 2017 and 2018 was 27.9 and 71.6 mm, respectively. During growing season, the precipitation in July and August in 2017 was 0.3 and 2.5 mm, respectively, while the precipitation in July, August and September of 2018 was 0.5, 1.8 and 2.8 mm, respectively. These values are much lower than the average precipitation in the past 30 years.

The average maximum and minimum temperature during the 2017 growing season was 25.0 and 7.9 °C in June, 32.8 and 9.9 °C in July, 32.2 and 9.0 °C in August, and 25.9 and 6.1 °C in September. In 2018, maximum and minimum temperatures were 21.7 and 6.7 °C in May, 23.7 and 6.8 °C in June, 32.0 and 9.1 °C in July, 30.4 and 8.8 °C in August, and 24.2 and 2.8 °C in September. The 30-year average temperature showed a similar seasonal pattern. The first killing frost (0 °C) at the site occurs no later than September 20th at the 50% probability level (NOAA, 2019).

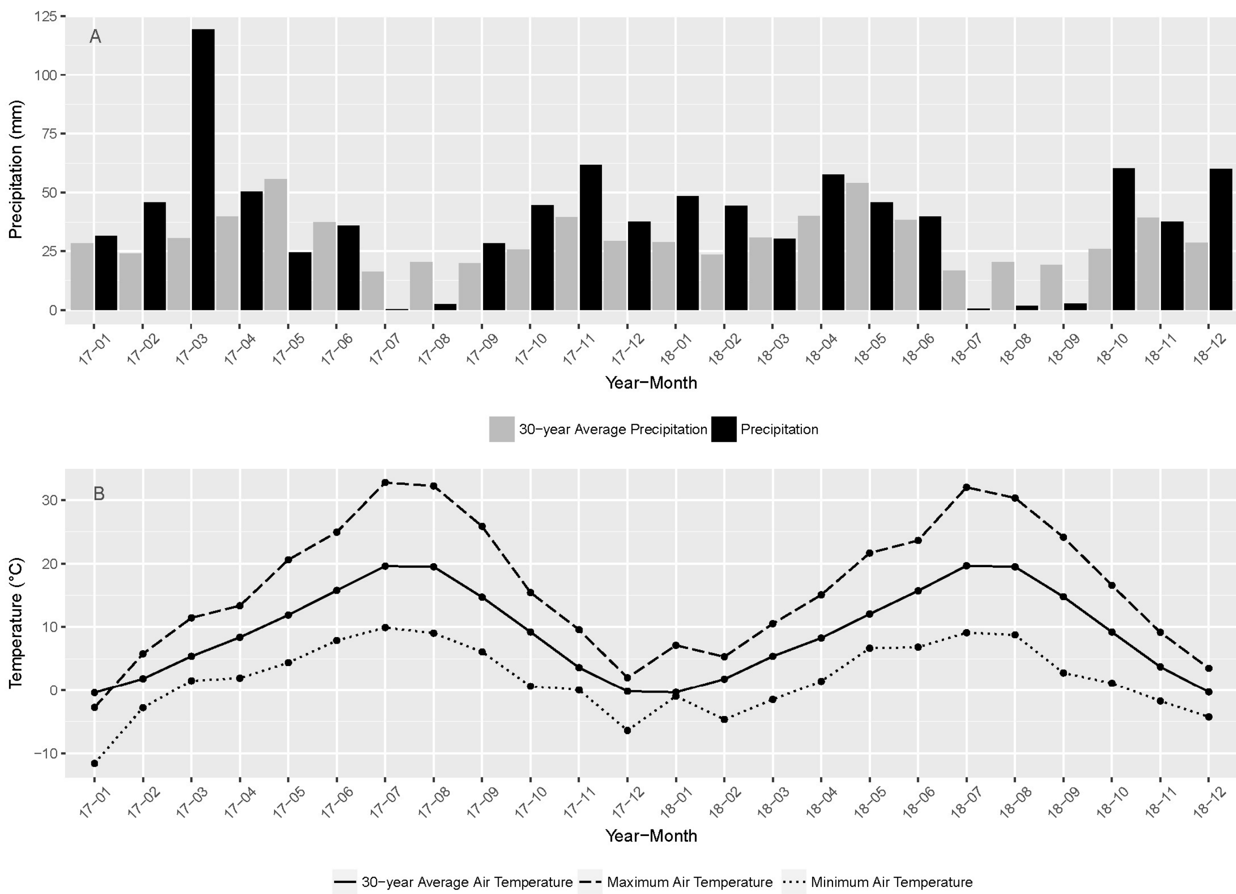

Fig. 3.1. Monthly precipitation (A) and mean monthly air temperature (B) for Union, OR, during 2017 and 2018 and the past 30 years.

Experiment Design

A randomized complete block split-plot design with four replications was used for this study. Main plots were four irrigation treatments: full season irrigation (W1), late season irrigation cutoff (W2), early season irrigation cutoff (W3), and no irrigation (W4). Subplots contained twenty annual forage species representing four functional groups: annual cool season grasses (AC3), annual warm season grasses (AC4), annual legumes (AL), and annual brassicas (AB) (Table 2.1). Each subplot was 114 cm by 457 cm and contained 7 rows spaced 19 cm apart. All species were drill-seeded at an appropriate seeding rate (Table 3.1) using a small plot seeder (Kincaid Equip. Manufacturing, Haven, KS).

Table 3.1. Common name, scientific name, cultivar, and seeding rate for annual forage species evaluated in a summer seeded cropping system for yield, phenology, water use efficiency and quality under different irrigation cutoff seasons in Union, OR.

Common name	Scientific name	Cultivar	Seeding rate
			kg/ha
Annual cool season grass			
Wheat	Triticum aestivum L.	Louise	135
Barley	Hordeum vulgare L.	Haybet	112
Triticale	Triticosecale rimpaui Wittm.	1010	135
Oat	Avena sativa L.	Monida	135
Annual ryegrass	Lolium multiflorum L	Tetraploid	45
Annual warm season grass			
Proso millet	Panicum miliaceum L.	White	34
Foxtail millet	Setaria italica L.	Golden German	22
Teff	Eragrostis tef (Zuccagni) Trotter	Tiffany	11
Pearl millet	Pennisetum glaucum (L.) R. Br.	MS2500	22
Sorghum-sudangrass	Sorghum bicolor (L.) Moench	CC BMR	45
Annual legume			
Crimson clover	Trifolium incarnatum L.	Dixie	34
Field pea	Pisum sativum L.	Journey	168
Chickling vetch	Lathyrus sativus L.	AC Greenfix	112
Cowpea	Vigna unguiculata (L.) Walp.	Iron&Clay	67
Soybean	Glycine max (L.) Merr	Bobwhite Trailing	112
Annual brassica			
Turnip	Brassica rapa L. var. rapa	Purple Top	8
Radish	Raphanus sativus L. var. longipinnatus	Ripper	13
Rape	Brassica napus L. var. oleifera	Dwarf Essex	7
Kale	Brassica oleracea var. acephala L.	Hunter	9
Brassica hybrid	B. campestris sensulato L. * Brassica napus L. var. oleifera	Winfred	9

A solid set irrigation system was used to irrigate weekly. Irrigation began on June 9th in 2017 and on May 15th in 2018 (Table 3.2). Sufficient water was applied at each irrigation to fully satisfy potential crop evapotranspiration. Potential crop evapotranspiration was determined based on alfalfa (*Medicago sativa* L.) evapotranspiration, and monitored using an on-site Imbler AgriMet Weather Station, which was 37.0 kilometers away from Union (https://www.usbr.gov/pn/agrimet/agrimetmap/imboda. html).

Field Management

Soil sampling to a depth of 30.5 cm was conducted on 15 April and 12 April in 2017 and 2018, respectively. In 2017, the soil had a pH of 6.6, 4.55% organic matter, 85 kg/ha N, 286.75 ppm K, and 39.5 ppm P. Since P and K levels were sufficient from 2016 fall fertilization, only urea was applied, at a rate of 146 kg/ha N, to grass and brassica plots before seeding. In 2018, the soil analysis indicated a pH of 7.375, 4.375% organic matter, 178 kg/ha N, 431.75 ppm K and 40 ppm P. Due to sufficient levels of nutrients, no fertilizer was applied before seeding.

The seeding date for twenty annual forages was shown in Table 3.3. Before seeding, 7.0 L/ha MAKAZE® Glyphosate (Loveland Products) was applied to all plots. After seeding, 1.2 L/ha of CLEAN AMINE® 2,4-D (Loveland Products) was applied to annual cool season grasses and annual warm season grasses to control broadleaf weeds while 365.0 mL/ha Raptor® {2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1h-imidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid; BASF Corporation}was applied to annual legumes to control broadleaf and grass weeds. For annual brassicas, 292.0 mL/ha of Mustang® Maxx [3-phenoxyphenylmethyl (+) cis/trans 3-(2,2-dichloro-ethenyl)-2,2 dimethylcyclopropane carboxylate; FMC Corporation] was applied twice to control flea beetles. Plots were also hand-weeded as needed.

All the necessary field management followed the best management practices (BMPs) whenever we can.

In 2017, all species were seeded on July 6th after harvesting winter triticale on June 26th (Table 3.3). Annuals under W3 and W4 irrigation treatments didn't emerge. In 2018, all species were seeded on June 12th after harvesting winter triticale on May 29th. Annual forages were harvested using a John Deer harvester at the appropriate harvesting stage for each species.

Table 3.2. The starting date, ending date, irrigation events, irrigation amount and rainfall amount of each irrigation treatments in a summer seeded cropping system in Union, OR in 2017 and 2018.

Irrigation treatments	2017					2018				
	Starting date	Ending date	Irrigation events	Irrigation amount	Rainfall amount	Starting date	Ending date	Irrigation events	Irrigation amount	Rainfall amount
				——mm——					——mm——	
Full-season Irrigation	June 9th	Sep. 15th	14	643.2		May 15th	Sep. 7th	18	694.4	
Late-season cutoff	June 9th	Aug. 3rd	8	380.4	27.9	May 15th	Aug. 1st	13	385.6	71.6
Early-season cutoff	June 9th	June 15th	3	115.8		May 15th	June 15th	6	127.0	
No irrigation	\	\	0	0		\	\	0	0	

Table 3.3. Seeding date, 1st cut harvesting date, harvesting stage and multiple cuts of twenty annual forage species, and harvesting data and stage of winter triticale in a summer seeded cropping system in Union, OR in 2017 and 2018.

Species	2017						2018					
	Winter triticale harvesting		Seeding date	1st cut harvesting date	Harvesting stage	Multiple cuts	Winter triticale harvesting		Seeding date	1st cut harvesting date	Harvesting stage	Multiple cuts
	date	stage					date	stage				
Wheat					Soft-dough	\				Aug. 14th	Soft-dough	\
Barley					Soft-dough	\				Aug. 14th	Soft-dough	\
Triticale					Soft-dough	\				Aug. 14th	Soft-dough	\
Oat					Soft-dough	\				Aug. 14th	Milking	2
Annual ryegrass					Vegetative	\				Aug. 14th	Anthesis	2
Proso millet					Hard-dough	\				Aug. 22nd	Milking	\
Foxtail millet					Milking	\				Sep. 18th	Milking	\
Teff				Sep. 25th‡	Milking	\				Aug. 22nd	Anthesis	\
Pearl millet					Vegetative	\				Sep. 18th	Anthesis	\
Sorghum-sudangrass	June 26th	Soft-dough	July 6th†		Vegetative	\	May 29th	Soft-dough	June 12th§	Sep. 18th	Anthesis	\
Crimson clover					Vegetative	\				Aug. 30th	Pod formation	\
Field pea					Pod formation	\				Aug. 13th	Pod formation	\
Chickling vetch					Pod formation	\				Sep. 17th	Pod formation	2
Cowpea					Vegetative	\				Sep. 17th	Vegetative	\
Soybean					Pod formation	\				Aug. 23rd	Pod formation	\
Turnip				\	\	\				Sep. 17th	\	\
Radish				\	\	\				Aug. 21st	\	\
Rape				\	\	\				Sep. 17th	\	\
Kale				\	\	\				Sep. 17th	\	\
Brassica hybrid				\	\	\				Sep. 17th	\	\

† July 6st was the seeding date for all annual forages in 2017
‡ Sep. 25th was harvesting date for all annual forages except brassicas in 2017
§ June 12th was the seeding date for all annual forages in 2018
Note: all the annual brassicas didn't survive in 2017

Measurements

DM

A 76-cm wide strip containing 5 rows in the center of each plot was harvested and weighed using a John Deer harvester and an Ohaus balance (Ohaus Corporation. USA), respectively. Stubble height was 5.1 cm. Dry matter (DM) yield of each plot was measured from a ~1.0 kg grab sample which was dried in the oven at 60°C for 120 h for brassicas and for 72 h for other annual forages, using a laboratory balance (Ohaus Corporation. PineBrook, NJ, USA). In addition to measuring harvest length and forage height, weed components were visually estimated by the same observer before every harvesting. Regrowth potential of each plot was evaluated visually as well at the end of growing season in both years.

Phenology

Phenological development was monitored every three days for annual grasses and annual legumes in 2018. Each plot was separated into four sections. For each section, the phenological data were recorded on days to 50% heading and days to 50% flowering for annual grasses while it was days to 50% flowering and days to 50% pod formation for annual legumes. The average of the dates of the four sections was used to assess species' phenology stage in each plot.

Water Use Efficiency

The water use efficiency (WUE) was defined as the ratio of annual forage DM yield (Kg/ha) to evapotranspiration (ET) (mm). ET was determined for each subplot from seeding to the time when all the irrigation treatments were terminated. The following equation was used to calculate ET (Garrity et al., 1982):

$$\mathrm{ET} = \Delta S + P + I - D - R \quad [1]$$

Where ΔS is soil water content change (mm), P is precipitation (mm), I is irrigation amount (mm), D is drainage and R is runoff. D and R were negligible since the slope of all plots was close to zero and plots were only irrigated to field capacity (FC) every time. Then ET calculation equation was:

$$\mathrm{ET} = \Delta S + P + I \quad [2]$$

It was assumed all plots soil profile was at FC before irrigation treatments were conducted. Soil water content was assumed at the FC for W1 treatment plots and at permanent wilting point (PWP) for W2, W3, and W4 treatment plots after all irrigation treatments were shut off. Estimated soil water for loamy soil was 96.52 mm (3.8 inches) every 304.8 mm (1 foot) of soil for FC while 45.72 mm (1.8 inches) every 304.8 mm (1 foot) of soil for PWP (PASSEL, 2019). Therefore, ΔS was 50.8 mm (2 inches) every 304.8 mm (1 foot) of soil for W2, W3, and W4. We assumed the average rooting depth was 914.4 mm (3 feet) so ΔS was 152.4 mm (6 inches) for W2, W3 and W4. ΔS was 0 for W1.

Quality

Dry samples were ground into coarse powder first with a Wiley Mill (Arthur H. Thomas Co. Philadelphia, USA). Then they were ground again into fine powder through Cyclone Sample Mill (UDY Corporation. Fort Collins, Colorado, USA). Near-infrared spectroscopy (NIR) was used to analyze crude protein (CP), acid detergent fiber (ADF), and neutral detergent fiber (NDF) of the first cut of annual legumes and annual grasses under W1 and W2 treatments in 2018. Reference methods used for NIR calibrations were as follows: CP using the Kjeldahl method; ADF and NDF by the method of Van Soest (1967).

Statistical Analysis

Forage DM yield, quality, WUE and phenology data were the response parameters. Original data were organized and summarized using Excel. ANOVA analysis was conducted using the PROC GLM procedure of the SAS ® University Edition statistical software package (SAS Institute, 2008) with year, block and block × irrigation assigned as random effects. Multiple comparisons were evaluated using Tukey's HSD test. For unequal sample sizes, Tukey-Kramer Method was used. Statistical significance of results was assessed at the 5% probability level unless otherwise indicated. All the line plots and bar plots were developed in R 3.5.0 using the package ggplot (RStudio, Inc., 2018).

Results

Yield

Winter triticale yield was not affected by irrigation treatment ($p = 0.84$), with average yields of 10.3, 10.0, 9.5, and 9.8 Mg/ha under W1, W2, W3, and W4 across two years. However, year effect was significant ($p < 0.001$) and winter triticale produced 4.2 Mg/ha more DM in 2017 compared to 2018.

The significance of main and interaction effects on summer seeded annual forage yield at the group level is shown in Table 3.4. Average yield of annual forage over four irrigation treatments and all the species was 2.8 Mg/ha in 2017 and 3.8 Mg/ha in 2018.

Table 3.4. Group level analysis of variance of year, irrigation, group, and their interactions for yield of annual forages in a summer seeded cropping system.

Source	DF	Type III SS	Mean Square	F value	Significance
Year	1	575.4	575.4	121.3	**
Irrigation	3	1479.3	493.1	103.9	**
Group	3	230.0	76.7	16.2	**
Irrigation × Group	9	308.6	34.3	7.2	**
Irrigation × Year	1	0.2	0.2	0.03	NS
Year × Group	2	294.9	147.4	31.1	**
Irrigation × Group × Year	2	42.7	21.3	4.5	*

* and ** indicate significance at the 0.05 and 0.01 probability levels, respectively; NS, not significant at the 0.05 level.

Summer seeded annual forage species right after winter triticale did not germinate under W3 and W4 treatments in 2017 and yielded low (1.6 Mg/ha for W3 and 0.6 Mg/ha for W4 averaged over species) in 2018 (Fig. 3.2). No significant differences were found between W3 and W4 and between any functional groups under W4 in 2018 (Fig. 3.2B).

The interaction between irrigation and group was insignificant ($p = 0.54$) while both group ($p = 0.0009$) and irrigation ($p = 0.02$) had significant effect on yield in 2017.The average yield under W1, 3.2 Mg/ha, was greater than that under W2, 2.4 Mg/ha (Fig 3.2A). Annual warm season grasses (AC4) produced the greatest average yield, 3.7Mg/ha, among groups, more than 2.5 Mg/ha for annual cool season grasses (AC3) and 2.2 Mg/ha for annual legumes (AL). No difference existed between AC3 and AL.

There was a significant interaction ($p < 0.0001$) between irrigation and group in 2018. A sharp yield loss was observed from W2 to W3 in all four groups in 2018, with decreases of 5.9

Mg/ha for AC4, 1.8 Mg/ha for AC3, 3.8 Mg/ha for AL, and 4.0 Mg/ha for annual brassicas (AB) (Fig 3.2B). No differences in yield were found between W1 and W2 for any functional group in 2018. AC4 yielded the greatest with 10.7 Mg/ha under W1 and 8.3 Mg/ha under W2 while AC3 yielded the least with 3.2 Mg/ha under W1 and 2.5 Mg/ha under W2. AL and AB produced 4.9 and 5.9 Mg/ha, respectively, under W1, and 5.8 and 5.6 Mg/ha, respectively, under W2. No significant difference was observed between AL and AB under both W1 and W2 treatments.

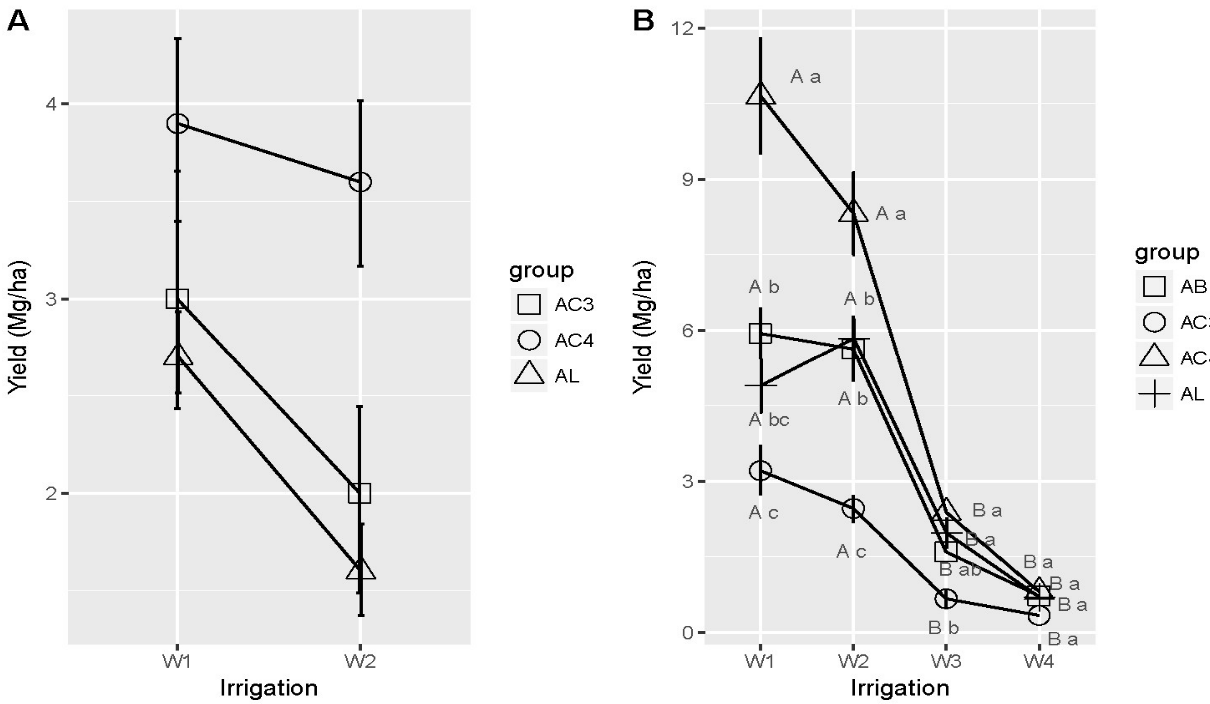

Fig. 3.2. Yields of annual forage functional groups grown in a summer seeded cropping system in 2017 (A) and in 2018 (B) in Union, OR.
Note: Means followed by the same capital letters are not significantly different at the 0.05 confidence level within each functional group while means followed by the same lowercase letters are not significantly different at the 0.05 confidence level within each irrigation treatment. W1, full season irrigation; W2, late-season cutoff; W3, early-season cutoff; W4, no irrigation; AB, AC3, AC4 and AL indicate annual brassicas, annual cool season grasses, annual warm season grasses, and annual legumes, respectively. Error bars represent the standard error.

Within AC4, the species level variance analysis is shown in Table 3.5. Only species effect was significant ($p < 0.0001$) in 2017 while significant interaction ($p = 0.034$) between species and irrigation existed in 2018. Sorghum-sudangrass produced 6.0 Mg/ha in 2017, which was greater than others except foxtail millet (4.8 Mg/ha) (Fig. 3.3A). In 2018, sorghum-sudangrass had 16.5, 11.9, 7.4 and 2.3 Mg/ha under W1, W2, W3 and W4, respectively (Fig. 3.3B). Its yield was greater than teff under W1, similar to foxtail millet but greater than others under W2, the greatest under W3 and greater than both teff and proso millet under W4. The yield of Teff (1.4 Mg/ha) was lower than others except pearl millet in 2017. In 2018, teff yielded 5.7, 3.8, 0.5 and 0 Mg/ha for W1, W2, W3 and W4, respectively, which was less than sorghum-sudangrass under W1, W3 and W4 and the least under W2.

Table 3.5. Species level analysis of variance of year, irrigation, species, and their interactions for annual forage yield within the annual warm season grass group in a summer seeded cropping system.

Source	DF	Type III SS	Mean Square	F value	Significance
Year	1	662.9	662.9	164.6	**
Irrigation	3	960.8	320.3	79.5	**
Species	4	299.5	74.9	18.6	**
Irrigation × Species	11	107.7	9.8	2.4	*
Irrigation × Year	1	21.2	21.2	5.3	*
Year × Species	4	82.7	20.7	5.1	**
Irrigation × Species × Year	4	28.1	7.0	1.7	NS

* and ** indicate significance at the 0.05 and 0.01 probability levels, respectively; NS, not significant at the 0.05 level.

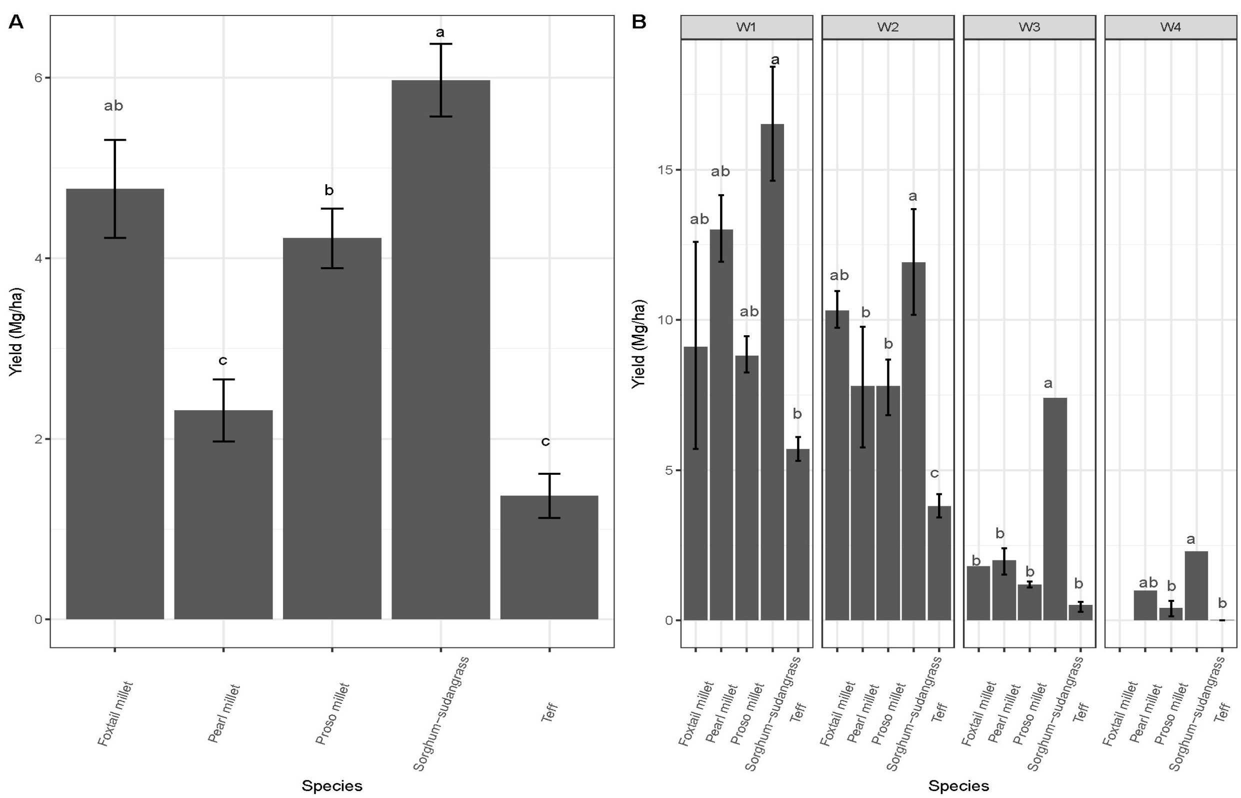

Fig. 3.3. The yield of annual forage species within the annual warm season grass group under variable irrigation treatments in a summer seeded cropping system in (A) 2017 and (B) 2018 in Union, OR.
Note: Means followed by the same letters are not significantly different at the 0.05 confidence level within each irrigation treatment. W1, full season irrigation; W2, late-season cutoff; W3, early-season cutoff; W4, no irrigation; Error bars represent the standard error.

Within AC3, the species level variance analysis is shown in Table 3.6. Year effect was not significant (p = 0.066). Oat outyielded other cool season grasses with an average yield of 6.7, 5.2, and 1.8 Mg/ha under W1, W2, and W3, respectively, across two years while in the W4 treatment, there was no difference among forage species (Fig. 3.4).

Table 3.6. Species level analysis of variance of year, irrigation, species, and their interactions for annual forage yield within the annual cool season grass group in a summer seeded cropping system.

Source	DF	Type III SS	Mean Square	F value	Significance
Year	1	2.2	2.2	3.5	NS
Irrigation	3	113.3	37.8	60.6	**
Species	4	139.6	34.9	56.0	**
Irrigation × Species	12	20.7	1.7	2.8	**
Irrigation × Year	1	0.5	0.5	0.8	NS
Year × Species	4	30.0	7.5	12.0	**
Irrigation × Species × Year	4	0.8	0.2	0.3	NS

** indicate significance at the 0.01 probability level; NS, not significant at the 0.05 level.

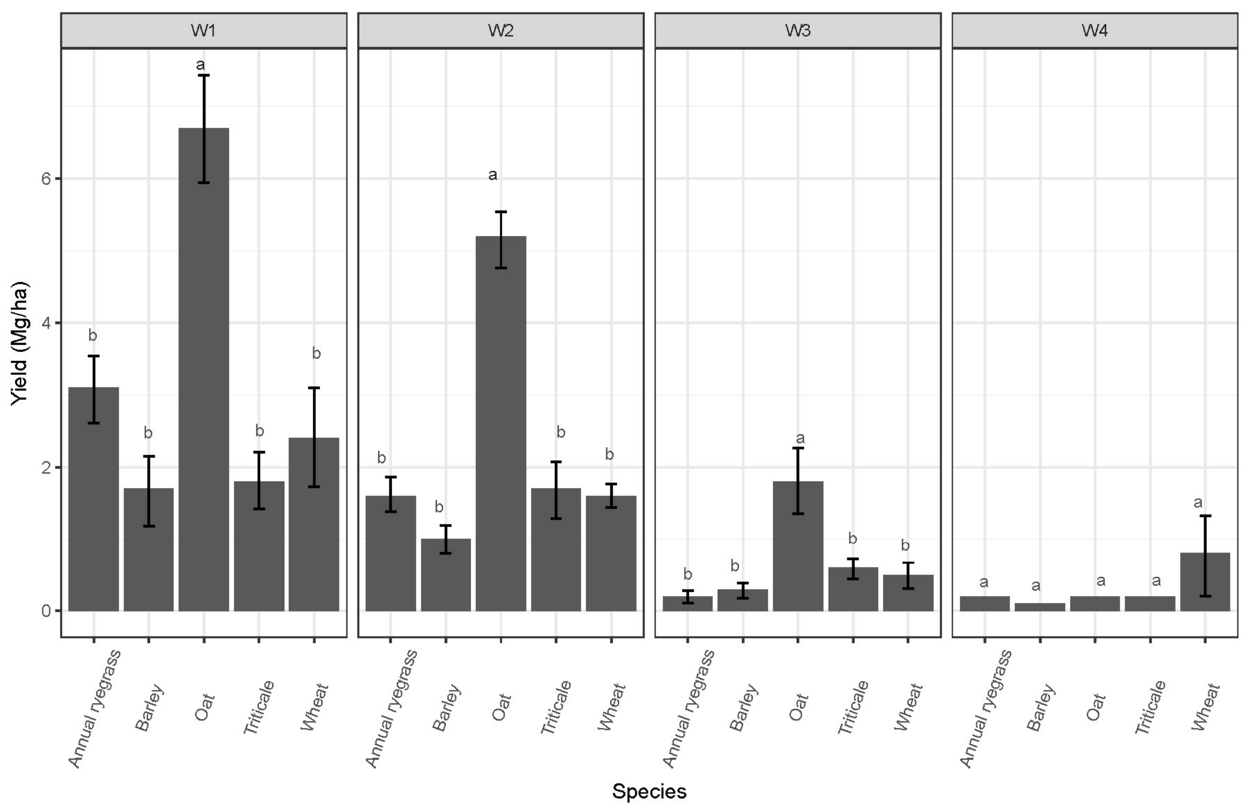

Fig. 3.4. The average yield of annual forage species within the annual cool season grass group under variable irrigation treatments in a summer seeded cropping system across 2017 and 2018 in Union, OR.

Note: Means followed by the same letters are not significantly different at the 0.05 confidence level within each irrigation treatment. W1, full season irrigation; W2, late-season cutoff; W3, early-season cutoff; W4, no irrigation; Error bars represent the standard error.

Within AL, the species level variance analysis is shown in Table 3.7. There was no significant interaction between irrigation and species in both years. Species had significant effect ($p < 0.0001$) on yield in 2017 with yield ranging from 3.3 Mg/ha for chickling vetch to 1.1 Mg/ha for crimson clover (Fig 3.5A). The yield of different annual legume species was similar to each other in 2018 (Fig 3.5B).

Table 3.7. Species level analysis of variance of year, irrigation, species, and their interactions for annual forage yield within the annual legume group in a summer seeded cropping system.

Source	DF	Type III SS	Mean Square	F value	Significance
Year	1	205.2	205.2	122.5	**
Irrigation	3	329.9	110.0	65.7	**
Species	4	21.3	5.3	3.2	*
Irrigation × Species	12	29.7	2.5	1.5	NS
Irrigation × Year	1	21.1	21.1	12.6	**
Year × Species	4	35.9	9.0	5.4	**
Irrigation × Species × Year	4	5.0	1.3	0.8	NS

* and ** indicate significance at the 0.05 and 0.01 probability levels, respectively; NS, not significant at the 0.05 level.

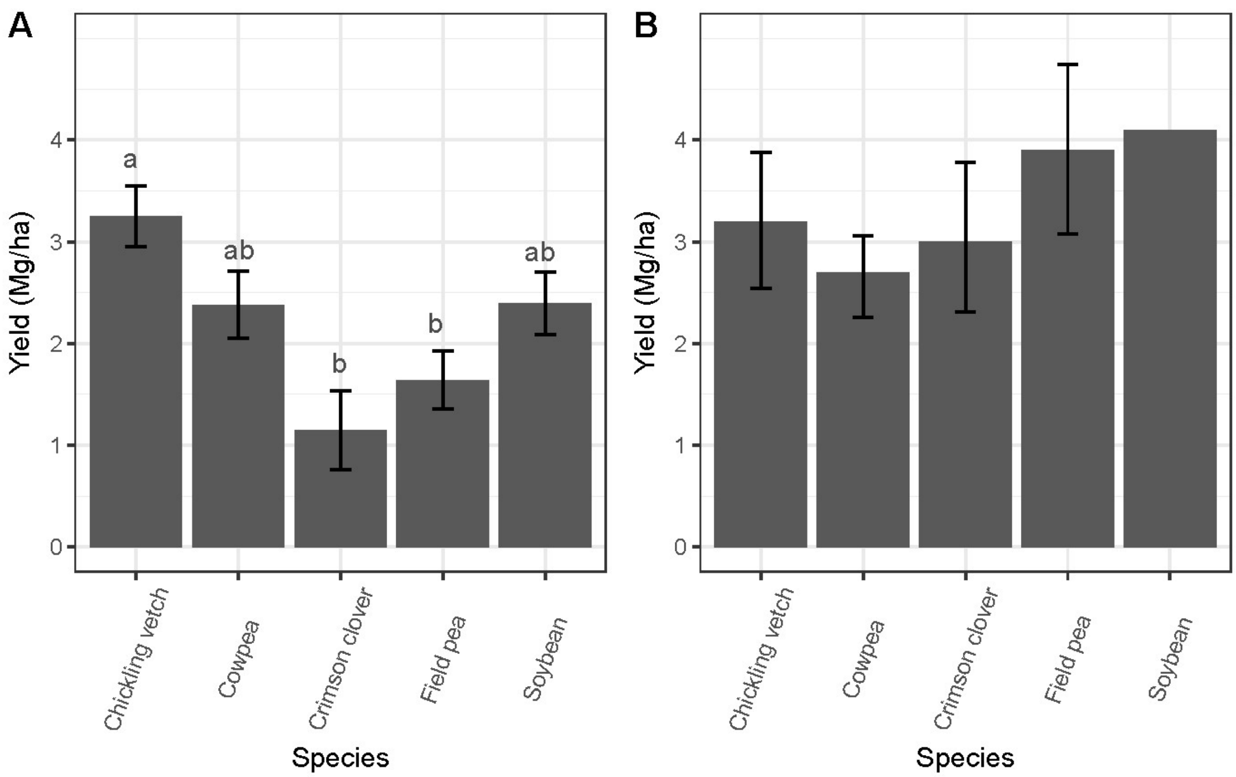

Fig. 3.5. The yield of annual forage species within the annual legume group in a summer seeded cropping system in (A) 2017 and (B) 2018 in Union, OR.
Note: Means followed by the same letters are not significantly different at the 0.05 confidence level.

Within AB, the species level variance analysis is shown in Table 3.8 and there was no significant interaction effect between irrigation and species. The yield ranged from highest yield 5.9 Mg/ha for radish to 2.6 Mg/ha for turnip.

Table 3.8. Species level analysis of variance of year, irrigation, species, and their interactions for annual forage yield within the annual brassica group in a summer seeded cropping system.

Source	DF	Type III SS	Mean Square	F value	Significance
Irrigation	3	217.7	72.6	23.4	**
Species	4	52.4	13.1	4.2	**
Irrigation × Species	12	21.2	1.8	0.6	NS

** indicate significance at the 0.01 probability levels; NS, not significant at the 0.05 level.

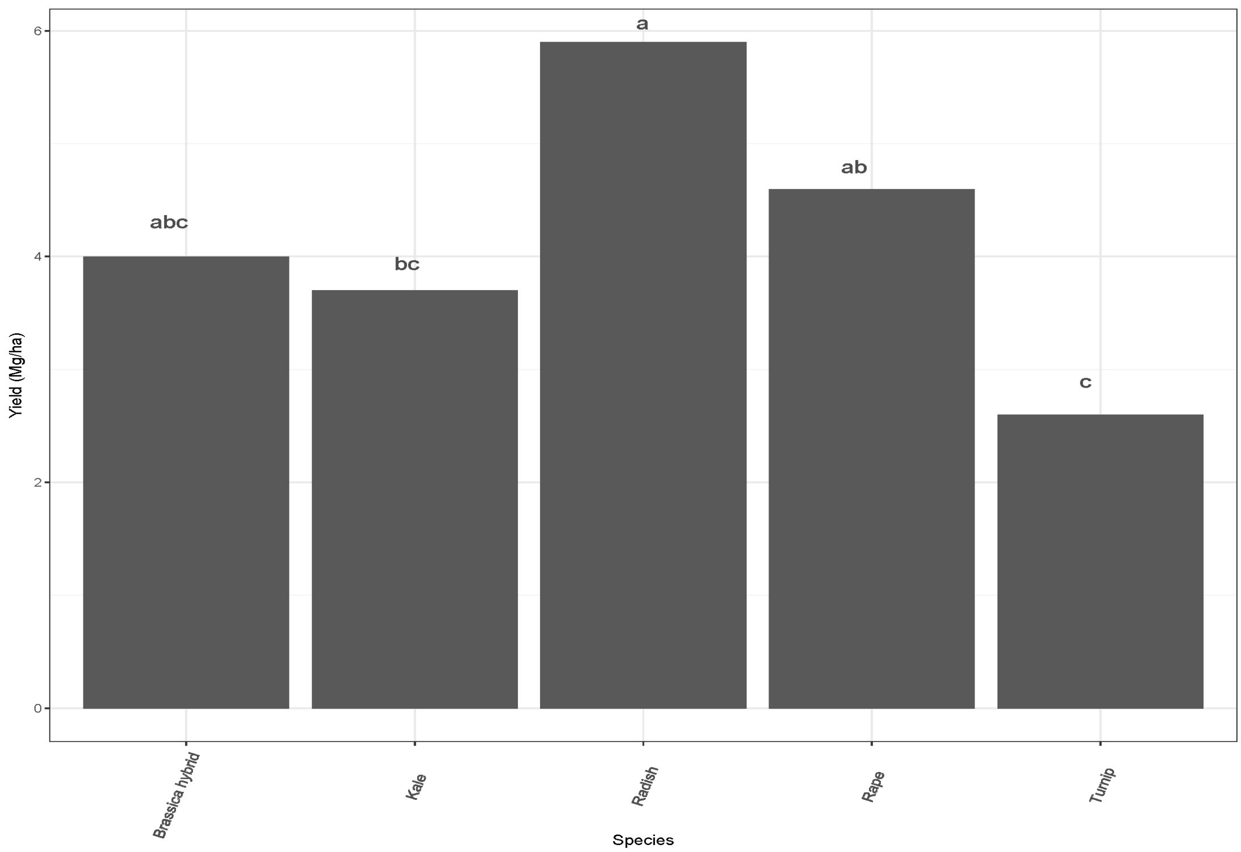

Fig. 3.6. The yield of annual forage species within the annual brassica group in a summer seeded cropping system in 2018 in Union, OR.
Note: Means followed by the same letters are not significantly different at the 0.05 confidence level.

The interaction between year and irrigation, and three way interaction effect were not significant (Table 3.9) when the twenty annual forage species were compared together. Yield ranged from 11.4 Mg/ha for sorghum-sudangrass to 1/7 Mg/ha for barley udner W1, from 8.8

Mg/ha for sorghum-sudangrass to 1.0 Mg/ha for barley under W2, from 7.4 Mg/ha for sorghum-sudangrass to 0.2 Mg/ha for annual ryegrass under W3 and from 2.3 Mg/ha for sorghum-sudangrass to 0 for both teff and crimson clover (Table 3.10). In addition, no difference in yield was observed between W1 and W2 for all species except teff and no yield difference existed between W3 and W4 for any species except sorghum-sudangrass.

Table 3.9. Significance of year, irrigation treatment, forage species, and their interactions in analysis of variance for forage yield in a summer seeded cropping system in 2017 and 2018 in Union, OR.

Source	DF	Type III SS	Mean Square	F value	Significance
Year	1	575.4	575.4	153.3	**
Irrigation	3	1317.8	439.3	117.1	**
Species	19	789.7	41.6	11.1	**
Irrigation × Species	56	544.7	9.7	2.6	**
Irrigation × Year	1	0.2	0.2	0.04	NS
Year × Species	14	443.4	31.7	8.4	**
Irrigation × Species × Year	14	76.6	5.5	1.5	NS

* and ** indicate significance at the 0.05 and 0.01 probability levels, respectively; NS, not significant at the 0.05 level.

Table 3.10. The average yield of annual forage species under variable irrigation treatments in a summer seeded cropping system across 2017 and 2018 in Union, OR.

	Irrigation treatment			
Species	W1	W2	W3	W4
	Mg/ha			
Sorghum-sudangrass	11.4 a† A‡	8.8 a A	7.4 a A	2.3 a B
Radish	7.6 ab A	7.3 abc A	2.1 bcd AB	0.4 ab B
Pearl millet	7.6 ab A	5.1 abcde AB	2.0 bcd BC	1.0 ab C
Brassica hybrid	6.9 ab A	5.3 abcde A	2.2 bc B	0.8 ab B
Foxtail millet	6.9 ab A	7.6 ab A	1.8 bcd A	NA‡
Proso millet	6.7 ab A	5.8 abcd A	1.2 bcd B	0.4 b B
Oat	6.7 ab A	5.2 abcde A	1.8 bcd B	0.2 b B
Rape	6.5 ab A	6.7 abcd A	1.6 bcd A	0.9 b A
Kale	4.4 b A	5.4 abcde A	1.4 bcd A	0.9 ab A
Turnip	4.4 b A	3.4 bcde A	0.4 cd B	0.6 ab B
Chickling vetch	4.1 b A	4.3 bcde A	1.7 bcd AB	0.9 ab B
Soybean	4.0 b A	4.1 bcde A	3.1 b AB	1.3 ab B
Crimson clover	3.9 b A	3.0 cde A	0.6 cd B	0 b B
Field pea	3.7 b AB	4.2 bcde A	2.4 bc AB	0.6 ab B
Teff	3.6 b A	2.5 cde B	0.5 cd C	0 b C
Cowpea	3.3 b A	2.9 cde A	2.1 bcd AB	0.8 ab B
Annual ryegrass	3.1 b A	1.6 de AB	0.2 d B	0.2 b B
Wheat	2.4 b A	1.6 de A	0.5 cd A	0.8 ab A
Triticale	1.8 b A	1.7 de A	0.6 cd B	0.2 b B
Barley	1.7 b A	1.0 e AB	0.3 d AB	0.1 b B

† Means followed by the same lowercase letter are not significantly different within each column at the 0.05 confidence level.

‡ Means followed by the same capital letter are not significantly different within each row at the 0.05 confidence level. NA, not applicable; MSD, minimum significant difference; W1, full season irrigation; W2, late season cutoff; W3, early season cutoff; W4, no irrigation.

Phenological Development

The analysis of variance for phenology is shown in Table 3.11. For annual legumes, species had significant effects on both days to 50% flowering and 50% pod formation. Crimson clover and soybean reached 50% flowering or 50% pod formation much later than chickling vetch and field pea (Table 3.12). Cowpea never reached flowering. The average days to 50% pod formation was 65.4, 64.3, 62.2, and 57.6 under W1, W2, W3 and W4, respectively. W4 treatment took significantly shorter days to reach 50% pod formation than others. No significance existed among W1, W2 and W3. AL group took 55.1 days to reach flowering and 62.9 days to reach pod formation.

Table 3.11. Significance of main and interaction effects in an analysis of variance for forage phenology in a summer seeded cropping system in 2018 in Union, OR.

Source	Days to 50% flowering (legumes)		Days to 50% pod formation (legumes)		Days to 50% heading (grasses)		Days to 50% flowering (grasses)	
	df	Significance	df	Significance	df	Significance	df	Significance
Irrigation	3	NS	3	*	3	**	3	NS
Species	3	**	3	**	9	**	9	**
Irrigation × Species	8	NS	8	NS	19	**	18	NS

* and ** indicate significance at the 0.05 and 0.01 probability levels, respectively; NS, not significant at the 0.05 probability level.

Table 3.12. Days to 50% flowering and 50% pod formation for annual legumes grown in a summer seeded cropping system in 2018 in Union, OR.

Species	Days to 50% flowering	Days to 50% pod formation
Chickling vetch	42.7 d†	52.0 c
Crimson clover	69.1 a	73.1 b
Field pea	48.6 c	52.2 c
Soybean	64.5 b	77.7 a

† Means followed by the same letter within a column are not significantly different at the 0.05 confidence level.

Species and irrigation produced a significant interaction effect on days to 50% heading of annual grasses. For proso millet, a significant increase of approximately 13 days for days to 50% heading was observed between W1 and W3 treatments (Table 3.13). For other annual warm season grasses, there was no significant difference among irrigation treatments. For the AC3 group, no significant difference existed for species among irrigation treatments, neither. For grasses days to 50% flowering, only species effect was significant. AC3 group took 49.1 and 53.7 days to reach 50% heading and 50% flowering, respectively, while it took the AC4 group 78.0 days to head out and 81.4 days to flower on average (date not shown).

Table 3.13. Days to 50% heading and 50% flowering for annual grasses grown in a summer seeded cropping system in 2018 in Union, OR.

Species	Days to 50% heading				MSD ($p \leq 0.05$) among irrigation treatments	Days to 50% flowering
	W1	W2	W3	W4		
Teff	61.5 d†	61.5 c	NA	NA	NS	67.9 c
Foxtail millet	70.3 c	74.3 b	NA	NA	NS	79.2 b
Sorghum-sudangrass	82.5 b	82.5 a	87.8 a	NA	NS	91.3 a
Pearl millet	87.4 a	87.1 a	87.6 a	89.6 a	NS	94.3 a
Proso millet	57.9 d	61.0 c	71.0 b	NA	3.1	65.1 c
Annual ryegrass	52.2 e	50.3 d	NA	NA	NS	56.7 d
Barley	49.3 e	50.4 d	51.6 c	51.5 b	NS	55.1 d
Oat	48.0 e	48.0 d	48.2 c	51.5 b	NS	51.3 e
Triticale	48.0 e	48.0 d	47.5 c	49.1 b	NS	51.0 e
Wheat	48.2 e	48.0 d	48.2 c	49.1 b	NS	55.9 d

† Means followed by the same letter within a column are not significantly different at the 0.05 confidence level.
NA, not applicable; MSD, minimum significant difference; NS, not significant. W1, full season irrigation; W2, late season cutoff; W3, early season cutoff; W4, no irrigation.

Water Use Efficiency

The irrigation and rainfall amount that annual forages received directly after annuals were planted following harvesting of winter triticale under each irrigation treatment is shown in Table 3.14. All main and interaction effects were significant except irrigation × group × year and irrigation × year at the group level (Table 3.15). WUE kept decreasing from W2 to W4 treatments but no significance was observed for WUE between W1 and W2 (Fig. 3.7). WUE of AC4 udner W1 and W2 was 11.7 and 12.6 kg/ha-mm, respectively, which were greater than others except AC3. AC4's WUE was similar to AL's or AB's under W3. AC3's WUE was consistently the lowest when irrigation was applied (W1, W2 and W3). No difference existed among groups under W4.

Table 3.14. The irrigation and rainfall amount that annual forages received after planting under each irrigation treatment in a summer seeded cropping system in Union, OR.

Irrigation treatments	2017		2018	
	Irrigation amount	Rainfall amount	Irrigation amount	Rainfall amount
	———mm———		———mm———	
Full-season irrigation	489.8		623.3	
Late-season cutoff	227.0	3.3	314.5	61.4
Early-season cutoff	0		55.9	
No irrigation	0		0	

Table 3.15. Group level analysis of variance of year, irrigation, group, and their interactions for water use efficiency (WUE) of annual forages in a summer seeded cropping system.

Source	DF	Type III SS	Mean Square	F value	Significance
Year	1	706.9	706.9	33.5	**
Irrigation	3	2110.2	703.4	33.4	**
Group	3	1148.6	382.9	18.2	**
Irrigation × Group	9	577.9	64.2	3.1	**
Irrigation × Year	1	39.2	39.2	1.9	NS
Year × Group	2	663.5	331.7	15.7	**
Irrigation × Group × Year	2	111.1	55.6	2.6	NS

** indicate significance at the 0.01 probability level; NS, not significant at the 0.05 probability level.

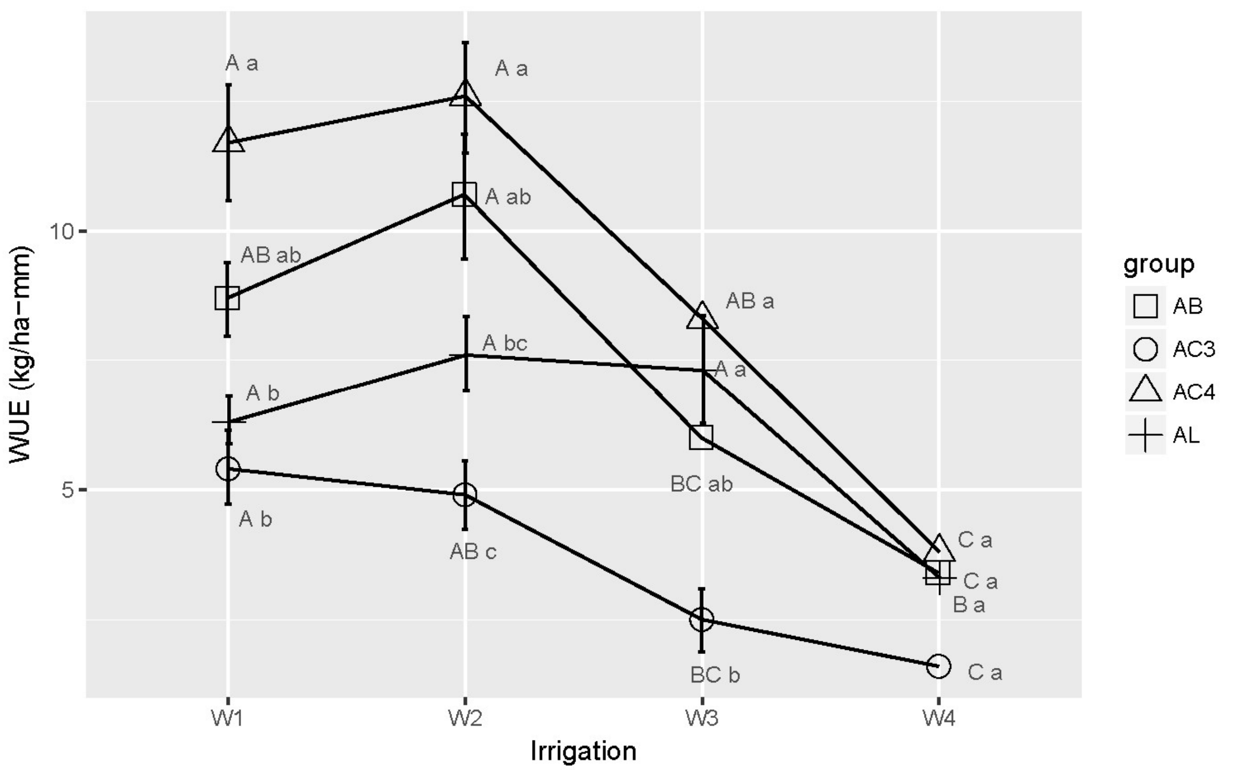

Fig. 3.7. The average water use efficiency (WUE) of annual forage functional groups grown in a summer seeded cropping system across 2017 and 2018 in Union, OR.
Note: Means followed by the same capital letters are not significantly different at the 0.05 confidence level within each functional group while means followed by the same lowercase letters are not significantly different at the 0.05 confidence level within each irrigation treatment. W1, full season irrigation; W2, late-season cutoff; W3, early-season cutoff; W4, no irrigation; AB, AC3, AC4 and AL indicate annual brassica, annual cool season grass, annual warm season grass, and annual legume groups, respectively. Error bars represent the standard error.

All main and interaction effects were significant except irrigation × species × year effect at the species level (Table 3.16). Sorghum-sudangrass had the highest WUE under all irrigation treatments; 18.5, and 27.6 Kg ha^{-1} mm^{-1} for W1 and W3, respectively (Table 3.17). Under W2, WUE of sorghum-sudangrass (18.6 Kg ha^{-1} mm^{-1}) was greater than others except foxtail millet, radish and rape. When W4 was applied, WUE ranged from 10.6 Kg ha^{-1} mm^{-1} for sorghum-sudangrass to 0 for both crimson clover and teff.

Table 3.16. Species level analysis of variance of year, irrigation, species, and their interactions for water use efficiency (WUE) of annual forages in a summer seeded cropping system.

Source	DF	Type III SS	Mean Square	F value	Significance
Year	1	706.9	706.9	79.5	**
Irrigation	3	1792.8	597.6	67.2	**
Species	19	4532.1	238.5	26.8	**
Irrigation × Species	56	1385.8	24.7	2.8	**
Irrigation × Year	1	39.2	39.2	4.4	*
Year × Species	14	1217.5	87.0	9.8	**
Irrigation × Species × Year	14	193.0	13.8	1.6	NS

* and ** indicate significance at the 0.05 and 0.01 probability levels, respectively; NS, not significant at the 0.05 probability level.

Table 3.17. The average water use efficiency (WUE) of annual forage species under variable irrigation treatments in a summer seeded cropping system across 2017 and 2018 in Union, OR.

Species	Irrigation treatment			
	W1	W2	W3	W4
	Kg ha^{-1} mm^{-1}			
Sorghum-sudangrass	18.5 ab	18.6 ab	27.6 a	10.6 b
Oat	12.0 a	11.9 a	6.7 b	0.8 c
Pearl millet	11.7 a	10.6 a	7.3 a	4.7 a
Foxtail millet	11.4 ab	16.2 a	4.4 b	NA
Proso millet	11.2 a	12.3 a	4.5 b	1.8 b
Radish	11.1 a	13.9 a	7.9 a	1.7 a
Brassica hybrid	10.0 a	10.0 a	8.3 ab	3.9 b
Rape	9.4 a	12.7 a	6.0 a	4.2 a
Chickling vetch	7.1 ab	9.1 a	6.3 ab	4.0 b
Soybean	6.7 b	8.5 ab	11.4 a	6.1 b
Kale	6.4 a	10.3 a	5.1 a	4.2 a
Turnip	6.4 a	6.4 a	1.6 b	2.7 ab
Crimson clover	6.3 a	5.8 a	2.3 b	0 b
Field pea	6.0 a	8.4 a	8.8 a	3.0 a
Teff	5.7 a	5.2 a	1.7 b	0 b
Cowpea	5.6 a	6.3 a	7.8 a	3.9 a
Annual ryegrass	5.3 a	3.4 ab	0.7 b	1.1 b
Wheat	4.1 a	3.6 a	1.8 a	3.6 a
Triticale	3.0 ab	3.4 a	2.2 ab	0.9 b
Barley	2.8 a	2.1 a	1.0 a	0.6 a
MSD ($p \leq 0.05$) among species	6.4	6.2	7.6	9.1

Note: means followed by the same letter within a row are not significantly different at the 0.05 confidence level; NA, not applicable. MSD, minimum significant difference.

Quality

For winter triticale, irrigation didn't have significant effect on the content of CP, ADF or NDF. The average CP content was 11.2, 11.7, 12.9 and 13.4% Under W1, W2, W3 and W4, respectively. ADF% was 38.7% for W1, 40.7% for W2, 38.3% for W3 and 38.6% for W4 while the percentage of NDF was 60.6% for W1, 64.2% for W2, 62.5% for W3 and 63.9% for W4.

All interaction effects on CP, ADF and NDF at group level were insignificant (Table 3.18). Difference was observed between any two functional groups. Average CP% for AL, AC3 and AC4 was 14.5%, 12.7% and 7.7%, respectively, with AL having the greatest CP% (Fig. 3.8A). Groups had ADF content of 37.0%, 35.0% and 33.3% for AC4, AL and AC3, respectively, while NDF% was 57.6% for AC4, 51.1% for AC3 and 42.6% for AL, with AC3 having the lowest ADF% and AL having the lowest NDF% (Fig. 3.8B; Fig. 3.8C). .

CP content was 11.4% for W1 and 12.0% for W2. ADF content was 35.9% for W1 and 34.2% for W2 while the concentration of NDF was 51.6% under W1 and 49.3% under W2 (data not shown). There was no difference between irrigation treatments for CP% but difference existed between W1 and W2 for ADF% and NDF%.

Table 3.18. Group level analysis of variance of main effect and their interactions for crude protein (CP), acid detergent fiber (ADF) and neutral detergent fiber (NDF) in a summer seeded cropping system.

Source	df	CP	ADF	NDF
Group	2	**	**	**
Irrigation	1	NS	**	**
Group × Irrigation	2	NS	NS	NS

** indicate significance at the 0.01 probability level; NS, not significant at the 0.05 level.

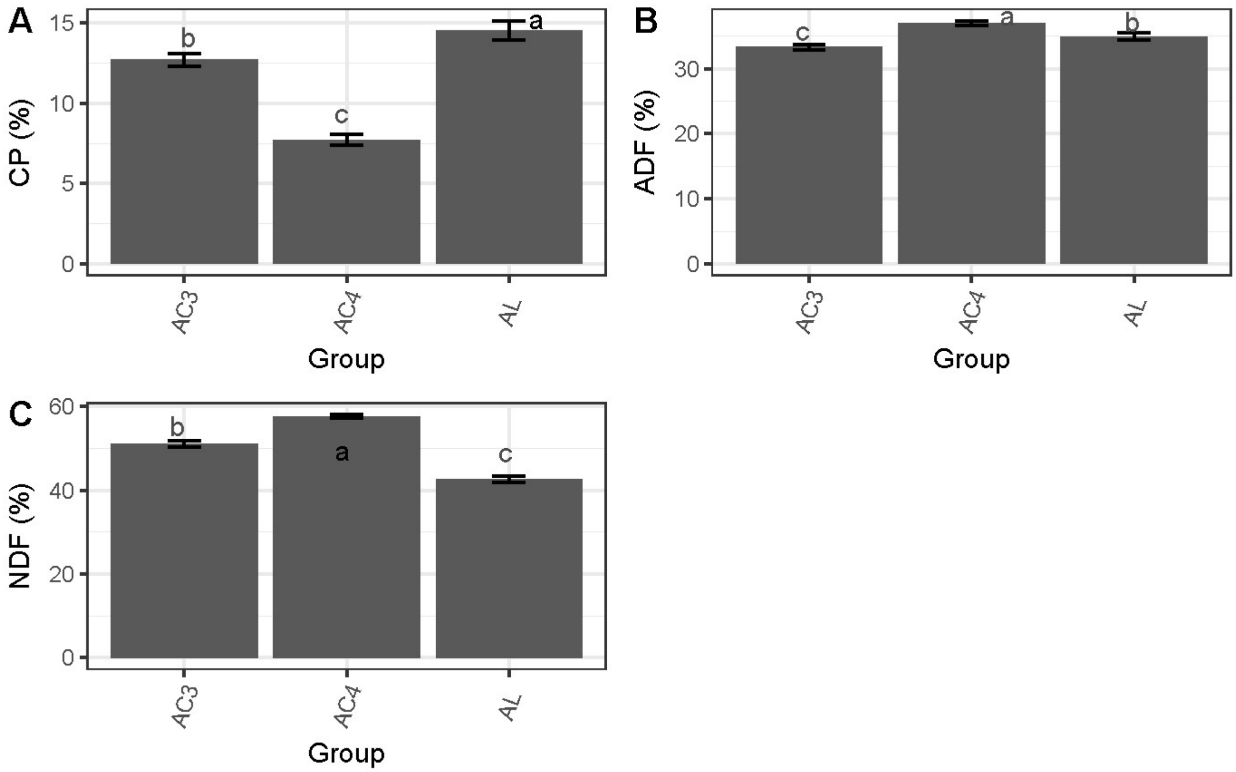

Fig. 3.8. The content of (A) crude protein (CP), (B) acid detergent fiber (ADF), and (C) neutral detergent fiber (NDF) of annual forage functional groups grown in a summer seeded cropping system in 2018 in Union, OR.
Note: Means followed by the same letters are not significantly different at the 0.05 confidence level; AC3, AC4 and AL indicate annual cool season grass, annual warm season grass, and annual legume group, respectively. Error bars represent the standard error.

No significant interaction between species and irrigation existed within groups (Table 3.19). Within AC4, with a value of 10.5%, teff had the greatest CP% (Fig. 3.9A). Foxtail millet had 39.7% ADF which was greater than others except pearl millet (Fig. 3.9B). Foxtail millet had greater NDF% than proso millet but it was similar to others (Fig. 3.9C). CP% was 7.2% for W1 and 8.2% for W2 and CP% showed an increasing trend (p = 0.08) as water stress increased. W1 produced higher percentage of ADF, 38.2%, than W2 which produced 35.8% (p = 0.0001), while with 59.1% for W1 and 56.1% for W2, W1 had greater NDF% than W2 (p = 0.0001) (data not shown).

Table 3.19. Species level analysis of variance of main effects and their interactions for crude protein (CP), acid detergent fiber (ADF), and neutral detergent fiber (NDF) of annual forages within annual warm season grass (AC4), annual cool season grass (AC3) and annual legume (AL) groups in a summer seeded cropping system.

Source	df	AC4			AC3			AL		
		CP	ADF	NDF	CP	ADF	NDF	CP	ADF	NDF
Species	4	**	**	*	**	**	**	**	**	**
Irrigation	1	NS	**	**	NS	NS	NS	NS	*	**
Species × Irrigation	4	NS	NS	NS	NS	NS	NS	NS	NS	NS

* and ** indicate significance at the 0.05 and 0.01 probability levels, respectively; NS, not significant at the 0.05 level.

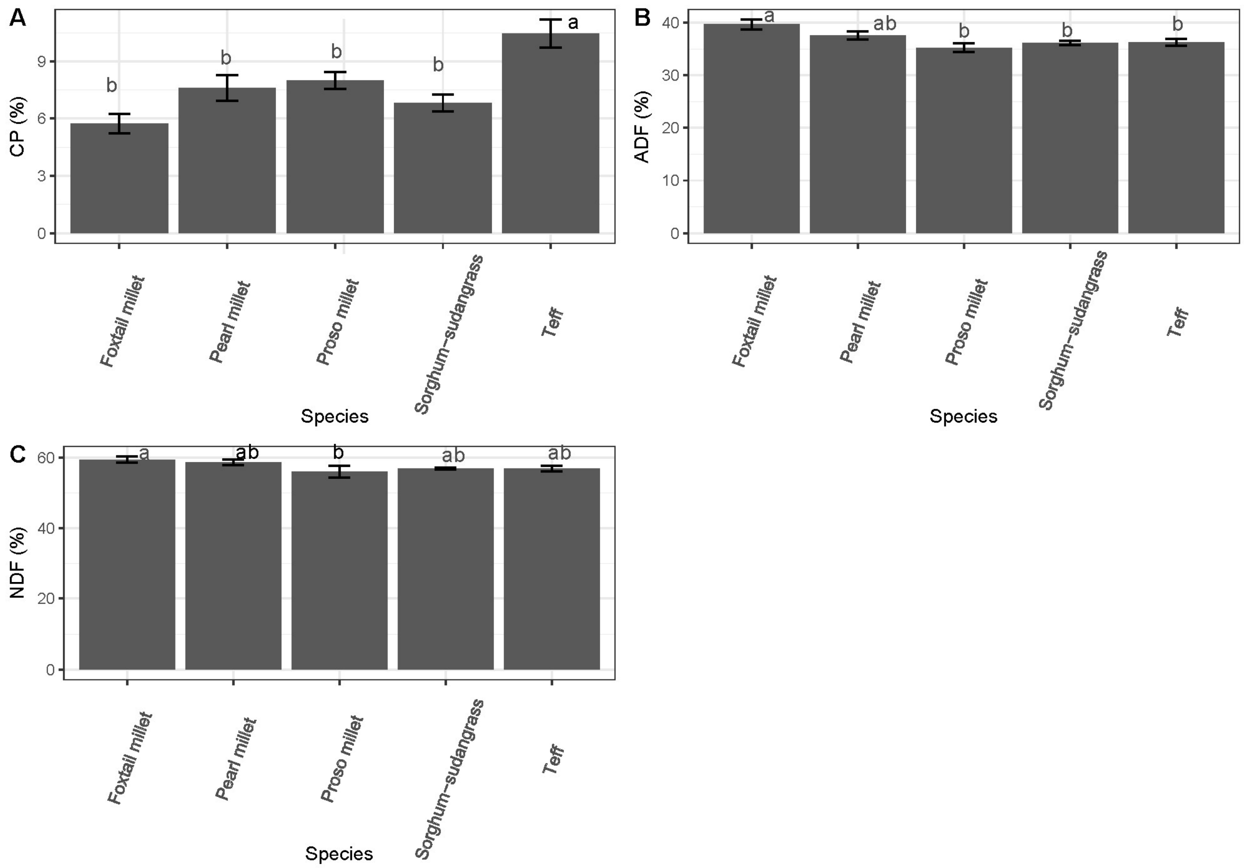

Fig. 3.9. The content of (A) crude protein (CP), (B) acid detergent fiber (ADF), and (C) neutral detergent fiber (NDF) of annual forages within the annual warm season grass (AC4) group in a summer seeded cropping system in 2018 in Union, OR.
Note: Means followed by the same letters are not significantly different at the 0.05 confidence level; Error bars represent the standard error.

Within AC3, only species had significant effect on quality. For CP%, annual ryegrass had the highest content, 16.2%. (Fig. 3.10A). ADF% ranged from 35.7% for oat to 30.7% for annual ryegrass (Fig. 3.10B) while NDF% ranged from 57.5% for oat to 46.1% for annual ryegrass (Fig. 3.10C). The content of CP, ADF, and NDF was 11.4%, 35.9% and 51.6%, respectively, under W1, and 12.0%, 34.3% and 49.3%, respectively, under W2 (data not shown). Irrigation produced no difference in CP, ADF or NDF content.

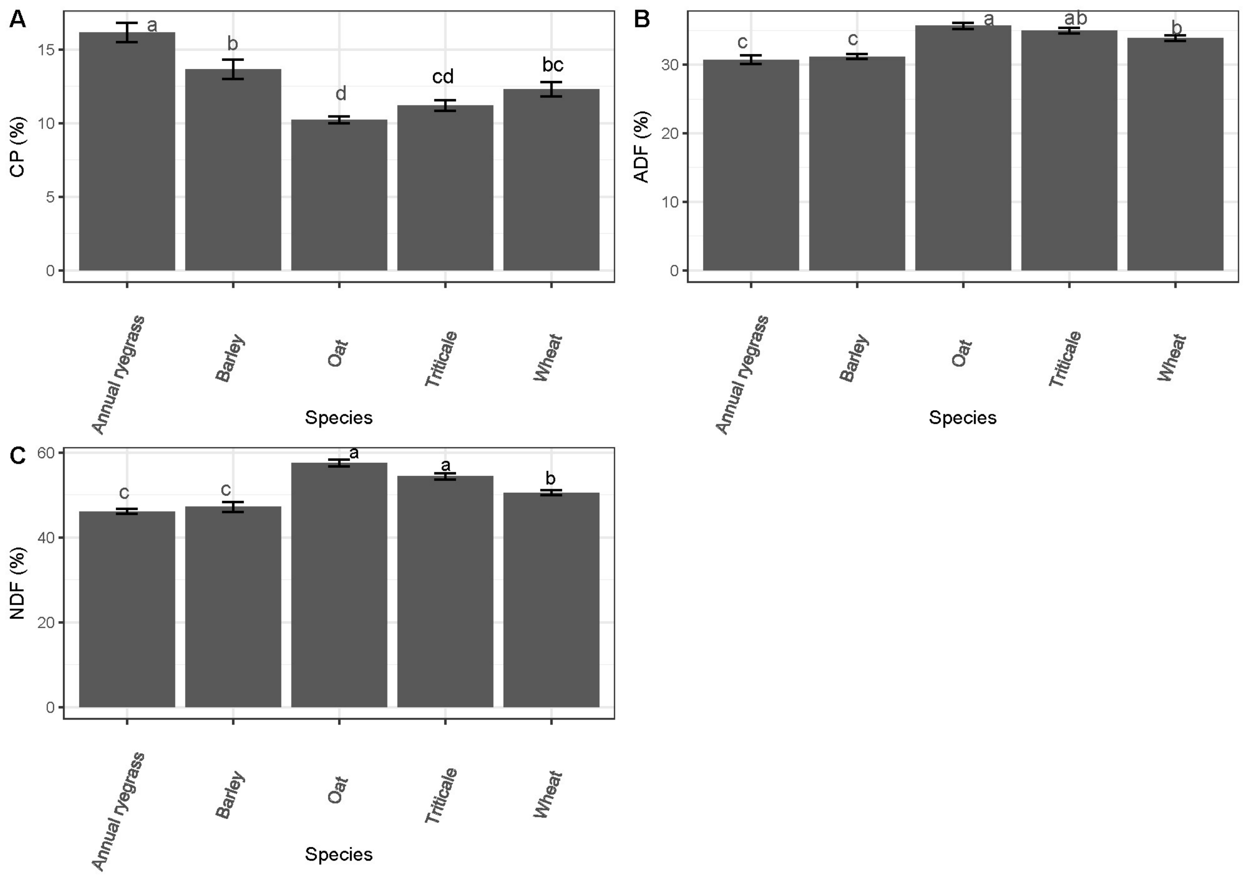

Fig. 3.10. The content of (A) crude protein (CP), (B) acid detergent fiber (ADF), and (C) neutral detergent fiber (NDF) of annual forages within the annual cool season grass (AC3) group in a summer seeded cropping system in 2018 in Union, OR.
Note: Means followed by the same letters are not significantly different at the 0.05 confidence level; Error bars represent the standard error.

Within AL, CP% ranged from 19.7% for chickling vetch to 9.6% for soybean (Fig. 3.11A). Soybean had 31.5% ADF which was significantly lower than others within the group except chickling vetch (Fig. 3.11B). Besides, soybean had lower NDF% than most legumes but there was no difference between soybean and cowpea (Fig. 3.11C). The percentage of CP was 14.2% for W1 and 14.9% for W2. ADF content was 35.9% for W1 and 34.0% for W2 while NDF% was 44.0% for W1 and 41.3% for W2 (data not shown). Significant difference existed between W1 and W2 for ADF and NDF but not for CP content.

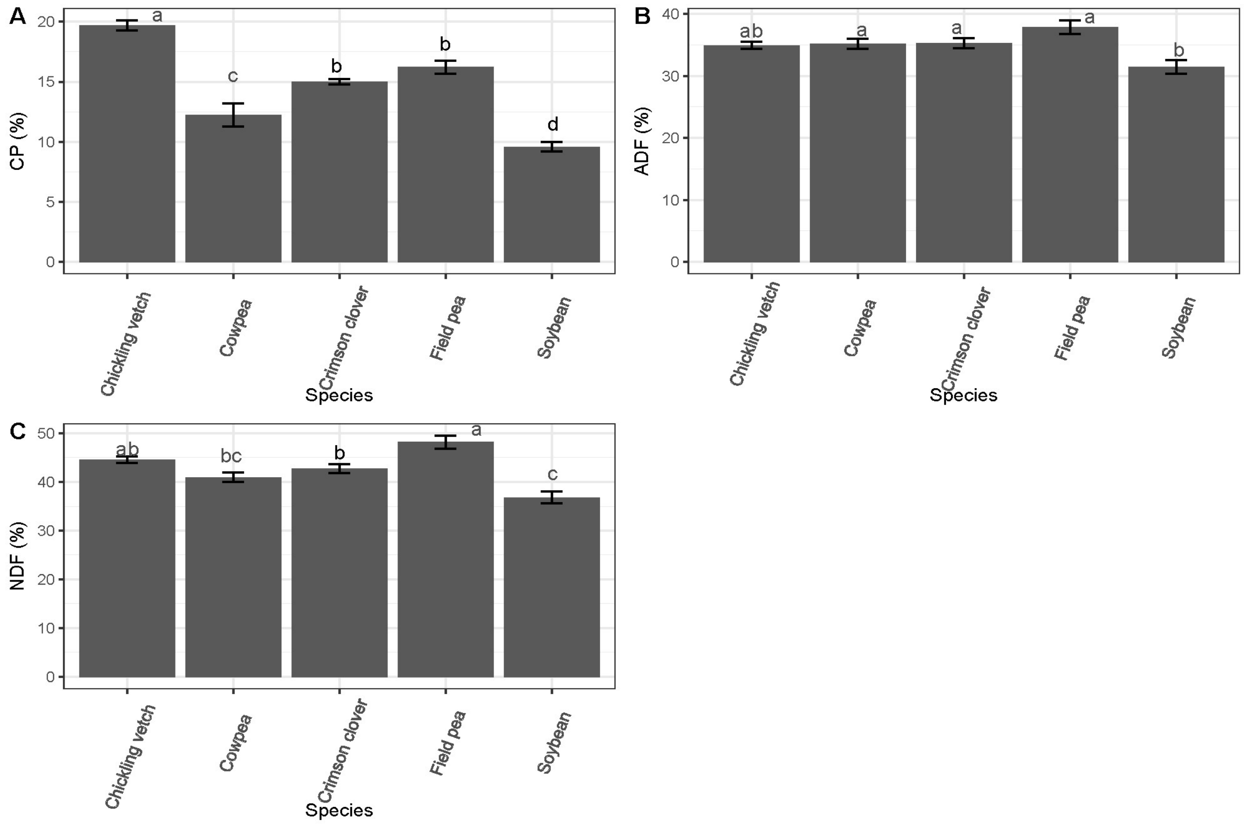

Fig. 3.11. The content of (A) crude protein (CP), (B) acid detergent fiber (ADF), and (C) neutral detergent fiber (NDF) of annual forages within the annual legume (AL) group in a summer seeded cropping system in 2018 in Union, OR. Note: Means followed by the same letters are not significantly different at the 0.05 confidence level; Error bars represent the standard error.

Significant interaction was not observed for all quality parameters when all species were analyzed together (Table 3.20). Chickling vetch had thegreatest CP content (19.7%) and there was an over three fold range difference in CP% existed between chickling vetch and foxtail millet (5.7%) (Table 3.21). The percentage of ADF ranged from 39.7% for foxtail millet to 30.7% for annual ryegrass with a difference as high as 9.0%. NDF% ranged from 59.5% for foxtail millet to 36.8% for soybean.

Table 3.20. Species level analysis of variance of main effects and their interactions for crude protein (CP), acid detergent fiber (ADF), and neutral detergent fiber (NDF) of annual forages in a summer seeded cropping system.

Source	df	CP	ADF	NDF
Species	14	**	**	**
Irrigation	1	*	**	**
Species × Irrigation	14	NS	NS	NS

* and ** indicate significance at the 0.05 and 0.01 probability levels, respectively; NS, not significant at the 0.05 level.

Table 3.21. The average content of crude protein (CP), acid detergent fiber (ADF), and neutral detergent fiber (NDF) of annual forage species in a summer seeded cropping system in 2018 in Union, OR.

Species	CP	ADF	NDF
		%	
Chickling vetch	19.7 a†	34.9 bc	44.6 efg
Field pea	16.2 b	37.9 ab	48.2 de
Annual ryegrass	16.2 b	30.7 d	46.1 ef
Crimson clover	15.0 b	35.3 bc	42.7 fg
Barley	13.7 bc	31.2 d	47.2 de
Wheat	12.3 cd	33.9 cd	50.5 cd
Cowpea	12.2 cd	35.2 bc	41.0 g
Triticale	11.2 cde	35.0 bc	54.4 bc
Teff	10.5 def	36.3 bc	56.9 ab
Oat	10.2 def	35.7 bc	57.5 ab
Soybean	9.6 efg	31.5 d	36.8 h
Proso millet	8.0 fgh	35.3 bc	56.0 ab
Pearl millet	7.6 gh	37.6 ab	58.7 a
Sorghum-sudangrass	6.8 h	36.1 bc	56.9 ab
Foxtail millet	5.7 h	39.7 a	59.5 a

† Means followed by the same letter within a column are not significantly different at the 0.05 confidence level.

Discussion

Yield

Year effect

2018 produced 1.0 Mg/ha significantly higher average yield than 2017 and this difference mainly result from different seeding time and different water amount of rainfall and irrigation in two years. Annuals were seeded on June 12th in 2018, which was one month earlier than 2017, enabling longer growing season for annuals. In addition, annual plots received an average amount of 67.6 mm more irrigation water over irrigation treatments and 43.7 mm more rainfall water in 2018 compared to 2017. Yield declined as water stress increased since soil moisture is a major determinant of forage yield, regardless of species or other environmental conditions (Orloff et al., 2016; Neal et al., 2010; Karrou and Oweis, 2012). Therefore, the greater yield in 2018 attributes to more water availability combing with longer growing season.

W3 and W4

In 2017, annuals under W3 and W4 treatments didn't establish successfully because winter triticale was harvested late and annuals were not seeded until July 6th. In addition, annuals received negligible rainfall in both July and August. Further, irrigation for the W3 treatment stopped on June 15th. Therefore, little water was available for annuals grown under both W3 and W4, which caused emergence failure. In 2018, although summer-seeded annuals survived under W3 and W4, almost all annual forages had very low productivity. Low rainfall, high air temperature, and dry soil conditions resulted in poor establishment and low productivity of summer-seeded annuals, similar to those reported by Sanderson et al. (2018). The same author reported that when annuals were used in a double cropping system, the preceding crop probably depleted soil moisture before the planting of cover crops and made it difficult for the second planting to access the needed soil moisture.

All groups were most sensitive to the W3 treatment with sharp yield decrease under W3 relative to W2 in 2018. The previous crop, winter triticale, exhausted the soil moisture. In 2018, annuals were seeded on June 12th and with inadequate rainfall in June, irrigation was needed. Irrigation cutoff was conducted on June 15th for W3 treatment after only three days of irrigation while the irrigation season for W2 lasted for 49 days. Therefore, yield under W3 showed sharp reduction compared to W2 for all groups.

W1 and W2

Applying moderate water stress won't reduce crop production significantly since no significant yield difference was found between full irrigation (W1) and the late season cutoff (W2) irrigation treatments in our results regardless of functional groups or species in 2018. This is in agreement with the insignificant grain yield reduction of teff between full irrigation and 25% deficit irrigation in Ethiopia reported by Yihun et al. (2013). Another non-forage study conducted in Japan also concluded that no significant difference in potato biomass was observed between applying 0.75 times water surface evaporation and applying irrigation water equal to that lost by evapotranspiration (Yuan et al., 2003). However, the annual forage yield under W1 was significantly higher than that under W2 in 2017. This was probably due to the late seeding of annuals in 2017. The maximum temperature reached 32.8°C when seeded in July of 2017 while it was 23.7°C when seeded in June of 2018. Much higher temperatures created higher evaporation, and the length of the irrigation season could possibly produce a significant impact on yield during hot days. In addition, late seeding allowed annuals shorter growing season and most annual forages didn't reach maturity by August 15th which was around two weeks after W2 irrigation termination. Thus, W1 effect would be significant for finishing their growth and produce more and significant difference was observed between W1 and W2 in 2017. In 2018, most species reached their growth potential around August 15th so more water applied until September 7th for W1 treatment only had marginal impact and no significant difference in yield existed between W1 and W2.

C3 vs. C4

The AC4 group of annual forages produced the highest yields while the AC3 group produced the lowest yields irrespective of irrigation treatments across two years. This is because warm season grasses possess a C4 photosynthesis system (Brown, 1999), enabling them to close stomata, reducing the water loss from the leaves and reduce photorespiration, leading to greater water use efficiency under water stress conditions (Tadele, 2016). Cools season and warm season grasses have different adaptation to temperature. AC4 adapts well to warm conditions and have highest growth rate in summer due to their C4 photosynthesis (Brow, 1999), thus yielding more than other groups. However, grasses of AC3 have a much lower temperature requirement for the optimal growth and their rates of photosynthesis and DM accumulation will be reduced as temperature increases (Barnes et al., 2003), thus yielding less when seeded with AC4 in the same day during summer.

Species specific characteristics within each group

Sorghum-sudangrass outyielded other forages in the AC4 group. Mut et al. (2017) reported a yield of 8.31Mg/ha for sorghum-sudangrass when optimal irrigation was applied in Turkey. This value was much lower than the average yield of sorghum-sudangrass under W1 in our study, while close to the average yield under W2. Under W4, sorghum-sudangrass still had reasonable yield while other warm season grasses yielded below 1.0 Mg/ha. As a warm season grass, sorghum-sudangrass has C4 photosynthesis. In addition, the yield performance under water stress conditions is likely due to its high crop water productivity (Mahmoudzadeh and Oad, 2018), high water use efficiency (Lenssen and Cash, 2011) plus deep-rooting potential and high root proportion in the subsoil (Schittenhelm and Schroetter, 2014). Teff has shallow rooting system which could partly explain its much lower yield under drought compared to other warm season grasses, especially under W3 and W4. In addition to low production under drought, teff also yielded least within AC4 when W1 was applied. This low yielding nature of teff relative to other annual warm season grasses under same irrigation treatments, might result from its low light use efficiency and this was probably due to its leaf size and orientation which reduce amount of photons intercepted for CO^2 fixation (Mengistu, 2009).

Within AC3, oat outyielded other species when irrigation was applied. It had an average yield of 6.7 Mg/ha under W1 across two years, comparable to the 7.7 Mg/ha of summer-seeded oat when soil moisture was not a limiting factor in the northern USA (Contreras-Govea and Albrecht, 2006).The greater yield potential of oat compared to other cereals was also reported by Lawes et al. (1971). The high yield of oat under irrigation in our study was partially due to its regrowth potential.

Within AL, crimson clover is cool season legume but soybean is warm season legume, so when planted at the same time during summer when temperature was high, soybean yielded more than crimson clover. Thus, the greatest yield difference happened between crimson clover and soybean within AL.

Within AB, radish had superior yield over other species. Radish was the only species that bolted before harvesting while other brassicas were still at vegetative stage. The reproductive production of radish may lead to its higher yield compared to other brassicas. Besides, radish matured the fastest among five brassicas. Its early-maturity could enable radish to escape late season drought better than other brassicas, thus yielding more.

Brassicas grown under W1 and W2 treatments didn’t survive in 2017, because of heavy flea beetle (*Psylliodes chrysocephala*) infestation and serious weed problems. Field visual observation in 2018 determined that rape and the brassica hybrid could resist flea beetle damage much better than the other three brassicas. The brassica hybrid used in this project is a cross between rape and Chinese cabbage. Therefore, rape’s higher insect resistance contributed to the improved hybrid’s resistance to flea beetle.

Phenological Development

Drought escape is one of the main strategies plants use to cope with drought. Drought escape is defined as the ability of a plant to reach maturity before drought occurs, including two different mechanisms, namely, rapid phenological development and developmental plasticity (Basu et al., 2016). Rapid phenological development refers to rapid growth and early flowering while developmental plasticity means that plants can match their growth to the rainfall distribution or soil water availability (Basu et al., 2016).

Annual legumes may use rapid phenological development to escape drought. This has been reported by Sionit and Kramer (1977) and Desclaus and Roumet (1996). Water stress significantly decreased the days to 50% pod formation of annual legumes in our study. No significant difference was observed for days to reach 50% flowering. Clarkson and Russell (1976) reported that annual medics will not flower earlier under drought but phasic development after flowering will be accelerated. This could explain the insignificant effect on days to reach 50% flowering with changes in irrigation treatments.

One of the mechanisms that annual grasses use to escape drought is developmental plasticity. For example, pearl millet is not affected a lot by mid-season drought since as long as moisture is available later, it can produce secondary tillers to compensate for main and primary tillers which are lost during mid-season drought (Vadez et al., 2012). Based on field observations, annual grasses generally showed little growth during dry seasons but once irrigation or precipitation events occurred, annual grasses headed out or flowered quickly. The observation that AC4 species match phenology to rainfall distribution under drought was also reported by Winkel et al. (1997) and Bidinger et al. (1987). No clear trend was observed on the effect of irrigation on DAS to reach heading of AC3 species. However, developmental plasticity on wheat was reported by Fisher and Maurer (1978) and this was observed in this study, with rapid growth occurring immediately after irrigation or a rain event.

Phenology stage observations were every three days in this study. If the observation frequency had been increased, a more obvious trend or a significant difference may have been obtained. Winkel et al. (1997) reported a delay of flowering for pearl millet under drought, while irrigation had no significant effect on grass flowering in our study. Drought escape, drought avoidance, and drought tolerance work together to develop plants' adaptation mechanisms under drought. It's very likely that some annual forage species mainly used drought avoidance or drought tolerance instead of drought escape to cope with drought conditions, thus no obvious phenological development change was observed.

Water stress during different stages can have different effects on phenological development (Winkel et al., 1996; Desclaus and Roumet, 1996). However, the irrigation in our study was not growth-stage based. Therefore, the effect that irrigation treatments produced on phenological development was integrated across the entire developmental process. To determine which phenological stage was shortened or prolonged by a specific stage of water stress, growth-stage-based irrigation experiments will be needed.

Water Use Efficiency

WUE showed no difference from W1 to W2 treatments for most species, which disagrees with what Jacobs et al. (2004) and Rostamza et al. (2011) reported. WUE decreased under W3 and W4. Annual forages had very poor production under W3 and W4 when summer seeded. In addition, WUE was mainly determined by the yield not total water use (Neal et al., 2011). Thus, annual forages had much lower WUE under W3 and W4 compared to W1 or W2. Sorghum-sudangrass showed great drought tolerance, which could be seen from its high WUE (Lenssen and Cash, 2011). Especially under seriously drought conditions, W3 and W4, WUE of sorghum-sudangrass even doubled that of the species with the second highest WUE. The much higher WUE of sorghum-sudangrass over other annual warm season grasses when summer seeded, and under no irrigation, was also confirmed by Lessen and Cash (2011) while the values in our study were much lower. This was primarily due to little rainfall at experiment site.

WUE in this study was calculated based on assumptions with a few limitations. We assumed all species had the same root length and W2, W3, and W4 plots consumed the same amount of soil water; soil at FC before seeding and at PWP when all irrigation was terminated. The root depth of different species and soil water content change of each plot should be determined if more accurate value of WUE is to be obtained. However, since forage yield was the primary factor contributing to WUE (Neal et al., 2011), WUE data in this work could still provide producers information about how differently annual forages used water under variable irrigation regimes.

Quality

Our findings indicated that when water stress occurred, forage nutritive value generally increased (higher CP%, lower NDF% and ADF%). These results were partly in agreement with Jensen et al. (2003) who found a higher CP content as water availability decreased but NDF didn't show a consistent trend across water availability. Higher CP content under water stress was also confirmed by Rostamza et al. (2011) and Mustafa Tahir et al. (2014). One possible reason for the increased CP percentage could be due to a higher N level and availability in the dry soil since CP% in forage is strongly impacted by available soil N (Buxton et al., 1996). Moreover, dilution effect of higher crop yield under W1 also resulted in a lower CP content compared to W2. Our results were in contrast to Montgomery (2009) who reported that CP content had no significant difference for hybrid corn between well watered (100ET) and drought stress (50ET) treatments and in addition, 50ET increased both ADF and NDF content significantly compared to 100ET.

AL outcompeted AC3 and AC4 groups in forage quality due to its higher CP and lower NDF (Barnes et al., 2003). AC4 had lower quality than AC3 because warm season grasses generally contained lower CP levels and their leaves had a higher proportion of highly lignified and less-digestible tissues than cool season grasses (Barnes et al., 2003), as shown by less CP, greater ADF and NDF content for AC4 than for AC3 in our findings.

Annual ryegrass was the species with the best forage quality within AC3 group. The potential of annual forage to produce high quality forage has been reported by Kallenbach et al. (2003) as well. Teff had the highest CP% among AC4 grasses, 10.5%, although this value was much lower than what Saylor (2017) reported for greenhouse-grown teff. This was because teff was harvested at anthesis in our research while Saylor (2017) harvested it before seed head development and CP decreased with advanced maturity (Contreras-Govea, and Albrecht, 2006). In addition to a later harvest, teff was seeded and grew in summer when temperatures were high in our study while greenhouse temperature was maintained at 24.6 °C for Saylor (2017) and forage grown under high temperature had lower quality than under cooler temperature (Barnes et al., 2003). The highest CP% went to chickling vetch within the AL group, 19.7%. Similar CP content of chickling vetch was also concluded by Karadag and Buyukburc (2004).

The NRC (2001) suggested that forage with no less than 15% CP maintain high-producing dairy cows on grazed pastures. Based on our findings, chickling vetch, field pea, crimson clover and annual ryegrass could satisfy the CP requirement of high-producing dairy cows. Both ADF and NDF values obtained were of acceptable levels (NRC 2001).

Conclusions

Yield decreased as water stress increased while forage quality was improved (lower ADF% and NDF%) from full season irrigation (W1) to late season cutoff (W2).W1 and W2 produced no significant difference in forage yield when annuals were early-summer seeded. Thus, when irrigation water is limited, W2, rather than W1, could be applied to allow reasonably good production and better quality. However, summer seeding of annual forage after winter triticale is not recommended in a Mediterranean climate when no irrigation (W4) or early season cutoff (W3) is applied.

The effect of irrigation cutoff season differed among annual forage species and functional groups. Annual warm season grass (AC4) group had the highest yield and WUE irrespective of irrigation treatments while annual legume (AL) had the best quality among AC4, AL and annual cool season grass (AC3) group.

Within the AC3, oat consistently outcompeted others in yield under irrigation. Within AL, different species had comparable yield to each other across irrigation treatments and years. Radish outyielded other brassicas when irrigation was applied. Sorghum-sudan seemed to be the best species in yield within AC4 or when twenty species were compared together based on its yield performance under all irrigation regimes. Most summer seeded annuals needed protein supplement when being grazed and annual ryegrass, chickling vetch and teff had the greatest CP% within AC3, AL and AC4, respectively.

In summary, raising fall seeded winter triticale can produce high quantity and decent quality forage. In the same time with matching species to water availability, summer seeded annuals after winter triticale can present the opportunity for late season grazing, soil cover, and increase land efficiency.

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General Conclusion

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Water supply is a major factor determining annual forage response. DM yield decreased while forage quality increased (higher CP%, lower ADF% and NDF%) when water stress occurred. Water use efficiency (WUE) generally increased under drought but it was mainly determined by forage yield. Full season irrigation (W1) and late season cutoff (W2) produced no significant difference in yield in both cropping systems. Thus, W2, rather than W1, could be applied to allow good production and better quality when irrigation water is limited. However, planting annuals as a cover crop after winter triticale in a summer seeded cropping system is not recommended when irrigation water is inadequate (early season cutoff (W3) or no irrigation (W4)) in a Mediterranean-type climate.

Annual warm season grass (AC4) generally had the highest yield while annual legumes (AL) had much better quality than AC4 or the annual cool season grass (AC3) group. Species performance under partial season irrigation deficit is species-specific within each group or when twenty species were compared together in both cropping systems. There was no single “super” species that can perform best under variable moisture levels so matching annual forage species with water availability would be more applicable and achievable. However, in a summer seeded cropping system, sorghum-sudangrass is closet to meet the requirement for “super” species considering its yield performance under all irrigation regimes. Teff, annual ryegrass and chickling vetch had the highest CP content within AC4, AC3 and AL, respectively.

High production didn’t always coincide with high quality in all forage species. For summer seeded cropping system, protein supplement for most annual forage species is necessary during grazing. Producers should consider which factor is more important, yield or quality, when selecting annual forages. In the future more collaboration with breeders may improve quality characteristics for high yielding annual forage species under drought.

In summary, when matching species selection and/or cropping systems with available water and other management constraints, annual forages could show great potential to augment the perennial forage shortage in the Pacific Northwest with flexible planting dates and short growing seasons.

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