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# Cool-Season Perennial Grasses Differ in Tolerance to Partial-Season Irrigation Deficits

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## ABSTRACT

The productivity and persistence of perennial grass species and individual cultivars of tall fescue [*Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons] and orchardgrass (*Dactylis glomerata* L.) were evaluated in response to early-season irrigation termination. Twenty-five perennial grass species/cultivars were evaluated under three irrigation regimes (full-season irrigation, early cutoff, and mid-season cutoff) over 3 yr at the Intermountain Research and Extension Center in the Klamath Basin, CA, on Tule Basin mucky silty clay loam (Andaqueptic Haplaquolls) in a cool temperate climate. Forage grasses included: 10 tall fescue cultivars, seven orchardgrass cultivars, four bromegrass species (*Bromus* spp), three wheatgrass species (*Thinopyrum* spp. and *Elymus hoffmannii* K.B. Jensen and K.H. Asay), and festulolium [×*Festulolium loliaceum* (Huds.) P. Fourn.]. Tall fescue cultivars were the highest yielding under full irrigation but the most drought tolerant species, tall wheatgrass [*T. ponticum* (Podp.) Z.-W. Liu and R.-C. Wang], intermediate wheatgrass [*T. intermedium* (Host) Barkworth and D.R. Dewey], and smooth bromegrass (*B. inermis* Leyss.), performed better with an early-season irrigation cutoff. There were significant differences in stand persistence among species and cultivars. Stand density for all orchardgrass cultivars declined with each progressively earlier irrigation cutoff date. Plant population for summer active tall fescue cultivars was unaffected by irrigation cutoff date, while stand density for both summer dormant cultivars was higher with the earliest irrigation cutoff. Smooth bromegrass, tall wheatgrass, and intermediate wheatgrass stands were also improved with an early irrigation cutoff. Overall, tall fescue appeared to be the best grass species for variable irrigation water supplies—highly productive under full irrigation when water supplies are adequate, reasonable production with an early season cut-off in drought years when water is scarce, and good persistence under both full and partial season irrigation.

In the Intermountain West, United States, a range of perennial cool-season grasses are produced under irrigated conditions for both on-farm livestock grazing and hay production. Grass pasture is a prominent land-use in the West with about 1.2 million hectares of irrigated pasture in the 11 western states, comprising 14.5% of the total irrigated area (USDA-NASS, Agriculture Statistics Service, 2014). The key economic product of this land use is primarily cattle and calves. This sector is the fourth most important agricultural product in California, worth US$3.05 billion in 2013 (CDFA, 2015). However, forages are among the largest users of irrigation water in most western states.

Water deficits for irrigated forages may originate from several sources, including periodic drought, diminishing groundwater reserves, voluntary or involuntary water transfers from agriculture to cities or for environmental purposes, or decisions to irrigate other crops on-farm which are more lucrative. For example, a biological decision to enhance habitat of endangered species caused a sudden loss of irrigation water in the Klamath Basin of California and Oregon in 2001 (Cooperman and Markle, 2003). Although supplies were restored the following year, this action led to hardship for farmers and caused political and economic disruption, since many forage crops received no irrigation water that year (Doremus and Tarlock, 2008). Western climates are characterized by periodic drought which create challenges for water users, especially grazing systems. Significant droughts occurred in 1862 to 1865, killing thousands of cattle in the years following the California gold rush. Droughts were recorded in 1928 to 1934, 1976 to 1977, 1987 to 1992, 1999 to 2002, and 2007 to 2009 in California, and more recently, severe drought in 2013 to 2015 caused hardship for agriculture and all water users (CDWR, 2015).

The overwhelming majority of precipitation in the intermountain area of northern California and much of the West occurs in winter and spring; therefore, summer and fall irrigation is critical for full yields. However, this is not possible under water-restricted conditions. One management option during water deficit is to completely fallow crops. However, complete fallowing has profoundly negative economic, social, and environmental consequences to the community; reducing employment and economic viability, especially for those agriculturally-dependent counties with low incomes (Lee and Sumner, 2001). Implications are not only social but

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**Abbreviation:** ET, evapotranspiration.

environmental: weed intrusion and wind erosion from parched agricultural fields occurred during the Klamath Basin dry-down (H. Carlson, Intermountain Research and Extension Center, personal communication, 2002). Thus, partial-year production that allows for at least reduced yields as well as plant cover may be highly preferred over complete fallowing.

There are significant questions as to the most appropriate forage species and cultivar that can withstand periodic droughts. Herbage yield in perennial forages is proportional to evapotranspiration (ET) (Hanks et al., 1977), but species differ in water demand and response to deficits (MacAdam and Barta, 2007). Alfalfa (*Medicago sativa* L.) is considered highly conducive to deficit irrigation strategies (Orloff and Hanson, 2008; Hanson et al., 2009), but cool season grasses differ significantly from alfalfa in rooting patterns, growth patterns, and water demand over the season. Additionally, growth and drought response differs significantly between species of grasses, and between cultivars within grass species (Frank et al., 1996; Neal et al., 2009). Drought responses include tolerance, avoidance, and resistance mechanisms (Bittman and Hunt, 2013). The primary survival strategies used by perennial grasses to tolerate drought consist of delayed dehydration by increasing water uptake during growth and reducing water loss from the plant (Volaire et al., 2009). Drought resistant cultivars often invest in a deep, dense rooting system to maintain water uptake despite dry soil.

Limited information exists comparing the relative drought tolerance of perennial grass species and cultivars under irrigated conditions in the western United States. Additionally, most studies have assessed grass performance under moisture-limiting conditions where less than full ET was supplied over the growing season by maintaining soil moisture at predetermined soil moisture deficits (Sheaffer et al., 1992; Asay et al., 2001, Jensen et al., 2001; Waldron et al., 2002; Neal et al., 2009;). However, the more likely deficit irrigation scenario in much of the West is partial-season irrigation, where irrigation continues until water supplies are exhausted and then irrigation ceases for the remainder of the growing season rather than full-season irrigation at a deficit level. Loss of stand is often the greatest risk associated with these deficit irrigation strategies, with long-term production implications for farmers. At present, few studies have evaluated partial-season irrigation for forage grasses likely to be common in the Intermountain West.

Irrigation water supplies in the West are highly variable and uncertain due to drought and competition for resources from other users. This uncertainty is likely to intensify due to rapid growth of competing uses, weather patterns, and climate change. Research is needed to identify grass species or cultivars that will perform well under full irrigation in years when water supplies are ample, yet withstand drought periods with early-season irrigation termination. Therefore, the objectives of this research were to determine the degree of sensitivity of different forage grass species and cultivars to partial-season irrigation in terms of yield and stand persistence.

## MATERIALS AND METHODS

A field experiment with a range of cool-season perennial forage grasses was conducted at the University of California Intermountain Research and Extension Center located in the

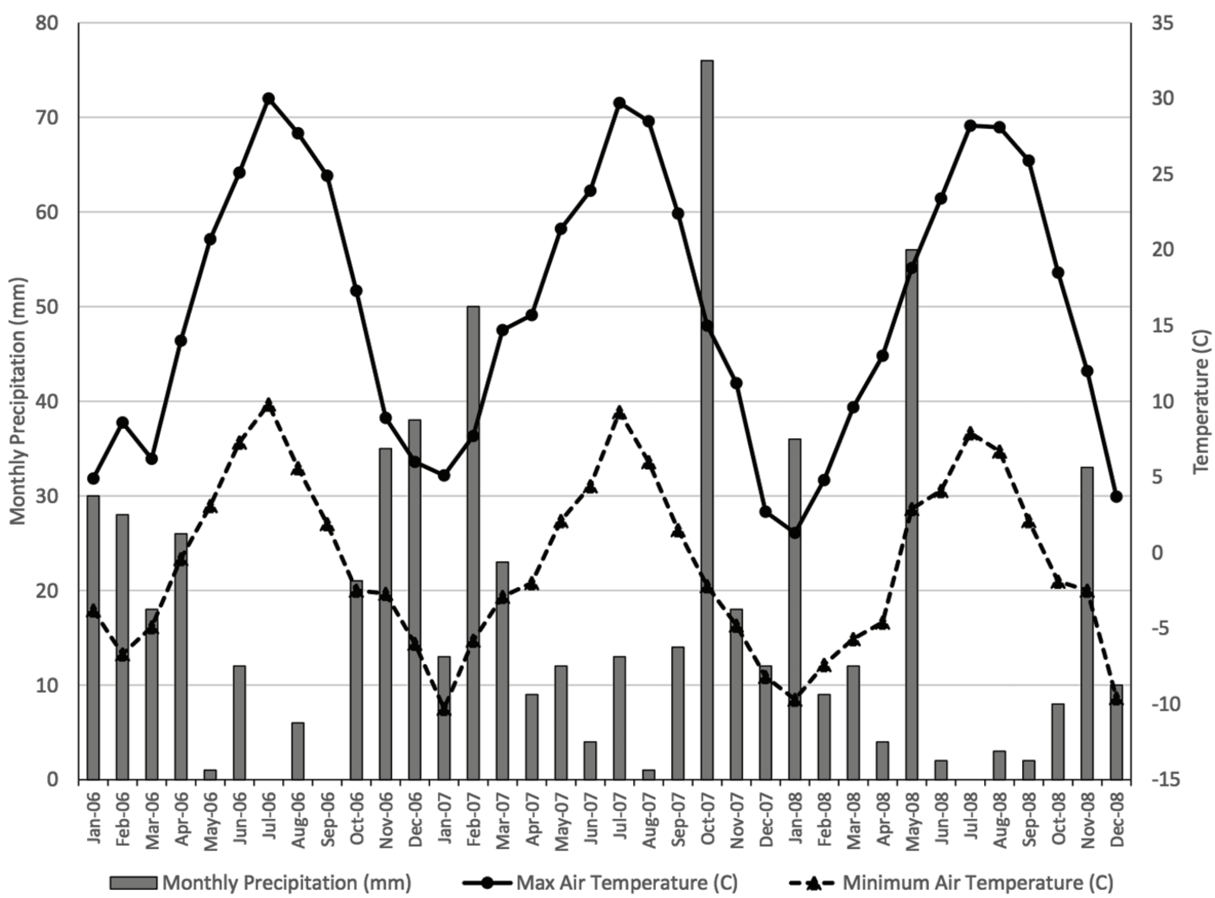


Fig. 1. Monthly precipitation and mean monthly maximum and minimum temperatures for Tulelake, CA, during the experimental period.

Klamath Basin (41°57′ N, 121°28′ W) area of northern California from 2005 to 2009. The elevation was approximately 1200 m and the soil type at the site was a Tule Basin mucky silty clay loam. Rainfall and temperature patterns were typical of those throughout the Intermountain West (Fig. 1), with cold winters and warm, dry summers. Grasses were drill-seeded at appropriate seeding rates (Table 1) for each species on 31 May 2005 using a cone seeder (Kincaid Equip. Manufacturing, Haven, KS). Twenty-five perennial grass cultivars were evaluated: 10 tall fescue cultivars, 7 orchardgrass cultivars, 4 bromegrass species, 3 wheatgrass species, and 1 festulolium cultivar (Table 1). A range of tall fescue and orchardgrass cultivars were evaluated because these are the two primary grass species produced in the region. Tall fescue cultivars included 8 summer-active and 2 summer-dormant cultivars. The experiment was fully irrigated matching potential ET for the entire 2005 growing season using solid-set sprinklers so that the grasses would be well established before imposing the deficit irrigation treatments.

A randomized complete block two-way factorial design with a split plot treatment structure was used, with irrigation treatment as the main plots and pasture grass species/cultivar as the subplots. Treatments were replicated four times. Each plot measured 1.5 by 6 m. Three irrigation regimes were evaluated: normal full-season irrigation, early irrigation cutoff (late May, before first harvest), and mid-season irrigation cutoff (mid-July, before second cutting). Irrigation treatments were designed to mimic observed seasonal water deficits, which tend to be greater later in the summer. Initial irrigations up to the earliest cutoff were applied using solid set sprinklers. Once the deficit irrigation treatments were initiated in 2006, 2007, and 2008, subsequent irrigations were applied using a traveling irrigation boom with a hose reel (ABI Irrigation, Villa Rica, GA), and nozzles spaced at 0.91 m. This enabled us to apply precise amounts of water uniformly while only irrigating selected treatment areas, avoiding the potential for lateral surface movement or overspray of irrigation water into deficit irrigated plots. Sufficient irrigation water was applied to satisfy full potential crop ET up to the point of irrigation cutoffs. Potential crop ET was considered equal to reference ET, and monitored using a California Irrigation Management Information System weather station (http://www.cimis.water.ca.gov/) located less than 1 km from the study site. Nitrogen was the only deficient nutrient with 88 kg N ha$^{-1}$ applied as urea in the spring and 55 kg N ha$^{-1}$ following each cutting.

Plots were harvested three times each year from 2006 to 2008 in early June, late July, and mid-September. The center 0.9 m of each plot was harvested using a flail-type forage harvester (Carter Manufacturing Company Inc., Brookston, IN). Wet forage yield for each plot was adjusted to dry weight by collecting subsamples at harvest and drying at 60°C for 48 h to calculate dry matter percentage. All plots were harvested a final time in June 2009 to assess carry-over effects of the irrigation treatments. We assessed three variables: total yield obtained by summing across harvests each year (2006–2008), first cut yield after the imposition of drought treatments

Table 1. Common name, scientific name, cultivar, and sowing rate for the grass species evaluated for yield and stand persistence under partial-season irrigation in Tulelake, CA.

| Common name | Scientific name | Cultivar | Sowing rate |
|---|---|---|---|
| | | | kg ha$^{-1}$ |
| Pasture bromegrass | *Bromus catharticus* Vahl var. *elatus* (E. Desv. Planchuelo) | Bareno | 34 |
| Bromus parodii† | *Bromus bonariensis* Parodi and J.H.Camara | VNS | 34 |
| Alaska brome | *Bromus sitchensis* Trin. | Hakari | 39 |
| Smooth bromegrass | *Bromus inermis* Leyss. | Manchar | 34 |
| Festulolium | ×*Festulolium loliaceum* (Huds.) P. Fourn. | Barfest | 39 |
| Orchardgrass | *Dactylis glomerata* L. | Century | 18 |
| Orchardgrass | | Command | 18 |
| Orchardgrass | | Extend | 18 |
| Orchardgrass | | Icon | 18 |
| Orchardgrass | | OG023G | 18 |
| Orchardgrass | | Pauite | 18 |
| Orchardgrass | | Seco | 18 |
| Tall fescue, SA‡ | *Schedonorus arundinaceus* (Schreb.) Dumort., nom. cons. | Arido | 18 |
| Tall fescue SA | | Baradiso | 18 |
| Tall fescue SA | | Barcarella | 18 |
| Tall fescue SA | | BarOptima PLUS E34 | 18 |
| Tall fescue SA | | Drover | 18 |
| Tall fescue SA | | Enhance | 18 |
| Tall fescue SA | | Fawn | 18 |
| Tall fescue, SD† | | Flecha MaxQ | 18 |
| Tall fescue SD | | Prosper | 18 |
| Tall fescue SA | | Tuscany | 18 |
| Intermediate wheatgrass | *Thinopyrum intermedium* (Host) Barkworth and D.R. Dewey | Oahe | 18 |
| Tall wheatgrass | *Thinopyrum ponticum* (Podp.) Z.-W. Liu and R.-C. Wang | AGRAE 101 | 18 |
| Hybrid wheatgrass | *Elymus hoffmannii* K.B. Jensen and K.H. Asay | Newhy | 18 |

† Commercial seed supplier referred to this entry as Bromus parodii and more commonly known as such in industry.

‡ SA = summer-active tall fescue; SD = summer-dormant tall fescue.

Table 2. Effect of irrigation deficits on total annual yields of various cool-season grass species, Tulelake, CA (average of 2006–2008).

| Species | Irrigation treatment: Full-season irrigation | Mid-season cutoff | Early-season cutoff | Irrigation mean | LSD ($P \leq 0.05$) among irrigation treatments |
|---|---|---|---|---|---|
| | Mg ha$^{-1}$ | | | | |
| Alaska bromegrass | 12.3bc† | 10.7ab | 6.2de | 9.7bd | 2.2 |
| Bromus parodii | 13.0b | 10.4bc | 6.4de | 9.9bc | 2.0 |
| Festulolium | 7.4d | 7.5e | 5.0f | 6.6f | 0.9 |
| Hybrid wheatgrass | 13.4b | 9.9bcd | 7.2cd | 10.2b | 1.3 |
| Intermediate wheatgrass | 7.4d | 10.4bc | 9.3a | 9.0de | 2.8 |
| Orchardgrass | 13.2b | 9.5cd | 6.8d | 9.8b | 0.5 |
| Pasture bromegrass | 10.6c | 7.4e | 3.9g | 7.3f | 1.7 |
| Smooth bromegrass | 10.8c | 10.0bc | 8.2b | 9.6be | 1.3 |
| Tall fescue-summer active | 15.6a | 11.7a | 8.2bc | 11.8a | 0.6 |
| Tall fescue-summer dormant | 12.8b | 8.8d | 6.1e | 9.2cde | 1.7 |
| Tall wheatgrass | 7.4d | 11.1ab | 8.1bc | 8.9d | 1.8 |
| Mean | 11.3 | 9.8 | 6.9 | 9.3 | 0.6 |

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

Table 3. Effect of irrigation deficits on second and third-cut yields of cool-season grass species, Tulelake, CA (average of 2006–2008).

| Species | Irrigation treatment: Full-season irrigation | Mid-season cutoff | Early-season cutoff | LSD ($P \leq 0.05$) among irrigation treatments |
|---|---|---|---|---|
| | Mg ha$^{-1}$ | | | |
| Alaska bromegrass | 6.0c† | 4.5abc | 0.4de | 1.4 |
| Bromus parodii | 6.7bc | 5.2ab | 1.1ac | 1.6 |
| Festulolium | 3.5d | 3.2de | 0.6cde | 1.2 |
| Hybrid wheatgrass | 6.8bc | 3.6cde | 0.7ce | 1.4 |
| Intermediate wheatgrass | 1.8e | 2.8e | 0.8cd | 1.0 |
| Orchardgrass | 7.2b | 3.8cd | 0.7cd | 0.9 |
| Pasture bromegrass | 6.9bc | 4.1cd | 0.9bcd | 1.5 |
| Smooth bromegrass | 3.8d | 2.9e | 0.3e | 0.9 |
| Tall fescue-summer active | 8.3a | 5.3a | 1.2a | 0.5 |
| Tall fescue-summer dormant | 7.2bc | 4.3c | 1.2ab | 0.8 |
| Tall wheatgrass | 2.4d | 4.3bc | 0.9ac | 0.4 |
| Mean | 5.5 | 4.0 | 0.8 | 0.7 |

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

(2007–2009), and the sum of second and third harvest yields after treatments began (2006–2008). Persistence was assessed in early spring of 2009 before regrowth after winter affected ground cover. Stand scores were made by visually estimating the percentage of the nine drill rows per plot occupied by plants, with each full row representing ~11% stand, in a manner similar to that done by Brummer and Moore (2000).

We initially tested a full model to determine differences for the main effects of year, irrigation treatment, cultivars, and their interactions on yield and persistence. Data were analyzed as a randomized complete block design with a split-plot treatment structure, with irrigation treatments as main plots and cultivars of the various species as subplots across years. Irrigation treatments, cultivar, and year were considered fixed effects; replications were random. We initially assessed differences among species averaged across the cultivars within species. Because many species were only represented by one cultivar, but others by multiple cultivars, this analysis was unbalanced. We considered summer-active and summer-dormant tall fescue as separate species because of the pronounced differences in their growth pattern. Based on the presence of interactions between variables, we subsequently analyzed the differences among species for each irrigation treatment and differences among irrigation treatments by species. We also analyzed differences among cultivars for tall fescue and orchardgrass by irrigation treatment. For yield variables, analyses were conducted across the set of years indicated in the previous paragraph. Analyses were conducted using PROC MIXED in SAS statistical software package (SAS Institute, 2001; Littell et al., 1996). Mean separations were based on Fisher's protected LSD (Steel and Torrie, 1980). The statistical significance of results was assessed at the 5% probability level unless otherwise indicated.

## RESULTS AND DISCUSSION

### Overall Irrigation Effects on Yield

Total forage yield differed among years, irrigation treatments, and species over the 3 yr. All two- and three-way interactions among these main effects were also present. Part of the difference among years was due to the first cutting in 2007 and 2008, but not 2006, being affected by the irrigation treatments from the previous year, since irrigation treatments were imposed beginning summer 2006. In addition, significant rainfall in late

May 2008 (Fig. 1), after the last irrigation event before the first cutting, resulted in higher yield for the early irrigation cutoff treatment that year. Our primary interest was to evaluate the performance of perennial grasses over multiple years, so despite a significant year × species interaction, we focused on yield across the 3 yr of the study. The interaction was largely due to a magnitude difference caused by the large year effects mentioned previously rather than crossover differences among species.

Irrigation treatment had a major effect on forage yield. Annual yield of the full-season irrigation, mid-season cutoff, and early-season cutoff treatments across all entries averaged across the 3 yr of production (2006–2008) was 11.3, 9.8 and 6.9 Mg ha$^{-1}$ yr$^{-1}$, respectively (Table 2). Cumulative yield over the entire study by species is illustrated in Fig. 2. These results are not surprising, as moisture supply is a major determinant of cool-season grass yield across many species and environments (Smeal et al., 2005; Lauriault et al., 2005; Jensen et al., 2001; Neal et al., 2009). Previous experiments examined water applications at some percentage of full ET applied throughout the growing season. In contrast, our study examined the effect of seasonal irrigation cutoffs, which restrict irrigation to portions of the year.

In-season rainfall is grossly inadequate in this environment to supply mid- to late-summer water needs, even though temperatures are favorable for plant growth (Fig. 1). Yield was severely reduced due to partial-season irrigation in the second and third harvests after an irrigation cutoff, as plants relied solely on residual soil moisture (Table 3). Across all species/cultivars, yield for the second plus third cuttings following the early cutoff dropped to 15% of the fully irrigated plots and ranged from only 0.6 to 1.2 Mg ha$^{-1}$ (Table 3). Third cutting alone was only 3% of the fully irrigated plots (data not shown). In contrast, a mid-season irrigation cutoff averaged across species resulted in yields that were 73% of the fully irrigated. Following a mid-season irrigation cutoff, third cutting yield fell to 13% of the fully irrigated plots (data not shown).

### Forage Yield Comparison among Species

Summer-active tall fescue yielded more than all other species at the full irrigation level (Table 2, Fig. 2). Hybrid wheatgrass (*Elymus hoffmannii* K.B. Jensen and K.H. Asay), orchardgrass, Bromus parodii (*Bromus bonariensis* Parodi and J.H.Camara), summer-dormant tall fescue, and Alaska bromegrass (*Bromus sitchensis* Trin) yield was similar under full irrigation, but their cumulative yield was approximately 7.0 Mg ha$^{-1}$ less than the mean of the tall fescue cultivars. The bromegrasses, Alaska bromegrass, smooth bromegrass, and pasture bromegrass [*Bromus catharticus* Vahl var. *elatus* (E. Desv. Planchuelo)], all had similar yield, while Bromus parodii had a higher yield than smooth bromegrass and pasture bromegrass, but not higher than Alaska bromegrass. Tall wheatgrass, festulolium, and intermediate wheatgrass had the lowest yield under full-season irrigation.

The ranking of species for cumulative yield, changed with a mid-season irrigation cutoff (Fig. 2). While tall fescue was still among the highest yielding species, its yield was no longer significantly different ($p > 0.05$) from that of Alaska bromegrass or tall wheatgrass. The relative yield of smooth bromegrass, tall wheatgrass, and intermediate wheatgrass compared with the other species increased under a mid-season irrigation cutoff. This was further accentuated under the early-cutoff irrigation regime, where these three species were elevated to the highest yielding group along with summer-active tall fescue. Intermediate wheatgrass actually had the highest cumulative yield at 28.0 Mg ha$^{-1}$, compared with 24.5 Mg ha$^{-1}$ for smooth bromegrass, the next highest yielding species. These results agree with those of Smeal et al. (2005). They found intermediate wheatgrass produced more forage than any of the other grasses tested under limited irrigation, but its production rate was only about half that of the other grasses tested with full irrigation. The irrigation treatment × species interaction indicated that total annual yield of some species was more affected by irrigation cutoff than others (Table 2, Fig. 2). The yield of most species, including Alaska bromegrass, hybrid wheatgrass, Bromus parodii, orchardgrass, and tall fescue, for the early-season irrigation termination treatment was about half that of the fully-irrigated plots. While summer-active tall fescue yielded higher than summer dormant, the effect of irrigation on seasonal yield was similar for both types. Seasonal yield of these species for the mid-season irrigation cutoff was intermediate between the fully irrigated and early-season cutoff ranging from 69 to 86% of the full-irrigated plots. Pasture bromegrass was highly affected by irrigation cutoff with early irrigation cutoff yielding only 37% of the fully irrigated plots (Fig. 2). In contrast, both intermediate and tall wheatgrass yields were higher with partial-season irrigation than full irrigation. Smooth bromegrass yield was less affected by irrigation level than most other grasses; plots irrigated until mid-season yielded similar to fully irrigated plots and plots with an early cutoff only yielded slightly less. Other studies (Jensen et al., 2001) found that smooth bromegrass did not yield as well as tall fescue, orchardgrass, and meadow bromegrass (*Bromus biegersteinii* Roem. and Schult.) at higher irrigation levels, but forage production was relatively stable regardless of the amount of irrigation.

The effect of irrigation cutoff on the combined second and third cut yield also varied by species (Table 3). Summer active tall fescue was the highest yielding species when fully irrigated, and performed as well as any other species when irrigation was withdrawn early- or mid-season. However, yield for the mid- and early-season cutoff treatments was only 64 and 14% of the fully irrigated, respectively. In contrast, intermediate and tall wheatgrass yield was significantly lower than tall fescue when fully irrigated, and actually yielded more when irrigation ceased mid-season than when fully irrigated. Hybrid wheatgrass, orchardgrass, Bromus parodii, and pasture bromegrass behaved more like tall fescue in that yield declined precipitously with each earlier irrigation cutoff. These data suggest that under the arid conditions encountered in the West, all the perennial grass species evaluated, regardless of drought tolerance, had relatively low forage yield following the irrigation cutoff, which depending on the timing of the irrigation cutoff and the species, may not justify harvesting costs.

Across the three irrigation treatments, summer-active tall fescue yielded significantly more (>1.6 Mg ha$^{-1}$ yr$^{-1}$) than all other species (Table 2). While summer-active tall fescue yields declined precipitously with partial-season irrigation, it still performed well under limited water regimes. Its yield was the same or higher than less drought affected species at the mid-season cutoff and was similar to the highest yielding species at the earliest irrigation cutoff (Fig. 2). Although the presence of an irrigation treatment × species interaction was present, we were nonetheless interested in examining mean performance across the three treatments.

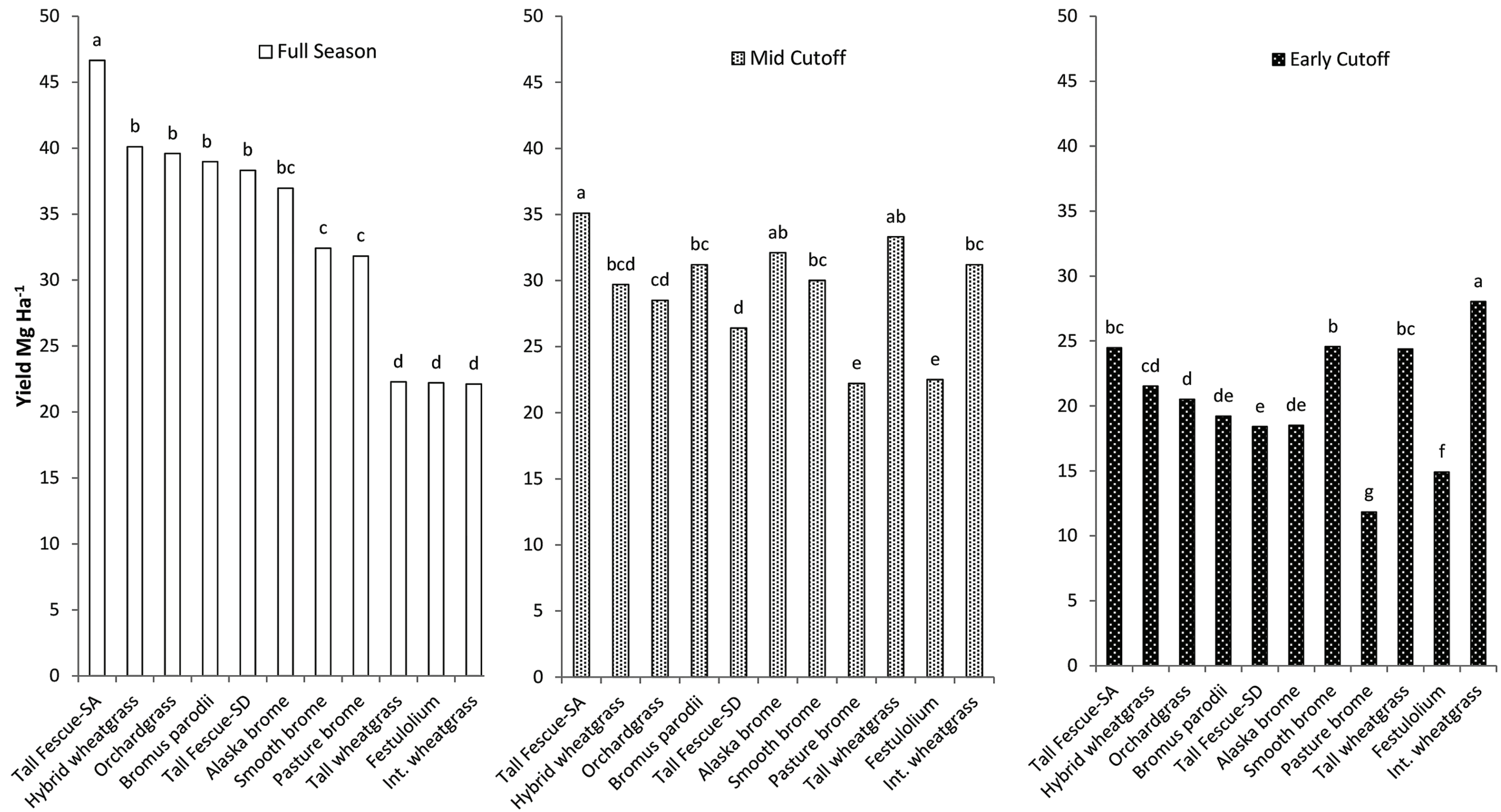


Fig. 2. The effect of irrigation cutoff timing on total cumulative yield for different perennial grass species grown in Tulelake, CA, 2006 to 2008. Species in each irrigation treatment ranked in order of yield (highest to lowest) for the full-season irrigation treatment. Bars with the same letter are not significantly different at the 0.05 confidence level at each irrigation level.

Identifying which species yields best under varied irrigation supply scenarios is important due to the increasing unpredictability of irrigation water supplies in the future, due to ever-increasing demands for water and potential climate change effects. Thus, in the future, during the life of a stand, grasses may encounter all three scenarios evaluated here. Previous studies found that tall fescue was among the highest yielding of 15 species under full irrigation in Camden, NSW Australia (Neal et al., 2009), and performed well in spite of a high percentage yield decline due to deficit irrigation (Jensen et al., 2001; Neal et al., 2009). Tall fescue rooted extensively below 40 cm and extracted more water from 45 to 75 cm than did white clover (*Trifolium repens* L.) (Burch and Johns, 1978), offering one possible reason for the superiority of this species under limited irrigation. Although the percentage decline due to irrigation cutoff was far less for tall wheatgrass, intermediate wheatgrass, and smooth bromegrass, the yield of these grasses was lower under full irrigation, making them less desirable for periods when adequate water is available for full-season irrigation.

## First Harvest Yield—Residual Effects of Irrigation Deficits

First harvest yield is an indication of crop vigor following significant water stress in the previous year. As with total seasonal yield, the effect of irrigation treatments averaged over the 3 yr varied among species (Table 4). First cutting yield of summer-active tall fescue and pasture bromegrass was highest when plots had been fully irrigated the preceding year compared with either partial-season irrigation treatment. In contrast, the yield of tall wheatgrass, intermediate wheatgrass, and festulolium was adversely affected by full-season irrigation and the first cut yield was higher if irrigation had ceased early or mid-season (Table 4). Smooth bromegrass was one of the highest yielding species for the first cut, and the yield level was nearly identical regardless of the irrigation treatment the preceding year. Sheaffer et al. (1992) also reported strong recovery of smooth bromegrass after a drought period and suggested that it may be capable of compensatory growth when rewatered. In contrast to tall fescue, first harvest yield of orchardgrass the year following the irrigation treatments was comparable between the fully irrigated treatment and the early cutoff. The mid-season irrigation cutoff averaged across all cultivars yielded approximately 0.8 Mg ha$^{-1}$ less than the full season irrigation treatment or the early cutoff. Other species, such as hybrid wheatgrass and Bromus parodii, did not show a consistent trend in response to the irrigation treatment in the previous year. First cutting yield was not indicative of total seasonal yield. Some species, primarily those well adapted to early irrigation termination, such as Alaska bromegrass, intermediate wheatgrass, smooth bromegrass, and tall wheatgrass, had high yield on first cutting but only average total seasonal yields. A previous study similarly found differences among grass species in recovery after drought, but that experiment also found that alfalfa was superior to all grass species, likely due to its deep tap-root (Neal et al., 2009).

## Forage Yield Comparison among Cultivars of Tall Fescue and Orchardgrass

Tall fescue and orchardgrass are the most widely grown species for pasture and hay in intermountain California, so we evaluated multiple cultivars of each species. There were some differences among cultivars (especially summer active and summer dormant cultivars as noted above in the section on species differences); however, differences among summer-active cultivars were minor compared with species differences (Supplemental Table S1). The ranking of cultivars was very similar across irrigation treatments and no irrigation treatment × cultivar interaction was observed. Asay et al. (2001) reported similar results. They found a 19% difference in annual yield among tall fescue cultivars but a cultivar × irrigation amount interaction was lacking. Total annual tall fescue yield in our study ranged from 12.25 to 16.61 Mg ha$^{-1}$ for the fully irrigated treatment, 9.32 to 11.80 Mg ha$^{-1}$ for the mid-season cutoff, and 5.75 to 8.83 Mg ha$^{-1}$ for the early cutoff. The two summer-dormant cultivars were the lowest yielding for all three irrigation regimes. Similar results were found in the southern Great Plains where annual and cumulative yields were significantly greater with summer-active than with summer-dormant cultivars over a 2 to 3 yr period (Bartholomew et al., 2013).

Table 4. Residual effect of previous year irrigation treatments on first cut yields for cool-season grass species, Tulelake, CA (average of 2007–2009).

| Species | Irrigation Treatment: Full season irrigation | Mid-season cutoff | Early-season cutoff | LSD ($P \leq 0.05$) among irrigation treatments |
|---|---|---|---|---|
| | Mg ha$^{-1}$ | | | |
| Alaska bromegrass | 5.8ab† | 5.6bc | 5.2bc | ns‡ |
| Bromus parodii | 5.0b | 4.6de | 4.7c | ns |
| Festulolium | 1.8d | 2.9f | 3.1de | 1.0 |
| Hybrid wheatgrass | 5.1b | 4.9cd | 5.6b | ns |
| Intermediate wheatgrass | 3.5c | 6.0ab | 6.5a | 1.1 |
| Orchardgrass | 5.3b | 4.5de | 5.3bc | 0.6 |
| Pasture bromegrass | 3.9c | 3.0f | 3.0e | 0.5 |
| Smooth bromegrass | 6.4a | 6.4a | 6.5a | ns |
| Tall fescue-summer active | 6.1a | 5.0d | 5.3bc | 0.4 |
| Tall fescue-summer dormant | 4.9b | 3.9e | 3.8d | ns |
| Tall wheatgrass | 3.6c | 5.0cd | 5.7ab | 0.9 |
| Mean | 4.7 | 4.7 | 5.0 | ns |

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

‡ ns, not significant.

Tall fescue first cut yield in the years following imposition of the irrigation treatments were affected by irrigation treatment and varied among cultivars, resulting in an irrigation treatment × cultivar interaction (Supplemental Table S1). Full-season irrigation resulted in higher first harvest yield the following year for all cultivars except Flecha MaxQ, a summer dormant cultivar.

Orchardgrass cultivars differed in total yield potential (Supplemental Table S2). Total annual yield and first harvest yield, after the irrigation treatments were imposed, differed among orchardgrass cultivars, but unlike the results of Jensen et al. (2001), no irrigation treatment × cultivar interaction was observed. They also found that the dryland cultivar Paiute outyielded the combined means of the other orchardgrass cultivars at the lower two water levels. However, their study evaluated different irrigation levels rather than the effects of partial-season irrigation possibly accounting for the irrigation treatment × cultivar interaction we did not observe. Additionally, we found no irrigation × cultivar interaction in the first cutting yield following irrigation cutoff the previous year.

## Stand Persistence

Due to the high cost of re-establishing a forage stand, stand persistence under partial-season irrigation is typically a more important factor for producers than yield losses. Initial stand ratings at the start of the trial were excellent, near 100% for all species and cultivars before imposition of the irrigation treatments. Percent stand (as a percentage of full cover) was evaluated in 2008 and 2009, but only 2009 data are presented, as results between the 2 yr were similar and 2009 data reflected the ultimate stand after 3 yr of partial-season irrigation. Species differed in stand persistence, and the effects of irrigation deficits on stand persistence varied by species as indicated by the species × irrigation treatment interaction (Table 5).

Stands of summer-active tall fescue cultivars and smooth bromegrass were largely unaffected by early irrigation termination (Table 5). The stand density of these grasses was equal to or exceeded that of other grasses at each of the three irrigation treatment levels.). There was no irrigation treatment effect on stand density for any of the eight summer-active tall fescue cultivars evaluated. Stand density of the two summer-dormant tall fescue varieties was lower than that of the summer-active cultivars (Table 5). In addition, stand density of summer-dormant cultivars was higher for the early irrigation cutoff treatment compared with either full-season irrigation or a mid-summer cutoff, suggesting that the summer-dormant types do not tolerate full-season irrigation (Table 5). However, even with partial-season irrigation treatments, stand persistence of these two summer dormant lines was significantly ($P < 0.05$) less than most of the summer active cultivars (data not shown). Summer irrigation likely prevents these grasses from fully entering a dormant state, which then reduces the survival value that the summer dormancy trait would be expected to impart to these cultivars. In general, our data do not suggest greater drought tolerance, in terms of yield or stand persistence, for summer-dormant tall fescue types, but the range of varieties was quite limited in this study. Therefore, further research on best management practices for a wider range of summer-dormant cultivars is warranted, as they are likely to be different from summer-active cultivars.

All orchardgrass cultivars declined with limited irrigation, with the earlier irrigation cutoff impacting stands more than mid-season termination. In general, orchardgrass cultivars had significantly lower survivability (34%) under the most severe water deficit, vs. 86 to 95% survivability with the summer-active tall fescues, bromegrasses, and tall wheatgrass cultivars (Table 5). The orchardgrass cultivars least affected by early irrigation cutoff were Paiute, often considered a well-adapted dryland cultivar (Jensen et al., 2001) and Seco (data not shown). Seco was selected for its stand persistence without irrigation (J. Dodd, Forage Genetics International, personal communication, 2005).

The effect of irrigation cutoff date on stands varied among bromegrass species, having little effect on Alaska and pasture bromegrass (Table 5). Stand declined with early irrigation cutoff for Bromus parodii, but increased for smooth bromegrass. Similarly, irrigation cutoff effects on stand density varied for the different wheatgrass species (Table 5). Intermediate and tall wheatgrass had improved stands under partial-season irrigation, while hybrid wheatgrass stand density was greatest under full irrigation and declined with early irrigation cutoff. Like orchardgrass, festulolium did not

Table 5. Effect of irrigation deficits on final stand rating of cool-season grass species, Tulelake, CA (2009, after 3.5 yr of production).

| Species | Irrigation treatment: Full-season irrigation | Mid-season cutoff | Early-season cutoff | LSD ($P \leq 0.05$) among irrigation treatments |
|---|---|---|---|---|
| | % Stand | | | |
| Alaska bromegrass | 79abc† | 80ab | 70cd | ns‡ |
| Bromus parodii | 64cd | 48d | 41e | ns |
| Festulolium | 69bcd | 69bc | 30e | 11.1 |
| Hybrid wheatgrass | 64cd | 58cd | 65d | ns |
| Intermediate wheatgrass | 16f | 91a | 79bc | 7.5 |
| Orchardgrass | 60d | 53d | 34e | 8.4 |
| Pasture bromegrass | 76abc | 74b | 73cd | ns |
| Smooth bromegrass | 86a | 91a | 95a | ns |
| Tall fescue-summer active | 82ab | 88a | 88a | 5.2 |
| Tall fescue-summer dormant | 43e | 54d | 68d | 16.0 |
| Tall wheatgrass | 26f | 78b | 86ab | 23.4 |
| Mean | 60 | 71 | 66 | 6.0 |

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

‡ ns, not significant.

tolerate early irrigation termination and suffered stand loss with early irrigation termination.

## CONCLUSIONS

Ideally, producers would prefer a perennial grass that is highly productive in years when there is adequate water for full irrigation, yet still survives and produces reasonably well in drought years when irrigation supplies are limited. Of the cool-season grass species we evaluated, tall fescue clearly comes the closest to satisfying these multiple objectives. Summer-active tall fescue cultivars yielded higher than any other species under full irrigation, and although its total seasonal yield decreased to a greater degree than some other grasses due to water deficits, its yield under partial-season irrigation was still among the highest. Grasses recognized for their drought tolerance, such as smooth bromegrass and intermediate and tall wheatgrasses, did perform well under deficit irrigation but generally no better than tall fescue. Summer-active tall fescue stand persistence was unaffected by early-season irrigation termination under the conditions of this study. However, the two summer-dormant tall fescue cultivars did not perform well. The adaptive advantage of summer dormant grasses, which can typically survive no rain or irrigation throughout the summer, suggests that further evaluation of the optimal management of these grasses should be undertaken, particularly as irrigation possibilities become more limited in the future. While small differences were observed in the performance of individual cultivars of summer-active tall fescue and orchardgrass, there was no irrigation treatment × cultivar interaction for either species, suggesting that species selection is far more important than cultivar selection when selecting a perennial grass for production under variable irrigation water supplies.

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