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RESEARCH ARTICLE

Assessment of Asian *Festuca rubra* germplasm for potential to improve rangeland sustainability in the western United States

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Abstract There is a need for drought tolerant grass germplasm for use in wildfire control on degraded landscapes of western US rangelands. In 2006, multinational plant expeditions collected eight fine-leafed *Festuca rubra* L. ($2n = 6x$–$8x$) accessions from the harsh semi-arid rangelands of Kyrgyzstan (KGZ) and the People's Republic of China (CHN) that may have potential for use in western U.S. rangelands. Morphological and marker-based genetic analyses compared these collections with nine commercial cultivars, and four previously described high performance KGZ *F. valesiaca* Schleich. ex Gaudin subsp. *valesiaca* plant introductions in the high desert of the U.S. Great Basin. Initially, accession morphology was evaluated over 3 years at Blue Creek, UT for relative vigor, height, width, total biomass, persistence, and seed yield. Subsequently, a subset of the *F. rubra* accessions and checks were evaluated at three locations (Malta, ID, Blue Creek, UT, and North Logan, UT) over 2 years. All entries differed for all traits over years and locations in both trials, and CHN PI 659984 was consistently the best performing *F. rubra* entry examined. Marker-based genetic comparisons differentiated the *F. rubra* from the *F. valesiaca* accessions and the *Festuca* checks examined, and the *F. rubra* accessions based on ploidy and geographic origin. Because the *F. rubra* accessions examined were erect (25.5–76.4 cm), green during summer months, and rhizomatous with substantial seed fecundity under harsh semi-arid growing conditions, they have potential for inclusion in plant improvement programs for increased sustainability and wildfire control of western U.S. rangelands.

Keywords AFLP · *Festuca rubra* · Genetic difference · Molecular markers · Morphology · Rangeland productivity

Introduction

Rangeland wildfires are becoming increasingly frequent and widespread worldwide (Pechony and Shindell 2010). Wildfire control and post-fire rehabilitation of rangelands in the semi-arid western U.S. has received considerable attention (Clements et al. 2009) given the substantial economic and environmental costs of wildfires (Dunn 2003; Mackes et al. 2007). Various plant species and landscape or "greenstripping" patterns have been proffered for use in modifying fire escalation and behavior (Finney 2001, Finney et al. 2007; Manzello et al. 2006). Plant species that enhance ecological function, possess salinity,

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drought, and heat tolerance, and remain green throughout the summer are particularly amenable for use in greenstripping on western U.S. rangelands (Monsen 1994; Pellant 1994).

The large and genetically variable genus *Festuca* of the Poaceae family houses approximately 450 grass species in nine subgenera that are found worldwide from tropical to alpine environments (Clayton and Renvoize 1986). The *Festuca* subgenus *Festuca* is the largest of these subgenera and contains the economically-important turfgrasses known as "fine fescues", which are characterized by their fine and very narrow (less than 1 mm) leaves (Beard, 1973). Fine fescues can be subdivided into two botanical complexes (aggregates), Rubra and Ovina, which are often cytologically difficult to differentiate (Vinall and Hein 1937; Pavlick 1984). The Rubra complex species are rhizomatous, morphologically diverse, polyploid, and outcrossing. Historically, this complex has consisted of *F. heterophylla* Lamarck and three *F. rubra* subspecies [subsp. *commutata* (Thuill.) Nyman, subsp. *litoralis* (G.F.W. Meyer) Auquier, and subsp. *rubra* Gaudin] (Darbyshire and Pavlick 2007; Ruemmele et al. 2003), while other *F. rubra* subspecies have more recently been cited by St. John et al. (2012). The Ovina complex includes seven non-creeping species, *F. ovina* L. (sheep fescue; 2*x*), *F. valesiaca* Schleich. ex Gaudin (Volga fescue; 2*x*–10*x*), *F. filiformis* Pourr. (hair fescue; 2*x*), *F. idahoensis* Elmer (Idaho fescue; 4*x*), *F. roemeri* (Pavlick) E. B. Alexeev (Roemer's fescue; 4*x*–6*x*), *F. trachyphylla* (hard fescue; 6*x*), and *F. viviparoidea* Krajina ex Pavlick subsp. *viviparoidea* (viviparous fescue; 4*x*–6*x*) (Pavlick 1984; Darbyshire and Warwick 1992; Arndt 2008).

Fine-leaved *Festuca* grass species can possess drought and shade tolerance and adaptation to infertile acid soils (pH 5.5–6.5) in cool-humid and semi-arid regions, but are not necessarily heat tolerant (Hanson 1972; Hanson et al. 1969; Beard, 1973; Ruemmele et al. 1995). They are often considered for low maintenance turf applications (cultured and roadside) and establishment of pastures in poorly drained soils, yet respond well to nitrogen fertilization (Beard 1973; Meyer and Funk 1989). Given their inherent tolerance to abiotic stresses (Ruemmele et al. 1995), they may have potential for use in greenstripping in the western US.

Collection of fine fescue grasses from areas of origin has provided genetic resources needed for targeted germplasm enhancement (Ruemmele et al. 2003). Thus, in 2006, two multi-national plant expeditions collected eight fine-leafed *F. rubra* L. accessions from fire prone, heavily grazed semi-arid rangelands of Kyrgyzstan (KGZ) and the People's Republic of China (CHN) (Johnson 2006a, b). These KGZ (4) and CHN (4) *F. rubra* ($2n = 6x$–$8x$) collections were evaluated herein to determine their genetic relatedness and agronomic potential for use in semi-arid western US rangelands. The morphology of these *F. rubra* collections were initially compared to eight commercial cultivars ($2n = 2x$, $6x$, $8x$), and four previously described KGZ *F. valesiaca* (2*x*) plant introductions (Ma et al. 2014) at a single-location, multi-year field trial (Experiment 1) in a high desert region of the U.S. Great Basin ($\sim$1400 m elevation). The genetic relatedness of these accessions and commercial cultivars was also evaluated using amplified fragment length polymorphism (AFLP) markers. Four accessions that represented the range of morphological variation present in Experiment 1 were then further evaluated in a second trial (Experiment 2) to assess their performance in three geographically diverse high desert locations over 2 years. If agronomic potential exists among these *F. rubra* collections, then breeding for drought/heat tolerant, erect, late flowering, wildfire resilient genotypes adapted to western U.S. growing conditions could result in plant types for rangeland applications (e.g., greenstrips and restoration) in Great Basin desert regions.

Materials and methods

Germplasm

We use herein the general taxonomic treatment of Catalán et al. (2004) and that of Barkworth et al. (2007) because of their historical context to North American flora and their recognition of worldwide *Festuca* species that have been introduced to the North American continent. However, Markgraf-Dannenberg's treatment of the Flora of Turkey indicates that *F. ovina* L. does not exist in Turkey (Markgraf-Dannenberg 1980) and perhaps not in the Middle-East (Wilkinson and Stace 1991). Therefore, we classified the *F. ovina* accessions with Middle-Eastern or Asian origins received from the U.S. Department of Agriculture, Agricultural Research Service, Plant Genetic

Resources Unit as identified in its Genetics Resources Information Network (GRIN; http://www.ars-grin.gov) as *F. valesiaca* according to Arndt (2008).

The seven *Festuca* species evaluated (20 entries total) for morphology and DNA genotyping in Experiment 1 were obtained from commercial [Granite Seed Co., Lehi, UT (GSC)] and public [U.S. National Plant Germplasm System (GRIN) and Utah State University (USU)] sources (Table 1). The commercial *Festuca* species checks and the *F. valesiaca* and *F. rubra* accessions examined were chosen based on their known or putative taxonomic relationships with *F. rubra* and collection site similarities. The commercial cultivars Manhattan 4 (*Lolium perenne* L.), Coronado [*Schedonorus arundinaceus* (Schreb.) Dumort. (syn. *Festuca arundinacea* Schreb.), nom. cons.], Black sheep (*F. ovina* L.), Cascade [*F. rubra* L. subsp. *commutata* (Gaudin) Markgr.-Dann.], Dawson E (*F. rubra* L. var. *littoralis* Vasey ex Beal; syn. *F. rubra* L. subsp. *densiuscula* Hack. ex Piper), Shademaster (*F. rubra* L. subsp. *rubra*), Durar [*F. trachyphylla* (Hack.) Krajina; synom. *F. lemanii* T. Bastard], and Scaldis (*F. trachyphylla*) were used as checks. *Festuca rubra* plant introductions (PI) were collected from overgrazed arid sites in 2006 near Naryn (41°43′59″N 75°27′2″E; PI 659946), Ysyk-Kol (42°10′58″N 78°0′28″E; PI 659899), and Chuy (42°11′34″N 73°45′22″E; PI 659950, PI 659954) KGZ, and Qinghai (35°N 96°E; PI 659984) and Inner Mongolia (Nei Mongol Autonomous Region near Xilinhot City, 43°54’60″N 115°57′30″E; PI 659965, PI 659966, and PI 659981) CHN (Johnson 2006a, b). The *F. valesiaca* accessions were chosen based on their superior performance for agronomic traits (Ma et al. 2014) and originate from the same regions in Kyrgyzstan [Naryn (PI 659923 and PI 659932) and Chuy (PI 670362 and PI 670364)]. For Experiment 2 (multiple locations), four *F. rubra* accessions demonstrating poor (PIs 659966 and 659981), average (PI 659965), and superior (PI 659984) performance in Experiment 1 were evaluated with four commercial check cultivars [Black Sheep, Shademaster, Durar, and Covar (*F. valesiaca* subsp. *valesiaca*)] and four *F. valesiaca* or *F. valesiaca* × *F. ovina* hybrids (R4S4, R4S6, R4S22, and R4S32; Table 1) developed at the Forage and Range Research Laboratory (FRRL) that were the best performing hybrid entries in a previous multi-location *Festuca* field trial (Robbins et al. 2016).

Morphological evaluation

Experiment 1 In January 2008, seeds of each accession were germinated on blotter paper, and then seedlings were established and maintained in a greenhouse in Logan, UT under environmental conditions according to Ma et al. (2014). Seedlings of each accession were transplanted in May 2008 to a field nursery at the Utah State University Blue Creek Experimental Farm in Box Elder County, UT (41°56′3.14″N 112°26′20.01″W, elevation = 1433 m) approximately 80 km northwest of Logan, UT, where the average annual precipitation during this experiment (2009–2011) was 388 mm (average 20-year precipitation = 307 mm) (PRISM 2015). The soil type was a Parley's deep silt loam (fine-silty, mixed, mesic, Calcic, Argrixerolls) having a neutral to slightly acidic pH (http://websoilsurvey.nrcs.usda.gov/). Plants were arranged in a randomized complete block design (RCBD) with five plants per plot in six replications spaced at 0.5 m within the rows and 1 m between rows (~20,000 plants/ha) with plants of PI 659984 (*F. rubra*; Qinghai, China) used as end- and side-borders. Although plants were given water at transplanting, no water or fertilizer was applied during the experiment, and weeds were controlled by hand and with a broadleaf herbicide (MEC Amine-D) according to Ma et al. (2014).

Phenotypic evaluation of all entries for above ground biomass, persistence, number of seeds per plant (evaluated 2009–2011), plant vigor, height, and width (2010–2011) were measured. Plant vigor was assessed by plot in early June using an 11-point visual rating scale from 0 to 5 (0.5 as units), where 0 = plant dead, 3 = moderate biomass with green foliage, and 5 = rich green plants with abundant biomass. Plant height (cm) and width (cm) was measured in early-middle July on each plant as the distance from the plant base (soil surface) to the top of the highest panicle at full anthesis and the diameter of the tussock ~10 cm above ground, respectively. For biomass, leaves and seed stalks were harvested ~10 cm above ground at seed maturity in late July and oven dried at 60 °C to measure above ground dry weight (g). Persistence was calculated as the number of plants alive at biomass harvest in each plot divided by the number of plants transplanted at the beginning of the experiment. The number of seeds per plant was determined by weighing the seeds of each

Table 1 Plant material evaluated in two experiments (Expts. 1 and 2) in Blue Creek, UT from 2008 to 2011 (Expt. 1) and in Malta, ID, Blue Creek, UT, and North Logan, UT from 2011 to 2013 (Expt. 2)

GRIN Accession[a]	Name	Entry type	Species	Ploidy	Source[b]	Origin(s)[c]	Expt. 1	Expt. 2
PI 632377	Manhattan 4	Check	*Lolium perenne* L.	$2x$	GSC	USA Cultivar	X	
PI 587184	Coronado	Check	*Schedonorus arundinaceus* (Schreb.) Dumort.	$6x$	GSC	USA Cultivar	X	
	Black Sheep	Check	*Festuca ovina* L.	$6x$	GSC	USA Cultivar	X	X
PI 578745	Cascade	Check	*Festuca rubra* L. subsp. *commutata* (Gaudin) Markgr.-Dann.	$6x$	USU	USA Cultivar	X	
W6 16594	Dawson E	Check	*Festuca rubra* L. var. *littoralis* Vasey ex Beal	$6x$	USU	Netherlands Cultivar	X	
	Shademaster	Check	*Festuca rubra* L. subsp. *rubra*	$8x$	USU	USA Cultivar	X	X
PI 578732	Durar	Check	*Festuca trachyphylla* (Hack.) Krajina	$6x$	GSC	USA Cultivar	X	X
PI 614892	Scaldis	Check	*Festuca trachyphylla* (Hack.) Krajina	$6x$	USU	Netherlands Cultivar	X	
PI 578733	Covar	Check	*Festuca valesiaca* Schleich. ex Gaudin subsp. *valesiaca*	$2x$	GSC	USA Cultivar; Turkey[d]		X
PI 659899	PI 659899	Rubra	*Festuca rubra* L.	$6x$	GRIN	Ysyk-Kol, Kyrgyzstan	X	
PI 659946	PI 659946	Rubra	*Festuca rubra* L.	$6x$	GRIN	Naryn, Kyrgyzstan	X	
PI 659950	PI 659950	Rubra	*Festuca rubra* L.	$6x$	GRIN	Chuy, Kyrgyzstan	X	
PI 659954	PI 659954	Rubra	*Festuca rubra* L.	$6x$	GRIN	Chuy, Kyrgyzstan	X	
PI 659965	PI 659965	Rubra	*Festuca rubra* L.	$6x$	GRIN	Inner Mongolia, China	X	X
PI 659966	PI 659966	Rubra	*Festuca rubra* L.	$6x$	GRIN	Inner Mongolia, China	X	X
PI 659981	PI 659981	Rubra	*Festuca rubra* L.	$6x$	GRIN	Inner Mongolia, China	X	X
PI 659984	PI 659984	Rubra	*Festuca rubra* L.	$8x$	GRIN	Qinghai, China	X	X
PI 659923	PI 659923	Valesiaca	*Festuca valesiaca* Schleich. ex Gaudin subsp. *valesiaca*	$2x$	GRIN	Naryn, Kyrgyzstan	X	
PI 659932	PI 659932	Valesiaca	*Festuca valesiaca* Schleich. ex Gaudin subsp. *valesiaca*	$2x$	GRIN	Naryn, Kyrgyzstan	X	
PI 670362	PI 670362	Valesiaca	*Festuca valesiaca* Schleich. ex Gaudin subsp. *valesiaca*	$2x$	GRIN	Chuy, Kyrgyzstan	X	
PI 670364	PI 670364	Valesiaca	*Festuca valesiaca* Schleich. ex Gaudin subsp. *valesiaca*	$2x$	GRIN	Chuy, Kyrgyzstan	X	
	R4S4	Hybrid	*F. val.* subsp. *val.* × *F. val.* subsp. *val.*	$2x$	FRRL	Turkey; Turkey		X
	R4S6	Hybrid	*F. val.* × *F. val.* subsp. *val.*	$2x$	FRRL	Russian Fed.; Turkey		X
	R4S22	Hybrid	*F. val.* × *F. ovina* (Covar)	$2x$	FRRL	Iran; USA cultivar		X
	R4S32	Hybrid	*F. val.* subsp. *val.* × *F. val.* subsp. *val.*	$2x$	FRRL	Russain Fed.; Russian Fed.		X

[a] Accession name from the USDA ARS Germplasm Resources Information Network (http://www.ars-grin.gov/)

[b] Source of the seed where GSC = Granite Seed Co., Lehi, UT; USU = Utah State University, Paul G. Johnson, Logan, UT; GRIN = USDA ARS Germplasm Resources Information Network; FRRL = Material was developed as hybrids at the USDA ARS Forage and Range Research Laboratory, Logan Utah (Robbins et al. 2016)

[c] Hybrid origins are designed by maternal and paternal parent, respectively

[d] Covar originated from PI 109497, which is from Turkey

plant (mechanically separated from chaff) and converting seed weight to seed number using the weight of one hundred seeds from at least three replicates for each entry.

Experiment 2 Seeds of each entry evaluated were germinated and seedlings were established and maintained as described above. Greenhouse established seedlings were transplanted in May 2011 to field nurseries at North Logan, Cache County, UT (41°47′9.27″N 111°48′51.76″W; elevation = 1392 m), Blue Creek, UT (site of Experiment 1), and at the University of Idaho L. A. Sharps Experimental Station (42°18′5.90″N 113°11′49.51″W, elevation = 1476 m) near Malta, ID approximately 176 km northwest of Logan, UT. The soil type at North Logan and Malta was a McMurdie silt loam, and a Declo silt loam, respectively (http://websoilsurvey.nrcs.usda.gov/). The average annual precipitation during the experiment (2011–2013) at North Logan, Blue Creek, and Malta was 440, 362, and 265 mm, respectively, while the 30-year averages at these locations were 484, 407, and 291 mm, respectively (PRISM 2015). Plants were arranged in an RCBD with ten (North Logan and Malta) or five (Blue Creek) plants per plot in six replications, with the same spacing and borders as in Experiment 1. No supplemental water or fertilizer was applied to plants at planting, during establishment, or at any point during the experiment and weeds were controlled as in Experiment 1.

All entries were evaluated for plant vigor, the number of seeds per plant, and persistence using methods for Experiment 1 above, and early and late biomass and early and late regrowth. Leaves and seed stalks of the first half of each plot (the first 5 plants of the plot in North Logan and Malta and the first 3 plants in Blue Creek) were harvested just before anthesis and oven dried at 60 °C to measure dry weight (g) for early biomass. The second half of the plot was similarly harvested when seeds were mature as a second, late-season measure of biomass (~30 days after the initial biomass harvest) and to estimate seed yield. Regrowth (leaf and stem growth from the first harvest to the end of the growing season in late September or early October) was harvested separately on plants from the early biomass and later biomass/seed harvests in each plot at the same height as the original harvest. Since not all entries in Experiment 1 were evaluated in Experiment 2 (i.e., ‘Covar’, R4S4, R4S6, R4S22, and R4S32), the weight of 100 seeds was not available for these entries. Therefore, for all entries in Experiment 2, seed number per plant was estimated from seed weights using the average value of 0.0574 g per 100 seeds from Experiment 1. Data for the second biomass, seed yield, and regrowth were not available for the Malta location in 2013 due to significant rabbit (*Lepus californicus deserticola* means) predation throughout the trial after the first biomass harvest.

Phenotypic trait analysis

Phenotypic data from both Experiments 1 and 2 were analyzed following the procedures outlined in Robbins et al. (2016). Briefly, trait data were analyzed separately for each experiment on per-plot means using a linear mixed models analysis. Residuals for all traits were tested for normality and homogeneity of variance, and the only data that required transformation were measurements of regrowth data at the late harvest. Although a natural log transformation improved normality (data not presented), the results are reported herein in their original scale (i.e., analyzed untransformed) for biological relevance and interpretation.

The main effects of year, location, and entry as well as the interaction effects of year by location, year by entry, location by entry, and year by location by entry were tested using a repeated measures model with compound symmetry covariance structure using year as the repeated factor and each plot as the subject with year, location, and entry as fixed effects and replication as a random effect (Robbins et al. 2016; Smith and Casler 2004). Due to missing data from rabbit predation (Malta), data for the second biomass, seed yield, and regrowth were analyzed separately by year as a RCBD using PROC MIXED in SAS software (Version 9.3 for Windows, SAS Institute, Cary, NC) employing data only from North Logan and Blue Creek in 2013. Entry means were separated using Fisher’s protected least-significant difference (LSD; $\alpha = 0.05$) test to produce lsmeans, which were used in a multivariate principal component analysis (PCA) to define relationships among entries. Differences between entry types (e.g., check vs. rubra; Table 1) were tested by comparing entry type means directly, using LSD values to declare significance. For significant entry by year interaction effects, Spearman’s rank correlation coefficients were computed on the lsmeans using PROC CORR applying the Spearman option in SAS to determine if interactions were significant due to changes in magnitude or rank. To assess the strength of associations among the traits examined, Pearson product-moment correlation coefficients were also produced to identify associated traits (Robbins et al. 2016; Székely et al. 2007).

Genotyping and AFLP-based cluster analysis

The DNA extraction and quantification, amplified fragment length polymorphism (AFLP) analysis, and cluster analysis that were used to produce a neighbor-joining tree were accomplished according to Ma et al. (2014). Leaf samples of each accession were collected and lyophilized, then total cellular DNA was extracted and the AFLP procedure was performed using the same selective primers as Jones et al. (2008): E-ACAC/M-CTAC, E-ACAG/M-CTCA, E-ACAC/M-CTAG, E-ACAC/M-CTTC, E-ACCT/M-CTCT, E-ACTC/M-CTTG, E-ACT/M-CTA, E-ACT/M-CTG, E-ATA/M-CAA, and E-AGG/M-CGC. The AFLP present/absent genotypes were used to create an outgroup rooted neighbor-joining dendrogram using the Nei and Li average pair-wise genetic distance method (Nei and Li 1979) with PAUP computer software version 4.0b10 (Swofford 2003). Internal support for cluster groupings was assessed using 1000 bootstrap replications (Felsenstein 1985). The cultivar Dawson E was excluded from the analysis because the percentage of missing data was too high even after repeated attempts to obtain sufficient data for examination.

Ploidy estimation

The determination of ploidy level of parental stocks is critical to strategic selection of parents for hybrid production in grasses (Ruemmele et al. 2003). Thus, the ploidy level of each accession was determined by cytological examination of mitotic chromosomes at metaphase following the methodology of Jensen et al. (2006). At least three samples from each accession were treated and chromosomes were visually counted (Table 1).

Results

Morphological evaluation

A significant ($P < 0.05$) main effect of year was detected for all traits in Experiments 1 and 2, except for early biomass in Experiment 2. The main effect of entry was highly significant ($P < 0.0001$) for all traits in both Experiments 1 and 2. In Experiment 1, the year by entry interaction was not significant for vigor, persistence, and width, but was highly significant ($P < 0.0001$) for biomass, height, and the number of seeds per plant. In contrast, a significant ($P < 0.01$) year by entry interaction was detected for all traits in Experiment 2. In Experiment 2, the main effect of location was not significant for vigor, but marginally significant ($P = 0.037$–0.015) for early and late regrowth, and highly significant ($P < 0.01$) for early and late biomass, persistence, and seed number. A highly significant ($P < 0.01$) location by entry interaction was detected for all traits in Experiment 2. However, since Spearman's rank correlation coefficients across locations ranked from 0.616 to 0.874 for all traits, this interaction was deemed to be based largely on magnitude rather than rank. Because of the detection of significant and numerous main effects due to year, results are presented separately by year for both Experiments 1 and 2 (Tables 1, 2). Moreover, since differences between locations in Experiment 2 were mostly based on magnitude and not rank, results are presented combined over locations for this experiment (Table 2).

Experiment 1 The mean values of all entries for all traits were significantly greater ($P < 0.05$) in 2011 than in 2010, except for persistence, which was significantly lower (Table 2). The mean of biomass in 2009 was not significantly different than in 2011, but was greater than in 2010. In contrast, the number of seeds per plant in 2009 was greater than in 2010, but lower than in 2011. Persistence was not significantly different between 2009 and 2010. On average, the *F. rubra* accessions PI 659899, PI 659946, PI 659950, PI 659954, PI 659965, PI 659966, PI 659981, and PI 659984 were not statistically different from the *Festuca* cultivar checks (i.e., Black Sheep, Cascade, Dawson E, Shademaster, Durar, and Scaldis) for any trait in any year, except for persistence in 2011 (*F. rubra* mean = 0.75 vs. *Festuca* check mean = 0.93). When compared to the best performing *F. valesiaca* accessions identified by Ma et al. (2014) (PI 659923, PI 659932, PI 670362, and PI 670364), the *F. rubra* accessions examined herein were not significantly different, except for seed yield in all years (20,527 vs. 5819 seeds/plant in 2009, 25,552 vs. 1890 seeds/plant in 2010, and 43,297 vs. 4462 seeds/plant in 2011) and

Table 2 Mean values of phenotypic traits of *Festuca* accessions and checks evaluated in Blue Creek, UT from 2008 to 2011 (Expt. 1)

Entry	2009			2010											
	Biomass (g/plant)[a]	Persistence[b]	Number seeds per plant	Biomass (g/plant)[a]	Persistence[b]	Vigor (rate 0–5)[c]	Height (cm)[d]	Width (cm)[e]	Number seeds per plant	Biomass (g/plant)[a]	Persistence[b]	Vigor (rate 0–5)[c]	Height (cm)[d]	Width (cm)[e]	Number seeds per plant
Manhattan 4	220.30	0.5	19556.0	9.14	0.5	0.4	17.6	14.8	0.0	42.18	0.5	0.9	52.6	49.0	3443.0
Coronado	262.36	1.0	19675.0	117.53	1.0	2.4	77.1	51.2	5152.5	121.00	0.9	2.3	64.3	59.1	11,041.0
Black Sheep	83.01	1.0	11,406.0	33.63	1.0	2.4	50.8	41.2	1666.6	52.67	1.0	2.3	54.4	48.8	8254.3
Cascade	73.38	0.9	8227.1	36.47	1.0	1.7	56.3	40.3	2440.7	96.95	1.0	2.8	72.2	52.3	16,092.0
Dawson E	82.05	1.0	9868.6	14.31	0.9	1.0	32.5	31.5	13.1	75.95	0.9	2.0	63.2	47.7	6779.6
Shademaster	74.40	0.9	5776.2	58.54	0.9	1.8	54.7	44.4	2815.0	160.21	0.9	3.7	74.8	64.3	9512.4
Durar	96.13	1.0	10,555.0	45.60	1.0	2.6	67.5	45.9	4737.6	119.27	1.0	3.0	81.5	55.3	6338.4
Scaldis	59.33	0.9	3503.7	24.79	0.8	1.6	36.3	31.3	149.9	42.14	0.7	1.5	55.8	39.3	3396.7
PI 659899	65.78	0.9	4901.1	15.97	0.7	1.1	25.5	22.1	0.0	59.69	0.6	1.4	70.3	51.8	2465.9
PI 659946	63.96	0.9	4570.8	36.20	0.9	2.2	51.4	38.9	1872.7	69.81	0.8	2.5	64.0	50.1	7928.6
PI 659950	78.85	1.0	4733.8	56.19	0.9	2.6	56.9	47.7	1868.2	86.64	0.7	2.7	76.4	58.9	7786.7
PI 659954	80.99	0.9	3986.0	47.44	0.9	2.2	54.4	44.0	1693.5	63.65	0.5	1.9	72.4	57.0	4553.6
PI 659965	60.73	0.9	8353.4	38.04	1.0	2.0	41.2	39.0	3008.1	55.37	0.8	2.2	56.8	51.2	2430.3
PI 659966	50.24	0.8	3185.2	24.03	0.8	1.3	28.0	31.8	0.0	47.28	0.7	1.5	51.2	50.7	224.8
PI 659981	47.40	0.8	3762.8	8.32	1.0	1.0	27.2	27.6	11.1	53.96	0.9	1.6	50.4	44.5	1566.7
PI 659984	181.65	1.0	13,057.0	108.75	1.0	2.7	73.2	52.2	6665.3	124.74	1.0	3.1	72.9	57.4	8739.4
PI 659923	58.52	0.9	19,255.0	64.57	0.9	2.8	52.2	34.5	28760.0	126.92	0.9	2.5	63.2	48.9	29,976.0
PI 659932	50.49	1.0	15,733.0	44.77	1.0	2.6	51.7	30.1	21,611.0	84.60	1.0	2.3	56.2	42.7	40,443.0
PI 670362	70.51	1.0	22,388.0	62.65	1.0	2.7	58.2	35.7	18,076.0	123.11	0.9	2.6	65.6	47.2	52,012.0
PI 670364	67.43	1.0	24,731.0	73.88	1.0	3.1	56.1	37.7	33,759.0	114.94	0.9	2.8	55.6	51.5	50,757.0
Mean	91.38	0.9	10,861.2	46.04	0.9	2.0	48.4	37.1	6715.0	86.05	0.8	2.3	63.7	51.4	13,687.1
$LSD_{(\alpha = 0.05)}$	21.49	0.13	6943.0	21.49	0.13	0.7	10.0	9.7	6943.0	21.49	0.13	0.7	10.0	9.7	6943.0
CV	30.18	18.9	71.2	59.90	19.0	35.5	21.5	27.2	85.7	32.05	20.9	31.4	16.4	19.6	65.2

[a] Dry weight of leaves and seed stalks harvested ~10 cm above ground at seed maturity

[b] Proportion of surviving plants (plants alive divided by the number of plants transplanted)

[c] Assessed as an 11-point visual rating scale from 0 to 5 (0.5 as units), where 0 = dead, 2.5 = moderate biomass, and 5 = greatest biomass

[d] The distance from the plant base (soil surface) to the top of the highest panicle at full anthesis

[e] The diameter of the tussock remaining after biomass harvest

vigor in 2010 (2.8 vs. 1.9), biomass in 2011 (112.4 vs. 70.1 g/plant), and persistence in 2011 (0.93 vs. 0.75). Only one *F. rubra* accession (PI 659984, CHN) consistently performed better or as well as the three *F. rubra* cultivar checks (Cascade, Dawson E, and Shademaster) in all 3 years (Table 1). However, the mean trait values of this accession were slightly lower than 'Shademaster' in 2011, though not significantly so for most traits. Compared to the best performing *F. valesiaca* accessions, PI 659984 exhibited significantly higher trait values for biomass, height, and width, and similar values for persistence in 2009 and 2010. However, mean persistence values for PI 659984 over years were not significantly different than the *F. valesiaca* accessions examined. Moreover, the mean seed number per plant of PI 659984 was significantly lower in all years tested. No significant difference was detected between PI 659984 and *F. valesiaca* entries for most traits in 2011.

Pearson correlation coefficients indicate that most traits were positively correlated, except for the number of seeds per plant (Table 4), and that trait correlations were generally higher in 2010 than in 2011. Seed number was correlated with vigor in 2010 ($r = 0.661$, $P < 0.01$) and biomass in 2011 ($r = 0.494$, $P < 0.05$). Likewise, vigor was highly positively correlated with all traits in 2010 ($r = 0.661$, $P < 0.01$ to $r = 0.839$, $P < 0.001$), though most correlations were not as high in 2011 ($r = 0.359$, not significant to $r = 0.846$, $P < 0.001$). The high positive correlations between biomass and height ($r = 0.872$, $P < 0.001$) and width ($r = 0.756$, $P < 0.001$) in 2010 were higher than in 2011 ($r = 0.581$, $P < 0.01$) and ($r = 0.565$, $P < 0.01$), respectively. Biomass was also correlated with persistence in both years ($r = 0.502$, $P < 0.05$ in 2010 and $r = 0.527$, $P < 0.05$ in 2011). Though persistence was correlated with all traits except seed number in 2010, significant correlations of persistence were only identified with vigor ($r = 0.650$, $P < 0.01$) and biomass ($r = 0.527$, $P < 0.05$) in 2011.

Least squares means of the traits examined were used in a PCA analysis (first three components) to assist in defining performance differences among entries across all traits (Fig. 1). While principal components (PC) 1 and 2 accounted for a combined 69.0% of the variation, PC3 provided an additional 13.2% to account for 82.2% of the observed variation. Based on the absolute value of the eigenvectors, the traits contributing the greatest influence on PC1 in order of contribution were height (2010), vigor (2010), vigor (2011), biomass (2011), and biomass (2010) (data not shown). The non-*Festuca* checks 'Manhattan 4' and 'Coronado' did not cluster near any other entries, while the Kyrgyzstan *F. valesiaca* entries PI 659923, PI 659932, PI 670362, and PI 670364 clustered apart from the rest of the *Festuca* entries. The *F. rubra* accessions PI 659899 (Kyrgyzstan), PI 659966 (Inner Mongolia CHN), and PI 659981 (Inner Mongolia CHN) grouped in relative proximity to each other compared to accessions PI 659946 (Kyrgyzstan), PI 659950 (Kyrgyzstan), PI 659954 (Kyrgyzstan), and PI 659965 (Inner Mongolia CHN), which were comparatively more dispersed. Although the best performing *F. rubra* accession, PI 659984 ($8x$, CHN), did not cluster near the other *F. rubra* accessions examined, it was somewhat proximate in position to the *F. rubra* cultivar Shademaster ($8x$).

Experiment 2 To further examine *F. rubra* accession performance differences detected in Experiment 1, a morphologically diverse subset of the *F. rubra* accessions from Experiment 1 were evaluated at three locations (Malta, ID, Blue Creek, UT, and North Logan, UT) over 2 years (2012 and 2013). Because of rabbit predation at Malta ID in 2013, the only traits that could be compared between years across all locations and entries were vigor, early biomass, and persistence. Although mean values decreased ($P < 0.05$) between 2012 and 2013 with respect to vigor (2.6 vs. 2.2) and persistence (0.93 vs. 0.85), early biomass was not significantly different (19.03 vs. 19.25 g/plant) over years (Table 1). When compared across Blue Creek, UT and North Logan, UT, late biomass, early regrowth, and late regrowth increased from 2012 to 2013 (37.85 vs. 51.26, 12.51 vs. 14.61, and 2.72 vs. 4.97 g/plant, respectively), while the number of seeds per plant decreased (11,388 vs. 7185) (data for 2012 not shown; data for 2013 in Table 3). In 2012, the combined mean of the CHN *F. rubra* accessions (PI 659965, PI 659966, PI 659981, and PI 659984) of any trait was not significantly different from the combined mean of the *Festuca* cultivars (Black Sheep, Shademaster, Durar, and Covar). However, the mean of the *F. rubra* accessions taken collectively was significantly lower than the mean of the checks for all traits in 2013, except seed number. Similarly, the mean of these CHN *F. rubra* accessions was not different from the mean of the four paired cross *F. valesiaca* or *F. valesiaca* × *F. ovina* hybrids

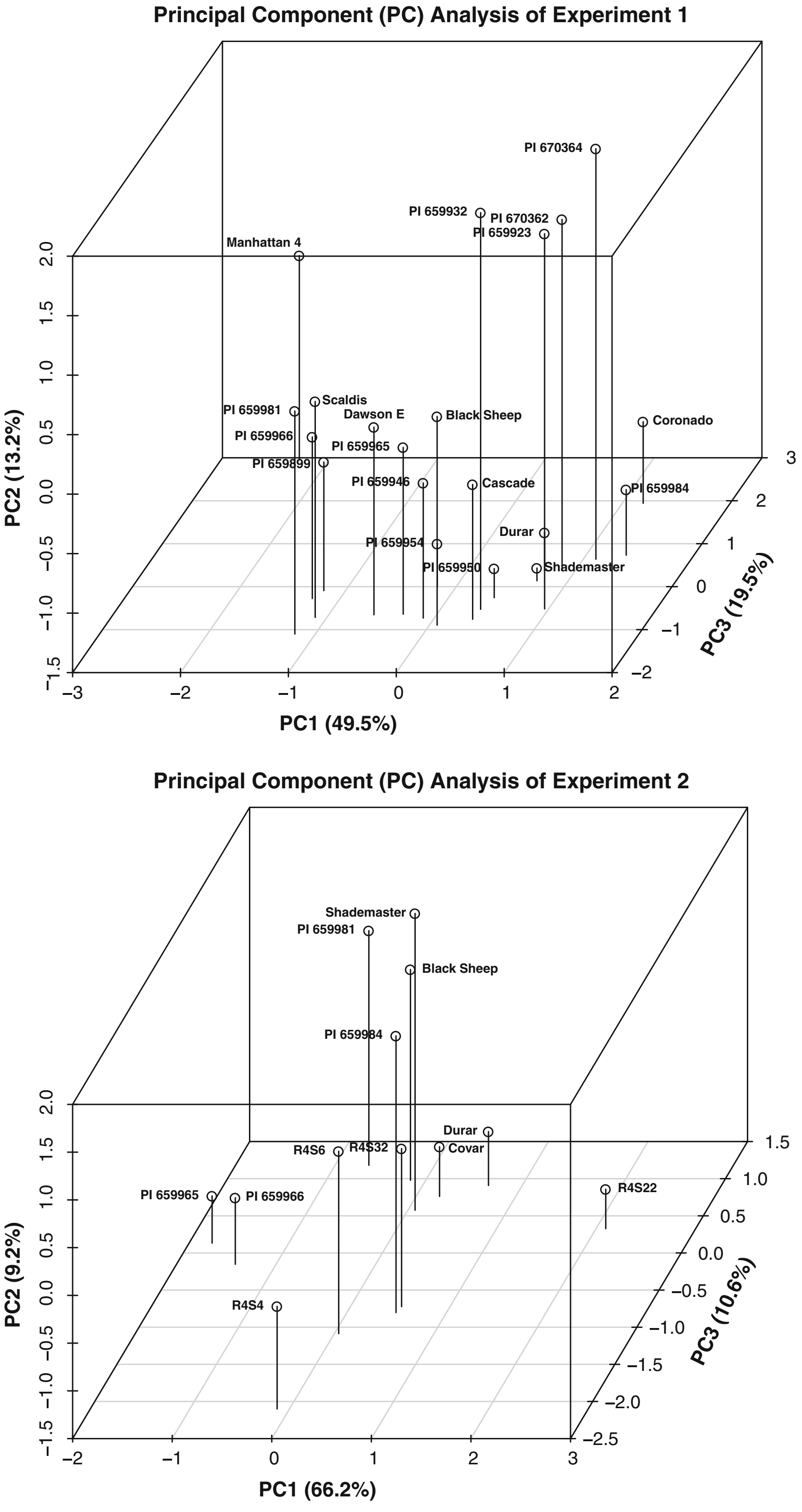

Fig. 1 Ordination after principal component analysis of all morphological characteristics taken collectively on *Festuca* accessions and checks evaluated in two experiments in Blue Creek, UT from 2008 to 2011 (Experiment 1) and in Malta, ID, Blue Creek, UT, and North Logan, UT from 2011 to 2013 (Experiment 2). The *numbers in parenthesis* along each axis indicate the percent variation explained by each principal component

Table 3 Mean values of phenotypic traits of *Festuca* accessions and checks evaluated in 2012 and 2013 in three locations (Malta, ID, Blue Creek, UT, and North Logan, UT) (Expt. 2)

Entry	Vigor (rate 0–5)[b]	Early biomass (g/plant)[c]	Late biomass (g/plant)[d]	Number seeds per plant	Persistence[e]	Early regrowth (g/plant)[f]	Late regrowth (g/plant)[g]
2012							
Black Sheep	2.3	18.80	23.50	10,057.0	0.97	7.75	4.01
Shademaster	2.9	17.09	27.95	10,394.0	0.98	11.00	2.81
Durar	2.4	20.85	28.49	8131.4	0.92	11.52	5.13
Covar	2.2	18.95	30.04	8366.0	0.90	9.80	4.68
PI 659965	1.7	10.24	11.28	2063.3	0.90	4.67	2.38
PI 659966	2.1	13.80	11.44	1896.5	0.89	7.61	2.74
PI 659981	2.6	14.27	26.45	5648.8	0.99	7.01	2.75
PI 659984	3.4	22.03	42.96	16,201.0	0.89	13.00	3.03
R4S4	2.4	18.13	34.68	2318.1	0.91	6.91	2.51
R4S6	2.8	20.46	28.29	7572.4	0.93	6.69	2.81
R4S22	3.3	32.19	36.99	10,792.0	0.91	16.96	6.28
R4S32	2.8	21.49	32.62	8642.4	0.93	11.68	3.77
Mean	2.6	19.03	27.89	7673.6	0.93	9.55	3.35
LSD$_{(\alpha = 0.05)}$	0.5	5.54	10.22	3781.2	0.13	2.97	2.39
CV (%)	19.8	25.0	38.9	51.6	8.92	33.0	40.5
2013[a]							
Black Sheep	1.6	9.54	42.13	9208.2	0.93	14.12	4.06
Shademaster	1.9	12.28	49.91	6296.4	0.96	14.62	6.52
Durar	2.5	29.61	71.15	10,830.0	0.88	22.66	9.60
Covar	1.9	22.28	59.21	10,287.0	0.81	18.51	7.94
PI 659965	0.9	1.31	2.21	1.7	0.60	1.79	0.71
PI 659966	1.0	1.51	3.44	432.0	0.73	1.92	1.01
PI 659981	1.4	4.77	28.92	5265.5	0.70	11.35	5.95
PI 659984	2.1	12.97	48.32	8013.7	0.82	19.46	2.82
R4S4	3.2	30.91	73.19	4340.9	0.91	10.53	1.78
R4S6	2.7	26.40	63.67	4525.1	0.94	13.90	3.87
R4S22	3.9	51.47	105.07	18,656.0	0.92	31.85	10.53
R4S32	3.3	27.90	67.90	8363.4	0.93	14.56	4.88
Mean	2.2	19.25	51.26	7185.0	0.85	14.61	4.97
LSD$_{(\alpha = 0.05)}$	0.5	5.54	24.33	6423.4	0.13	6.37	3.53
CV (%)	23.1	24.8	40.4	67.9	9.76	37.1	61.0

[a] Data for late biomass, number seeds per plant, early regrowth, and late regrowth was not available in Malta in 2013 because of rabbit predation

[b] Assessed as an 11-point visual rating scale from 0 to 5 (0.5 as units), where 0 = dead, 2.5 = moderate biomass, and 5 = greatest biomass

[c] Dry weight of leaves and seed stalks harvested ~10 cm above ground within 1 week before anthesis

[d] Dry weight of leaves and seed stalks harvested ~10 cm above ground at seed maturity

[e] Proportion of surviving plants (plants alive divided by the number of plants transplanted)

[f] Dry weight of leaves grown from plants previously harvested for early biomass (see footnote[c])

[g] Dry weight of leaves grown from plants previously harvested for late biomass (see footnote[d])

(R4S4, R4S6, R4S22, and R4S32) in 2012 for any traits, except early biomass (15.09 vs. 23.07 g/plant). Nevertheless, these *F. rubra* accessions performed lower than the hybrids in all traits, except seed number and late regrowth in 2013. The best performing *F. rubra* accession in Experiment 1 (PI 659984) was also the best performer in Experiment 2. Similar to Experiment 1, this accession did as well as or better than the *Festuca* controls for most traits in both years. However, the mean trait values for PI 659984 were significantly lower than the best performing *Festuca* cultivar (Durar) in 2013 with respect to early biomass (12.97 vs. 29.61 g/plant) and late regrowth (2.82 vs. 9.60 g/plant). Compared to the best performing *Festuca* hybrid evaluated (R4S22; *F. valesiaca* × *F. ovina*), PI 659984 was similar in 2012 for vigor, late biomass, and persistence, and higher in seed number (10,792 vs. 16,201), but it was lower in early biomass (32.19 vs. 22.03 g/plant), early regrowth (16.96 vs. 13.00 g/plant) and late regrowth (6.28 vs. 3.03 g/plant). In 2013, however, PI 659984 was lower than R4S22 for all traits, although not significantly so for persistence.

While several trait correlations in Experiment 2 were similar to those in Experiment 1, there were some notable differences (Table 4). As with Experiment 1, vigor and late biomass were positively correlated ($r = 0.674$–0.948; $P < 0.05$) with most traits in both 2012 and 2013, as was early biomass ($r = 0.627$–0.956; $P < 0.05$). In contrast to Experiment 1, persistence was not correlated with any trait in 2012, but positively correlated ($r = 0.577$–0.765; $P < 0.05$) with all traits except seed number and late regrowth in 2013. Also, seed number was correlated with most traits except persistence both years and late regrowth in 2012. Early regrowth was positively correlated ($r = 0.577$–0.961; $P < 0.05$) with all traits both years, except for persistence in 2012. Late regrowth was highly positively correlated with early regrowth [$r = 0.745$, $P < 0.01$ (2012) and $r = 0.849$, $P < 0.001$ (2013)], but, by comparison, was less correlated with other traits (e.g., vigor and persistence).

No distinct trait-based groupings could be identified among entries after PCA (Fig. 1). The total variation explained by the first three PCs was 86%, where PCs 1 and 2 accounted for 75.4% of the variation. Eigenvector values indicated that early regrowth (2013), early biomass (2012), late biomass (2013), seed number (2013), early regrowth (2012), and vigor (2013) had the greatest influence on the spatial orientation in the first component (data not shown). Where PI 659981 (6*x*, Inner Mongolia CHN) was in relatively close spatial proximity to the *Festuca* cultivars Shademaster (8*x*) and Black Sheep (6*x*), PI 659965 (6*x*, Inner Mongolia CHN) and PI 659966 (6*x*, Inner Mongolia CHN) were not spatially associated with these cultivars and were themselves distinct from the other accessions examined. In contrast to Experiment 1, PI 659981 did not associate with PI 659965 and PI 659966. However, similar to Experiment 1, PI 659984 (8*x*, Qinghai CHN) did not cluster with the other *F. rubra* accessions examined. Although the four *F. valesiaca* or *F. valesiaca* × *F. ovina* hybrids were spatially distinct and not in close proximity to each other or the Ovina complex cultivars Black Sheep, Durar, and Covar, hybrids R4S6 and R4S32 were in relative close proximity to each other.

Genotypic analysis

The genetic similarity among the *Festuca* accessions and cultivars included in Experiment 1 was assessed using AFLP marker analysis. Ten AFLP selective amplification primer combinations produced 1515 consistently bright, polymorphic bands (an average of 151.5 polymorphic markers per primer combination). A mid-point rooted (‘Coronado’ and ‘Manhattan 4’) neighbor-joining tree constructed from Nei and Li genetic distance estimates (Fig. 2) resulted in the predictable partitioning of entries into Rubra and Ovina Complex groupings at Node 1. The Ovina Complex group, consisting of hexaploid and diploid entries, was further divided at Nodes 3 and 5, where Node 3 partitioned cultivars Black Sheep (2*x*, *F. ovina*) and Scaldis (6*x*, *F. trachyphylla*) from a bifurcate cluster (Node 5) consisting of diploid *F. valesiaca* entries (4) collectively and the cultivar Durar (6*x*, *F. trachyphylla*). Rubra Complex accessions were divided at Node 2 into subspecies with ‘Cascade’ (6*x*, *F. rubra* subsp. *commutata*) residing in a single clade and a bifurcate cluster containing seven hexaploid and two octoploid (‘Shademaster’ and PI 659984) *F. rubra* accessions (Node 4). The hexaploid accessions were further divided into two geographically unique clades (Node 6) consisting of accessions from Inner Mongolia CHN (4) and Kyrgyzstan (3).

Table 4 Pearson correlation coefficients of phenotypic traits of *Festuca* accessions and checks evaluated in two experiments (Expts. 1 and 2) in Blue Creek, UT (Expt. 1) in 2010 (top diagonal) and 2011 (bottom diagonal) and in Malta, ID, Blue Creek, UT, and North Logan, UT (Expt. 2) in 2012 (top diagonal) and 2013 (bottom diagonal)

	Vigor[a]	Early biomass[b]	Late biomass[c]	Height[d]	Width[e]	No. seeds per plant	Persistence[f]	Early regrowth[g]	Late regrowth[h]
Expt. 1									
Vigor		–[i]	0.739***[j]	0.839***	0.692***	0.661**	0.719***	–	–
L. biomass	0.846***	–		0.872***	0.756***	0.433^{NS}	0.502*	–	–
Height	0.603**	–	0.581**		0.891***	0.338^{NS}	0.711***	–	–
Width	0.556*	–	0.565**	0.688***		0.033^{NS}	0.700***	–	–
Seed No.	0.359^{NS}	–	0.494*	−0.075^{NS}	−0.199^{NS}		0.340^{NS}	–	–
Persistence	0.650**	–	0.527*	0.097^{NS}	−0.066^{NS}	0.403^{NS}		–	–
Expt. 2									
Vigor		0.753**	0.824***	–	–	0.784**	0.110^{NS}	0.759**	0.290^{NS}
E. biomass	0.948***		0.740**	–	–	0.627*	−0.143^{NS}	0.864***	0.779**
L. biomass	0.939***	0.956***		–	–	0.715**	−0.026^{NS}	0.674*	0.365^{NS}
Seed No.	0.667*	0.768**	0.821**	–	–		0.116^{NS}	0.714**	0.411^{NS}
Persistence	0.712**	0.635*	0.765**	–	–	0.539^{NS}		−0.143^{NS}	−0.129^{NS}
E. regrowth	0.704*	0.791**	0.864***	–	–	0.961***	0.577*		0.745**
L. regrowth	0.475^{NS}	0.630*	0.685*	–	–	0.851***	0.409^{NS}	0.849***	

[a] Assessed as an 11-point visual rating scale from 0 to 5 (0.5 as units), where 0 = dead, 2.5 = moderate biomass, and 5 = greatest biomass

[b] Dry weight of leaves and seed stalks harvested ~10 cm above ground within 1 week before anthesis

[c] Dry weight of leaves and seed stalks harvested ~10 cm above ground at seed maturity

[d] The distance from the plant base (soil surface) to the top of the highest panicle at full anthesis

[e] The diameter of the tussock remaining after biomass harvest

[f] Proportion of surviving plants (plants alive divided by the number of plants transplanted)

[g] Dry weight of leaves grown from plants previously harvested for early biomass

[h] Dry weight of leaves grown from plants previously harvested for late biomass

[i] A dash indicates data not collected

[j] Significant correlations at $P < 0.05$, 0.01, and 0.001, and non-significant designated as *, **, **, and ^{NS}, respectively

Discussion

Festuca species have been considered for use in low maintenance roadside and golf course applications, railway embankments, and reclamation on disturbed landscapes (Weibull et al. 1991). Some species of the genetically variable fine-leaved Ovina and Rubra complexes possess considerable abiotic stress tolerances (Aronson et al. 1987; Kanapeckas et al. 2008; Wallner et al. 1982), and certain *F. rubra* species may possess ruminant forage value (Bovolenta et al. 2008; Carrère et al. 2010) and wildfire resilience (Fernández-Abascal et al. 2003; Musser 1947) under rangeland conditions. We present herein a morphological assessment of recently collected Asian *F. rubra* and *F. valesiaca* accessions originating from heavily grazed semi-arid growing environments where water is often severely limiting. These accessions showed variable phenotypic responses under several western U.S. rangeland growing environments.

Incorporation of these phenotypic characteristics will be increasingly important as improved plant materials are developed for sustained productivity on novel ecosystems (i.e., emergence of species that

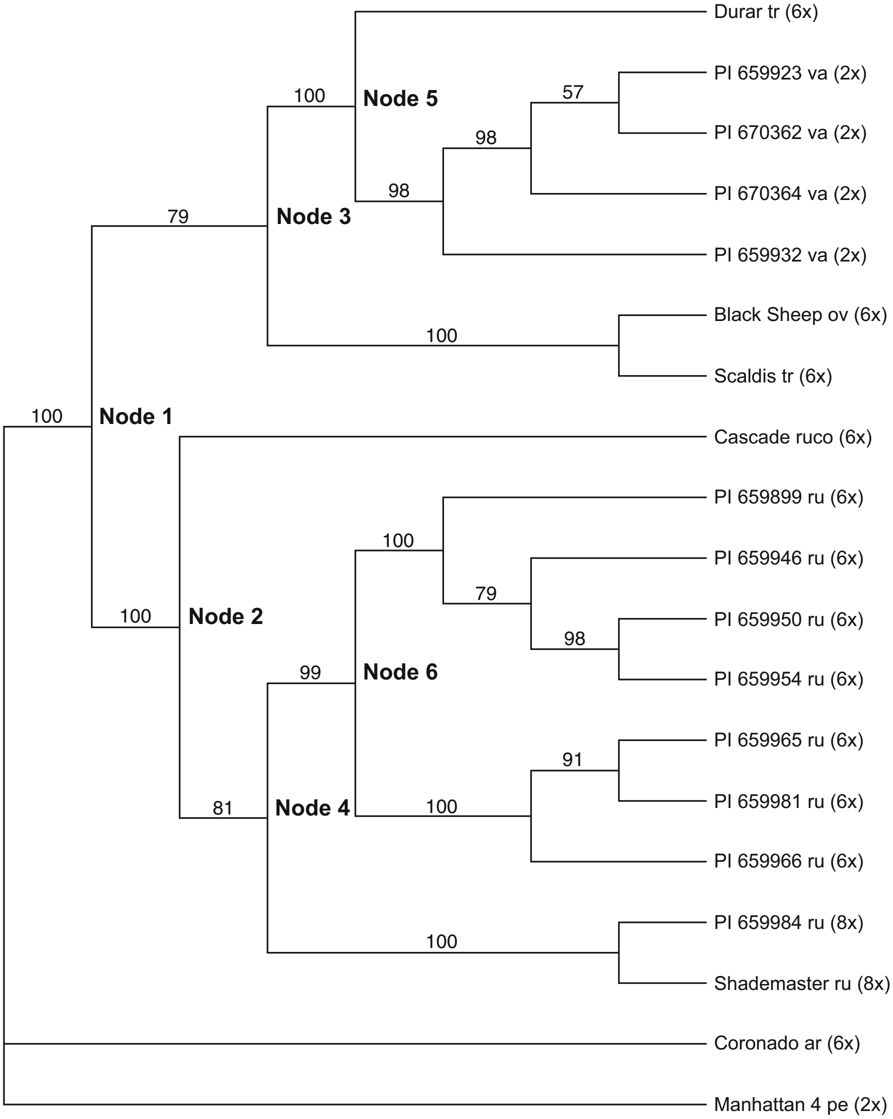

Fig. 2 Rooted neighbor-joining tree illustrating genetic relationships among *Festuca* accessions and checks based on Nei and Li's (1979) genetic distance among AFLP profiles. Numbers at each node indicate bootstrap values after 1000 bootstrap permutations (Swofford 2003). *Letters* after accession names indicate species where ar = *Schedonorus arundinaceus*, ov = *F. ovina*, pe = *Lolium perenne*, ru = *F. rubra*, ruco = *F. rubra* subsp. *commutata*, tr = *F. trachyphylla*, and va = *F. valesiaca*, and numbers in parenthesis after the species designation indicate ploidy level

occur in combinations and relative abundances that have not occurred previously within a given biome) that are emerging on western U.S. rangelands (Choi et al. 2008). Novel ecosystems are also emerging in the areas where collections where made in China and Kyrgyzstan. In China, for instance, 50-year records of cooling in its subtropical zones (southern China; 0.14–0.34 °C/decade) and warming in temperate zones (northern China; 0.20–0.27 °C/decade) are indicative of changing climates in its agricultural growing regions (Shen and Varis 2001). Similarly, changes in climatic conditions in Kyrgyzstan are typified by temperature increases, as documented by the retreat (>32% between 1955 AND 1999) of glaciers in the northern Tien Shan province (Bolch 2007). Predictions by climate change models for U.S. semi-arid rangelands likewise indicate hotter and drier conditions (Christensen et al. 2007), which could increase the already high rate of rangeland degradation (D'Antonio and Vitousek, 1992).

The *F. rubra* collections characterized herein were obtained in the semi-arid Cholpon-Ata region of Issyk-Kul (2327 m elevation; annual precipitation = 205 mm), in the Kochkorka region of Naryn (3056–3221 m elevation; annual precipitation = 278 mm) and in the Panfilov and Dzhaiyl

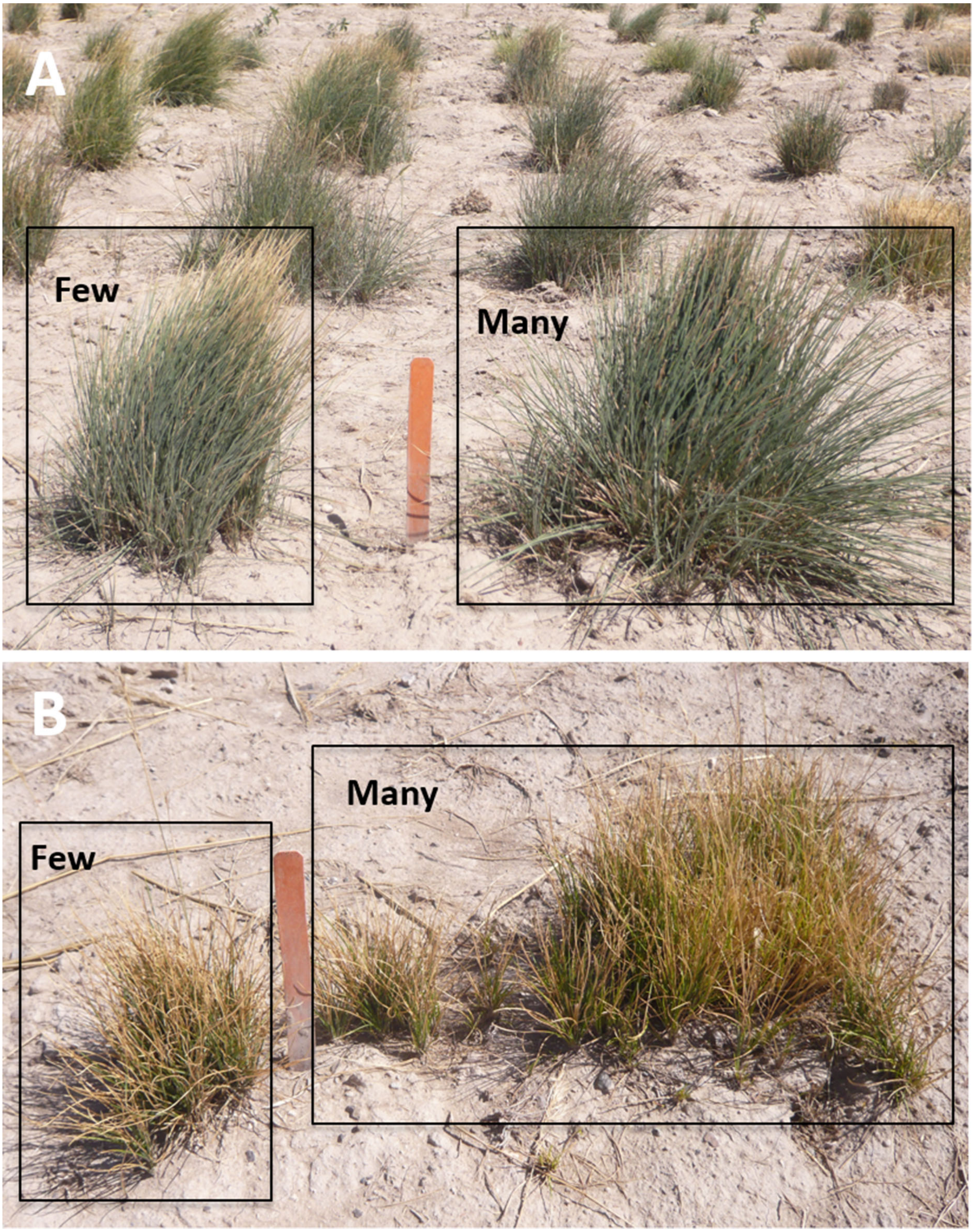

Fig. 3 *Festuca rubra* L. accession PI 659984 (People's Republic of China, 8*x*) as observed in Malta, ID in August (**A**) and September (**B**) 2012 illustrating green color and rhizomes under harsh western US semi-arid growing conditions. Few or many indicates fewer or many rhizomes, respectively, in relation to a plant stake (30 cm). (Color figure online)

regions of Chuy (2425–2978 m elevation; annual precipitation = 300–400 mm) provinces of Kyrgyzstan (Johnson 2006a, b). Collections made in CHN originated from the Qinghai Province (~3000 m elevation; annual precipitation = 200 mm) and Keshiketeng County Chifeng Inner Mongolia (1309–1313 m elevation; annual precipitation = 371 mm). In Issyk-Kul Kyrgyzstan, collections were made along river bottoms and meadow openings associated with spruce forests in granite and loam soils. While Naryn collections were made in the harsh environment of Tien Shan at the Son-Kel River Pass and near lake Son-Kel, Chuy collections were obtained in the Suusamyr Valley between the Suusamyr Too and the Kyrgyz Ala-Too ranges of the Tien Shan mountains along stony roadsides and grassy steppes in dry gravely and loamy soils. In contrast, China collections (e.g., PI 659984) were made near the Haolaihule village in lowland areas between sand dunes and hilly meadows in sandy and clay loam soils and in the foothills of the Tibetan Plateau (Qinghai-Tibet Plateau).

In the main, the Kyrgyzstan and CHN collection environments are harsher (i.e., annual precipitation and/or temperature) than those of Blue Creek and North Logan UT, but comparable to Malta ID. In Blue Creek and Malta (specific location data not presented), plants of *F. rubra* PI 659984 (Qinghai, CHN) were persistent, vigorous, possessed substantial regrowth attributes after an initial early season biomass harvest, and consistently produced an abundant amount of seeds. The performance of other Asian *F. rubra* accessions (e.g., PI 659981, Inner Mongolia, CHN) was also noteworthy. Thus, it appears that some of the Asian *F. rubra* accessions examined herein may possess genes for abiotic stress tolerance (e.g., heat, drought) predictive of their origins.

Festuca rubra is used in low input turfgrass applications in China, where various species exhibit cold (Sun et al. 2008a) and salt (Liu et al. 2001) tolerance, and thus are potential genetic sources for plant improvement (Campbell and Xia 2002). As in the western U.S., mixed perennial gramineous grasses have been used in China for rehabilitation of degraded sites in desertified areas (He et al. 2008). *Festuca rubra* species have been found to either contribute effectively (Su and Zhang 1997) or ineffectively (He et al. 2008; Sun et al. 2008b) when used in grass mixtures for rehabilitation of such Chinese landscapes. Likewise, *F. rubra* species may (Bezeau and Johnston 1962; Van Ruijven and Berendse 2003; Smith and Bradshaw 1979) or may not (Pontes et al. 2007; Khaled et al. 2006) possess forage value and/or contribute to species richness for grazing ruminants depending on growing environment (e.g., season, rangeland or pasture, minelands) and management requirements (e.g., irrigated or non-irrigated applications).

Wildfires are most prevalent in the western U.S. during July and August (Dibble et al. 2007; Littell et al. 2009). Greenstrips (typically ~91 m wide) can modify wildfire effects and behavior to control wildfire speed and spread (Pellant 1994; Finney et al. 2007). Characteristics of perennial grasses suitable for use in greenstrips include livestock and wildlife palatability as well as an ability to establish and persist, a low growth habit, and a propensity for high ignition temperatures and low burning intensities (i.e., relatively high water content) (Pellant, 1994).

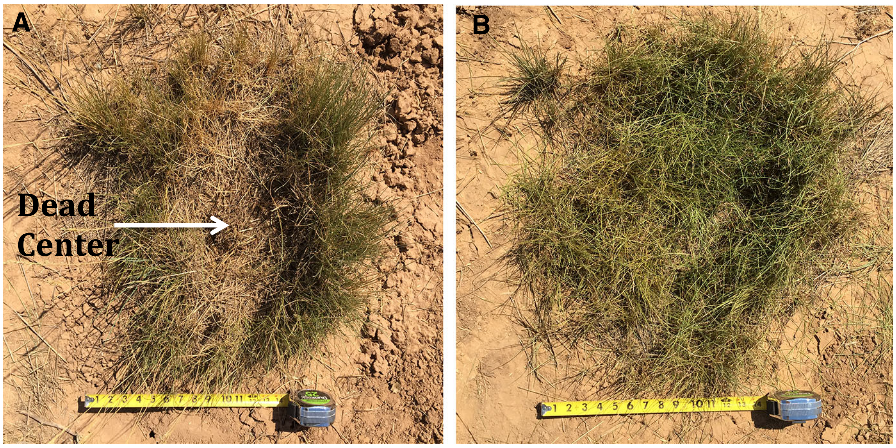

Fig. 4 *Festuca rubra* L. accession PI 659984 (People's Republic of China, 8*x*) as observed in Nephi, UT (annual precipitation = 305 mm) showing segregates with dead center (**A**) and continuous grass mat (**B**) in August 2016 after being mowed in 2015 and 2016. Plant size defined in relation to a measuring tape (*yellow portion* 30 cm). (Color figure online)

Under the harsh growing conditions of Malta, ID, plants of PI 659984 remained green through August and early September until frost (Fig. 3). This "stay green" characteristic is in stark contrast to typical bunch type perennial gasses currently used in the western U.S. as greenstrip components, which typically senesce in July becoming fuel for wildfires (Monsen 1994; Pellant 1994). Thus, since the stay green trait may provide a for high ignition rates and low burning intensity, rhizomatous PI 659984 or its derivatives may be attractive genetic resources for incorporation into western U.S. rangeland greenstrips.

Plants of *F. rubra* Ps PI 659984 and 659981 segregated for the frequency and intensity of tussock "dead centers" (lack of regrowth) during our experimentation (data not presented). Dead centers manifested themselves after early and/or late harvesting and were often prominent after several seasons of growth (Fig. 4). The rhizomatous growth typical of *F. rubra* plants possessing dead centers resulted in a vegetative ring (10–30 cm in diameter) that enclosed bear ground where dead centers appeared. Although markedly smaller in size, this vegetative ring growth habit is similar to that of *Muhlenbergia torreyi* (Kunth) Hitchc. ex Bush (ring muhly). Plants possessing such ring growth characteristics may or may not be desirable components of greenstrips for wildfire control. Thus, it will be important evaluate the value of ring and non-ring producing rhizomatous segregates derived from PI 659984 and 659981 for their performance as grass components in greenstrips. Likewise, derivatives from PI 659984 and 659981 will need to be evaluated for their palatability and forage value under intensive western U.S. rangeland grazing conditions.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Arndt S (2008) Novelties in the *Festuca valesiaca* group (Poaceae) from the central Alps. Plant Syst Evol 271:129–142

Aronson LJ, Gold AJ, Hull RJ (1987) Cool-season turfgrass responses to drought stress. Crop Sci 27:1261–1266

Barkworth ME, Capels KM, Long S, Andeton LK, Piep MB (eds) (2007) Flora of North America. Oxford University Press, New York

Beard JB (1973) Turf-grass: science and culture. Prentice-Hall, Englewood Cliffs

Bezeau LM, Johnston A (1962) In vitro digestibility of range forage plants of the *Festuca scabrella* association. Can J Plant Sci 42:692–697

Bolch T (2007) Climate change and glacier retreat in northern Tien Shan (Kazakhstan/Kyrgyzstan) using remote sensing data. Global Planet Change 56:1–12

Bovolenta S, Spanghero M, Dovier S, Oriandi D, Clementel F (2008) Chemical composition and net energy content of alpine pasture species during the grazing season. Anim Feed Sci Tech 140:164–177

Campbell TA, Xia ZL (2002) Agronomic evaluations of grass and legume forage species collected in the Xinjiang Autonomous Region of the People's Republic of China and Mongolia. Genet Resour Crop Evol 49:295–303

Carrère P, Pontes LD, Andueza D, Louault F, Rosseel D, Taini E, Pons B, Toillon S, Soussana JF (2010) Changes in the nutritive value of pasture grasses during their cycle of development. Fourrages 201:27–35

Catalán P, Torrecilla P, López-Rodríguez J-A, Olmstead RG (2004) Phylogeny of the festucoid grasses of subtribe Loliinae and allies (Poeae, Pooideae) inferred from ITS and *trn*L-F sequences. Mol Phylogenet Evol 31:517–541

Choi YD, Temperton VM, Allen EB, Grootjans AP, Halassy M, Hobbs RJ, Naeth MA, Torok K (2008) Ecological restoration for future sustainability in a changing environment. Ecoscience 15:53–64

Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli RK, Kwon W-T, Laprise R, Magaña Rueda V, Mearns L, Menéndez CG, Räisänen J, Rinke A, Sarr A, Whetton P (2007) Regional climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: the physical science basis. Contribution of Working Group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 847–940

Clayton WD, Renvoize SA (1986) Genera *Graminum*: grasses of the world. Royal Botanical Gardens, Kew, London, pp 1–389

Clements CD, McCuin G, Shane RS, McAdoo K, Harmon DN (2009) Wildfire rehabilitation and restoration: triage in the pursuit of resilience. Rangelands 31:30–35

D'Antonio CM, Vitousek PM (1992) Biological invasions by exotic grasses, the grass/fire cycle, and global change. Annu Rev Ecol Syst 23:63–87

Darbyshire SJ, Pavlick LE (2007) *Festuca*. modified by Barkworth from Barkworth et al In: Barkworth ME, Capels KM, Long S, Anderton LK, Piep MB (eds) Flora of North America, vol 24. http://herbarium.usu.edu/webmanual. Accessed 4 Oct 2016

Darbyshire SJ, Warwick SI (1992) Phylogeny of North American *Festuca* (Poaceae) and related genera using chloroplast DNA restriction site variation. Can J Bot 70:2415–2429

Dibble AC, White RH, Lebow PK (2007) Combustion characteristics of north-eastern USA vegetation tested in the cone calorimeter: invasive versus non-invasive plants. Int J Wildland Fire 16:426–443

Dunn A (2003) The Old, Grand Prix, and Padua wildfires: how much did these fires really cost? USDA, Forest Service http://www.fs.fed.us/psw/publications/adunn/2003_wildfires_report.pdf. Accessed 4 Oct 2016

Felsenstein J (1985) Confidence-limits on phylogenies: an approach using the bootstrap. Evolution 39:783–791

Fernández-Abascal I, Tárrega R, Luis-Calabuig E, Marcos E (2003) Effects of sowing native herbaceous species on the post-fire recovery in a heathland. Acta Oecol 24:131–138

Finney MA (2001) Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. Forest Sci 47:219–228

Finney MA, Selia RC, McHugh CW, Ager AA, Bahro B, Agree JK (2007) Simulation of long-term landscape-level fuel treatment effects on large wildfires. Int J Wildland Fire 16:712–727

Hanson AA (1972) Grass varieties in the United States. USDA Agricultural Handbook 170. US Department of Agriculture, Agricultural Research Service, Washington

Hanson AA, Juska FV, Burton GW (1969) Species and varieties. In: Hanson AA, Juska FV (eds) Turfgrass science. Agronomy monograph 14. American Society of Agronomy, Madison, pp 370–409

He W, Li H, Chen F (2008) Community characteristics of grassland sowed with mixed perennial gramineous species on desertified areas of northwest Sichuan. Shengtaixue Zazhi. 27:2079–2082

Jensen KB, Larson SR, Waldron BL, Asay KH (2006) Cytogenetic and molecular characterization of hybrids between 6*x*, 4*x*, and 2*x* ploidy levels in crested wheatgrass. Crop Sci 46:105–112

Johnson DA (2006a) Plant germplasm collection report. Collection of low-maintenance turf germplasm in Kyrgyzstan and Inner Mongolia. US Department of Agriculture, Agricultural Research Service. http://www.ars.usda.gov/SP2UserFiles/Place/20801000/kyrgyzstan06.pdf. Accessed 4 Oct 2016

Johnson DA (2006b) Plant germplasm collection report. Collection of low-maintenance turf germplasm and seed/scientific exchange with China. US Department of Agriculture, Agricultural Research Service. http://www.ars.usda.gov/SP2UserFiles/Place/20801000/china06.pdf. Accessed 4 Oct 2016

Jones TA, Larson SR, Wilson BL (2008) Genetic differentiation and admixture among *Festuca idahoensis, F. roemeri*, and *F. ovina* detected in AFLP, ITS, and chloroplast DNA. Botany 86:422–434

Kanapeckas J, Lemeziene N, Stukonis V, Tarakanovas P (2008) Drought tolerance of turfgrass genetic resources. Biologija 54:121–124

Khaled RAH, Duru M, Decruyenaere V, Jouany C, Cruz P (2006) Using leaf traits to rank native grasses according to their nutritive value. Rangeland Ecol Manag 59:648–654

Littell JS, McKenzie D, Peterson DL, Westerling AL (2009) Climate and wildfire area burned in western US ecoprovinces, 1916–2003. Ecol Appl 19:1003–1021

Liu H, Guo Y, Wang J, Hu M, Yang Z (2001) A comparison on salt tolerance of 28 breeds of cold type lawn grass. Acta Prataculturae Sinica 10:52–59

Ma Y, Staub JE, Robbins MD, Johnson P, Larson SR (2014) Phenotypic and genetic characterization of Kyrgyz fine-leaved *Festuca valesiaca* germplasm for use in semi-arid, low-maintenance turf applications. Genet Resour Crop Ev 61:185–197

Mackes KH, Lynch DL, Kelly SK, Eckhoff M (2007) Missionary ridge fire cost assessment. J Test Eval 35:1–4

Manzello SL, Cleary TG, Shield JR, Yang JC (2006) Ignition of mulch and grasses by firebands in wildland-urban interface fires. Int J Wildland Fire 15:427–431

Markgraf-Dannenberg I (1980) *Festuca*. In: Tutin TG, Heywood VH, Burges NA, Moore DM, Valentine DH, Walters SM, Webb DA (eds) Flora Europaea. Cambridge University Press, Cambridge, pp 125–153

Meyer WA, Funk CR (1989) Progress and benefits to humanity from breeding cool-season grasses for turf. In: Sleper DA, Asay KH, Pedersen JF (eds) Contributions from breeding forage and turf grasses, CSSA special publication number 15. Crop Science Society of America, Madison, pp 31–48

Monsen SB (1994) Selection of plants for fire suppression on semiarid sites. In: Monsen SB, Kitchen SG (eds) Proceedings-symposium on ecology and management of annual rangelands. USDA Forest Service, Intermountain Research Station, Ogden, pp 363–373

Musser HB (1947) The effect of burning and various fertilizer treatments on seed production of red fescue. J Am Soc Agron 39:335–340

Nei M, Li WH (1979) Mathematical model for studying genetic variation in terms of restriction endonucleases. P Natl Acad Sci USA 76:5269–5273

Pavlick LE (1984) Studies on the *Festuca ovina* complex in the Canadian Cordillera. Can J Bot 62:2448–2462

Pechony O, Shindell DT (2010) Driving forces of global wildfires over the past millennium and the forthcoming century. P Natl Acad Sci USA 45:19167–19170

Pellant M (1994) History and applications of the intermountain greenstripping program. In: Monsen SB, Kitchen SG (eds) Proceedings-symposium on ecology and management of annual rangelands. USDA Forest Service, Intermountain Research Station, Ogden, pp 63–68

Pontes LDS, Carrere P, Andueza D, Louault F, Soussana JF (2007) Seasonal productivity and nutritive value of temperate grasses found in semi-natural pastures in Europe: responses to cutting frequency and N supply. Grass Forage Sci 62:485–496

PRISM Climate Group (2015) Oregon State University. http://prism.oregonstate.edu, created 5 June 2015

Robbins MD, Staub JE, Bushman BS (2016) Development of fine-leaved *Festuca* grass populations identifies genetic resources having improved forage production with potential for wildfire control in the western United States. Euphytica 209:377–393

Ruemmele BA, Brilman LA, Huff DR (1995) Fine fescue germplasm diversity and vulnerability. Crop Sci 35:313–316

Ruemmele BA, Wipff JK, Brilman L, Hignight KW (2003) Fine-leaved *Festuca* species. In: Casler MD, Ducan RR (eds) Turf-grass biology, genetics, and breeding. Wiley, Hoboken, pp 129–174

Shen D, Varis O (2001) Climate change in China. Ambio 30:381–383

Smith RAH, Bradshaw AD (1979) The use of metal tolerant plant populations for the reclamation of metalliferous wastes. J Appl Ecol 16:595–612

Smith KF, Casler MD (2004) Spatial analysis of forage grass trials across locations, years, and harvests. Crop Sci 44:56–62

St. John L, Tilley D, Hunt P, Wright S (2012) Plant guide for red fescue (*Festuca rubra*). USDA Natural Resources Conservation Service, Plant Materials Center, Aberdeen. http://plants.usda.gov/plantguide/pdf/pg_feru2.pdf. Accessed 4 Oct 2016

Su X, Zhang D (1997) Introduction of lawn grass varieties in semi-desert area in Hexi corridor of Gansu, China. Grassland of China 66:36–39

Sun T, Suri G, Ma W, Wu J (2008a) Study on cold tolerance of 10 poaceous grasses. Chin J Grassl 30:56–60

Sun T, Suriguga MW, Wu J (2008b) Drought resistance of ten seedling grasses. Acta Prataculturae Sinica 17:42–49

Swofford DL (2003) PAUP*: phylogenetic analysis using parsimony (*and other methods). Version 4.0. Sinauer Associates, Sunderland, Massachusetts (prerelease test version)

Székely GJ, Rizzo ML, Bakirov NK (2007) Measuring and testing independence by correlation of distances. Annal Stat 35:2769–2794

Van Ruijven J, Berendse F (2003) Positive effects of plant species diversity on productivity in the absence of legumes. Ecol Lett 6:170–175

Vinall HN, Hein MA (1937) Breeding miscellaneous grasses. In: USDA yearbook of agriculture 1937. United States Government Printing Office, Washington, p 1032

Wallner SJ, Becwar MR, Butler JD (1982) Measurement of turfgrass heat tolerance in vitro. J Am Soc Hortic Sci 107:608–613

Weibull P, Ghatnekar L, Bengtsson BO (1991) Genetic variation in commercial varieties and natural populations of sheep’s fescue, *Festuca ovina*. Plant Breed 107:203–209

Wilkinson MJ, Stace CA (1991) A new taxonomic treatment of the *Festuca ovina* L. aggregate (Poaceae) in the British Isles. Bot J Linn Soc 106:347–397