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Productivity, stability, and resilience of cool-season perennial grasses used for rangeland revegetation

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Abstract

An analysis of biomass and ground cover data collected from six rangeland sites in the Intermountain and Northern Great Plains areas of the United States from 2000 to 2004 was undertaken to characterize the productivity, stability, and resilience of cool-season perennial grass species. Among the 13 included species, and the 48 cultivars, intermediate wheatgrass [*Thinpyrum intermedium* (Host) Barkworth & D.R. Dewey], tall wheatgrass [*Thinpyrum elongatum* (Host) D.R. Dewey], and to a lesser extent crested wheatgrass [*Agropryon cristatum* (L.) Gaertn. and *A. desertorum* (Fisch. ex Link) Schult.] possessed the greatest biomass productivity and ground cover. Basin wildrye [*Leymus cinereus* (Scribn. & Merr.) Á. Löve], thickspike wheatgrass [*Elymus lanceolatus* (Scribn. & J.G. Sm.) Gould], and bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) Á. Löve] were least productive and stable. There were no differences among species or cultivars for biomass resilience and differences for ground cover resilience were limited. Overall, these three statistics provide an interesting comparison among rangeland species, but more long-term datasets are necessary for greater inferences and more definitive conclusions.

1 | INTRODUCTION

Rangelands support mainly grass and/or shrubs in primarily semi-arid to arid regions, cover nearly 50% of the earth's surface, and are a major source of forage for livestock production worldwide (Derner et al., 2017; Heady & Child, 1994). In the United States, rangelands comprise approximately 300 million ha, mostly in the western states (Havstad, Peters, Skaggs, & Wright, 2007). In addition to livestock production, healthy rangelands provide improved watersheds, recreational opportunities, endangered species habit, resilience to weed invasion, and sustainable wildfire cycles, among other things (Boyd & Svejcar, 2009; Derner et al., 2018; National Research Council, 1994). Livestock overgrazing and other disturbances result in degraded rangelands that are more susceptible to invasive annual plants and increased wildfire frequencies (DiTomaso, Masters, & Peterson, 2010). This combination can cause a feedback in which annual invasive plants, such as downy brome, or cheatgrass (*Bromus tectorum* L.), change the fuel properties of the rangeland, which in turn increases the wildfire frequency, and favors the invasive annual species over the previously established perennial plant community (Brooks et al., 2004). This results in loss of ecosystem function through soil erosion, changes in soil structure, and changes in nutrient cycling. If left unchecked, the changes to ecosystem function caused by annual species invasion may become nearly permanent (Norton, Monaco, Norton, Johnson, & Jones, 2004).

To combat invasions by annual species, land managers use revegetation with desirable perennial plant species.

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Historically, they relied heavily on perennial cool-season grass species, such as crested wheatgrass [*Agropyron desertorum* (Fisch. ex Link) Schult. and *A. cristatum* (L.) Gaertn.]. Crested wheatgrass seedings proved to be successful at stabilizing soil resources and increasing forage resources (Holechek, 1981). More recent revegetation objectives, particularly on public rangelands, focus on biodiversity rather than simply forage production. In response, public land managers now include native perennial plant species, such as bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) Á. Löve] in most revegetation projects (Roundy, 1999). Native species often possess poorer establishment, persistence, and productivity than the introduced species, especially at drier sites (Asay, Horton, Jensen, & Palazzo, 2001; Robins et al., 2013).

To address the need for improved plant materials for revegetation, plant breeders develop improved perennial grass and legume cultivars (Asay et al., 2003). Ongoing variety trials provide evidence of the improvement gains from these efforts and the area of adaptation of the new cultivars (Robins et al., 2007, 2013). Unfortunately, variation in rangeland climate conditions, both short- and long-term, add uncertainty to the success of rangeland revegetation attempts. Climate change models suggest that future climate will increasingly vary and that plant materials used for revegetation will require a greater ability to adapt to the conditions. From the perspective of rangeland agriculture and ecosystem function, there is a need for plants that do more than maximize forage production. Recent work in forages focuses on the concepts of stability (minimum trait variability over time) and resilience (ability to maintain high trait values in a climate extreme), in addition to productivity (average trait value over normal years; Picasso, Casler, & Undersander, 2019; Tracy et al., 2018). The objectives of this research were to (i) characterize the productivity, stability, and resilience of 13 cool-season grass species, and their corresponding cultivars, under rangeland revegetation conditions at six locations in the Great Basin and Great Plains; (ii) examine the relationship among the three measures; and (iii) identify those species, and cultivars, best suited to rangeland revegetation based on these measures.

Core Ideas

- The concepts of productivity, stability, and resilience provide a way to characterize differences in species and cultivars in the context of normal and crisis years.
- Intermediate, tall, and crested wheatgrass exhibit high biomass and ground cover productivity and stability.

2 | MATERIALS AND METHODS

We evaluated 13 perennial cool-season grasses for biomass (kg ha^{-1}) and ground cover (%) at six field sites from 1999 to 2003. Previously, using a subset of the species data, we reported on the relationship between the locations and the genotype × environment interaction (Robins et al., 2007), and separately on phenotypic main effects (Robins et al., 2013). However, we have not previously used analyses of productivity, stability, and resilience on this data set.

Details of the experimental design, including site conditions, study conduct, and data analyses, are found in Robins et al. (2007, 2013). Briefly, we dormant-seeded 48 cultivars corresponding to 13 cool-season grass species (Tables 1 and 2) in fall 1999 at six field locations: Miles City, MT; Ithaca, and Sidney, NE; Mandan, ND; and Blue Creek, and North Logan, UT. Using either three or four replications per site, we collected biomass and ground cover data annually from each site except the Utah sites, for which ground cover was measured only during 2001. We began data collection in 2000 at the Mead, NE, site and in 2001 at the remaining sites.

We used the productivity, stability, and resilience equations presented by Picasso et al. (2019) for the data analysis. The basis of these concepts is the concept of the crisis year, a year in which the mean trait performance in a variety trial is significantly lower than other years in the evaluation.

Cultivar productivity (P) at a location is calculated as

$$P_{jl} = \frac{\sum_{i}^{n-1} Y_{ijl}}{n-1} \quad (1)$$

where Y_{ijl} is the trait performance in year i of cultivar j at location l, and $n - 1$ is the number of non-crisis years of evaluation. Larger productivity values correspond to cultivars with greater mean trait performance.

Cultivar stability (S) at a location is calculated as

$$S_{jl} = \frac{P_{jl}}{\mathrm{SE}\left(P_{jl}\right)} \quad (2)$$

which is the ratio of cultivar productivity to the standard error of cultivar productivity [SE(P_{jl})]. More stable cultivars exhibit lower variability relative to the mean.

Cultivar resilience (R) at a location is defined as

$$R_{jl} = \frac{Yc_{jl}}{P_{jl}} \quad (3)$$

which is the ratio of the performance in the crisis year (Yc_{jl}) to the cultivar productivity. More resilient cultivars exhibit a higher trait performance when compared to the cultivar productivity.

TABLE 1 Productivity, stability, and resilience values for biomass and ground cover measured on 13 perennial cool-season grass species at six Intermountain and northern Great Plains rangeland sites from 2000 to 2003

	Biomass kg ha^{-1}			Ground cover %		
Species	**P**	**S**	**R**	**P**	**S**	**R**
Intermediate wheatgrass	5595^{a†}	28.5^{a}	0.3	98^{a}	58.3^{a}	0.6^{abcde}
Tall wheatgrass	5043^{a}	17.8^{b}	0.3	95^{ab}	36.0^{cd}	0.5^{bcde}
Crested wheatgrass	3818^{b}	19.6^{b}	0.4	86^{abcd}	49.9^{ab}	0.9^{ab}
Western wheatgrass	3781^{b}	12.7^{c}	0.4	97^{a}	37.1^{cd}	0.8^{abc}
RS Hybrid wheatgrass	3634^{bc}	10.6^{cde}	0.4	86^{abcd}	27.9^{def}	0.5^{bcde}
Meadow brome	3379^{bcd}	11.6^{cd}	0.4	90^{abc}	34.7^{cde}	0.7^{abcd}
Smooth bromegrass	3193^{bcde}	9.3^{cdef}	0.5	86^{abcd}	27.9^{def}	0.7^{abcd}
Siberian wheatgrass	3112^{bcde}	11.2^{cd}	0.4	84^{abcd}	32.1^{cdef}	0.8^{abc}
Altai wildrye	2812^{bcde}	8.0^{def}	0.5	75^{bcd}	23.4^{efg}	0.4^{cde}
Russian wildrye	2658^{cdef}	10.4^{cde}	0.8	87^{abc}	41.6^{bc}	1.0^{a}
Basin wildrye	2339^{def}	6.7^{ef}	0.8	66^{d}	21.2^{fg}	0.4^{cde}
Thickspike wheatgrass	2206^{ef}	7.7^{def}	0.5	72^{cd}	26.9^{defg}	0.3^{de}
Bluebunch wheatgrass	1630^{f}	5.9^{f}	0.5	40^{e}	15.1^{g}	0.2^{e}
P value	<.0001	<.0001	>.30	<.0001	<.0001	<.05

Note. P, productivity; S, stability; R, resilience. Species: intermediate wheatgrass, *Thinpyrum intermedium* (Host) Barkworth & D.R. Dewey; tall wheatgrass, *Thinpyrum elongatum* (Host) D.R. Dewey; crested wheatgrass, *Agropryon cristatum* (L.) Gaertn. and *A. desertorum* (Fisch. ex Link) Schult.; western wheatgrass, *Pascopyrum smithii* Rydb.; RS Hybrid wheatgrass, *Elymus hoffmannii* K.B. Jensen & K.H. Asay; meadow brome, *Bromus biebersteinii* Roem. & Schult.; smooth bromegrass, *Bromus inermis* Leyss.; Siberian wheatgrass, *Agropyron fragile* (Roth) P. Candargy; Altai wildrye, *Leymus angustus* (Trin.) Pilg.; Russian wildrye, *Psathyrostachys juncea (Fisch.) Nevski*; basin wildrye, *Leymus cinereus* (Scribn. & Merr.) Á. Löve; thickspike wheatgrass, *Elymus lanceolatus* (Scribn. & J.G. Sm.) Gould; bluebunch wheatgrass, *Pseudoroegneria spicata* (Pursh) Á. Löve.

†Column values followed by different superscript letters differ significantly.

We calculated productivity, stability, and resilience for each species, and cultivar, in each location for biomass and ground cover (Picasso et al. (2019). To identify differences among cultivars, we used a mixed model analysis that considered cultivars as fixed effects and locations as random effects using the ASReml-R package (Butler et al., 2009) of R (R Core Team, 2018).

3 | RESULTS

There were crisis years for each site and trait combination except for ground cover at Blue Creek, Mandan, North Logan, and Sidney (Table 3). Thus, only the Ithaca and Miles City sites were included in the ground cover analysis. For Miles City biomass, the difference between the 2002 and 2003 estimates differed at $\alpha < .15$ but is included for completeness of the biomass dataset.

The highest biomass productivity corresponded to intermediate and tall wheatgrass, and the highest ground cover productivity corresponded to nine species (Table 1). This included the high biomass productivity of the nine intermediate wheatgrass and two tall wheatgrass cultivars and the high ground cover productivity of 34 cultivars (Table 2). The lowest biomass productivity corresponded to Russian wildrye, basin wildrye, thickspike wheatgrass, and bluebunch wheatgrass. Bluebunch wheatgrass also had the lowest ground cover productivity (Table 1). The cultivars with the lowest biomass productivity were Stabilizer Siberian wheatgrass, two Russian wildrye cultivars, Magnar basin wildrye, two thickspike wheatgrass cultivars, and three bluebunch wheatgrass cultivars. The cultivars with the lowest ground cover productivity were P7 and Goldar bluebunch wheatgrass (Table 2).

Intermediate wheatgrass had the greatest biomass stability and was only similar to crested wheatgrass for ground cover stability. Smooth brome, basin wildrye, thickspike wheatgrass, and bluebunch wheatgrass had the lowest biomass stability, whereas thickspike wheatgrass, altai wildrye, basin wildrye, and bluebunch wheatgrass had the lowest ground cover stability (Table 1). Thirty-five cultivars possessed the greatest stability, and the three bluebunch wheatgrass cultivars possessed the lowest ground cover stability (Table 2).

There were no differences among species or cultivars for biomass resilience (Tables 1 and 2). Differences among species for ground cover resilience were limited and resulted in groupings of six high species and six low species (Table 1)—intermediate wheatgrass fell in the middle and did not differ from either the high or low species. Twenty-five cultivars possessed the greatest ground cover resilience, and 15 cultivars exhibited the lowest ground cover resilience (Table 2).

TABLE 2 Productivity, stability, and resilience values for biomass and ground cover measured on 48 cultivars from 13 perennial cool-season grass species at six Intermountain and northern Great Plains rangeland sites from 2000 to 2003

		Biomass kg ha^{-1}			Ground cover %		
Species	**Cultivar**	**Productivity**	**Stability**	**Resilience**	**Productivity**	**Stability**	**Resilience**
Intermediate wheatgrass							
	Manifest	6160^{a†}	14.9^{a}	0.3	98$^{a–c}$	25.7$^{a–c}$	0.7$^{a–d}$
	Reliant	5876^{a}	14.2^{a}	0.4	98$^{a–c}$	25.9$^{a–c}$	0.6$^{a–e}$
	Oahe	5863^{a}	14.2^{a}	0.4	99^{ab}	26.0^{ab}	0.6$^{a–e}$
	Haymaker	5648^{ab}	13.5^{ab}	0.3	99^{ab}	26.0^{ab}	0.6$^{a–e}$
	Luna	5470$^{a–c}$	13.9^{a}	0.4	97$^{a–d}$	25.5$^{a–c}$	0.7$^{a–d}$
	Manska	5400$^{a–c}$	13.2$^{a–c}$	0.3	98$^{a–c}$	25.9$^{a–c}$	0.7$^{a–d}$
	Rush	5378$^{a–c}$	13.1$^{a–c}$	0.9	97$^{a–d}$	25.5$^{a–c}$	0.6$^{a–e}$
	Beefmaker	5288$^{a–c}$	12.7$^{a–c}$	0.3	99^{ab}	26.1^{a}	0.7$^{a–d}$
	Greenar	5245$^{a–c}$	12.8$^{a–c}$	0.4	96$^{a–d}$	25.2$^{a–c}$	0.6$^{a–e}$
Tall wheatgrass							
	Jose	5258$^{a–c}$	12.9$^{a–c}$	0.4	95$^{a–d}$	25.1$^{a–c}$	0.5$^{b–e}$
	Alkar	5173$^{a–d}$	12.7$^{a–c}$	0.4	93$^{a–d}$	24.5$^{a–d}$	0.5$^{b–e}$
	Platte	4696$^{b–e}$	11.2$^{b–d}$	0.4	95$^{a–d}$	25.0$^{a–c}$	0.5$^{b–e}$
Crested wheatgrass							
	NU-ARS AC2	4380$^{c–f}$	10.8$^{c–e}$	0.4	87$^{a–g}$	23.1$^{a–h}$	1.0^{a}
	Hycrest	4353$^{c–g}$	11.0$^{c–e}$	0.4	86$^{a–h}$	22.8$^{a–i}$	1.0^{a}
	ForageCrest	4108$^{d–h}$	10.2$^{d–f}$	0.4	95$^{a–d}$	25.0$^{a–c}$	0.9^{ab}
	CD2	4069$^{d–h}$	9.9$^{d–f}$	0.4	93$^{a–d}$	24.5$^{a–d}$	0.9^{ab}
	Hycrest II	4044$^{d–i}$	10.0$^{d–f}$	0.4	92$^{a–d}$	24.1$^{a–e}$	1.0^{a}
	Nordan	4028$^{e–i}$	9.9$^{d–f}$	0.4	92$^{a–d}$	24.1$^{a–e}$	0.9^{ab}
	Fairway	3234$^{g–n}$	8.0$^{f–m}$	0.4	89$^{a–f}$	23.4$^{a–h}$	1.0^{a}
	Douglas	2324$^{m–r}$	5.9$^{k–p}$	0.4	60^{ijk}	15.9^{ijk}	0.3^{de}
Western wheatgrass							
	Flintlock	4007$^{e–i}$	9.1$^{d–h}$	0.4	100^{a}	26.3^{a}	0.7$^{a–d}$
	Arriba	3908$^{e–i}$	9.2$^{d–g}$	0.4	94$^{a–d}$	25.0$^{a–c}$	0.8$^{a–c}$
	Rodan	3429$^{f–m}$	7.8$^{f–n}$	0.5	97$^{a–d}$	25.6$^{a–c}$	0.8$^{a–c}$
RS Hybrid wheatgrass							
	NewHy	3762$^{e–j}$	8.9$^{d–i}$	0.4	91$^{a–e}$	24.1$^{a–e}$	0.5$^{b–e}$
	RSH	3508$^{f–l}$	8.2$^{f–k}$	0.3	82$^{b–h}$	21.9$^{a–i}$	0.5$^{b–e}$
Meadow bromegrass							
	Cache	3570$^{e–k}$	8.6$^{e–j}$	0.4	94$^{a–d}$	24.8$^{a–c}$	0.7$^{a–d}$
	Fleet	3395$^{f–m}$	8.1$^{f–l}$	0.3	87$^{a–g}$	23.0$^{a–i}$	0.7$^{a–d}$
	Regar	3173$^{h–n}$	7.4$^{g–o}$	0.4	90$^{a–e}$	23.8$^{a–f}$	0.7$^{a–d}$
Smooth bromegrass							
	Lincoln	3719$^{e–j}$	8.7$^{e–j}$	0.6	91$^{a–e}$	24.0$^{a–f}$	0.9^{ab}
	Manchar	2666$^{j–q}$	6.4$^{j–p}$	0.4	83$^{a–h}$	22.2$^{a–i}$	0.6$^{a–e}$
Siberian wheatgrass							
	Vavilov	4043$^{d–i}$	9.9$^{d–f}$	0.4	92$^{a–d}$	24.3$^{a–d}$	0.9^{ab}
	P27	3291$^{f–n}$	8.0$^{f–m}$	0.5	90$^{a–e}$	23.6$^{a–h}$	0.8$^{a–c}$
	Stabilizer	2002$^{o–r}$	5.0$^{o–q}$	0.5	71$^{g–j}$	18.6$^{h–k}$	0.6$^{a–e}$
Altai wildrye							
	Mustang	3351$^{f–n}$	7.4$^{g–o}$	0.5	81$^{c–i}$	20.9$^{b–j}$	0.6$^{a–e}$
	Pearl	2410$^{l–q}$	5.7$^{l–q}$	0.5	69$^{h–k}$	17.8$^{i–k}$	0.3^{de}

(Continues)

TABLE 2 (Continued)

Species	Cultivar	Biomass kg ha^{-1} Productivity	Biomass kg ha^{-1} Stability	Biomass kg ha^{-1} Resilience	Ground cover % Productivity	Ground cover % Stability	Ground cover % Resilience
Russian wildrye							
	Bozoisky-Select	3012$^{h–o}$	6.7$^{h–p}$	0.8	92$^{a–d}$	24.1$^{a–e}$	1.0^{a}
	Bozoisky	2927$^{i–p}$	6.5$^{i–p}$	0.9	90$^{a–e}$	23.6$^{a–h}$	1.0^{a}
	Mankota	2914$^{i–q}$	6.4$^{j–p}$	0.7	93$^{a–d}$	24.6$^{a–d}$	1.0^{a}
	Tetra-1	2399$^{l–r}$	5.4$^{n–q}$	0.6	89$^{a–f}$	23.5$^{a–h}$	1.0^{a}
	Tetracan	2022$^{o–r}$	4.3^{pq}	0.7	74$^{e–j}$	19.6$^{d–j}$	1.0^{a}
Basin wildrye							
	Trailhead	2445$^{k–q}$	5.6$^{m–q}$	0.5	72$^{f–j}$	19.0$^{e–j}$	0.4$^{c–e}$
	Magnar	2234$^{n–r}$	5.2$^{o–q}$	0.7	60^{jk}	16.0^{jk}	0.4$^{c–e}$
Thickspike wheatgrass							
	Bannock	2487$^{k–q}$	6.0$^{k–p}$	0.5	64$^{i–k}$	16.2^{jk}	0.3^{de}
	Critana	2231$^{n–r}$	5.5$^{n–q}$	0.3	74$^{e–j}$	18.9$^{f–k}$	0.3^{de}
	Sodar	1901$^{o–r}$	4.5^{pq}	0.4	80$^{d–i}$	20.8$^{c–j}$	0.3^{de}
Bluebunch wheatgrass							
	Anatone	1821$^{p–r}$	4.4^{pq}	0.5	53^{k}	13.8^{kl}	0.3^{de}
	P7	1791^{qr}	4.5^{pq}	0.5	32^{l}	8.3^{l}	0.2^{e}
	Goldar	1278^{r}	3.3^{q}	3.0	35^{l}	9.1^{l}	0.2^{e}
P value		<.0001	<.0001	>.50	<.0001	<.0001	<.0005

Note. Species: intermediate wheatgrass, *Thinpyrum intermedium* (Host) Barkworth & D.R. Dewey; tall wheatgrass, *Thinpyrum elongatum* (Host) D.R. Dewey; crested wheatgrass, *Agropryon cristatum* (L.) Gaertn. and *A. desertorum* (Fisch. ex Link) Schult.; western wheatgrass, *Pascopyrum smithii* Rydb.; RS Hybrid wheatgrass, *Elymus hoffmannii* K.B. Jensen & K.H. Asay; meadow bromegrass, *Bromus biebersteinii* Roem. & Schult.; smooth bromegrass, *Bromus inermis* Leyss.; Siberian wheatgrass, *Agropyron fragile* (Roth) P. Candargy; Altai wildrye, *Leymus angustus* (Trin.) Pilg.; Russian wildrye, *Psathyrostachys juncea* (Fisch.) Nevski; basin wildrye, *Leymus cinereus* (Scribn. & Merr.) Á. Löve; thickspike wheatgrass, *Elymus lanceolatus* (Scribn. & J.G. Sm.) Gould; bluebunch wheatgrass, *Pseudoroegneria spicata* (Pursh) Á. Löve.

†Column values followed by different superscript letters differ significantly.

TABLE 3 Annual biomass and ground cover best linear unbiased estimates from each of six locations used to characterize rangeland revegetation using perennial cool-season grass species. Crisis years are the single year at each location whose estimate significantly differs from each of the other years

	Blue Creek, UT		Mandan, ND		Ithaca, NE		Miles City, MT		North Logan, UT		Sidney, NE	
	BM	GC	BM	GC	BM	GC	BM	GC	BM	GC	BM	GC
Year	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%
2000	–	–	–	–	3363^{d†}	97^{a}	–	–	–	–	–	–
2001	900^{b}	–	2573^{b}	73^{b}	9084^{a}	96^{a}	2134^{a}	80^{a}	2518^{a}	–	4204^{a}	69^{ab}
2002	1278^{a}	–	1577^{c}	72^{b}	6157^{b}	82^{b}	695^{b}	77^{a}	1566^{b}	–	478^{c}	73^{a}
2003	719^{c}	–	4155^{a}	84^{a}	5228^{c}	75^{c}	883^{b}	29^{b}	974^{c}	–	2188^{b}	63^{b}

Note. BM, biomass; GC, ground cover.

†Column values followed by different superscript letters differ significantly.

4 | DISCUSSION

The objective of this analysis was the characterization of productivity, stability, and resilience for cool-season grass species and cultivars commonly seeded on rangelands. The high productivity and stability of intermediate wheatgrass and, to a lesser extent, tall and crested wheatgrass, and the low productivity and stability of basin wildrye, thickspike wheatgrass, and bluebunch wheatgrass for biomass and ground cover was consistent with previous findings (Asay et al., 2001; Robins et al., 2007, 2013). The intermediate, tall, and crested wheatgrasses originally came in favor for rangeland revegetation because of their ability to rapidly establish, persist, and produce forage under the harsh conditions (Richards, Chambers, & Christopher, 1998). In contrast, basin wildrye, thickspike wheatgrass, and bluebunch wheatgrass did not evolve under conditions of domestic livestock grazing or weed invasion and exhibited limited ability to establish, persist, or

produce forage, even with the crisis year excluded from the analysis.

Although the ability to produce large of amounts of biomass is critical only to privately owned rangelands, the ability to establish and persist is critical to both public and private rangelands to rapidly stabilize soil resources and limit erosion and weed invasion. This is particularly of note considering the relatively mild conditions of the sites included in this study. Only the Blue Creek site received less than ~300 mm of precipitation in any single year (Robins et al., 2007). All the remaining sites had excellent conditions for establishment and persistence of these species, although the increased humidity of the Ithaca site may have increased disease pressures.

The species with higher biomass resilience (although not significant) possessed low productivity and suggested that biomass resilience is associated with generally low biomass production in all years—high ratio of crisis year production to overall productivity. Overall, the lack of differences for biomass resilience and limited differences for ground cover resilience may have been attributed to one of two possibilities. First, 3 yr is a limited amount of time to conduct this type of analysis and there may simply have not been enough inference space. Second, although the data collection of this analysis occurred in the early 2000s drought of western North America (McNeeley, 2014), there may not have been large enough differences among the non-crisis years and the crisis year within each site to identify resilience. Likely, the issue was a combination of both possibilities—too few years compared to the crisis year. Although we admit the dataset is limited for this type of analysis, we considered this to be a preliminary analysis. Our hope was to begin a discussion of the use of these statistics to better characterize rangeland plant materials.

4.1 | Implications

The high productivity and stability of intermediate, tall, and crested wheatgrass, and their cultivars, suggested these to be the best choices for rangeland revegetation under these site conditions. Despite growing desire to include native North American species in revegetation efforts, with the exception of western wheatgrass (*Pascopyrum smithii* Rydb.), the low productivity, stability, and in the case of ground cover, resilience of the Native North American species basin wildrye, thickspike, and bluebunch wheatgrass suggested that these species possess limited ability to successfully stabilize disturbed sites, at least when planted in monoculture. These species will require the identification of useful genetic variation and subsequent plant breeding to markedly improve their ability to stabilize disturbed sites. Unfortunately, the inference space of this analysis was limited to only 3 yr. More long-term analyses will be required to more definitively characterize these statistics, and particularly resilience in rangeland species.

DISCLOSURE

The authors declare no conflict of interest.

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