

Weather effects on herbaceous yields: Wyoming big sagebrush steppe, southeastern Oregon

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ABSTRACT.—Describing relationships among weather variables and herbage yield is important for planning livestock grazing, assessing wildlife habitat, and evaluating short- and long-term vegetation dynamics. We investigated the effects of weather on herbage yields from 44 Wyoming big sagebrush (*Artemisia tridentata* subsp. *wyomingensis* Beetle & Young) steppe sites across eastern Oregon from 2003 to 2012. We used linear and multiple linear regression to relate herbaceous total and functional group yields to monthly and seasonal precipitation, reference evapotranspiration (RET), and temperature. Functional groups were large perennial bunchgrasses, Sandberg bluegrass (*Poa secunda* J. Presl.), perennial forbs, annual forbs, and annual grasses. Yields and weather variables were normalized prior to regression analysis to account for differences in site characteristics. Normalized variables were obtained by dividing yield and weather variables by their 10-year means. Fall-through-spring (e.g., October–May, September–May) and spring precipitation and RET all contributed to significant predictive models for both functional groups and total herbage. Spring precipitation provided the strongest predictor of perennial bunchgrasses (March–May and June; $R^2 = 0.91$), perennial forbs (May; $R^2 = 0.79$), annual grasses (March; $R^2 = 0.79$), and total herbage (March–May; $R^2 = 0.83$) yields. Yields of Sandberg bluegrass and annual forbs were most strongly associated with RET for October–May ($R^2 = 0.86$) and October–April ($R^2 = 0.79$), respectively. Overall, we found a greater influence of late-winter and spring precipitation than that of models developed several decades ago where crop-year (September–June) precipitation provided more accurate herbage biomass estimates.

RESUMEN.—Describir la relación de las variables climáticas y las de producción de forraje es importante para planificar el pastoreo del ganado, evaluar el hábitat de la vida silvestre y la dinámica de la vegetación a corto y largo plazo. Investigamos los efectos del clima en el forraje de 44 sitios esteparios de artemisa grande de Wyoming (*Artemisia tridentata* subsp. *wyomingensis* Beetle & Young) en todo el este de Oregón entre 2003 y 2012. Utilizamos regresión lineal y lineal múltiple para relacionar la producción total y los grupos funcionales herbáceos con la precipitación mensual y estacional, la evapotranspiración de referencia (RET, por sus siglas en inglés) y la temperatura. Los grupos funcionales fueron: pasto perenne grande, Sandberg bluegrass (*Poa secunda* J. Presl.), hierba perenne, hierba y pasto anuales. Las variables de producción y climáticas se normalizaron antes del análisis de regresión con el propósito de controlar las diferencias en las características de los sitios. Las variables normalizadas se obtuvieron dividiendo las variables de producción y climáticas por su promedio de los últimos 10 años. Del otoño hasta la primavera (es decir, octubre–mayo, septiembre–mayo), la precipitación de primavera y la RET contribuyeron en la obtención de modelos predictivos significativos tanto para los grupos funcionales como para el forraje total. La precipitación de primavera proporcionó el mejor indicador de la producción de pasto perenne (marzo–mayo y junio; $R^2 = 0.91$), hierba perenne (mayo; $R^2 = 0.79$), pasto anual (marzo; $R^2 = 0.79$), y forraje total (marzo–mayo; $R^2 = 0.83$). La producción de Sandberg bluegrass y de herbáceas anuales se asociaron más con la RET en octubre–mayo ($R^2 = 0.86$) y octubre–abril ($R^2 = 0.79$), respectivamente. En general, encontramos una mayor influencia de las precipitaciones de finales de invierno y primavera que los modelos presentados hace varias décadas, donde la precipitación del año de cosecha (septiembre a junio) proporcionó estimaciones más precisas de la biomasa del forraje.

Estimating herbage yield is particularly challenging in arid and semiarid rangelands that are characterized by high variability in precipitation timing and amount (Sloat et al. 2018). Numerous models have been developed for many of

the world’s rangeland plant communities relating herbage yields to multiple abiotic drivers, in particular, precipitation, evapotranspiration, and soil water content (McNaughton et al. 1993, Polley et al. 2013, Hartman et al. 2020). Assessing

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climatic influences on herbage yields is important for planning livestock grazing and wildlife management, and for weighing climatic influences on short- and long-term vegetation dynamics, especially in drought years when forage is limiting.

The sagebrush steppe biome of the Intermountain Region of the western United States received widespread study relating annual herbage yields to precipitation at site and regional scales between 1950 and the early 1980s (Hutchings and Stewart 1953, Blaisdell 1958, Sneva 1982, Hanson et al. 1983). Across much of the region, fall-through-spring precipitation has been accepted as the critical driver of herbage yields (Sampson 1918, Passey et al. 1982). Significant correlations between herbage yield and crop-year (e.g., September–March, October–June) precipitation were obtained at specific sites in southeastern Oregon (Sneva 1982, $R^2 = 0.62$ to 0.85), eastern Idaho (Blaisdell 1958, $R^2 = 0.53$ to 0.74 ; Hanson et al. 1983, $R^2 = 0.59$), and regionally across eastern Oregon, southern Idaho, and northern Utah and Nevada (Sneva and Hyder 1962, $R^2 = 0.59$; Sneva and Britton 1983, $R^2 = 0.74$). In central Utah and southeastern Idaho, significant correlations were found for combinations of herbage and browse yields with crop-year precipitation (Craddock and Forsling 1938, $R^2 = 0.79$; Hutchings and Stewart 1953, $R^2 = 0.61$ to 0.88). Sneva (1977, 1982) also measured highly significant correlations between yields and precipitation for common bunchgrass species and palatable and unpalatable broadleaf forbs in a Wyoming big sagebrush (*Artemisia tridentata* ssp. *wyomingensis* Beetle & Young) community. However, there remain several deficiencies in the previous studies. Most have focused on total herbage yield or yields of vegetation palatable to livestock (e.g., Hutchings and Stewart 1953, Hanson et al. 1983). There is little information on the effects of annual weather variation on herbage yields of perennial and annual forbs and early-growing-season bunchgrasses, mainly Sandberg bluegrass (*Poa secunda* J. Presl.).

Ascertaining these relationships is difficult as consistent long-term sampling is required. Copeland et al. (2022) concluded that spring precipitation was the most consistent predictor of yields ($R^2 < 0.50$) at the functional group level on Wyoming big sagebrush steppe associations in eastern Oregon over a 10-year period. Previous studies often conducted harvests after bunch-

grasses finished growth in July and August (Sneva and Hyder 1962, Sneva 1982). By mid-June, many plant species and functional groups in Wyoming big sagebrush communities are well past peak growth and lose weight as they senesce, especially annuals, forbs, and Sandberg bluegrass (Bates et al. 2023).

In addition, herbaceous yields have likely been affected by recent climate change in the region through increased spring temperatures, shifting precipitation patterns, and greater precipitation extremes (Tang and Arnone 2013, Tang et al. 2015, Xue et al. 2017). These changes may have altered linkages among weather variables and herbage yields, which makes it important to reexamine past weather–yield relations. Because of the increasing importance of remote sensing in land management, long-term data sets and updated information regarding weather–yield interactions can augment and complement remote sensing efforts to determine rangeland productivity, vegetation dynamics, and fuel load monitoring at large regional scales (Elmendorf et al. 2015, Jones et al. 2018, Allred et al. 2022, Poděbradská et al. 2022).

We evaluated weather influences on pooled peak growing season (late May to early June) herbage yields from 44 Wyoming big sagebrush communities in southeastern Oregon. Sites were sampled over a 10-year period (2003–2012) with the intent of developing useful weather–yield models for total herbage and associated functional groups (e.g., Sandberg bluegrass, perennial bunchgrasses, perennial forbs, annual forbs, and annual grasses). Past and current research have demonstrated that regional annual herbage yields in sagebrush steppe are correlated to precipitation and evapotranspiration (Sneva and Hyder 1962, Engda et al. 2016, Copeland et al. 2022). Thus, we hypothesized that this relationship would carry over to individual functional groups. Aside from annual grass, air temperature has not been highly correlated with herbage yields in the sagebrush steppe (Blaisdell 1958, Sneva and Hyder 1962, Sneva 1982). Therefore, we hypothesized that herbage yields of Sandberg bluegrass, large perennial bunchgrasses, perennial forbs, and annual forbs would not be correlated to air temperature and that air temperature would be of little use for determining herbage yields in Oregon’s sagebrush steppe. Cheatgrass (*Bromus tectorum* L.) was the predominant annual grass in the study area (Bates and Davies 2019), and yields are commonly

related to combinations of winter and spring precipitation and temperature (Sneva 1982, George et al. 1989, Pilliod et al. 2017). Thus, we hypothesized that annual grass herbage yields would be correlated to winter and spring precipitation and temperature.

METHODS

Site Descriptions

Study sites were located in southeastern Oregon in Lake, Harney, and Malheur Counties within the Northern Basin and Range Ecoregion. Sites were on private property and public land administered by the Bureau of Land Management and USDA–Agricultural Research Service. All sites were intact, late-seral Wyoming big sagebrush–bunchgrass communities (Davies et al. 2006, Bates and Davies 2019) located in the High Desert, Humboldt, and on the western edge of the Snake River ecological provinces (Anderson et al. 1998, Bailey 2016). Study sites were mainly in the Malheur High Desert Major Land Resource Area (MLRA), with some in the Owyhee High Plateau, northern Humboldt, and western Snake River MLRAs (NRCS 2022). All sites met requirements of reference areas for rangeland health assessments (Davies et al. 2006, Pellant et al. 2020). Range health assessment on each site assured that departure of soil/stability, hydrologic function, and biotic integrity were none to slight based on interpreting criteria (Pellant et al. 2020).

Of the original 107 sites surveyed by Davies et al. (2006), we sampled biomass on 44 sites over a 10-year period (2003–2012), at peak growing season from late May to mid-June. Wyoming big sagebrush associations were identified by dominant perennial bunchgrass species by Bates and Davies (2019) and included bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] Á. Löve), Thurber's needlegrass (*Achnatherum thurberianum* [Piper] Barkworth), Idaho fescue (*Festuca idahoensis* Elmer), needle-and-thread (*Hesperostipa comata* [Trin. & Rupr.] Barkworth), bluebunch wheatgrass, and high desert mix, with a codominant association of bluebunch wheatgrass, Thurber's needlegrass, and Idaho fescue. Annual grasses were mainly the nonnative annual cheatgrass (*Bromus tectorum* L.) with the occasional presence of native annual fescues (*Vulpia* C.C. Gmel. species).

Elevation at sites ranged from 1160 to 1760 m (\bar{x} = 1472 m, SE = 27). Aspects include

all main compass directions, and slopes were flat to mostly less than 20%. Soils consisted of Aridisols and Mollisols, well drained, with loamy to sandy loam surface textures. Since 1980, annual precipitation (1 October–30 September) has ranged between 250 and 350 mm and has been highly variable year to year and seasonally (Abatzoglou 2013, 2019).

Sampling

Standing crop biomass was measured by herbaceous functional group in late May to mid-June (2003–2012). Functional groups were the shallow-rooted perennial bunchgrass Sandberg bluegrass, large perennial bunchgrasses, hereafter “perennial bunchgrasses” (e.g., Idaho fescue, Thurber's needlegrass, and bluebunch wheatgrass), annual grasses, perennial forbs, and annual forbs. Perennial bunchgrasses, Sandberg bluegrass, and perennial forbs were harvested from twenty 1-m² randomly located frames per site, avoiding areas clipped in prior years. Annual grass and forbs were collected from a 0.20-m² nested plot inside the 1-m² (1 × 1 m) frames. Perennial bunchgrasses were clipped to a 2.5-cm stubble; all other groups were clipped to about ground level (0–0.5 cm). Standing crop biomass comprises current year's growth (yield) and residual standing herbage from previous year's growth. Harvested herbage was dried at 60 °C to a constant weight prior to weighing. For Sandberg bluegrass and perennial bunchgrasses, yield was determined by separating current year's growth from standing crop. Ten 10–15-g subsamples of Sandberg bluegrass and perennial bunchgrasses per site were sorted into current year's growth (annual yield) and residual (previous year's growth). The percentage of current year's growth was calculated by dividing current year's growth by standing crop. Standing crop values of Sandberg bluegrass and perennial bunchgrasses were multiplied by the respective percentages of current year's growth to derive annual yield of these 2 functional groups. Samples of other herbaceous functional groups were equivalent to annual yield, and their standing crop values required no further sorting.

Precipitation (mm; Fig. 1A), reference evapotranspiration (RET, mm; Fig. 1B), and temperature (°C) were obtained for 28 grid points (several sites were within the same grid cell) from the GridMet historical gridded weather database (Abatzoglou 2013, 2019, Huntington et al. 2017). RET values used were ASCE

We used linear and multiple regression procedures (SAS Institute Inc., Cary, NC) to test relationships of herbaceous functional groups (perennial bunchgrasses, Sandberg bluegrass, perennial forbs, annual forbs, and annual grasses) and total herbaceous yield with precipitation (monthly and seasonal totals [e.g., winter, spring, etc.]), temperature (monthly and seasonal totals), and reference evapotranspiration (RET; monthly and seasonal totals). The level of significance used for model development was 0.05. Akaike's information criterion (AIC) and R^2 were used to compare the regression models and assist in determining which model best fit the data for the various herbaceous functional groups (deLeeuw 1992, Richards 2005, Burnham et al. 2010, Aho et al. 2014). The model(s) with the lowest AIC and highest R^2 were selected to describe weather and herbaceous yield relationships for Wyoming big sagebrush steppe.

RESULTS

Herbage Yield

Total herbage yield was positively correlated to precipitation ($R^2 = 0.37$ to 0.85) and negatively correlated to RET ($R^2 = 0.37$ to 0.67) for several periods, from early fall through mid-spring (e.g., September or October–May) and late winter and spring (e.g., March–May) (Table 1). Several combinations of late-winter–spring precipitation together with crop-year and spring RET provided the strongest predictors of herbage yield ($R^2 = 0.70$ to 0.82). Temperature was not correlated to herbage yields alone nor in tandem with precipitation and RET because of multicollinearity. The best regression models selected by AIC analysis were described using (1) March–May precipitation (PI) and October–April reference evapotranspiration (RETI) as independent variables and (2) March–May precipitation:

$$(1) \text{ Herbage Yield Index (YI)} = 2.798 + 0.500(\text{Mar–May PI}) - 2.297(\text{Oct–Apr RETI})$$

$$P < 0.001, F = 44.9, R^2 = 0.91$$

$$(2) \text{ Herbage Yield Index (YI)} = 0.0135 + 0.8965(\text{Mar–May PI})$$

$$P < 0.001, F = 43.6, R^2 = 0.83$$

For example, if the precipitation index for a year were 1.4 and 1.0 for March–May and October–April RET precipitation, respectively, then

the herbage yield index would equal 1.2, or 120% of the long-term mean. Across the 10-year study, herbage yield varied 2.9-fold (60% to 170% of normal) across years ($P < 0.001$; Fig. 2A). The strongest linear regression model also demonstrates the importance of spring precipitation to herbage yield (Fig. 2B).

PERENNIAL BUNCHGRASSES.—Perennial bunchgrass yield varied 2.5-fold (65% to 160% of normal) across years ($P < 0.001$; Fig. 3A). Perennial bunchgrass yield was positively correlated to precipitation and negatively correlated to RET for the crop year and late winter through mid-spring for linear and multiple regression models (Table 1). There were no significant models combining precipitation and RET as independent variables. Temperature was not correlated to bunchgrass yield alone or in combination with precipitation and RET because the introduction of temperature into models resulted in multicollinearity. The best models for estimating perennial bunchgrass yield were with spring precipitation where yield was positively related to March–May precipitation (Fig. 3B).

$$(3) \text{ Perennial bunchgrass YI} = 0.348 + 0.652(\text{March–May PI})$$

$$P < 0.001, F = 37.0, R^2 = 0.80$$

$$(4) \text{ Perennial bunchgrass YI} = 0.197 + 0.803(\text{April–May PI})$$

$$P = 0.001, F = 36.5, R^2 = 0.72$$

PERENNIAL FORBS.—Perennial forb yield was positively correlated to precipitation and negatively correlated to RET (Table 1). There were no significant models combining precipitation and RET as independent variables. Temperature was not correlated to perennial forb yield alone or in combination with precipitation and RET because of multicollinearity. Perennial forb yield varied 2.4-fold (65% to 165% of normal) across years ($P < 0.001$; Fig. 4A), and the best model indicated that perennial forb yield was positively correlated to May precipitation (Fig. 4B):

$$(5) \text{ Perennial forb YI} = 0.572 + 0.428(\text{May PI})$$

$$P < 0.001, F = 35.7, R^2 = 0.79$$

SANDBERG BLUEGRASS.—Sandberg bluegrass yield was positively correlated to precipitation and negatively correlated to RET (Table 1). There were no significant models combining precipitation and RET as independent variables. Sandberg bluegrass yield varied 6.5-fold (30% to 230% of normal) across years ($P < 0.001$;

TABLE 1. Adjusted R^2 , P values, F values, and AIC values, for herbaceous yields (total yield, perennial bunchgrasses, perennial forbs, Sandberg bluegrass [*Poa secunda*], annual grasses, and annual forbs) and precipitation and reference evapotranspiration (RET), Wyoming big sagebrush complex, southeast Oregon, 2003–2012. Bolded values express best-models solutions by functional group for the independent variables (precipitation, RET, and precipitation & RET). N.S. = nonsignificant.

	Total yield				Perennial bunchgrasses				Perennial forbs			
	R^2	P	F	AIC	R^2	P	F	AIC	R^2	P	F	AIC
Precipitation												
May	0.584	0.006	13.6	-26.8	0.580	0.006	13.5	-32.0	0.794	< 0.001	35.7	-38.7
March–April	0.375	0.035	6.4	-21.9	0.348	0.043	5.8	-27.6			N.S.	
March–May ^b	0.825	0.001	43.6	-34.6	0.800	< 0.001	37.0	-39.4	0.462	0.018	8.8	-29.1
April–May	0.738	0.001	24.2	-29.9	0.721	0.001	36.5	-39.3			N.S.	
October–May	0.605	0.005	14.8	-28.1	0.458	0.019	8.6	-29.4			N.S.	
September–April & May	0.740	0.004	13.7	-30.0			N.S.				N.S.	
September–May	0.594	0.006	14.2	-26.2	0.433	0.023	8.6	-29.0			N.S.	
March–April & May	0.788	0.002	17.8	-35.8			N.S.				N.S.	
March–June	0.526	0.011	11.0	-24.7	0.405	0.029	7.1	-26.2			N.S.	
Reference evapotranspiration												
May	0.366	0.005	14.8	-26.5	0.607	0.005	14.9	-32.6	0.587	0.006	9.8	-31.7
March–May	0.557	0.001	27.5	-30.5	0.522	0.011	10.8	-30.6			N.S.	
April–May	0.543	0.009	14.2	-30.5	0.539	0.010	11.5	-31.0	0.358	0.040	6.0	-27.4
October–April	0.527	0.001	24.8	-30.1			N.S.				N.S.	
October–May	0.672	<0.001	42.2	-34.3			N.S.				N.S.	
Precipitation & RET												
March–May & October–MayRET	0.907	< 0.001	44.9	-6.3			N.S.				N.S.	
May & March–MayRET	0.710	<0.001	25.1	-4.3			N.S.				N.S.	
May & October–AprilRET	0.702	<0.001	24.2	-4.1			N.S.				N.S.	
Sandberg bluegrass												
March			N.S.		0.794	< 0.001	35.8	-16.5			N.S.	
May	0.441	0.022	8.1	-11.6			N.S.		0.373	0.036	6.4	-3.7
March–April			N.S.		0.582	0.006	13.5	-9.4	0.372	0.036	6.4	-3.7
March–May	0.656	0.003	18.4	-16.5	0.534	0.010	11.8	-8.4	0.664	0.003	18.8	-9.8
October–April			N.S.		0.534	0.030	6.9	-9.4	0.419	0.026	7.47	-4.2
October–May	0.546	0.009	11.8	-13.6	0.483	0.015	9.4	-7.3	0.660	0.003	18.8	-9.9
September–May	0.452	0.008	12.2	-13.9	0.452	0.020	8.4	-6.7	0.672	0.002	19.4	-10.1
October–April & May			N.S.				N.S.		0.680	0.008	10.6	-9.7
Reference evapotranspiration												
May			N.S.				N.S.		0.400	0.030	18.8	-4.1
March–May	0.834	< 0.001	47.6	-24.0	0.442	0.020	8.3	-6.6	0.766	< 0.001	30.5	-13.5
April–May	0.766	<0.001	30.5	-20.3	0.384	0.044	5.7	-4.9	0.607	0.005	14.9	-8.3
October–April	0.787	0.008	34.0	-21.2	0.482	0.016	9.4	-7.3	0.790	< 0.001	34.8	-14.8
October–May	0.863	< 0.001	57.9	-25.2	0.465	<0.018	8.8	-6.9	0.768	< 0.001	30.8	-13.6

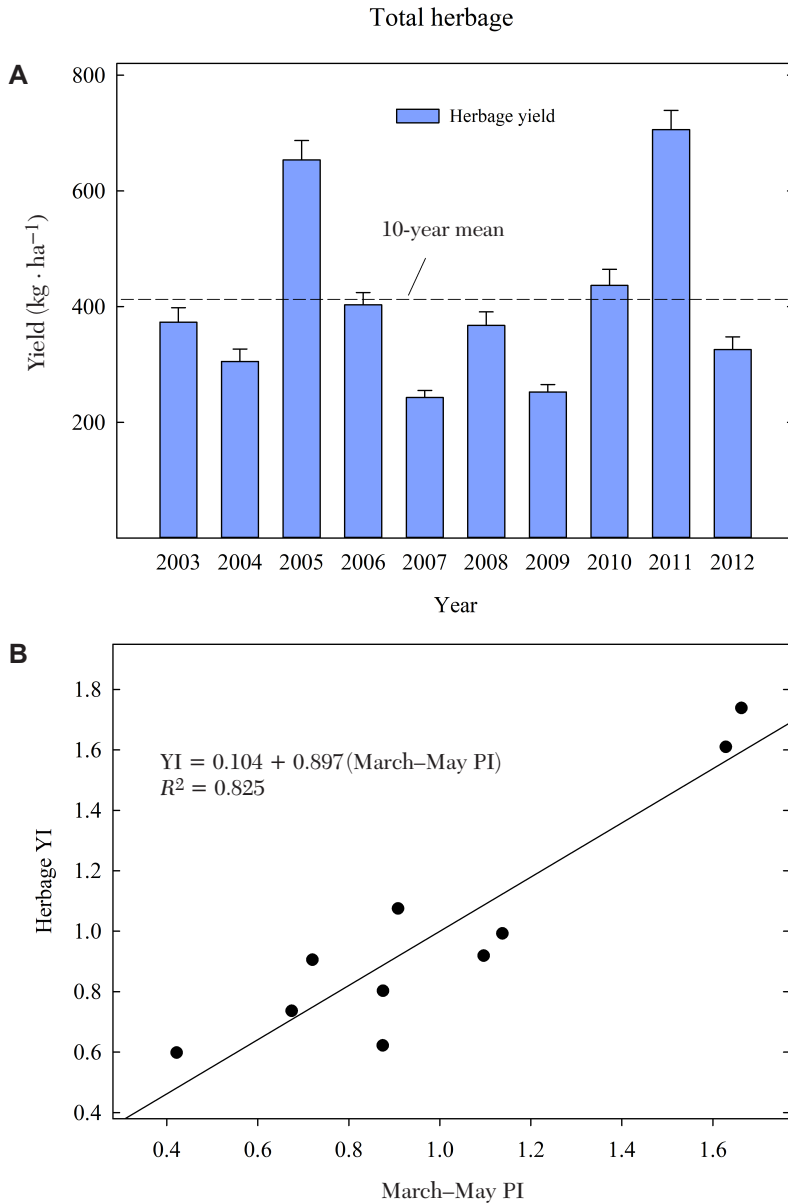


Fig. 2. **A**, Total herbage yield means + standard errors for 44 Wyoming big sagebrush sites. **B**, Best linear regression model for herbage yield index (YI) and March–May precipitation index (PI), southeast Oregon, 2003–2012.

Fig. 5A). There were 2 nearly identical models predicting Sandberg bluegrass yield using RET as the independent variable:

(6) Sandberg bluegrass YI = 8.69 – 7.69(Oct–May RETI)
 $P < 0.001, F = 58.2, R^2 = 0.86$, (Fig. 5B)

(7) Sandberg bluegrass YI = 7.106 – 6.111(Mar–May RETI)
 $P < 0.001, F = 47.6, R^2 = 0.83$

Sandberg bluegrass yield was negatively correlated to average temperature for the months of April ($P = 0.033, F = 6.6, R^2 = 0.37$), May ($P = 0.027, F = 7.3, R^2 = 0.41$), March–May ($P = 0.011, F = 11.0, R^2 = 0.52$), April and May ($P = 0.007, F = 13.1, R^2 = 0.58$), February–April ($P = 0.038, F = 6.1, R^2 = 0.37$), and October–May ($P = 0.031, F = 6.6, R^2 = 0.40$). AIC analysis indicated that temperature for the April

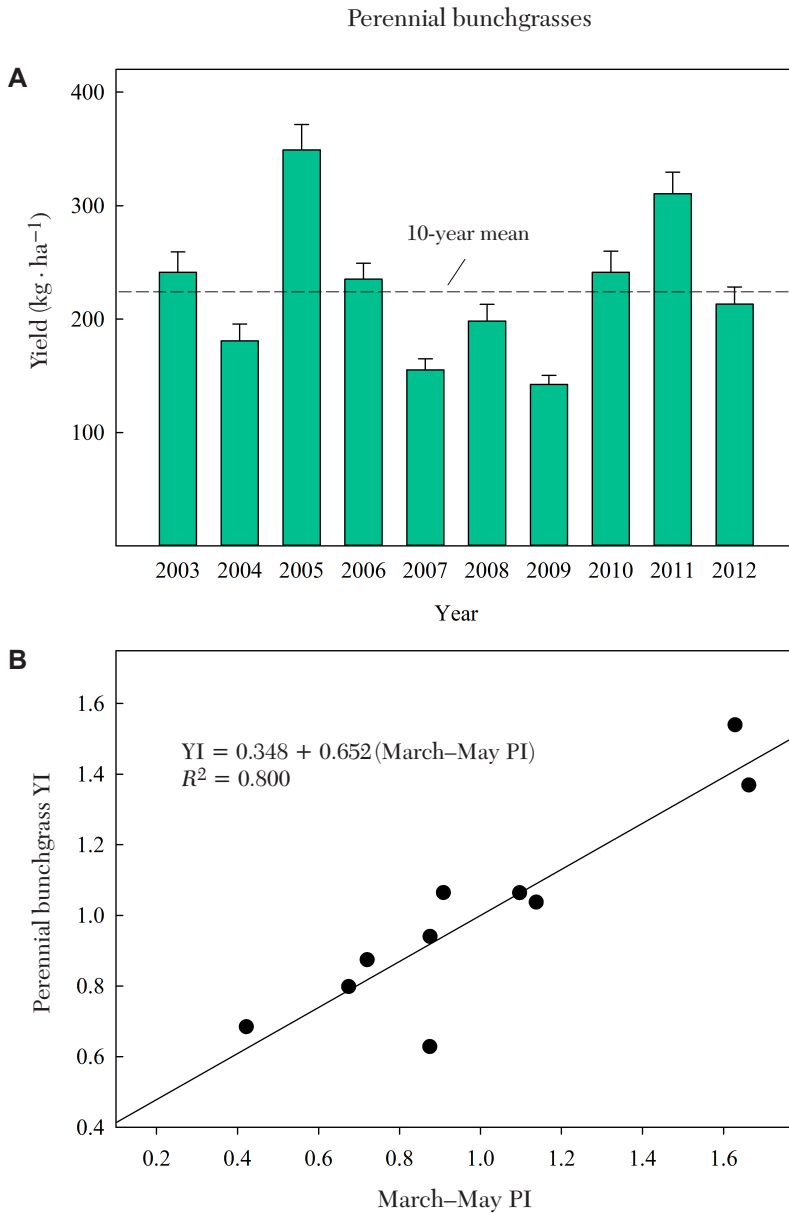


Fig. 3. **A**, Perennial bunchgrass yield means + standard errors for 44 Wyoming big sagebrush sites. **B**, Best linear regression model for perennial bunchgrass yield index (YI) and March–May precipitation index (PI), southeast Oregon, 2003–2012.

through May period provided the best fit for estimating Sandberg bluegrass yield. Temperature in combination with precipitation and RET failed to provide significant models estimating Sandberg bluegrass yield because of multicollinearity issues.

ANNUAL GRASSES.—Annual grass yield was positively correlated to precipitation and nega-

tively correlated to RET (Table 1). There were no significant models combining precipitation and RET as independent variables. Temperature was not correlated to annual grass yield alone or in combination with precipitation and RET because of multicollinearity. Annual grass yield varied 8.5-fold (30% to 340% of normal) across

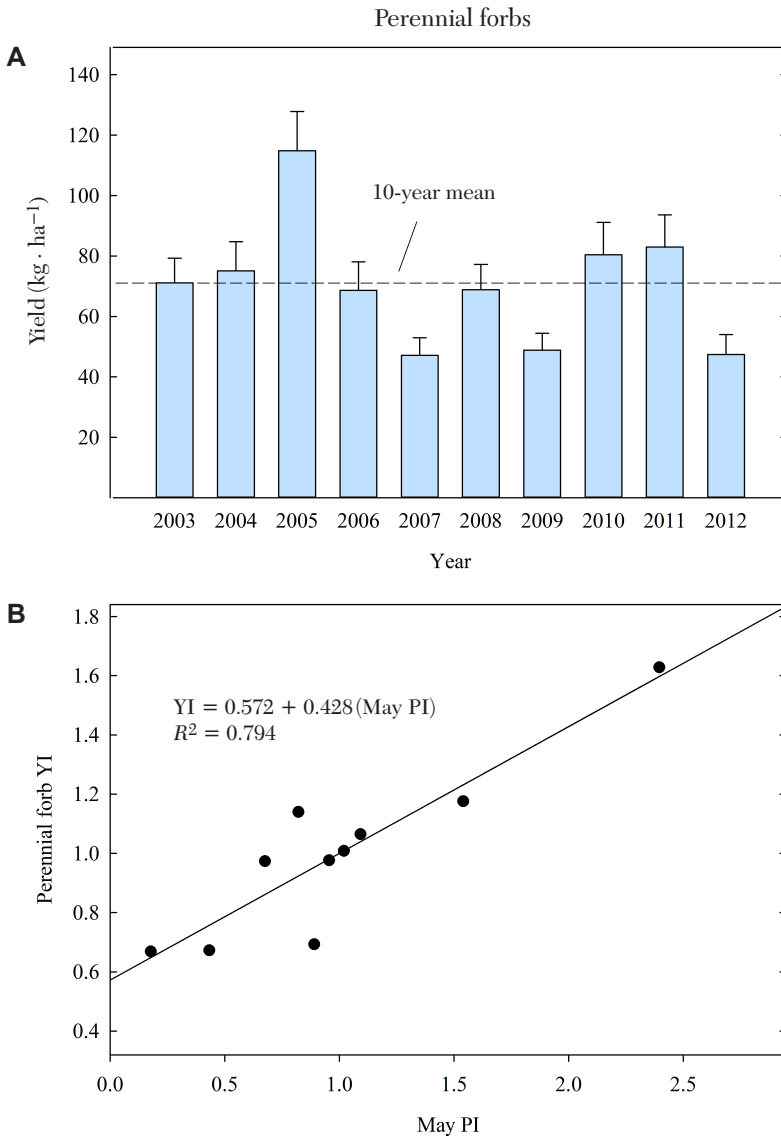


Fig. 4. **A**, Perennial forb yield means + standard errors (2003–2012) for 44 Wyoming big sagebrush sites. **B**, Best linear regression model for perennial forb yield index (YI) and May precipitation index (PI), southeast Oregon, 2003–2012.

years ($P < 0.001$; Fig. 6A). The best model for annual grass yield was described using March precipitation as the independent variable (Fig. 6B):

$$(8) \text{ Annual grass YI} = -1.461 + 1.460(\text{March PI})$$

$$P < 0.001, F = 35.8, R^2 = 0.79$$

ANNUAL FORBS.—Annual forb yield was positively correlated to precipitation and negatively correlated to RET (Table 1). There were no significant models combining precipitation and

RET as independent variables. Temperature was not correlated to annual forb yield alone or in combination with precipitation and RET because of multicollinearity. Annual forb yield varied 8.5-fold (23% to 310% of normal) across years ($P < 0.001$; Fig. 7A). The best models were described with RET as the independent variable (Fig. 7B):

$$(9) \text{ Annual Forb YI} = 11.760 - 10.757(\text{Oct–Apr RETI})$$

$$P < 0.001, F = 34.9, R^2 = 0.79$$

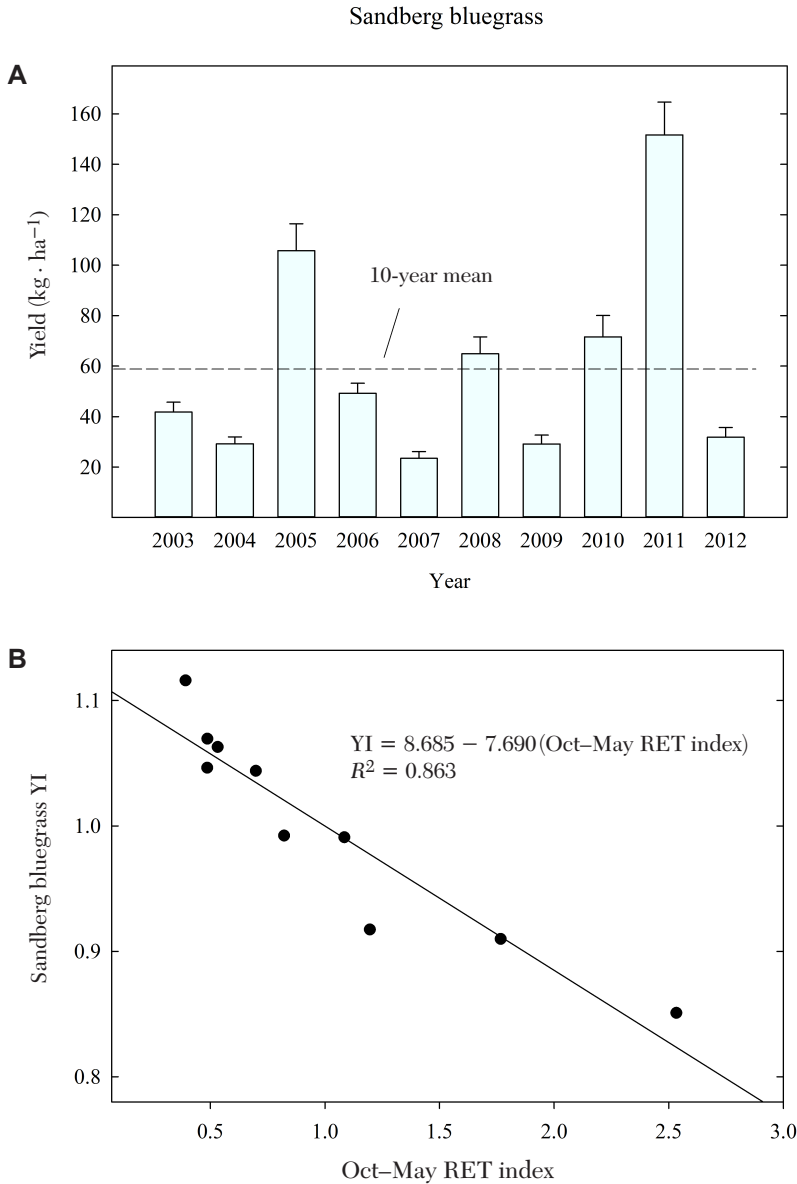


Fig. 5. **A**, Sandberg bluegrass (*Poa secunda*) yield means + standard errors for 44 Wyoming big sagebrush sites. **B**, Best linear regression model for Sandberg bluegrass yield index (YI) and Oct–May RET index, southeast Oregon, 2003–2012.

(10) $11.210 - 10.210(\text{Oct–May RETI})$

$P < 0.001, F = 30.8, R^2 = 0.77$

(11) $9.259 - 8.259(\text{March–May RETI})$

$P < 0.001, F = 30.5, R^2 = 0.77$

DISCUSSION

Functional group and total herbage yields were highly correlated to precipitation and RET

for Wyoming big sagebrush steppe of southeast Oregon; thus, the first of our hypotheses was accepted. This confirms previous studies that established that herbage yields in sagebrush steppe can be estimated from precipitation and evapotranspiration data with high accuracy (Blaisdell 1958, Sneva and Hyder 1962, Sneva and Britton 1983, Engda et al. 2016, Copeland et al. 2022).

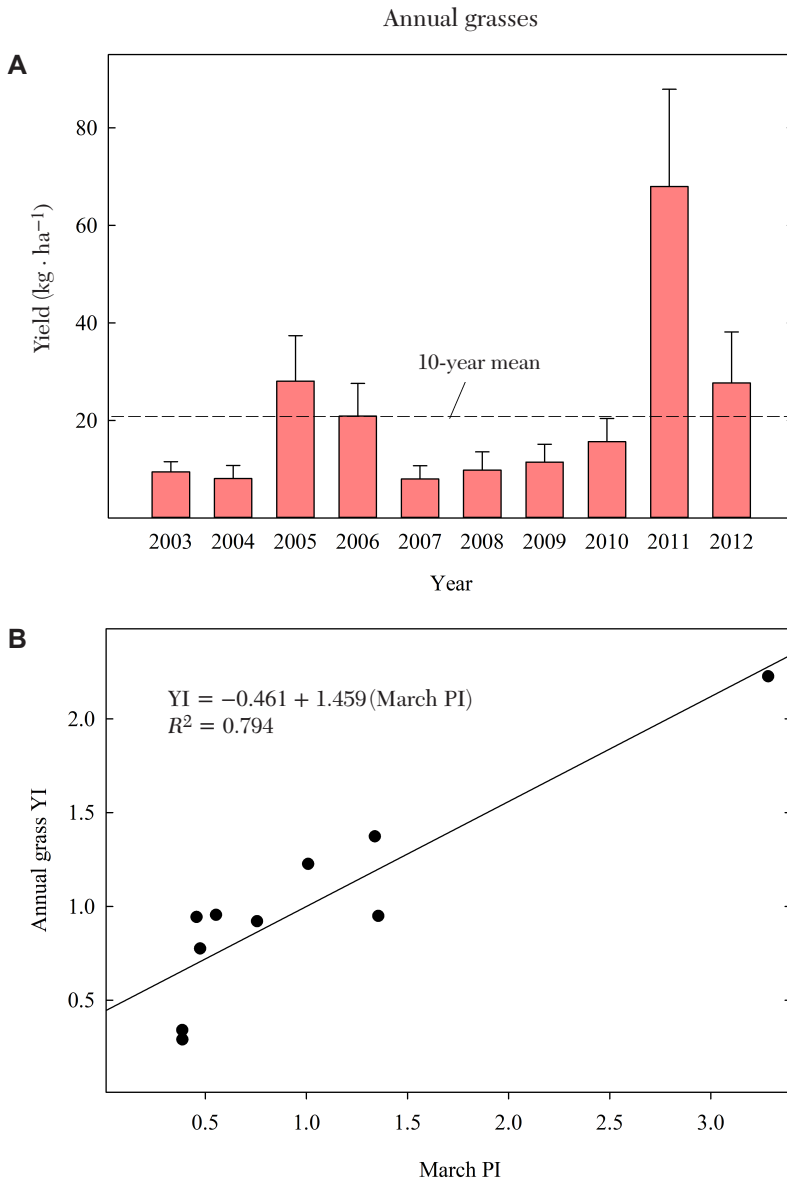


Fig. 6. **A**, Annual grass yield means + standard errors for 44 Wyoming big sagebrush sites. **B**, Best linear regression model for annual grass yield index (YI) and March precipitation index (PI), southeast Oregon, 2003–2012.

Precipitation and Herbage Yield

Total herbage yield and its corresponding relationship to precipitation generated both similarities and differences with past models in the Intermountain Region. Previous studies determined that precipitation between midsummer (July) or late summer–early fall (September and October) through early to mid-spring (March–May) provided the most useful predictor of

herbage yield in sagebrush steppe, with R^2 values of 0.59 to 0.79. Our results for September or October through May generated similar R^2 values of 0.59 to 0.74. In contrast to previous studies in the Great Basin, however, our results measured stronger relationships for herbage yield and growing season precipitation from late winter into mid-spring ($R^2 = 0.37$ to 0.83; e.g., March, March–May). Blaisdell (1958) found

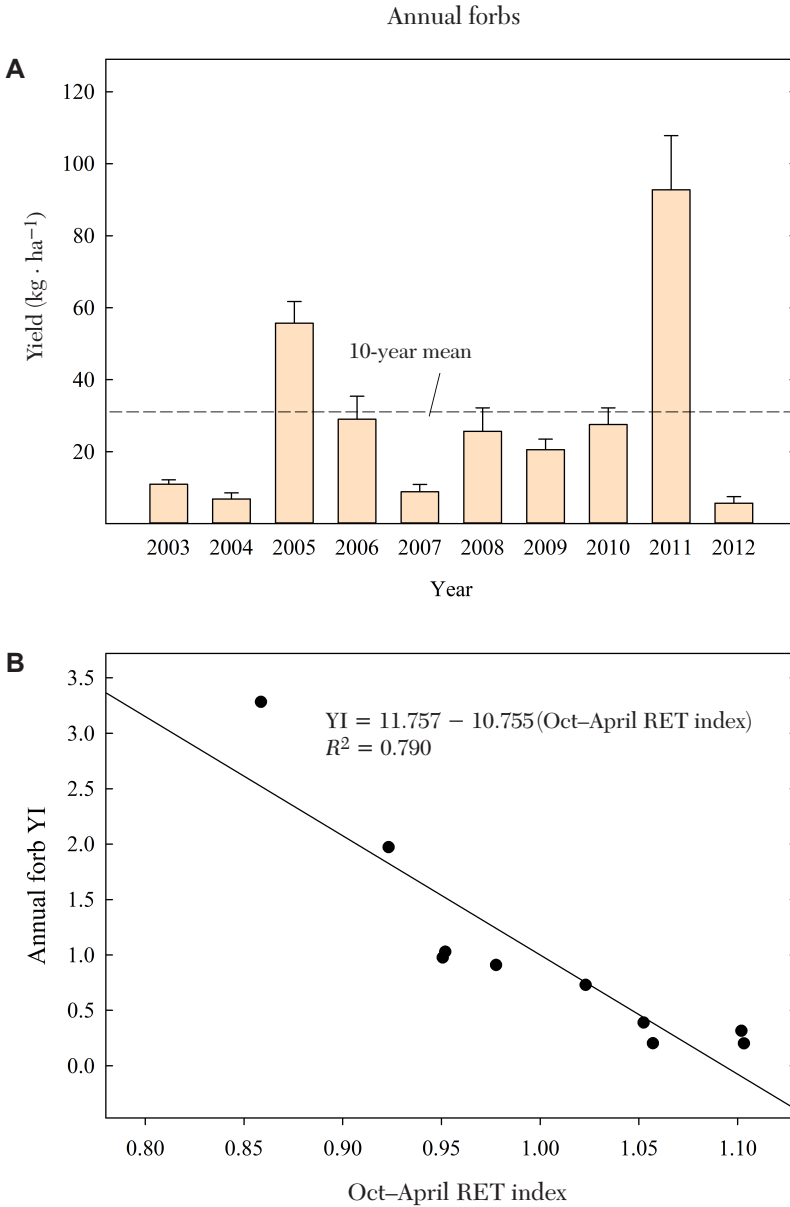


Fig. 7. **A**, Annual forb yield means + standard errors for 44 Wyoming big sagebrush sites. **B**, Best linear regression model for annual forb yield index (YI) and Oct–April RET index, southeast Oregon, 2003–2012.

that precipitation periods beginning in March or April were not significantly correlated to herbage yields. Sneva (1982) found significant positive correlations for herbage yield and growing season precipitation; however, overall correlation coefficients were less ($R^2 = 0.33$ to 0.50) than attained in our study. Hanson et al. (1983) determined that spring precipitation was more effec-

tive for enhancing herbaceous annual yield in mountain big sagebrush steppe above 1680 m in Idaho.

The greater importance of late-winter and spring precipitation attached to herbaceous yield possibly derives from several factors including potential changes in the amount and seasonality of late-winter through spring (March–May)

precipitation, higher atmospheric CO₂ levels, and herbage collection methods. At the sites used by Blaisdell (1958; 1932–1954) and Sneva (1982; 1950s–1970s), March–May precipitation during 2003–2012 was 25 to 30 mm greater than observed in their studies and as a percentage of crop-year precipitation (September–May) increased by 21% to 28% (Supplementary Material). Across our study sites, March–May precipitation (2003–2012) was greater (compared to the 1950s through the late 1970s) and as a percentage of crop-year total increased by 24% (from 32.8% to 40.8%) (see Supplementary Material). Changes in precipitation amounts and timing coupled with increased atmospheric CO₂ are affecting rangeland productivities and altering herbage yields and their relationships to climatic variables (Polley et al. 2013, 2017). Studies that collect herbage biomass after early June underestimate yields of many species and several functional groups especially annuals, perennial forbs, and Sandberg bluegrass, which all rapidly lose weight upon senescence (Bates et al. 2023). Sneva (1982) and Sneva and Hyder (1962) harvested herbage in July and August, after peak growth in late May and early June; thus, regression estimates between yields and late-winter–spring precipitation may have been weakened. Nevertheless, precipitation inputs prior to the growing season remain key to ensuring adequate soil water availability for growth initiation in the late winter and early spring (Copeland et al. 2022).

Several combinations of spring precipitation and crop-year and spring RET were strongly associated with total herbage yield. These associations indicated that years of highest herbage yield were associated with above-average spring precipitation combined with lower crop-year or spring RET. Thus, the highest herbage yields occurred in 2005 and 2011, which were cooler combined with high spring precipitation, and lowest yields in 2007 and 2009 because of warm and dry conditions.

Precipitation and Functional Group Yield

Aside from perennial forbs, other functional groups and Sandberg bluegrass developed herbage yield–precipitation regressions similar to total herbage yield for the crop year (e.g., September or October–May) and spring (e.g., March–May) precipitation periods. Unfortunately, relatively few previous studies have assessed precipitation influences on functional group or species yields.

Sneva (1982) evaluated precipitation influences on common bunchgrass species yields and then grouped perennial forbs into livestock-palatable and unpalatable categories for the northern Great Basin. Blaisdell (1958) only grouped herbage into bunchgrasses and perennial forbs.

Our crop-year precipitation–herbage yield correlations for perennial bunchgrasses ($R^2 = 0.42$ to 0.45) and Sandberg bluegrass ($R^2 = 0.55$) were similar ($R^2 = 0.35$ to 0.79) to other studies in the Great Basin (Blaisdell 1958, Sneva 1982). However, herbage–precipitation correlations in the spring period (e.g., March–May) of our study were generally superior to crop-year periods for bunchgrasses ($R^2 = 0.35$ to 0.80) and Sandberg bluegrass ($R^2 = 0.44$ to 0.66) and higher than reported by Sneva (1982, $R^2 = 0.21$ to 0.37). Blaisdell (1958) reported no significant correlations between perennial bunchgrass yields and spring precipitation.

Similarities with Copeland et al. (2022) are that we both identified the importance of spring precipitation as a predictor of perennial bunchgrass yield and crop-year precipitation and spring precipitation as predictors of Sandberg bluegrass yield. In our study, however, we evaluated a pooled response by normalizing yields and weather variables at the regional level, while Copeland et al. (2022) developed weather (precipitation and RET)–yield relationships at the site level and by plant association. At the site scale, herbage yields were influenced by not only weather variables but also by variation in site characteristics, mainly soil attributes (e.g., depth, horizonation, texture, water-holding capacity) as well as aspect, elevation, and slope, which affect growing season soil water availability (Sneva and Hyder 1962, Sneva and Britton 1983). For example, several of our sites were in the same GridMet cells, sharing identical weather inputs, yet producing different herbage yield potentials in total and for the functional groups. Thus, by evaluating sites independently across the region, the results from Copeland et al. (2022) revealed a complex relationship among herbage yields, association, site, and weather.

Our results showed that only spring precipitation ($R^2 = 0.46$ to 0.79) correlated to perennial forb yield. These values are similar to spring precipitation and livestock-palatable perennial forb yield correlations ($R^2 = 0.31$ to 0.69) measured by Sneva (1982). Crop-year precipitation was positively correlated to yields of

unpalatable perennial forbs (Sneva 1982, $R^2 = 0.49$ to 0.59) and total perennial forbs (Blaisdell 1958, $R^2 = 0.50$ to 0.82). Yield–precipitation relationships could likely be improved by subdividing perennial forbs into early maturing (early to mid-May) and late-maturing groups (late May to early June). Perennial forbs often have 2 peak yield dates during the growing season, because of variable species maturity dates, though the main peak occurs in late May (Rhodes et al. 2010, Bates et al. 2023). Time constraints limited our herbage collections to one visit per site annually, which likely resulted in undervaluing several early maturing perennial forbs.

Crop-year, late-winter, and spring precipitation–annual grass yield correlations ($R^2 = 0.45$ to 0.79) were higher than past measurements made in the northern Great Basin (Sneva 1982, $R^2 = 0.19$ to 0.37) and central California (Duncan and Woodmansee 1975, $R^2 = 0.45$; George et al. 1989, $R^2 = 0.40$). Annual grasses in the northern Great Basin are considered winter annuals but may act as spring annuals without adequate fall precipitation to germinate (Stewart and Hull 1949). There is frequently little fall green-up of annual grasses in intact Wyoming big sagebrush communities in the northern Great Basin; thus, it is not surprising that late-winter and spring precipitation were the main drivers of annual grass yield in the study.

Annual forbs had similarly strong crop-year, late-winter, and spring precipitation–yield regressions ($R^2 = 0.45$ to 0.79) as the other functional groups. Annual forbs in the northern Great Basin are spring annuals with shallow, poorly developed root systems compared to other functional groups (Harris 1967, Passey et al. 1982, Johnson et al. 2022); thus, timely arrivals of spring precipitation produce fairly high annual yields, such as in 2005 and 2011. In particularly droughty springs, annual forb yield is extremely low, as occurred in 2007 and 2012. Consequently, annual forbs exhibited the highest inter-annual variability in yields among the herbaceous functional groups. Passey et al. (1982) arrived at the same conclusions in a multistate (Idaho, Utah, Nevada) study spanning a 10-year period in sagebrush steppe.

RET and Herbage Yield

Evapotranspiration has been used to estimate herbage yield, mainly in the Great Plains grasslands (Dahl 1963, Torell et al. 2011, Engda et al. 2016). Copeland et al. (2022) determined that

RET was a significant driver of herbage yields on a site-by-site basis for Wyoming big sagebrush communities in eastern Oregon. In our study, total and functional group herbage yields showed similarly strong relationships with RET as with precipitation at the regional level. While herbage yields were positively correlated to precipitation, yields were negatively correlated to crop-year and late-winter–spring RET. This indicates that the highest herbage yields in Wyoming big sagebrush communities are associated with cooler growing seasons, meaning lower temperatures, more cloudy days, and higher humidity. These conditions tend to coincide with periods of greater precipitation, especially in the spring. Similarly, Blaisdell (1958) noted that herbage yields were greatest during cooler, wetter growing seasons and measured a positive relationship with cloudiness on herbage production.

Sandberg bluegrass and annual forbs had greater correlations between yield and RET than precipitation. This indicates that their annual yield responses were more sensitive to RET variability than the other functional groups were, possibly because they often grow in the spring when soil moisture isn't limited. Both Sandberg bluegrass and annual forbs had their highest yields in years with lowest RET (2005, 2011) and particularly low yields in years with high RET (2004, 2007, 2012). In wetter, cooler years, all functional groups tended to have extended growing seasons, with peak yield dates occurring 10 to 30 days later than average, which contributed to higher annual yields (Bates et al. 2023).

The relationships between yield and RET in our region differ from sites and regions of the western and central Great Plains. In central and eastern Wyoming, total herbage ($R^2 = 0.69$), grass ($R^2 = 0.78$), and forb yields ($R^2 = 0.51$) were positively related to actual evapotranspiration (Engda et al. 2016). Dahl (1963) determined that herbage yields in the Nebraska Sandhills were positively related to evapotranspiration. The contrasting relationships are likely related to differences in precipitation timing, active growing season periods, and species attributes. In our region of the northern Great Basin the bulk of annual precipitation occurs from late fall to mid-spring and plant communities are dominated by cool-season (C3) species, with the active growing season beginning in mid-March and concluding in late May to mid-June. The

growing season in the Great Plains regions begins in April and continues into midsummer, receives a higher amount of summer precipitation, and produces various mixes of warm- (C4) and cool- (C3) season species (Comstock and Ehleringer 1992, Cook and Irwin 1992).

Temperature

Aside from Sandberg bluegrass, there were no significant relationships between herbage yields and temperature, alone or in tandem with precipitation and RET. This was not altogether surprising as temperature has not been correlated with herbage yields in the sagebrush steppe except for specific periods of growth and for some species (Blaisdell 1958, Sneva and Hyder 1962, Sneva 1982). Blaisdell (1958) did find that late-winter to early spring temperatures were good predictors of growth initiation and early spring yields but that by mid-spring, temperature was not useful for estimating herbage yields. Readers should not conclude that temperatures are not influencing herbage yields, because minimum and maximum temperatures are incorporated into the calculation of evapotranspiration. Temperature indirectly affects soil water use efficiencies, thus, influencing herbage yield, which is why RET was an effective and strong predictor of total and functional herbage yields. Direct temperature effects on herbage yield may be influenced by individual site characteristics. Several studies have established that herbage yields at different sites were related to differing combinations of weather variables (George et al. 1989, Smart et al. 2007, Copeland et al. 2022). Sandberg bluegrass yield correlations to temperature, though mainly weaker, were similar in pattern to its relationships with RET, reinforcing the conclusion that cooler, wetter growing seasons result in higher Sandberg bluegrass yields. The result also indicates that Sandberg bluegrass yield is more sensitive to temperature variation than total herbage and other functional group annual yields.

The lack of a temperature effect, combined with precipitation, to describe annual grass yield departs from previous analyses. Murray et al. (1978) and Sneva (1982) accounted for 99% and 95% of the variation in cheatgrass yield to various combinations of crop-year and spring precipitation and late-winter and spring temperature at sites in southern Idaho and eastern Oregon. At 2 sites in central California, annual grass yields were related to different combinations of grow-

ing degree days, winter RET, length of winter dry period, and fall, winter, and spring precipitation, resulting in R^2 values of 0.61 and 0.72 (George et al. 1989). In our study, March precipitation explained 79% of the variation in annual grass yield. This suggests that annual grass yield at the regional level is dependent on precipitation at critical growth periods, an observation made previously by Bently and Talbot (1951) and Duncan and Woodmansee (1975). In addition, the lack of a direct temperature effect on annual grass yield could result from a difference in scale. Our study was conducted on a regional basis on a variety of soil types with less accurate weather data, while Murray et al. (1978), Sneva (1982), and George et al. (1989) worked at a site level on single soil types with nearby stations providing precise weather measurements.

CONCLUSION

Annual herbage yields varied widely in response to crop-year and late-winter–spring precipitation and RET for Wyoming big sagebrush steppe communities of southeast Oregon. Analyses revealed strong correlations between precipitation and RET and functional group herbage yields. The results did not provide useful yield estimates until herbage was at peak yield or nearing peak yield (late May to early June). Thus, planning livestock grazing or estimating weather impacts to wildlife habitat are likely to be deferred until the mid to late spring.

Our results showed a much greater influence of late-winter and spring precipitation than models developed several decades ago (e.g., Sneva and Britton 1983), where crop-year (September–June) precipitation provided more accurate yield estimates. We think this change is in response to greater amounts of late-winter and early spring precipitation than in the past (Supplementary Material 1), which may have moderated the generally drier conditions occurring across the western United States during the past 20 years (Williams et al. 2022). At one site in eastern Oregon, there has not been an observable decreasing trend in yields of the various herbaceous functional groups (Bates et al. 2020) despite about a 10% decrease in crop-year precipitation in the past 2 decades (Bates et al. 2023).

To remain useful, yield–weather models require regular updating in response to future climate change. Future climate change in the form of higher temperatures (Tang and Arnone

2013) and greater precipitation inputs and alteration of seasonal precipitation timing and intensity in the Intermountain Region (Xue et al. 2017), combined with increased atmospheric CO₂, have already caused earlier phenological development (Bloom et al. 2022, Brown et al. 2022) and are likely to alter the relationships among weather variables and herbage yields of the sagebrush steppe (Synder et al. 2019). Production forecasts for the remainder of the 21st century have indicated that, despite increased summer aridity, herbage yields will increase in the sagebrush steppe (Hufkens et al. 2016).

SUPPLEMENTARY MATERIAL

One online-only supplementary file containing 3 tables accompanies this article (<https://scholarsarchive.byu.edu/wnan/vol84/iss1/8>).

SUPPLEMENTARY TABLE 1.1. Precipitation and percentage of spring precipitation for the US Sheep Station, Dubois, Idaho, for 1932–1954 and 2003–2012.

SUPPLEMENTARY TABLE 1.2. Precipitation and percentage of spring precipitation for the Northern Great Basin Experimental Range, Riley, Oregon, for 1950–1977 and 2003–2012.

SUPPLEMENTARY TABLE 1.3. Precipitation and percentage of spring precipitation for the northern Great Basin region (11 stations), Oregon, for 1950–1979 and 2003–2012 (28 sites).

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