Appendix S1 for “Soil climate underpins year effects driving divergent outcomes in semi-arid cropland to grassland restoration”

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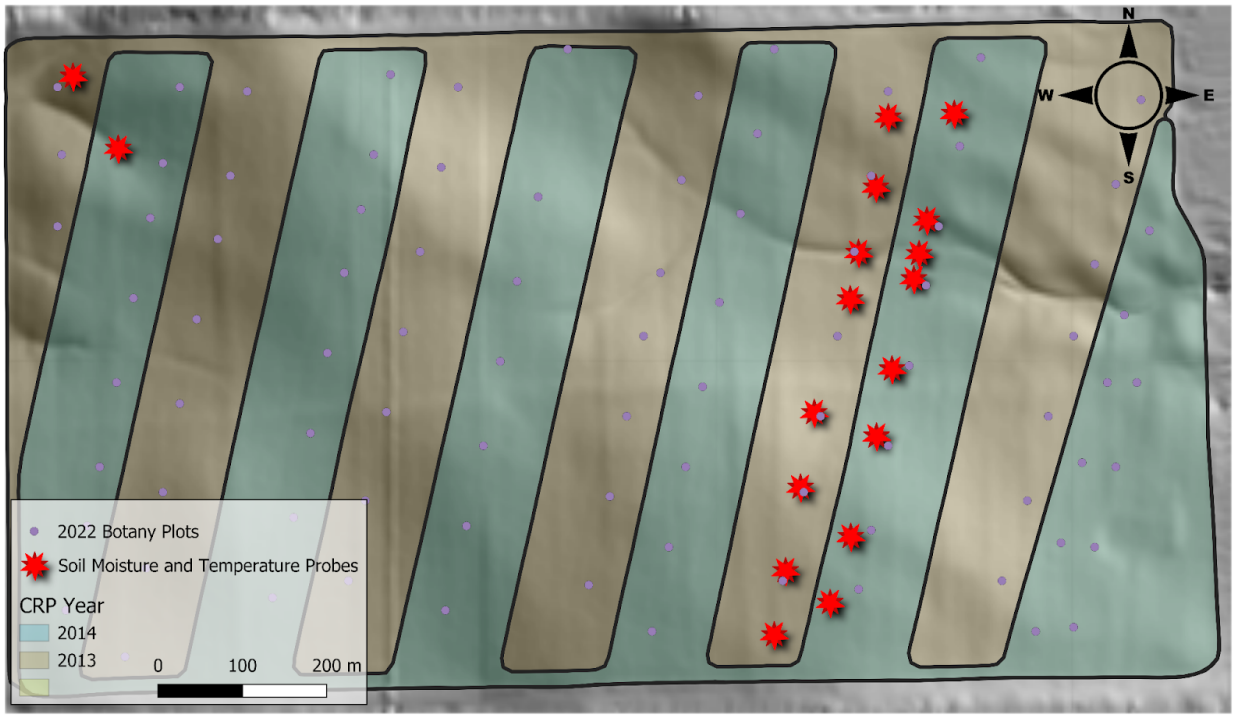

Figure S1. The study site. The background is a 5m digital elevation model, stars indicate the locations of soil temperature and moisture probes, dots indicate the location of 2022 botany plots, and the shaded areas indicate the year that the CRP seeding application was conducted. Probe locations were chosen to represent the range of topographic complexity while also allowing for the comparison of the effect of management. .

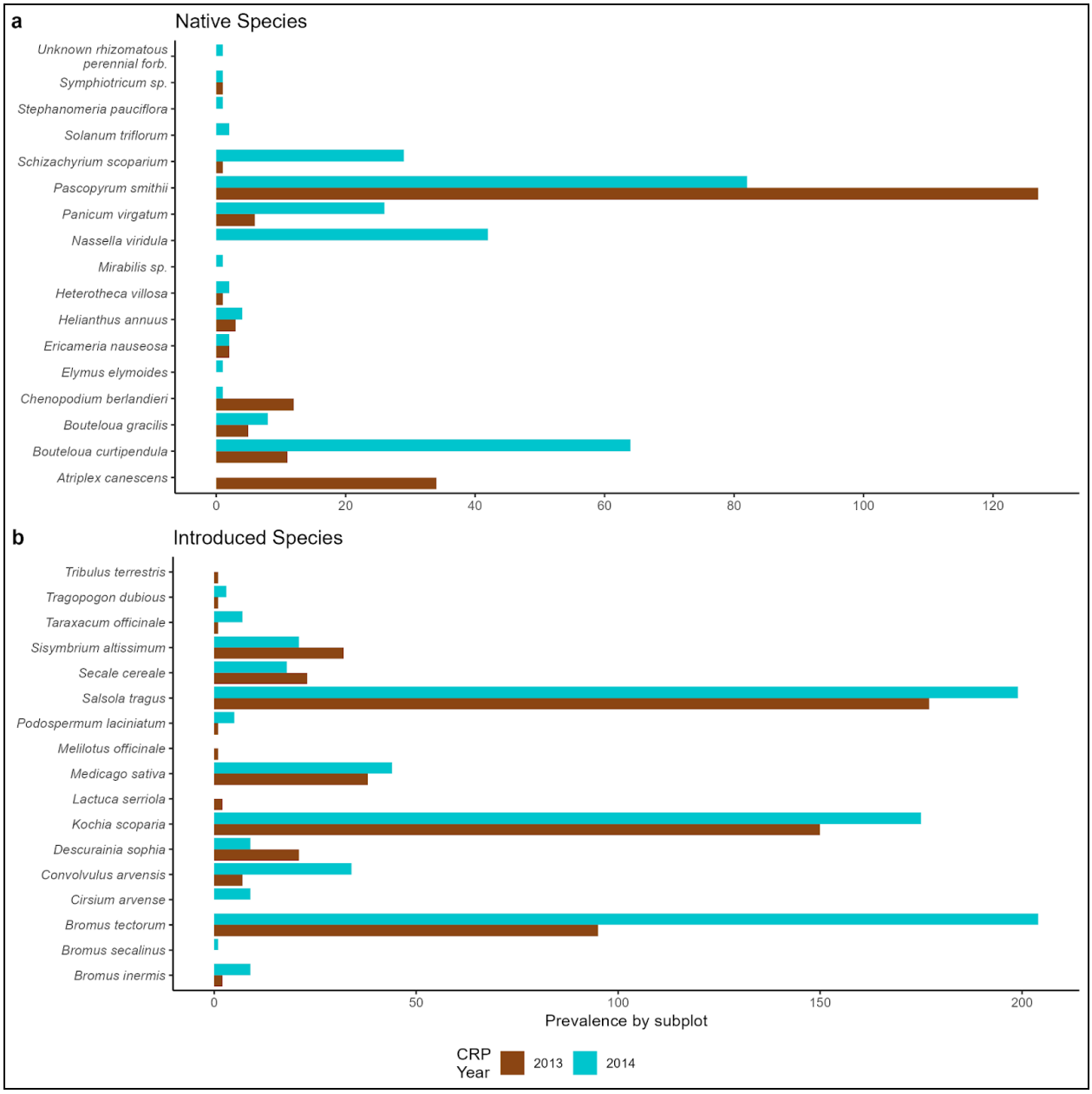

Figure S2. Species prevalence. Prevalence (number of 0.1m^2 plots in which a species was encountered) for each plant species encountered across the study site for native species (a) and introduced species (b).

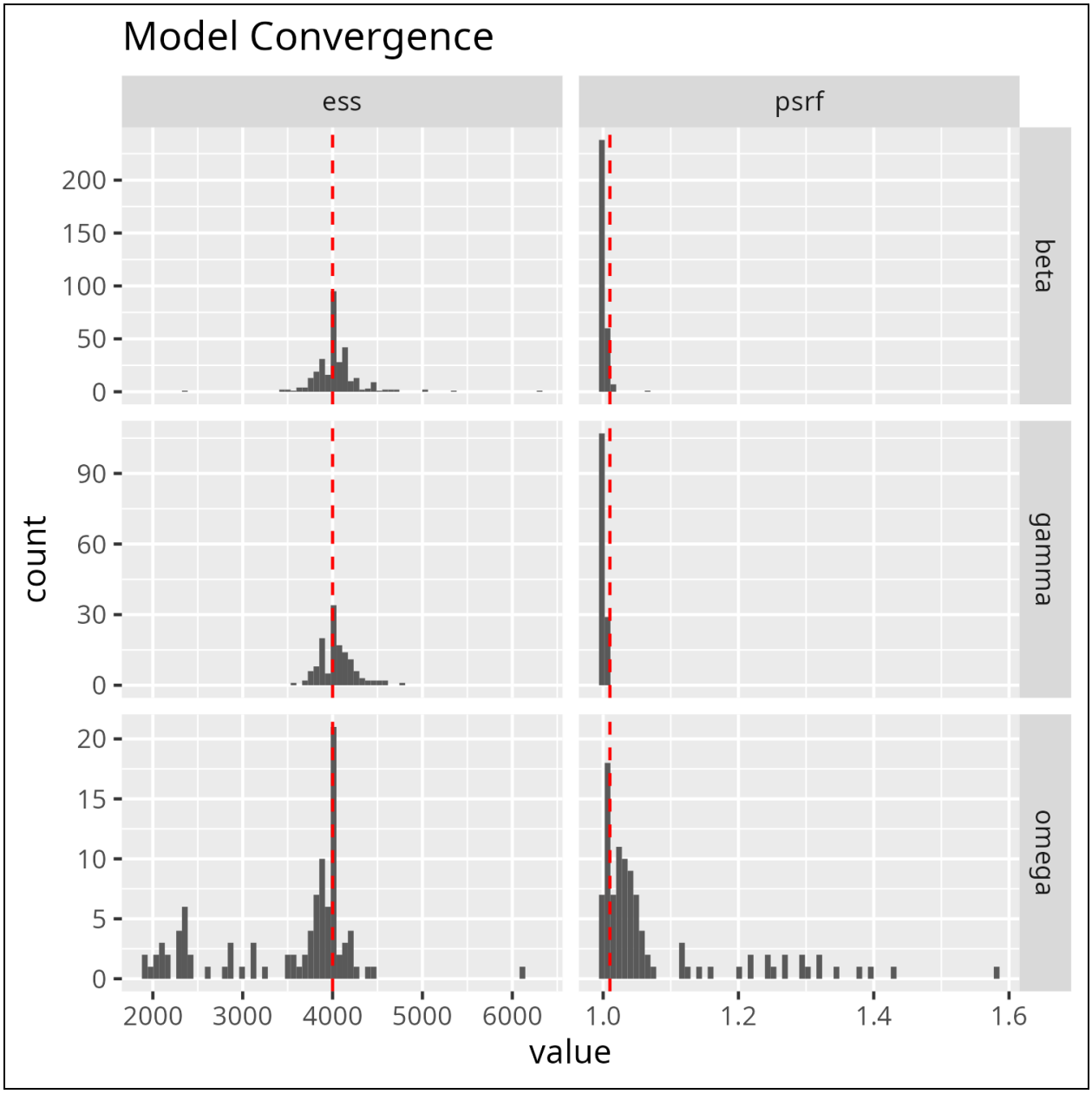
Model Convergence
ess
psrf
beta
gamma
omega
count
value
200
150
100
50
0
90
60
30
0
20
15
10
5
0
2000
3000
4000
5000
6000
1.0
1.2
1.4
1.6

FIgure S3: Model convergence diagnostics. The potential scale reduction factor (PSRF) measures the convergence among chains, and being closer 1.0 is ideal. The vertical red dashed line lies at 1.001, a sensible target for most values to fall under. Effective sample size (ESS) measures autocorrelation between successive iterations within each chain, and higher values are better. Ideally ESS matches the number of posterior samples (indicated by the vertical red dashed line), but that is not fully necessary. Betas are the parameters for environmental filters, gammas are the parameters for the traits, and omegas are the parameters for the species associations.

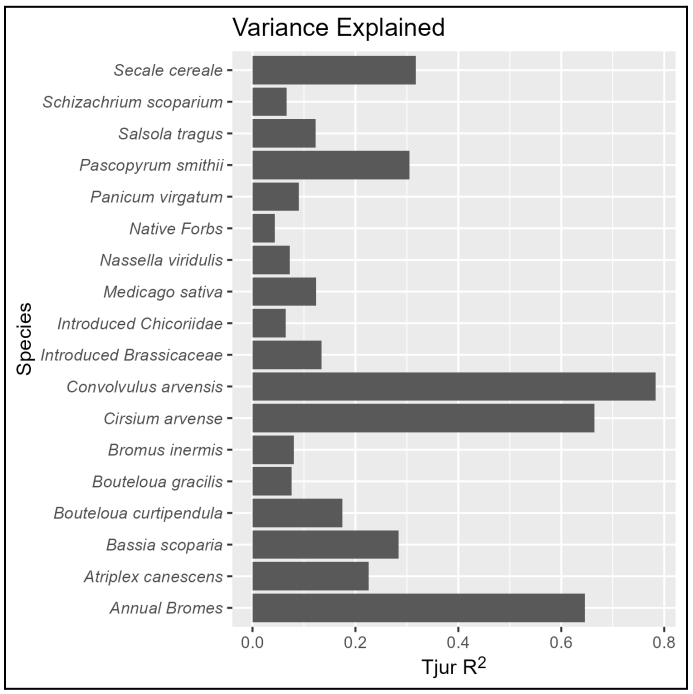

Figure S4: R^2 values from the Joint Species Distribution Model for each species or species group.

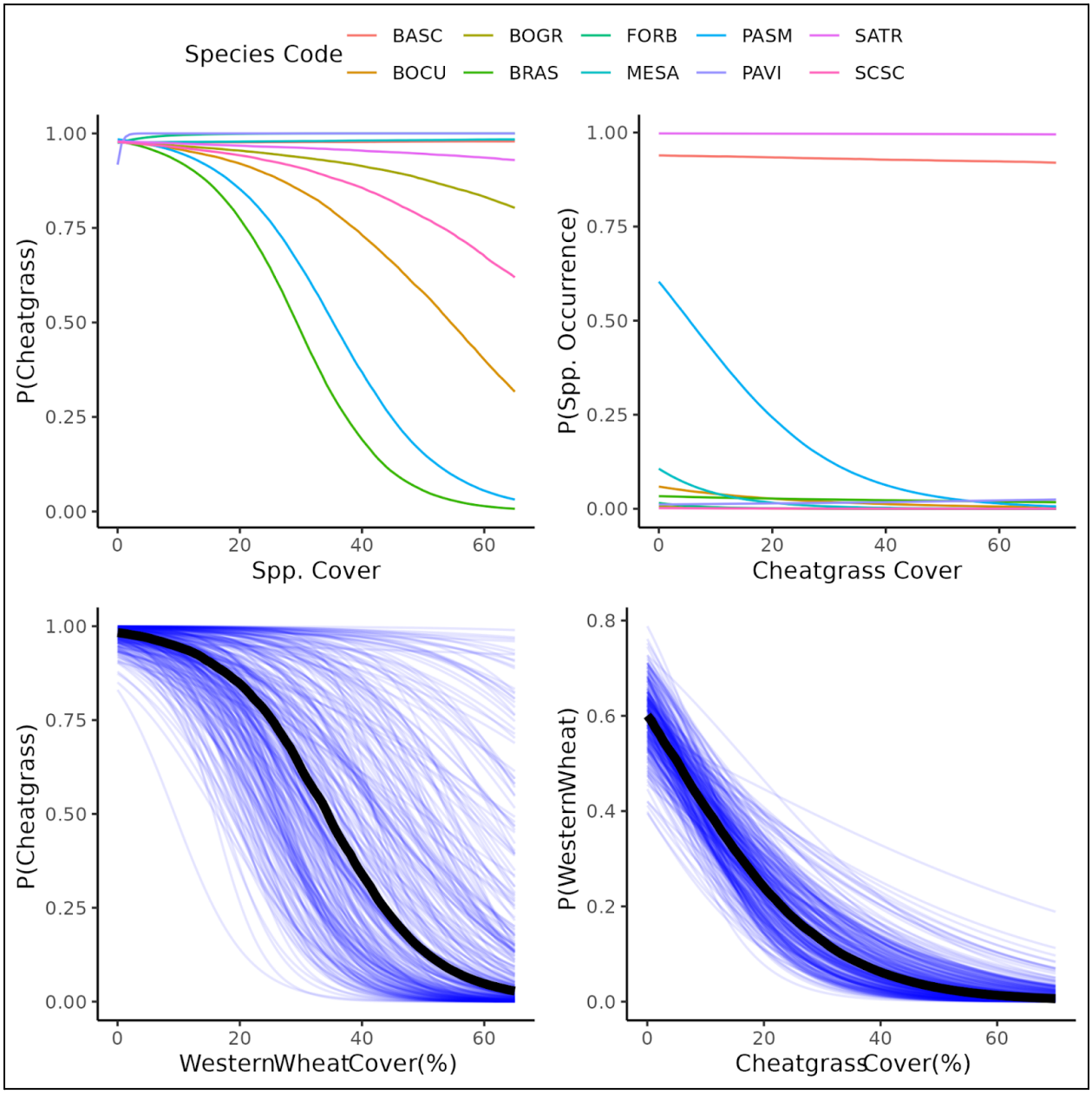
Species Code
BASC
BOCU
BOGR
BRAS
FORB
MESA
PASM
PAVI
SATR
SCSC
P(Cheatgrass)
Spp. Cover
P(Spp. Occurrence)
Cheatgrass Cover
WesternWheatCover(%)
P(WesternWheat)
CheatgrassCover(%)

Figure S5. Western wheatgrass and cheatgrass interactions, compared to other species. This is using abundance data on the X axes to estimate the occurrence of a given species. Western wheatgrass and cheatgrass had strong effects on each others' occurrence, compared to other species. This was consistent with field observations. Abbreviations are defined in Table S1.

Table S1: All species encountered. Many species were encountered outside of the 0.1 m2 quadrats used for the JSDM. Therefore these species were not assigned to groups, but were still used in the diversity calculations. Nomenclature follows the United States Department of Agriculture's Plant Database (https://plants.usda.gov).

Family	Genus	Specific epithet	Group Code	Group Name	CRP Mix	origin	Pure Live Seed (kg/ha)
Asteraceae	*Gutierrezia*	*sarothrae*	GUSA	*Gutierrezia sarothrae*	no	native	
Asteraceae	*Ericameria*	*nauseosa*	ERNA	*Ericameria nauseosa*	no	native	
Asteraceae	*Heterotheca*	*villosa*	HEVI	*Heterotheca villosa*	no	native	
Asteraceae	*Helianthus*	*annuus*	HEAN	*Helianthus annuus*	no	native	
Asteraceae	*Stephanomeria*	*pauciflora*	FORB	Native Forbs	no	native	
Asteraceae	cf *Aster*	d_081_herb_05	FORB	Native Forbs	no	native	
Asteraceae	*Antennaria*	sp.	ANSP	*Antennaria* sp	no	native	
Asteraceae	*Artemisia*	*arbuscula*	ARAR	*Artemisia arbuscula*	no	native	
Chenopodiaceae	*Atriplex*	*canescens*	ATCA	*Atriplex canescens*	yes	native	0.2676
Chenopodiaceae	*Chenopodium*	*berlandieri*	FORB	Native Forbs	no	native	
Malvaceae	*Sphaerelcea*	*coccinea*	SPCO	*Sphaerelcea coccinea*	no	native	
Papaveraceae	*Argemone*	cf *hispida*	ARHI	*Argemone cf hispida*	no	native	
Poaceae	*Bouteloua*	*curtipendula*	BOCU	*Bouteloua curtipendula*	yes	native	0.6244

Poaceae	*Panicum*	*virgatum*	PAVI	*Panicum virgatum*	yes	native	0.1784
Poaceae	*Schizachyrium*	*scoparium*	SCSC	*Schizachyrium scoparium*	yes	native	0.3568
Poaceae	*Nassella*	*viridula*	NAVI	*Nassella viridula*	yes	native	0.7136
Poaceae	*Pascopyrum*	*smithii*	PASM	*Pascopyrum smithii*	yes	native	1.784
Poaceae	*Bouteloua*	*gracilis*	BOGR	*Bouteloua gracilis*	yes	native	0.1784
Poaceae	*Elymus*	*elymoides*	ELEL	*Elymus elymoides*	no	native	
Solanaceae	*Solanum*	*triflorum*	FORB	Native Forbs	no	native	
Nyctaginaceae	*Mirabilis*	sp	FORB	Native Forbs	no	native	
unknown	Rhizomatous perennial forb	d_141_herb_09	FORB	Native Forbs	no	native	
Asteraceae	*Scorzonera*	*laciniata*	LACT	Introduced Cichorioideae	no	introduced	
Asteraceae	*Taraxacum*	*officinale*	LACT	Introduced Cichorioideae	no	introduced	
Asteraceae	*Tragopogon*	*dubious*	LACT	Introduced Cichorioideae	no	introduced	
Asteraceae	*Cirsium*	*arvense*	CIAR	*Cirsium arvense*	no	introduced	
Asteraceae	*Onopordium*	*acanthium*	ONAC	*Onopordium acanthium*	no	introduced	
Asteraceae	*Lactuca*	*serriola*	LASE	*Lactuca serriola*	no	introduced	
Brassicaceae	*Sisymbrium*	*altissimum*	BRAS	Introduced Brassicaceae	no	introduced	
Brassicaceae	*Descurainia*	*sophia*	BRAS	Introduced Brassicaceae	no	introduced	
Chenopodiaceae	*Salsola*	*tragus*	SATR	*Salsola tragus*	no	introduced	
Chenopodiaceae	*Bassia*	*scoparia*	BASC	*Bassia scoparia*	no	introduced	
Convolvulaceae	*Convolvulus*	*arvensis*	COAR	*Convolvulus arvensis*	no	introduced	
Fabaceae	*Medicago*	*sativa*	MESA	*Medicago sativa*	yes	introduced	0.3568

Fabaceae	*Melilotus*	*officinale*	MEOF	*Melilotus officinale*	no	introduced
				Introduced Annual		
Poaceae	*Bromus*	*tectorum*	BROM	*Bromus*	no	introduced
Poaceae	*Secale*	*cereale*	SECE	*Secale cereale*	no	introduced
Poaceae	*Bromus*	*inermis*	BRIN	*Bromus inermis*	no	introduced
				Introduced Annual		
Poaceae	*Bromus*	*secalinus*	BROM	*Bromus*	no	introduced
Poaceae	*Agropyron*	*cristatum*	AGCR	*Agropyron cristatum*	no	introduced
Zygophyllaceae	*Tribulus*	*terrestris*	TRTE	*Tribulus terrestris*	no	introduced

Table S2: R packages used in the analysis.

Package	Purpose	Citation
sf	Spatial vector data management	Pebesma 2018
terra	Raster data management	Hijmans 2023a
raster	Raster data management	Hijmans 2023b
vegan	Diversity and NMDS	Oksanen et al 2022
SPEI	Calculating SPEI	Beguería and Vicente-Serrano 2023
microclima	Calculating air temperature	Mosedale et al 2023
NicheMapR	Calculating air	Kearney 2022

	temperature	
topmodel	Calculating TWI	Buytaert 2022
tidyverse	Data wrangling	Wickham et al 2019
lubridate	Date wrangling	Grolemond and Wickham 2011
vroom	Data wrangling	Hester et al 2023
Hmsc	Joint species distribution modeling	Tikhonov et al 2023
gghmsc	Visualization	Mahood et al 2024
snow	parallelization	Tierney et al 2021
fields	spatial process models	Nychka et al 2021
ggpubr	visualization	Kassambara 2023
ggcorrplot	visualization	Kassambara 2022
ggthemes	visualization	Arnold 2021
ggtext	visualization	Wilke 2021
ggrepel	visualization	Slowikowski 2023
ggmcmc	visualization	Fernandez i Marin 2016
geomtextpath	visualization	Cameron and van den Brand 2022

Table S3. Species included in the CRP mix.

Common Name	Scientific Name	Pure Live Seed Applied (kg/ha)	Origin
Western wheatgrass	*Pascopyrum smithii*	1.784	native

Green needlegrass	*Nassela viridula*	0.7136	native
Sideoats gramma	*Bouteloua curtipendula*	0.6244	native
Alfalfa	*Medicago sativa*	0.3568	introduced
Little bluestem	*Schizachyrium scoparium*	0.3568	native
Fourwing Saltbush	*Atriplex canescens*	0.2676	native
Blue gramma	*Bouteloua gracilis*	0.1784	native
Switchgrass	*Panicum virgatum*	0.1784	native

Table S4 life history traits of species used in the JSDM analysis.

species group	Mean height	introduced	perennial	w oody	graminoid	rhizomatous	Photosynthetic pathw ay
Invasive Annual *Bromus*	19	yes	no	no	yes	no	c3
Bassia scoparia	11	yes	no	no	no	no	c3
Salsola tragus	10	yes	no	no	no	no	c4
Pascopyrum smithii	22	no	yes	no	yes	yes	c3
Bouteloua curtipendula	24	no	yes	no	yes	no	c4
Medicago sativa	27.5	yes	yes	no	no	no	c3
Invasive annual Brassicaceae	21	yes	no	no	no	no	c3
Nasella viridulis	41.5	no	yes	no	yes	no	c4

Invasive Chicorioideae	10.5	yes	yes*	no	no	no	c3
Native Forbs	6	no	yes	no	no	no	c4
Cirsium arvense	12	yes	yes	no	no	yes	c3
Convolvulus arvensis	8.5	yes	yes	no	no	yes	c3
Panicum virgatum	27.5	no	yes	no	yes	no	c4
Schizachyrium scoparium	19	no	yes	no	yes	no	c4
Atriplex canescens	115	no	yes	yes	no	no	c4
Bouteloua gracilis	19	no	yes	no	yes	no	c4
Bromus inermis	33	yes	yes	no	yes	yes	c3
Secale cereale	38.5	yes	no	no	yes	no	c3

* tw o species (5 occurrences) are perennial/biennial, one species (1 occurrence) is annual/biennial

Table S5: Precipitation (mm) measured at the study site. Highest monthly values are bold. Highest and lowest years are italicized and bold.

Year	**02**	**03**	**04**	**05**	**06**	**07**	**08**	**09**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**Mean**
Jan	7	1	10	5	1	7	0	0	3	2	1	9	21	3	11	19	9	6	0	3	**6**
Feb	20	7	8	3	6	2	0	0	10	11	13	7	7	16	12	7	17	3	7	8	**8**
Mar	6	45	2	33	22	37	13	7	18	8	0	15	26	5	44	29	24	46	29	23	**22**
Apr	7	**64**	28	47	9	20	17	69	**94**	26	13	70	4	56	**59**	57	16	32	21	48	**38**
May	**42**	55	33	37	26	29	41	43	79	**119**	45	47	82	***153***	46	**111**	**95**	**66**	**47**	**68**	**63**
Jun	33	43	**55**	**104**	6	11	50	83	51	35	15	17	52	51	38	4	33	44	43	21	**39**
Jul	9	4	28	6	**28**	**62**	9	51	75	94	**91**	43	**101**	57	12	32	41	21	3	17	**39**
Aug	16	44	35	14	10	37	**105**	31	37	5	0	40	24	20	23	54	8	17	11	9	**27**
Sep	23	11	53	3	16	24	37	12	2	17	40	**111**	31	2	8	35	5	25	13	11	**24**
Oct	11	1	24	74	20	0	12	**132**	18	56	21	21	12	54	10	26	16	15	15	7	**27**
Nov	10	6	8	6	9	3	2	10	24	10	4	5	16	23	4	9	10	20	8	10	**10**

Year	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	Mean
Dec	0	8	0	1	**28**	7	6	18	8	12	3	9	10	22	8	4	1	21	11	8	**9**
Sum	183	289	285	334	***181***	238	293	456	418	396	247	394	386	***462***	276	388	275	316	210	232	**313**

Supplementary References

Jeffrey B. Arnold (2021). ggthemes: Extra Themes, Scales and Geoms for 'ggplot2'. R package version 4.2.4.

https://CRAN.R-project.org/package=ggthemes

Santiago Beguería and Sergio M. Vicente-Serrano (2023). SPEI: Calculation of the Standardized Precipitation-Evapotranspiration Index. R package version 1.8.1.

https://CRAN.R-project.org/package=SPEI

Wouter Buytaert (2022). topmodel: Implementation of the Hydrological Model TOPMODEL in R. R package version 0.7.5.

https://CRAN.R-project.org/package=topmodel

Allan Cameron and Teun van den Brand (2022). geomtextpath: Curved Text in 'ggplot2'. R package version 0.1.1.

https://CRAN.R-project.org/package=geomtextpath

Xavier Fernández i Marín (2016). ggmcmc: Analysis of MCMC Samples and Bayesian Inference. Journal of Statistical Software, 70(9), 1-20

www.doi.org/10.18637/jss.v070.i09

Garrett Grolemund, Hadley Wickham (2011). Dates and Times Made Easy with lubridate. Journal of Statistical Software, 40(3), 1-25.
https://www.jstatsoft.org/v40/i03/

Jim Hester, Hadley Wickham and Jennifer Bryan (2023). vroom: Read and Write Rectangular Text Data Quickly. R package version 1.6.3.
https://CRAN.R-project.org/package=vroom

Robert J. Hijmans (2023a). terra: Spatial Data Analysis. R package version 1.7-29.
https://CRAN.R-project.org/package=terra

Robert J. Hijmans (2023b). raster: Geographic Data Analysis and Modeling. R package version 3.6-20.
https://CRAN.R-project.org/package=raster

Alboukadel Kassambara (2022). ggcorrplot: Visualization of a Correlation Matrix using 'ggplot2'. R package
version 0.1.4. https://CRAN.R-project.org/package=ggcorrplot

Alboukadel Kassambara (2023). ggpubr: 'ggplot2' Based Publication Ready Plots. R package version 0.6.0.
https://CRAN.R-project.org/package=ggpubr

Michael Kearney (2022). NicheMapR: R implementation of Niche Mapper software for biophysical modelling. R package version 3.2.0.
https://github.com/mrke/NicheMapR

Adam L. Mahood (2024). gghmsc: Make nice plots for working with Hmsc JSDMs. R package version 0.1.2. https://github.com/admahood/gghmsc

Jonathan Mosedale, Jonathan Bennie and James Duffy (2023). microclima: microclimate modelling with R. R package version 0.1.0.
https://github.com/ilyamaclean/microclima

Douglas Nychka, Reinhard Furrer, John Paige, Stephan Sain (2021). “fields: Tools for spatial data.” R package version 14.1.
https://github.com/dnychka/fieldsRPackage

Jari Oksanen, Gavin L. Simpson, F. Guillaume Blanchet, Roeland Kindt, Pierre Legendre, Peter R. Minchin, R.B. O'Hara, Peter Solymos, M. Henry H. Stevens, Eduard Szoecs, Helene Wagner, Matt Barbour, Michael Bedward, Ben Bolker, Daniel Borcard, Gustavo Carvalho, Michael Chirico, Miquel De Caceres, Sebastien Durand, Heloisa Beatriz Antoniazi Evangelista, Rich FitzJohn, Michael Friendly, Brendan Furneaux, Geoffrey Hannigan, Mark O. Hill, Leo Lahti, Dan McGlinn, Marie-Helene Ouellette, Eduardo Ribeiro Cunha, Tyler Smith, Adrian Stier, Cajo J.F. Ter Braak and James Weedon (2022). vegan: Community Ecology Package. R package version 2.6-4.
https://CRAN.R-project.org/package=vegan

Pebesma, E., 2018. Simple Features for R: Standardized Support for Spatial Vector Data. The R Journal 10 (1), 439-446,

https://doi.org/10.32614/RJ-2018-009

Kamil Slowikowski (2023). ggrepel: Automatically Position Non-Overlapping Text Labels with 'ggplot2'. R package version 0.9.3.
https://CRAN.R-project.org/package=ggrepel

Gleb Tikhonov, Otso Ovaskainen, Jari Oksanen, Melinda de Jonge, Oystein Opedal and Tad Dallas (2023). Hmsc: Hierarchical Model of Species Communities. R package version 3.0-14.
https://www.helsinki.fi/en/researchgroups/statistical-ecology/software/hmsc

Wickham H, Averick M, Bryan J, Chang W, McGowan LD, François R, Grolemund G, Hayes A, Henry L, Hester J, Kuhn M, Pedersen TL, Miller E, Bache SM, Müller K, Ooms J, Robinson D, Seidel DP, Spinu V, Takahashi K, Vaughan D, Wilke, Woo K, Yutani H (2019). “Welcome to the tidyverse.” Journal of Open Source Software, 4(43), 1686.
https://doi.org/10.21105/joss.01686

Claus O. Wilke and Brenton M. Wiernik (2022). ggtext: Improved Text Rendering Support for 'ggplot2'. R package version 0.1.2.
https://CRAN.R-project.org/package=ggtext