Supplement of Biogeosciences, 20, 2707–2725, 2023
https://doi.org/10.5194/bg-20-2707-2023-supplement

Biogeosciences
Open Access

Supplement of

Assessing carbon storage capacity and saturation across six central US grasslands using data–model integration

Kevin R. Wilcox et al.

Correspondence to: Kevin R. Wilcox (k_wilcox@uncg.edu)

Supplemental information:

S1 Supplemental Figures S1-S10

S2. Supplemental Tables S1-S6

S3. Supplemental text describing data collection and cleaning methods

S4. Model evaluation text, Table S7, Figures S11-S13

S5. Land use history of study sites

S1. Supplemental figures S1-S10

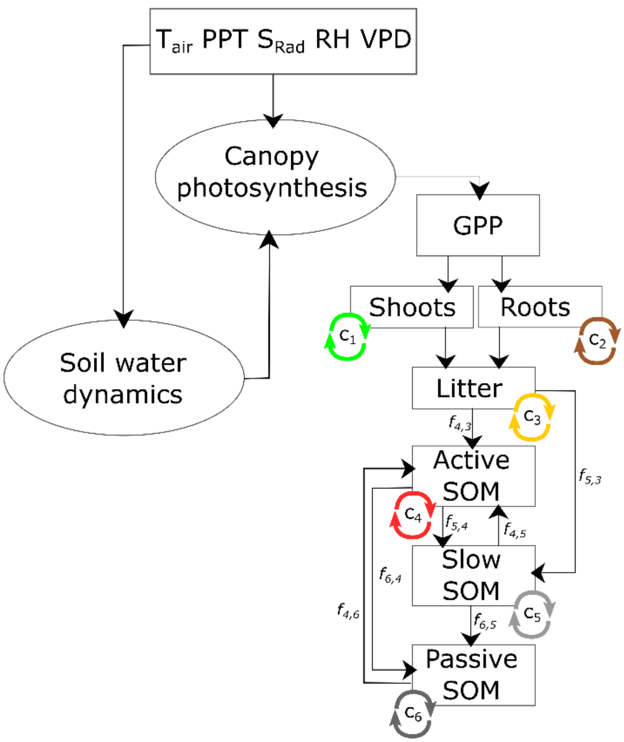

Figure S1. Schematic of the submodels making up the Terrestrial Ecosystem model. Canopy photosynthesis is determined by hourly meteorological information through direct impacts (e.g., vapor pressure deficit) and alterations to soil environmental conditions (e.g., soil moisture and temperature). GPP is estimated from the canopy photosynthesis model. Carbon from the canopy model is transferred to different components of vegetation, which is summed over an annual time step to estimate NPP (GPP – autotrophic respiration). See Weng and Luo (2008) for additional details of the model. The soil C model incorporates turnover rates for aboveground vegetation (c_1), roots (c_2), litter (c_3), active SOM (c_4), slow SOM (c_5), and passive SOM (c_6).

Turnover rates are modified by an environmental scalar (τ) at each time step. The proportion of C transferred between pools are controlled by the $f_{i,j}$ parameters, which represent the proportion of C turnover transferred from C pool *j* to pool *I*, with the pool numbers corresponding to the subscripts by the C turnover parameters.

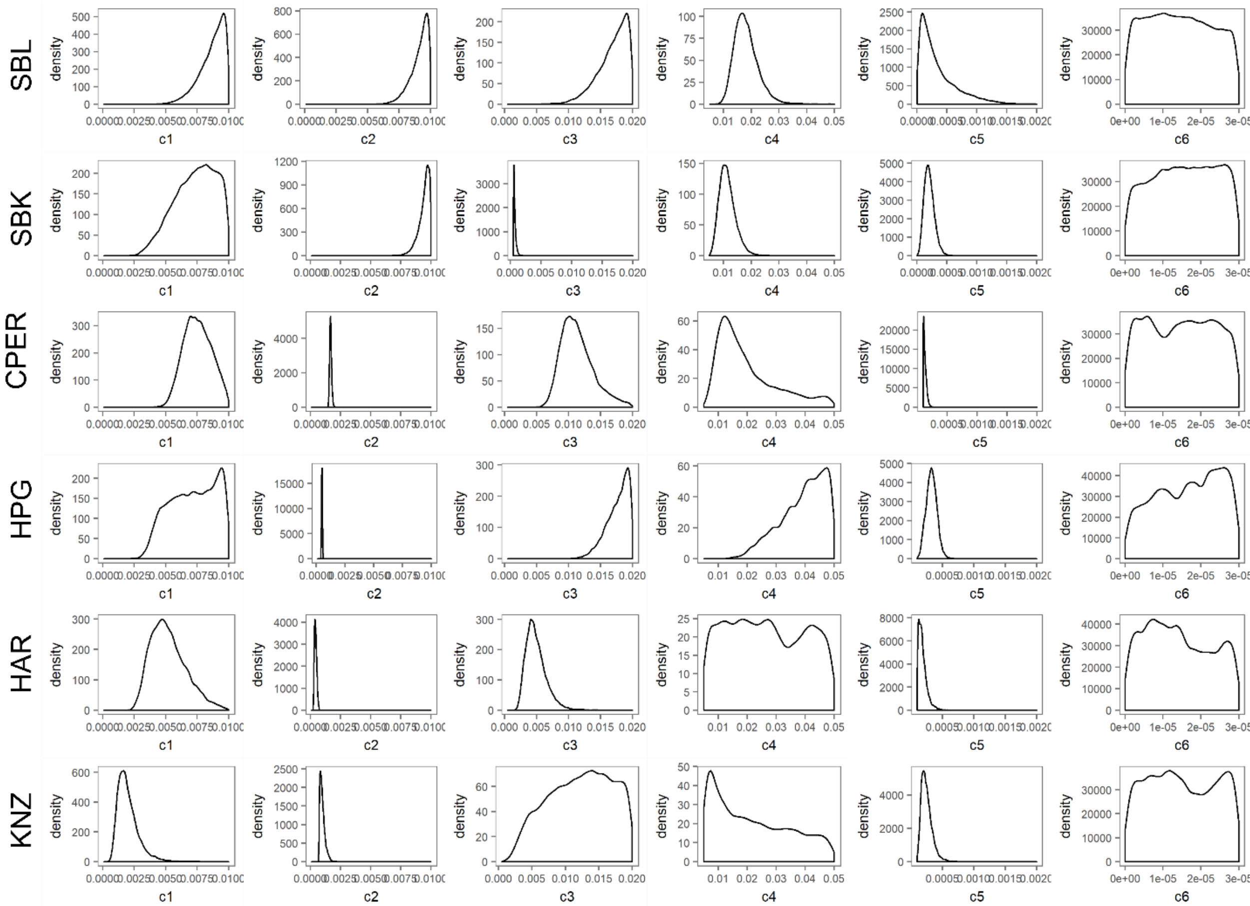

Figure S2. Density plots showing distribution of estimated carbon turnover parameters (columns) using data assimilation techniques with a 6 pool carbon model and 4-5 data sets describing carbon pools and fluxes at each of the six sites (rows). Densities reflect 4 chains of 360k simulations each, with the first 20k simulations removed. SBL= Blue grama dominated site at the Sevilleta National Wildlife Refuge; SBK= Black grama dominated site at the Sevilleta National Wildlife Refuge; CPER=central plains experimental range; HPG=High Plains Grassland Research Station; HAR=Hays Agricultural Research Station; KNZ=Konza Prairie Biological Station. All carbon turnover parameters are in units of gC lost gC^{-1} day^{-1}: c1=leaf turnover; c2=root turnover; c3=litter turnover; c4=fast SOM turnover; c5=slow SOM turnover; c6=passive SOM turnover.

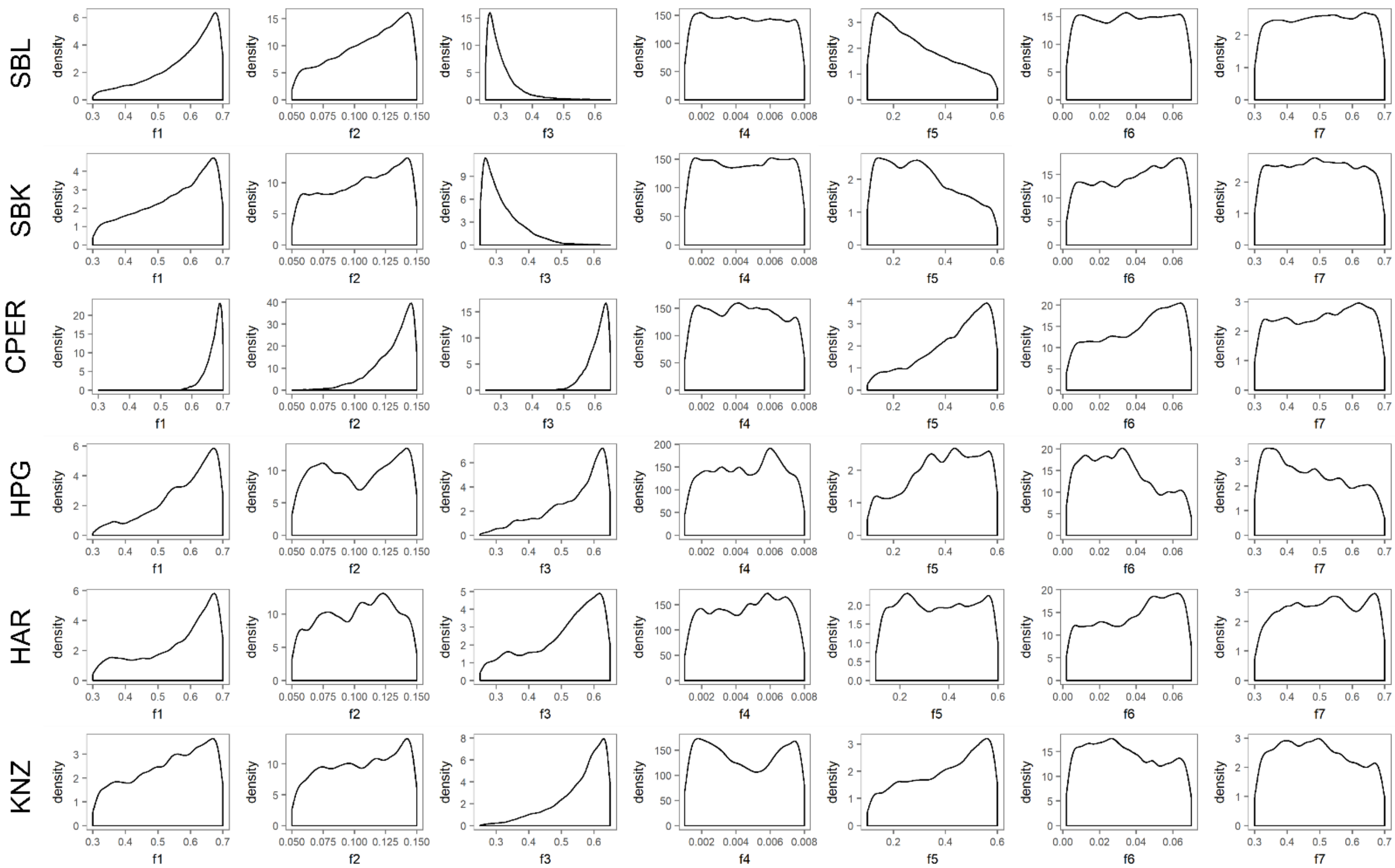

Figure S3. Density plots showing distribution of estimated carbon transfer parameters (columns) using data assimilation techniques with a 6 pool carbon model and 4-5 data sets describing carbon pools and fluxes at each of the six sites (rows). Densities reflect 4 chains of 360k simulations each, with the first 20k simulations removed. SBL= Blue grama dominated site at the Sevilleta National Wildlife Refuge; SBK= Black grama dominated site at the Sevilleta National Wildlife Refuge; CPER=central plains experimental range; HPG=High Plains Grassland Research Station; HAR=Hays Agricultural Research Station; KNZ=Konza Prairie Biological Station. Transfer parameters (fx,y) dictate the proportion of C turnover in pool y transferring to pool x: f1=f43; f2=f53; f3=f54; f4=f64; f5=f45; f6=f65; f7=f46.

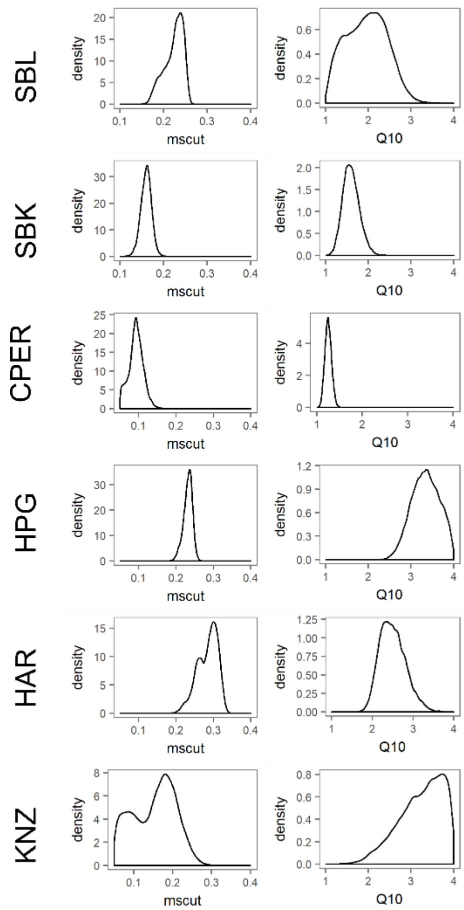

Figure S4. Density plots showing distribution of environmental scaling parameters (columns) dictating decomposition rates. We used data assimilation techniques with a 6 pool carbon model and 4-5 data sets describing carbon pools and fluxes at each of the six sites (rows). Densities reflect 4 chains of 360k simulations each, with the first 20k simulations removed. SBL= Blue grama dominated site at the Sevilleta National Wildlife Refuge; SBK= Black grama dominated site at the Sevilleta National Wildlife Refuge; CPER=central plains experimental range; HPG=High Plains Grassland Research Station; HAR=Hays Agricultural Research Station; KNZ=Konza Prairie Biological Station. Mscut is the soil moisture level at which decomposition rates begin to become water limited; Q10 is the temperature sensitivity of decomposition.

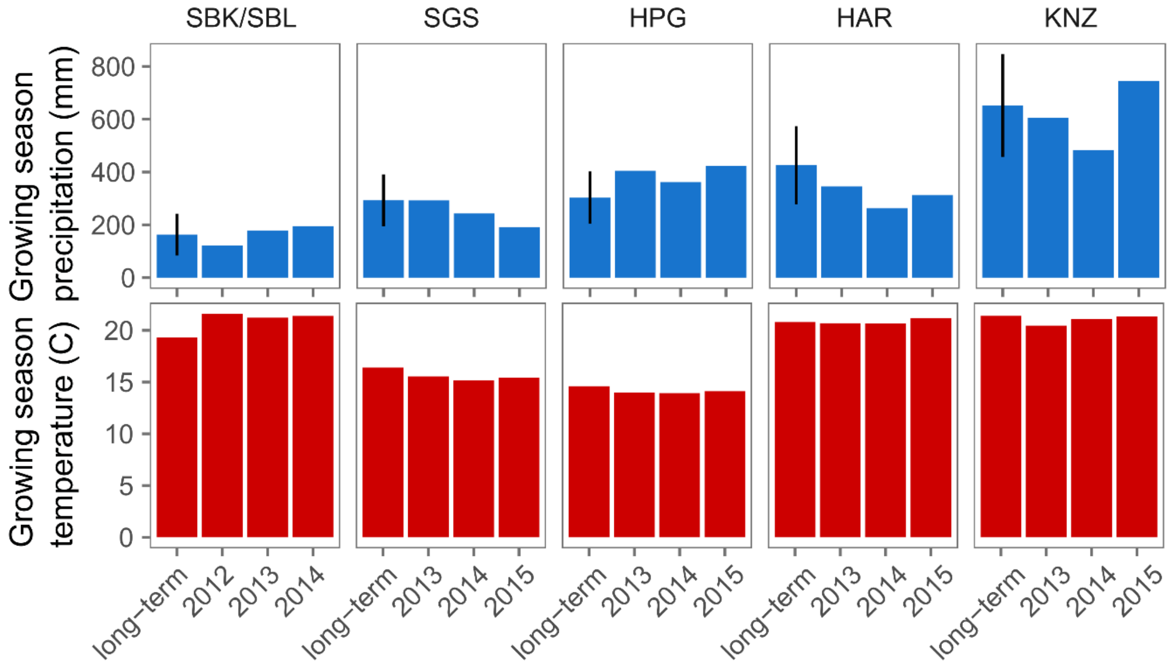

Figure S5. Precipitation and air temperature during the growing season (Apr-Oct for SBK and SBL, Apr-Sept for all other sites) during the three focal years at each site compared with the long-term mean precipitation and air temperature. Averages represent the period of 1982-2012 obtained from Knapp et al. 2015, and error bars represent 1 standard deviation from the mean.

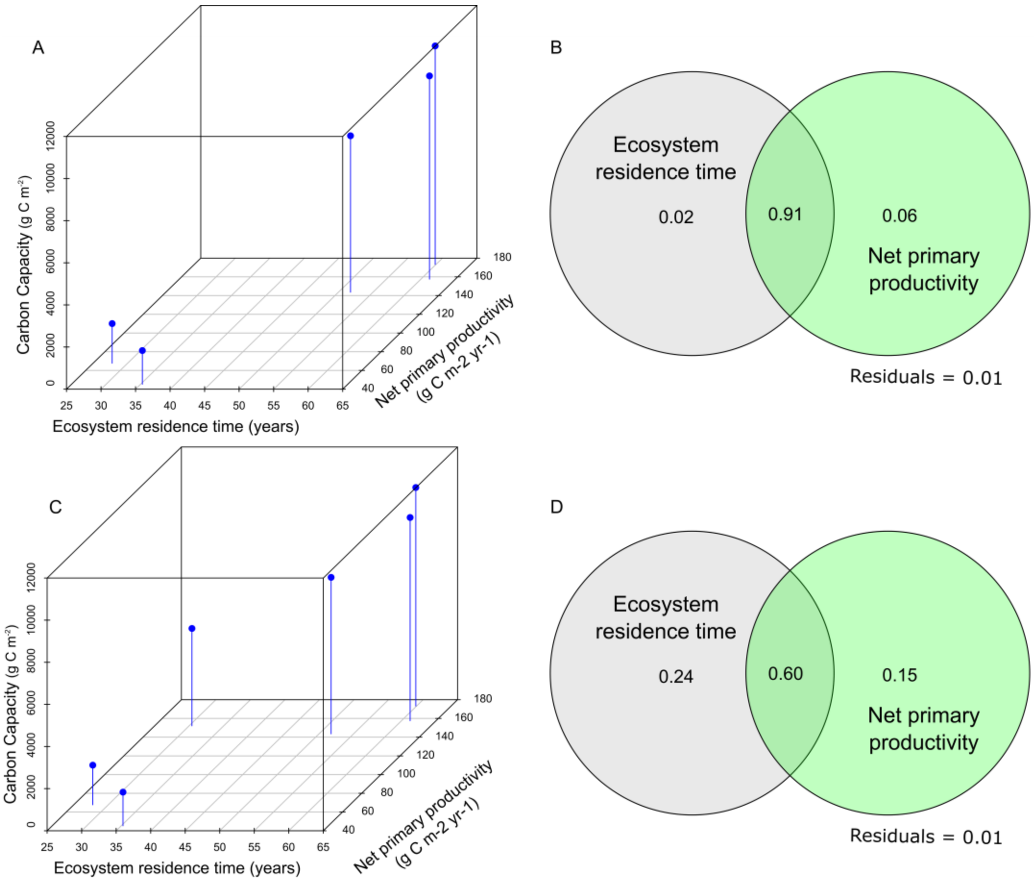

Figure S6. Three-dimensional plots (A,C) and variance partitioning results (B,D) showing the importance of ecosystem residence time and net primary productivity in making up the systems carbon capacity for our six focal ecosystems. A and B panels show results without KNZ, C and D include KNZ. In (B,D), numbers within the circles represent the amount of cross-site variance in carbon capacity explained solely by ecosystem residence time or net primary productivity. The number in the intersection represent variance explained jointly by both components.

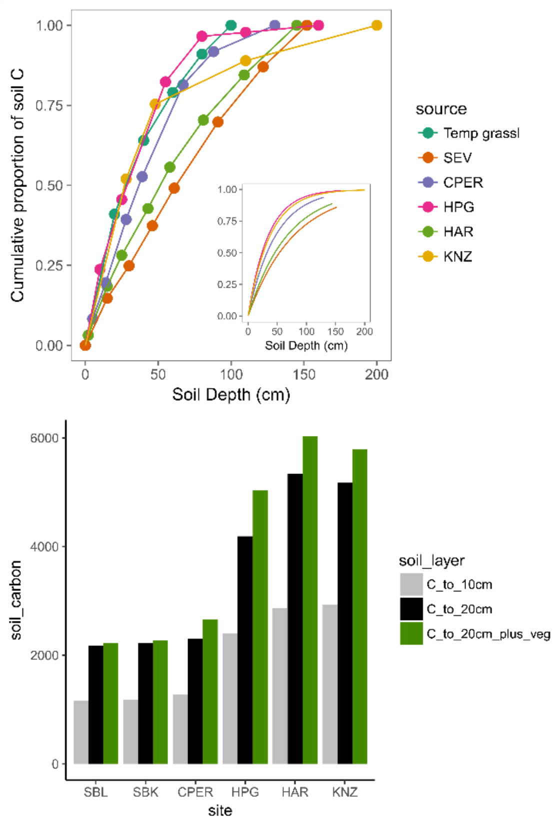

Figure S7. Top panel: Cumulative proportion of soil C along depth profile (main) and beta distribution of proportion by depth (inset). Data were obtained from the International Soil Carbon Network (see table B4) from areas close to study sites and having similar cover types and management regimes. In main panel, we included estimated proportions for temperate grasslands (Temp grass) from Jobbágy and Jackson (2000). Bottom panel: soil C measured at each study site from 0-10 cm and soil C estimates from 0-20 cm based on relationships in top panel. Estimates were obtained using: $C_{20}=C_{10}/C_{P10} \cdot C_{P20}$, where C_{10} is the soil C measured in the top 10 cm, C_{P10} is the proportion of C in the top 10 cm based on the beta regression, and C_{P20} is the proportion of C in the top 20 cm. Green bars represent soil C estimates from 0-20 cm plus vegetation C.

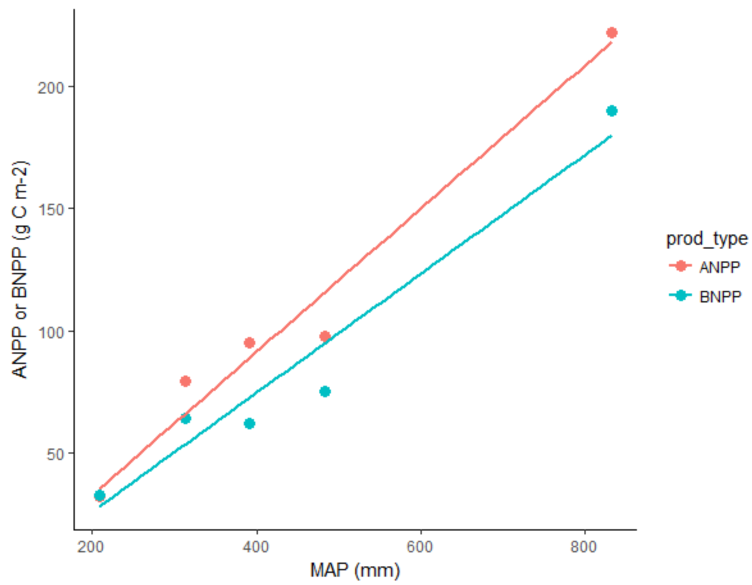

Figure S8. Average ANPP and BNPP simulation output across mean annual precipitation of our six grassland sites.

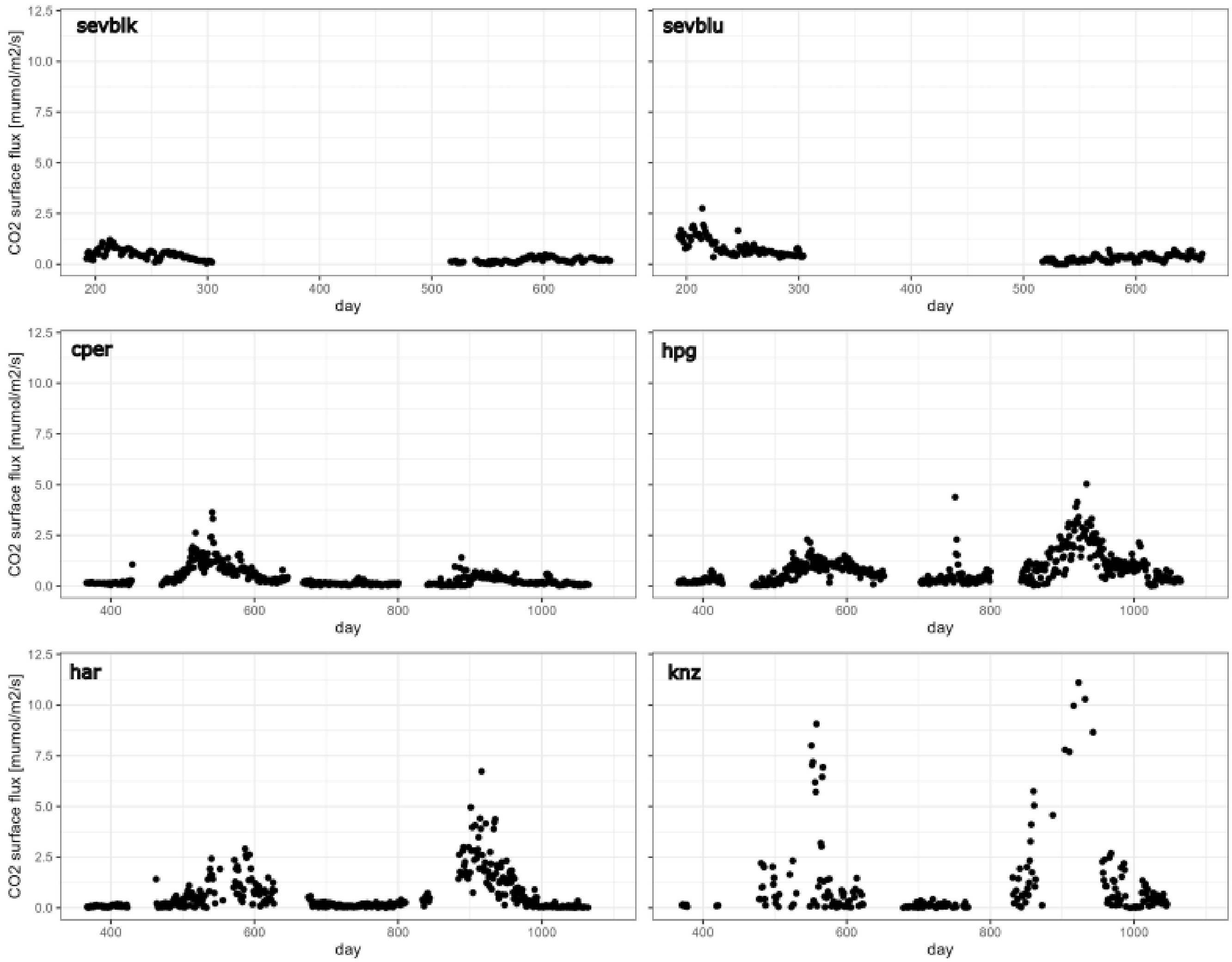

Figure S9. Soil surface CO_2 flux estimates at midday for all six sites throughout the study period, used within the data assimilation process to compare with model output. Units are µmol m^{-2} s^{-1}. Average daily standard error among plots are as follows: sevblk: 0.075, sevblu: 0.14, cper: 0.10, hpg: 0.49, hys: 0.57, knz: 0.47, although plot to plot variation is not included in data assimilation procedure.

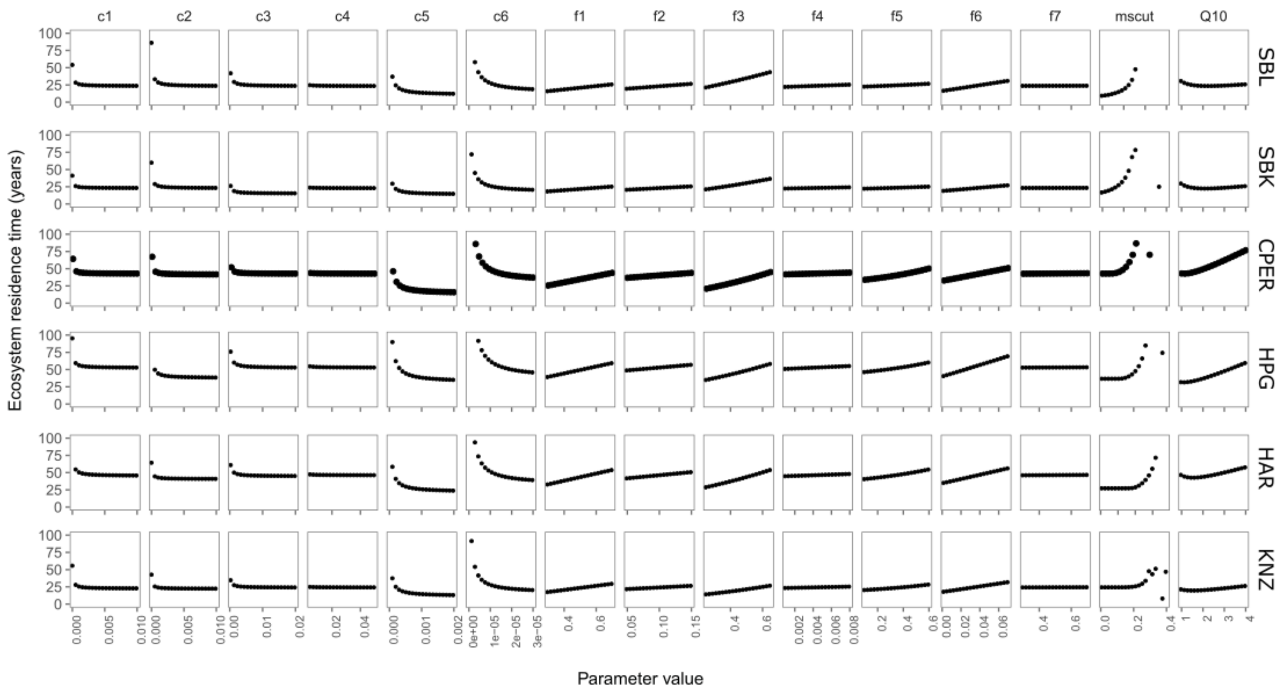

Figure S10. Results from sensitivity analysis where ecosystem C residence time was calculated when altering one parameter value at a time. Rows of panels correspond to different sites with: SBL= Blue grama dominated site at the Sevilleta National Wildlife Refuge; SBK= Black grama dominated site at the Sevilleta National Wildlife Refuge; CPER=central plains experimental range; HPG=High Plains Grassland Research Station; HAR=Hays Agricultural Research Station; KNZ=Konza Prairie Biological Station. Ecosystem carbon residence time was often very high at very extreme parameter values so the y axis was set for clarity. Transfer parameters (f1-7) are as in Fig. 3.

S2. Supplemental tables S1-S6

Table S1. Constraints and descriptions of carbon cycling and environmental scaling parameters used in data assimilation.

Param.	Default	Lower	Upper	Description	Units
c1	1.00E-03	1.00E-04	1.00E-02	The proportion of leaf C turning over each day	gC gC-1 day-1
c2	9.00E-03	1.00E-04	1.00E-02	The proportion of root C turning over each day	gC gC-1 day-1
c3	9.00E-03	5.00E-04	2.00E-02	The proportion of litter C turning over each day	gC gC-1 day-1
c4	1.50E-02	5.00E-03	5.00E-02	Proportion of fast SOM turning over each day	gC gC-1 day-1
c5	6.00E-04	1.00E-05	2.00E-03	Proportion of slow SOM turning over each day	gC gC-1 day-1
c6	2.00E-05	1.00E-08	3.00E-05	Proportion of passive SOM turning over each day	gC gC-1 day-1
f43	2.50E-01	3.00E-01	7.00E-01	Proportion of litter C turnover going to fast SOM pool	-
f53	1.00E-01	5.00E-02	1.50E-01	Proportion of litter C turnover going to slow SOM pool	-
f54	5.00E-01	2.50E-01	6.50E-01	Proportion of fast SOM turnover going to slow SOM pool	-
f64	4.00E-03	1.00E-03	8.00E-03	Proportion of litter C turnover going to passive SOM pool	-
f45	4.20E-01	1.00E-01	6.00E-01	Proportion of slow SOM turnover going to fast SOM pool	-
f65	5.00E-02	2.00E-03	7.00E-02	Proportion of slow C turnover going to passive SOM pool	-
f46	4.50E-01	3.00E-01	7.00E-01	Proportion of passive C turnover going to fast SOM pool	-
Q10	2.20E+00	1.00E+00	4.00E+00	Temperature sensitivity of decomposition	-
mscut	2.00E-01	1.00E-02	4.00E-01	Soil moisture level at which decomposition starts to become water limited	-

Table S2. C cycling and environmental scaling parameters estimated via data assimilation with a six pool C model and 4-5 C pool and flux data sets for each of six grassland sites. 95% confidence intervals (CLl and cLu) are estimated from normal, log-normal, or Weibull distributions depending on the magnitude and direction of skew. Gelman-Rubin statistics (G-R) indicate convergence among independent chains.

	SBL				SBK			
Param	MLE	CLl	cLu	G-R	MLE	CLl	cLu	G-R
c1	0.009107	6.75E-03	1.00E-02	1.0	0.007977	0.004471	0.009999	1.0
c2	0.009405	7.70E-03	1.00E-02	1.0	0.00963	0.008492	0.01	1.0
c3	0.017967	1.24E-02	2.00E-02	1.0	0.00068	0.0005	0.001112	1.0
c4	0.017657	1.06E-02	2.67E-02	1.0	0.01101	0.006237	0.0172	1.0
c5	0.000232	1.00E-05	1.02E-03	1.0	0.000188	5.61E-05	0.000374	1.0
c6	1.46E-05	8.02E-07	2.87E-05	1.0	1.55E-05	1.41E-06	2.93E-05	1.0
f43	0.618122	3.74E-01	7.00E-01	1.0	0.593098	0.347119	0.699949	1.0
f53	0.110032	6.02E-02	1.50E-01	1.0	0.1055	0.056978	0.149515	1.0
f54	0.298433	2.50E-01	4.10E-01	1.0	0.312915	0.250004	0.435435	1.0
f64	0.004441	1.16E-03	7.71E-03	1.0	0.004506	0.001239	0.007792	1.0
f45	0.262651	1.00E-01	5.45E-01	1.0	0.31254	0.103977	0.552567	1.0
f65	0.036233	4.11E-03	6.77E-02	1.0	0.038417	0.005276	0.068779	1.0
f46	0.504545	3.17E-01	6.90E-01	1.0	0.497965	0.312594	0.681608	1.0
mscut	0.223073	1.78E-01	2.56E-01	1.0	0.159795	0.135553	0.18398	1.0
Q10	1.895981	1.07E+00	2.76E+00	1.0	1.597074	1.231482	1.986987	1.0

	CPER				HPG			
Param	MLE	CLl	cLu	G-R	MLE	CLl	cLu	G-R
c1	0.00746	0.005609	0.00966	1.0	0.007872	0.004192	0.009959	1.1
c2	0.001675	0.001518	0.00184	1.0	0.000488	0.000417	0.000562	1.0
c3	0.011091	0.006979	0.016717	1.0	0.018395	0.0143	0.019997	1.0
c4	0.017479	0.006234	0.041909	1.0	0.042184	0.024925	0.049978	1.1
c5	0.000128	0.0001	0.000181	1.0	0.000314	0.000164	0.000482	1.0
c6	1.49E-05	7.57E-07	2.86E-05	1.1	1.64E-05	1.97E-06	2.92E-05	1.2
f43	0.68024	0.618193	0.699996	1.0	0.576301	0.377749	0.699959	1.1
f53	0.137347	0.099531	0.149997	1.0	0.102849	0.057045	0.14747	1.3
f54	0.62252	0.546666	0.649987	1.0	0.574702	0.35944	0.649937	1.1
f64	0.004421	0.001187	0.007682	1.1	0.004583	0.001361	0.00768	1.2
f45	0.427899	0.176967	0.599756	1.0	0.388533	0.150328	0.587869	1.2
f65	0.040839	0.007248	0.069772	1.1	0.032149	0.002948	0.060738	1.1
f46	0.506596	0.316463	0.687456	1.0	0.473907	0.305835	0.667426	1.2
mscut	0.073406	0.014973	0.125796	1.0	0.231396	0.205847	0.253547	1.0
Q10	1.248167	1.10994	1.393126	1.0	3.482896	2.773369	3.950379	1.0

	HAR				KNZ			
Param	MLE	CLl	cLu	G-R	MLE	CLl	cLu	G-R

c1	0.005025	0.002799	0.007883	1.0	0.001854	0.000722	0.00367	1.0
c2	0.000414	0.000257	0.0006	1.0	0.000967	0.000699	0.001413	1.0
c3	0.004664	0.002313	0.007928	1.0	0.013651	0.004197	0.019902	1.0
c4	0.026455	0.006518	0.047266	1.0	0.021989	0.005002	0.045437	1.0
c5	0.000171	0.0001	0.000308	1.0	0.000233	0.000106	0.00041	1.0
c6	1.41E-05	9.88E-07	2.88E-05	1.0	1.50E-05	1.46E-06	2.94E-05	1.0
f43	0.561531	0.34928	0.699978	1.0	0.531489	0.347243	0.696558	1.1
f53	0.102973	0.057002	0.146251	1.1	0.104992	0.05725	0.148682	1.1
f54	0.54796	0.303471	0.649941	1.3	0.586921	0.387489	0.649992	1.0
f64	0.004599	0.001247	0.007561	1.2	0.004439	0.001255	0.007846	1.0
f45	0.354072	0.125197	0.577835	1.3	0.39581	0.156163	0.599482	1.1
f65	0.03924	0.006196	0.069346	1.1	0.034188	0.004299	0.066817	1.1
f46	0.509573	0.327535	0.691565	1.0	0.490831	0.314648	0.683017	1.1
mscut	0.283857	0.231203	0.328458	1.0	0.114386	0.013291	0.232586	1.1
Q10	2.503186	1.929534	3.128982	1.0	3.445054	2.277028	3.999685	1.0

Table S3. Cross correlations between Markov Chain Monte Carlo output of different model parameters during data assimilation.

Site	param	c1	c2	c3	c4	c5	c6	f43	f53	f54	f64	f45	f65	f46	mscut	Q10
SBL	c1	1	0.06	0.05	0.14	0.11	0.02	-0.04	-0.04	0.04	0.01	-0.02	0.02	-0.01	-0.09	-0.17
SBL	c2	0.06	1	0.04	0.13	0.02	0	-0.04	-0.02	0	0	0.01	0.01	0	0.05	-0.07
SBL	c3	0.05	0.04	1	0.1	-0.02	0.03	0.11	-0.01	-0.02	0.01	0.01	0.01	-0.02	0.01	-0.07
SBL	c4	0.14	0.13	0.1	1	0.47	0.02	0	-0.05	0.17	0.02	-0.05	0.02	-0.01	-0.18	-0.43

SBL	c5	0.11	0.02	-0.02	0.47	1	-0.03	-0.03	0.02	0.41	0.03	-0.21	0.06	0	-0.79	-0.86
SBL	c6	0.02	0	0.03	0.02	-0.03	1	0.01	-0.01	0	0.05	-0.02	-0.02	-0.05	0.02	0
SBL	f43	-0.04	-0.04	0.11	0	-0.03	0.01	1	0.01	-0.01	-0.02	0.04	0	-0.04	0.1	0.18
SBL	f53	-0.04	-0.02	-0.01	-0.05	0.02	-0.01	0.01	1	0.01	0	-0.04	0	0.01	0.04	0.09
SBL	f54	0.04	0	-0.02	0.17	0.41	0	-0.01	0.01	1	-0.03	-0.08	-0.01	0.03	-0.22	-0.21
SBL	f64	0.01	0	0.01	0.02	0.03	0.05	-0.02	0	-0.03	1	-0.04	-0.01	0	-0.04	-0.04
SBL	f45	-0.02	0.01	0.01	-0.05	-0.21	-0.02	0.04	-0.04	-0.08	-0.04	1	-0.03	0.03	0.25	0.28
SBL	f65	0.02	0.01	0.01	0.02	0.06	-0.02	0	0	-0.01	-0.01	-0.03	1	0.02	-0.03	-0.02
SBL	f46	-0.01	0	-0.02	-0.01	0	-0.05	-0.04	0.01	0.03	0	0.03	0.02	1	0.01	0.01
SBL	mscut	-0.09	0.05	0.01	-0.18	-0.79	0.02	0.1	0.04	-0.22	-0.04	0.25	-0.03	0.01	1	0.87
SBL	Q10	-0.17	-0.07	-0.07	-0.43	-0.86	0	0.18	0.09	-0.21	-0.04	0.28	-0.02	0.01	0.87	1
SBK	c1	1.00	0.05	0.01	0.09	0.11	0.01	0.03	0.03	0.02	0.04	-0.01	-0.02	0.04	0.00	-0.16
SBK	c2	0.05	1.00	0.05	0.15	0.17	-0.01	-0.01	0.00	0.02	0.01	-0.01	0.00	0.01	0.07	-0.21
SBK	c3	0.01	0.05	1.00	0.05	-0.17	0.01	0.08	0.06	0.01	0.00	0.01	-0.02	0.00	0.05	-0.16
SBK	c4	0.09	0.15	0.05	1.00	0.52	-0.01	0.00	-0.02	0.06	-0.01	0.04	0.02	0.02	-0.01	-0.44
SBK	c5	0.11	0.17	-0.17	0.52	1.00	-0.07	0.09	0.01	0.27	0.01	0.11	0.06	0.01	-0.31	-0.75
SBK	c6	0.01	-0.01	0.01	-0.01	-0.07	1.00	0.04	0.04	-0.02	-0.06	-0.05	-0.01	0.03	-0.02	0.00
SBK	f43	0.03	-0.01	0.08	0.00	0.09	0.04	1.00	-0.05	0.09	0.00	0.01	-0.08	0.06	-0.02	0.00
SBK	f53	0.03	0.00	0.06	-0.02	0.01	0.04	-0.05	1.00	0.02	0.04	0.04	-0.08	-0.10	0.00	0.02
SBK	f54	0.02	0.02	0.01	0.06	0.27	-0.02	0.09	0.02	1.00	-0.02	0.02	-0.03	0.01	0.03	-0.02
SBK	f64	0.04	0.01	0.00	-0.01	0.01	-0.06	0.00	0.04	-0.02	1.00	-0.02	-0.01	0.00	-0.01	-0.01
SBK	f45	-0.01	-0.01	0.01	0.04	0.11	-0.05	0.01	0.04	0.02	-0.02	1.00	-0.06	0.00	0.06	0.07
SBK	f65	-0.02	0.00	-0.02	0.02	0.06	-0.01	-0.08	-0.08	-0.03	-0.01	-0.06	1.00	0.01	-0.01	-0.02
SBK	f46	0.04	0.01	0.00	0.02	0.01	0.03	0.06	-0.10	0.01	0.00	0.00	0.01	1.00	0.00	-0.01
SBK	mscut	0.00	0.07	0.05	-0.01	-0.31	-0.02	-0.02	0.00	0.03	-0.01	0.06	-0.01	0.00	1.00	0.53
SBK	Q10	-0.16	-0.21	-0.16	-0.44	-0.75	0.00	0.00	0.02	-0.02	-0.01	0.07	-0.02	-0.01	0.53	1.00
CPER	c1	1.00	0.18	-0.05	-0.08	0.02	0.04	-0.01	0.04	0.05	0.01	0.02	0.02	-0.02	0.17	-0.16
CPER	c2	0.18	1.00	0.09	0.00	0.06	0.02	-0.02	-0.03	-0.03	0.01	-0.02	-0.02	0.00	0.50	-0.47
CPER	c3	-0.05	0.09	1.00	-0.30	-0.01	0.07	0.08	0.02	-0.06	-0.07	-0.05	-0.04	0.00	0.08	-0.02
CPER	c4	-0.08	0.00	-0.30	1.00	0.01	-0.04	-0.03	-0.09	0.08	0.06	0.00	0.01	0.10	-0.03	0.01
CPER	c5	0.02	0.06	-0.01	0.01	1.00	-0.02	0.09	0.09	0.17	0.00	0.18	0.05	-0.03	0.03	-0.13
CPER	c6	0.04	0.02	0.07	-0.04	-0.02	1.00	0.03	0.05	0.05	0.02	-0.04	0.05	0.03	0.00	-0.02
CPER	f43	-0.01	-0.02	0.08	-0.03	0.09	0.03	1.00	-0.08	-0.11	0.03	-0.06	-0.02	-0.02	-0.02	0.08
CPER	f53	0.04	-0.03	0.02	-0.09	0.09	0.05	-0.08	1.00	-0.16	-0.13	-0.03	0.05	-0.04	-0.03	0.06
CPER	f54	0.05	-0.03	-0.06	0.08	0.17	0.05	-0.11	-0.16	1.00	0.01	-0.05	-0.05	0.01	-0.03	0.10
CPER	f64	0.01	0.01	-0.07	0.06	0.00	0.02	0.03	-0.13	0.01	1.00	-0.02	0.01	-0.03	0.01	0.00
CPER	f45	0.02	-0.02	-0.05	0.00	0.18	-0.04	-0.06	-0.03	-0.05	-0.02	1.00	0.01	-0.11	-0.01	0.07
CPER	f65	0.02	-0.02	-0.04	0.01	0.05	0.05	-0.02	0.05	-0.05	0.01	0.01	1.00	0.02	-0.03	0.01
CPER	f46	-0.02	0.00	0.00	0.10	-0.03	0.03	-0.02	-0.04	0.01	-0.03	-0.11	0.02	1.00	0.01	-0.01

CPER	mscut	0.17	0.50	0.08	-0.03	0.03	0.00	-0.02	-0.03	-0.03	0.01	-0.01	-0.03	0.01	1.00	-0.03
CPER	Q10	-0.16	-0.47	-0.02	0.01	-0.13	-0.02	0.08	0.06	0.10	0.00	0.07	0.01	-0.01	-0.03	1.00
HPG	c1	1.00	-0.11	0.21	0.16	-0.10	-0.04	0.03	-0.07	-0.22	0.13	-0.17	-0.01	-0.08	-0.09	0.01
HPG	c2	-0.11	1.00	0.04	-0.04	0.46	-0.01	0.06	0.08	0.11	-0.06	0.02	-0.07	0.02	0.46	-0.44
HPG	c3	0.21	0.04	1.00	-0.07	-0.06	-0.02	-0.12	-0.13	-0.14	0.05	-0.01	0.00	-0.11	0.01	-0.03
HPG	c4	0.16	-0.04	-0.07	1.00	-0.07	-0.14	-0.13	0.02	-0.05	-0.01	-0.05	0.14	0.04	0.02	0.06
HPG	c5	-0.10	0.46	-0.06	-0.07	1.00	0.04	0.43	0.16	0.57	0.05	0.39	-0.10	0.12	0.02	-0.47
HPG	c6	-0.04	-0.01	-0.02	-0.14	0.04	1.00	0.21	0.05	0.14	0.12	0.03	-0.12	0.11	0.04	0.05
HPG	f43	0.03	0.06	-0.12	-0.13	0.43	0.21	1.00	0.05	0.17	-0.03	0.06	-0.17	0.11	0.04	-0.01
HPG	f53	-0.07	0.08	-0.13	0.02	0.16	0.05	0.05	1.00	0.01	-0.13	-0.13	-0.09	0.14	-0.02	-0.11
HPG	f54	-0.22	0.11	-0.14	-0.05	0.57	0.14	0.17	0.01	1.00	0.06	0.08	-0.17	0.11	0.11	-0.01
HPG	f64	0.13	-0.06	0.05	-0.01	0.05	0.12	-0.03	-0.13	0.06	1.00	0.15	0.02	0.00	-0.02	0.04
HPG	f45	-0.17	0.02	-0.01	-0.05	0.39	0.03	0.06	-0.13	0.08	0.15	1.00	-0.02	0.01	-0.04	-0.06
HPG	f65	-0.01	-0.07	0.00	0.14	-0.10	-0.12	-0.17	-0.09	-0.17	0.02	-0.02	1.00	-0.11	0.00	0.07
HPG	f46	-0.08	0.02	-0.11	0.04	0.12	0.11	0.11	0.14	0.11	0.00	0.01	-0.11	1.00	0.01	-0.01
HPG	mscut	-0.09	0.46	0.01	0.02	0.02	0.04	0.04	-0.02	0.11	-0.02	-0.04	0.00	0.01	1.00	0.54
HPG	Q10	0.01	-0.44	-0.03	0.06	-0.47	0.05	-0.01	-0.11	-0.01	0.04	-0.06	0.07	-0.01	0.54	1.00
HAR	c1	1.00	0.86	0.55	0.04	0.45	0.10	-0.03	-0.10	-0.24	0.00	0.00	-0.06	0.00	0.66	-0.45
HAR	c2	0.86	1.00	0.63	0.03	0.51	0.08	-0.10	-0.10	-0.29	0.00	0.00	-0.07	0.03	0.76	-0.48
HAR	c3	0.55	0.63	1.00	0.02	0.32	0.01	-0.01	-0.06	-0.13	0.00	0.05	-0.08	0.03	0.48	-0.33
HAR	c4	0.04	0.03	0.02	1.00	-0.01	-0.06	-0.18	-0.02	0.15	0.05	-0.13	0.11	0.08	0.03	0.01
HAR	c5	0.45	0.51	0.32	-0.01	1.00	0.03	0.25	-0.10	0.23	0.04	0.23	-0.04	-0.03	0.31	-0.36
HAR	c6	0.10	0.08	0.01	-0.06	0.03	1.00	0.12	0.01	-0.06	-0.06	0.01	-0.05	-0.28	0.02	-0.13
HAR	f43	-0.03	-0.10	-0.01	-0.18	0.25	0.12	1.00	-0.30	-0.01	0.09	0.13	-0.10	-0.21	-0.12	0.03
HAR	f53	-0.10	-0.10	-0.06	-0.02	-0.10	0.01	-0.30	1.00	-0.06	-0.12	-0.02	-0.01	-0.06	-0.03	0.12
HAR	f54	-0.24	-0.29	-0.13	0.15	0.23	-0.06	-0.01	-0.06	1.00	-0.05	-0.11	0.03	-0.01	-0.16	0.28
HAR	f64	0.00	0.00	0.00	0.05	0.04	-0.06	0.09	-0.12	-0.05	1.00	0.08	0.17	-0.04	-0.02	-0.02
HAR	f45	0.00	0.00	0.05	-0.13	0.23	0.01	0.13	-0.02	-0.11	0.08	1.00	-0.12	0.04	-0.01	0.00
HAR	f65	-0.06	-0.07	-0.08	0.11	-0.04	-0.05	-0.10	-0.01	0.03	0.17	-0.12	1.00	-0.10	-0.06	0.01
HAR	f46	0.00	0.03	0.03	0.08	-0.03	-0.28	-0.21	-0.06	-0.01	-0.04	0.04	-0.10	1.00	0.03	-0.02
HAR	mscut	0.66	0.76	0.48	0.03	0.31	0.02	-0.12	-0.03	-0.16	-0.02	-0.01	-0.06	0.03	1.00	0.12
HAR	Q10	-0.45	-0.48	-0.33	0.01	-0.36	-0.13	0.03	0.12	0.28	-0.02	0.00	0.01	-0.02	0.12	1.00
KNZ	c1	1.00	0.52	0.04	-0.07	0.28	-0.07	-0.03	0.00	-0.07	-0.02	0.02	0.03	0.01	0.04	-0.48
KNZ	c2	0.52	1.00	0.01	-0.13	0.55	-0.05	-0.07	-0.02	-0.10	-0.06	0.03	0.04	0.02	0.08	-0.93
KNZ	c3	0.04	0.01	1.00	-0.05	0.08	0.09	0.10	0.04	0.02	-0.12	0.03	0.01	0.05	0.04	-0.01
KNZ	c4	-0.07	-0.13	-0.05	1.00	-0.21	-0.02	-0.05	0.11	0.03	0.08	-0.12	-0.04	-0.07	-0.09	0.11
KNZ	c5	0.28	0.55	0.08	-0.21	1.00	-0.05	0.19	0.08	0.23	-0.02	0.34	0.13	0.03	0.17	-0.48
KNZ	c6	-0.07	-0.05	0.09	-0.02	-0.05	1.00	0.02	0.06	0.12	-0.10	0.02	-0.08	-0.03	-0.02	0.03

KNZ	f43	-0.03	-0.07	0.10	-0.05	0.19	0.02	1.00	-0.02	0.05	0.10	0.01	0.01	-0.01	-0.04	0.07
KNZ	f53	0.00	-0.02	0.04	0.11	0.08	0.06	-0.02	1.00	0.05	0.09	0.05	-0.13	-0.12	0.04	0.04
KNZ	f54	-0.07	-0.10	0.02	0.03	0.23	0.12	0.05	0.05	1.00	0.00	-0.12	-0.02	-0.05	-0.02	0.09
KNZ	f64	-0.02	-0.06	-0.12	0.08	-0.02	-0.10	0.10	0.09	0.00	1.00	-0.14	0.07	-0.11	0.05	0.06
KNZ	f45	0.02	0.03	0.03	-0.12	0.34	0.02	0.01	0.05	-0.12	-0.14	1.00	0.08	0.14	0.09	-0.02
KNZ	f65	0.03	0.04	0.01	-0.04	0.13	-0.08	0.01	-0.13	-0.02	0.07	0.08	1.00	0.00	-0.07	-0.06
KNZ	f46	0.01	0.02	0.05	-0.07	0.03	-0.03	-0.01	-0.12	-0.05	-0.11	0.14	0.00	1.00	0.01	-0.02
KNZ	mscut	0.04	0.08	0.04	-0.09	0.17	-0.02	-0.04	0.04	-0.02	0.05	0.09	-0.07	0.01	1.00	0.16
KNZ	Q10	-0.48	-0.93	-0.01	0.11	-0.48	0.03	0.07	0.04	0.09	0.06	-0.02	-0.06	-0.02	0.16	1.00

Table S4. Descriptions of soil profile data sets obtained from the International Soil Carbon Network

Location	Site code	Latitude	Longitude	Profile depth (cm)
Sevilleta National Wildlife Refuge, New Mexico	81NM053005	34.18703	-107.21	152
Central Plains Experimental Range, Colorado	S1991CO123007	40.82806	-104.786	130
Cheyenne, Wyoming	S1989WY021007	41.20889	-104.931	160
Hays, Kansas	S1968KS051001	39.01528	-99.1258	145
Konza Priarie Biological Station, Kansas	KZP 1D	39.07597	-96.5638	200

Table S5. Variance partitioning results comparing among site variation in net primary productivity explained by site-level estimates of average annual precipitation, average annual temperature, soil bulk density, grass:forb, C3:C4, and annual species abundance.

	Variable 1	Variable2	Test	AdjR2	Fval	Pval
NPP	MAP	MAP	X1|X2	1.17	123.71	0.01
			X1X2 colin.	-0.21	NA	NA
			X2|X1	0.00	0.58	0.51
			X1+X2	0.96	63.84	<0.01
		Bulk Density	X1|X2	0.36	32.70	0.01
			X1X2 colin.	0.61	NA	NA
			X2|X1	-0.01	0.03	0.84
			X1+X2	0.95	53.74	0.02
		Grass:forb	X1|X2	0.09	11.44	0.05
			X1X2 colin.	0.87	NA	NA
			X2|X1	0.00	0.82	0.43
			X1+X2	0.96	68.27	<0.01
		C3:C4	X1|X2	1.15	103.19	<0.01
			X1X2 colin.	-0.18	NA	NA
			X2|X1	-0.01	0.04	0.83
			X1+X2	0.95	54.02	0.01
		Annual species abundance	X1|X2	0.50	74.70	0.01
			X1X2 colin.	0.47	NA	NA
			X2|X1	0.01	2.06	0.24
			X1+X2	0.97	90.77	<0.01

Eco_{RT}	MAT	MAP	X1|X2	0.54	4.10	0.18
			X1X2 colin.	-0.16	NA	NA
			X2|X1	-0.09	0.10	0.71
			X1+X2	0.70	2.05	0.33
		Bulk Density	X1|X2	0.22	2.21	0.22
			X1X2 colin.	-0.18	NA	NA
			X2|X1	0.24	0.02	0.86
			X1+X2	0.72	1.97	0.37
		Grass:forb	X1|X2	0.60	4.74	0.16
			X1X2 colin.	-0.10	NA	NA
			X2|X1	-0.15	0.38	0.52
			X1+X2	0.64	2.38	0.24
		C3:C4	X1|X2	0.22	2.22	0.23
			X1X2 colin.	-0.18	NA	NA
			X2|X1	0.23	0.01	0.95
			X1+X2	0.73	1.95	0.25
		Annual species abundance	X1|X2	0.36	3.16	0.22
			X1X2 colin.	-0.12	NA	NA
			X2|X1	0.10	0.29	0.69
			X1+X2	0.66	2.27	0.30

Table S6. Average soil moisture and soil temperature during June-September at our six focal grassland sites.

Site	Volumetric soil moisture (%)	Soil temperature (°C)
SBL	13.3	26.3
SBK	11.9	27.6
CPER	11.4	22.9
HPG	15.4	21.1
HAR	21.0	24.6
KNZ	20.9	24.0

S3. Detailed description of data collection and cleaning methods

S3.1 Aboveground net primary productivity (ANPP)

At CPER, HPG, HAR, and KNZ, ANPP was collected annually by clipping two 0.1 m^2 subplots per replicate in September, sorted to remove previous years' growth, dried at 60 C for 48 hours, and weighed. At SBK and SBL, ANPP was estimated using species-specific allometric methods (Muldavin et al. 2008, Rudgers et al. 2019) within four 1 m^2 subplots within each of the 10 control plots.

S3.2 Vegetative litter

Litter estimates were obtained by collecting previous year's biomass to ground level in the same subplots as ANPP. Litter was not present at SBL or SBK due to rapid decomposition at the soil surface at these sites, nor at KNZ due to annual burning.

S3.3 Belowground net primary productivity (BNPP) and root standing crop

BNPP was estimated from 0-20 cm at each site using two root ingrowth cores per plot (Persson 1980). Ingrowth cores were constructed from 2 mm fiberglass screen molded into a 5 cm diameter 22 cm long cylinder (2 cm was left above soil surface). In April-May, a soil auger was used to drill 20 cm deep in the soil. Ingrowth cores were then inserted, filled with sieved, root free soil from the site, and packed to approximate soil density. Ingrowth cores were removed in late September and stored at 4 C until processing. Samples were elutriated to separate root biomass from soil. Samples were sorted to remove soil organic matter, dried at 60 C for 48 hours, and weighed. Finally, samples were fired at 450 C and resulting ash subtracted from the biomass value to generate an ash free estimate of BNPP. 5 cm root standing crop samples were also taken from 0-20 cm in two subplots. Standing crop root samples were processed similarly to BNPP samples, with the exception that dead roots were sorted out of the samples at the same time as SOM.

S3.4 Soil CO_2 efflux

Surface soil respiration was calculated using measurements of soil CO_2 concentrations (GMP 220 series probes, Vaisala Corp., Helsinki, Finland) in three replicates per site at 5, 10, and 20 cm depths, combined with diffusion rates calculated using soil temperature and moisture data collected simultaneously with CO_2 concentration. See Vargas & Allen (2008), and Vargas et al. (2010) for more information about calculating soil respiration rates using this method. We averaged 15 minute soil respiration measurements between 10:00 am and 2:00 pm to obtain daily soil respiration values.

S3.5 Soil moisture and temperature

Volumetric soil moisture integrated from 0-15 cm was measured in all 10 plots every 15 minutes using time domain reflectometry probes (CS-616 model, Campbell Scientific, Inc., Logan, UT, USA). Soil temperature was measured in 3 plots at 5 cm and 10 cm depths using thermocouples (K-type, OMEGA Engineering Inc., Stamford, CT, USA).

S3.6 Soil bulk density

Bulk density was measured at each site from ten 7 cm diameter soil cores taken 0-30 cm. Soil cores were extracted in segments to reduce compaction. All aboveground vegetation was removed, and cores were dried at 105 C for 48 hours, then weighed. Bulk density was then calculated as:

$$BD = \frac{M_{dry}}{\pi r^2 x\ D} \quad \text{(C1)}$$

Where M_{dry} is the dry mass, r is the radius, and D is the depth of the soil core.

S3.7 Meteorological data

Hourly air temperature, precipitation, relative humidity, vapor pressure deficit (VPD), and incident photosynthetically active radiation data were obtained from nearby weather stations to run the terrestrial ecosystem model (TECO; Weng and Luo, 2008). Gaps of < 10 time steps (hours) were filled by splining, and all splined sections examined to ensure values were within reasonable bounds. Gaps of longer time steps were filled from next closest meteorological stations of the same elevation. When unavailable, we calculated VPD as actual vapor pressure (e_a) minus saturation vapor pressure (e_s). e_a is estimated as:

$$e_a = \frac{RH}{100} e_s \quad \text{(C2)}$$

where RH is relative humidity, and e_s is estimated as:

$$e_s = 0.6108 e^{\frac{17.27t}{t+237.3}} \quad \text{(C3)}$$

where t is air temperature.

S3.8 Soil total organic carbon

At CPER, HGR, HAR, and KNZ, percent C was measured in three 2 cm diameter 10 cm deep soil cores per plot. Subsamples were aggregated, sieved with a 2 mm soil sieve to remove root material, dried, and ground. Samples were then measured for total C via dry combustion and grass chromatography using a LECO CN 2000 combustion analyzer (LECO Corp., Saint Joseph, MI, USA). For SBL and SBK, percent organic matter was estimated in soil from 0-10 cm depths from nearby areas having similar soils and vegetation to the EDGE sites. Organic matter values were then converted to percent C by dividing the percent organic matter by 1.72 (assumes 58% C stoichiometry of organic matter). Percent C for all sites was then converted to total C using:

$$C_T = D \ x \ BD \ x \ C_p x \ 10000 \qquad \text{(C4)}$$

Where C_T is total carbon, D is the depth in cm to which the sample was collected, BD is the bulk density in g per cm^{-2}, and C_p is the proportion of carbon.

S3.9 Plant species abundance

Abundance of plant species was estimated visually in June and August in four 1 x 1 m^2 subplots per plot to the nearest percent. Species having less than 1% cover were rounded up to 1%. Calibrations of visual estimates were performed across researchers and with measurements seasonally. Maximum cover of each species was taken for each subplot, then all abundances were averaged across subplots to get plot-level estimates.

S4. Model evaluation text, Table S7, Figures S11-S13

Model validation exercises were conducted to compare the ability of the model to represent (1) average plant growth across sites and (2) variability of plant growth across years within each site. To this end, models were parameterized for each site based on soil texture, field capacity, wilting point, latitude, and root:shoot ratios. Additionally, maximum and minimum specific leaf area and Vcmax parameters were adjusted to better match measured above and belowground plant growth. Table 1 shows the parameter sets used for each site.

Empirical observations of ANPP and BNPP (n=10) were compared to leaf+stem biomass and root productivity from the model at the time of data collection. At CPER, HPG, HAR, and KNZ, ANPP was collected annually by clipping two 0.1 m2 subplots per replicate in September, sorted to remove previous years' growth (leaf litter), dried at 60 C for 48 hours, and weighed. At SBK and SBL, ANPP was estimated using species-specific allometric methods (Muldavin et al. 2008) within four 1m2 subplots within each of the 10 replicates. BNPP within each replicate at each site was estimated from 0-20 cm using two 20 cm x 5 cm diameter root ingrowth cores per plot (Persson 1980). See Appendix 3 for additional details about empirical data collection.

Models were spun up for 500 years using cycled meteorological data from each site – all carbon pools stabilized after 200-400 years. Then simulations were conducted for 2014-2017 for all sites. Empirical ANPP data were available from 2014-2017 for all sites, and BNPP was available for CPER, HPG, HAR, and KNZ for 2014-2017. BNPP was available at SBL and SBK from 2015-2017. To assess model performance, we calculated various validation metrics, including R2, RMSE, and the correlation coefficient.

Generally, cross-site averages of model output and observations were tightly correlated, but within-site model output was less correlated to interannual empirical observations (Table 1). However, it is important to note the variation associated with empirical measurements and that most model simulations fell within one standard error of empirical observations (error bars in Fig. S12 and S13). A notable exception to this occurred in 2014 at CPER and HPG sites, where BNPP was observed as much greater than model simulations. We are unsure what drove the high BNPP at these sites in 2014 since environmental conditions were within normal ranges (Fig. S11). It could be that other unmeasured variables (e.g., belowground animal activity, small mammal activity) were responsible for this high growth belowground.

Table S7. Model output for comparisons between empirical and simulated data.

Site	Productivity type	R2	RMSE	Correlation coefficient
means	anpp	0.988738	17.96882	0.994353
means	bnpp	0.93693	23.4836	0.967952
sbl	anpp	0.431519	9.568253	-0.6569
sbl	bnpp	0.009114	18.25828	-0.09547
sbk	anpp	0.667188	10.51358	0.816816
sbk	bnpp	0.059729	13.3254	-0.2444
cper	anpp	0.087017	33.30121	0.294986
cper	bnpp	0.181185	98.48398	0.425659
hpg	anpp	0.018955	35.10083	-0.13768
hpg	bnpp	0.022188	131.1703	0.148957
har	anpp	0.526963	28.82132	0.725922
har	bnpp	0.330895	34.27893	0.575235
knz	anpp	0.004173	162.8426	-0.0646
knz	bnpp	0.637154	36.67331	-0.79822

anpp=aboveground net primary productivity, bnpp=belowground net primary productivity, sbl=Sevilleta National Wildlife Refuge blue grama grassland; sbk=Sevilleta National Wildlife Refuge black grama grassland; cper=Central Plains Experimental Range;

hpg=High Plains Grasslands Research Station; har=Hays Agricultural Research Center; knz=Konza Prairie Biological Station

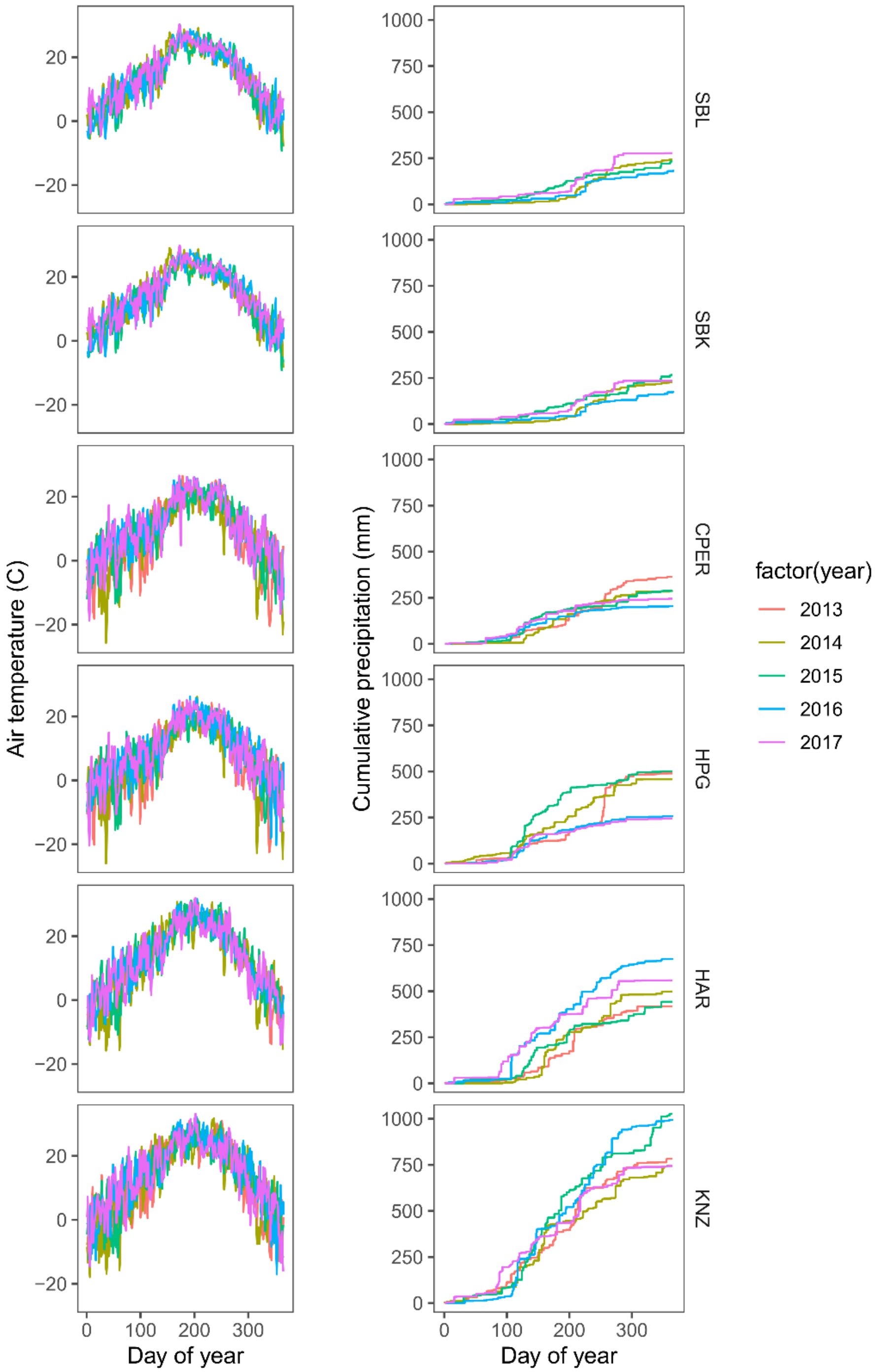

Figure S11. Cumulative hourly precipitation and hourly air temperature throughout each year simulated within each site.

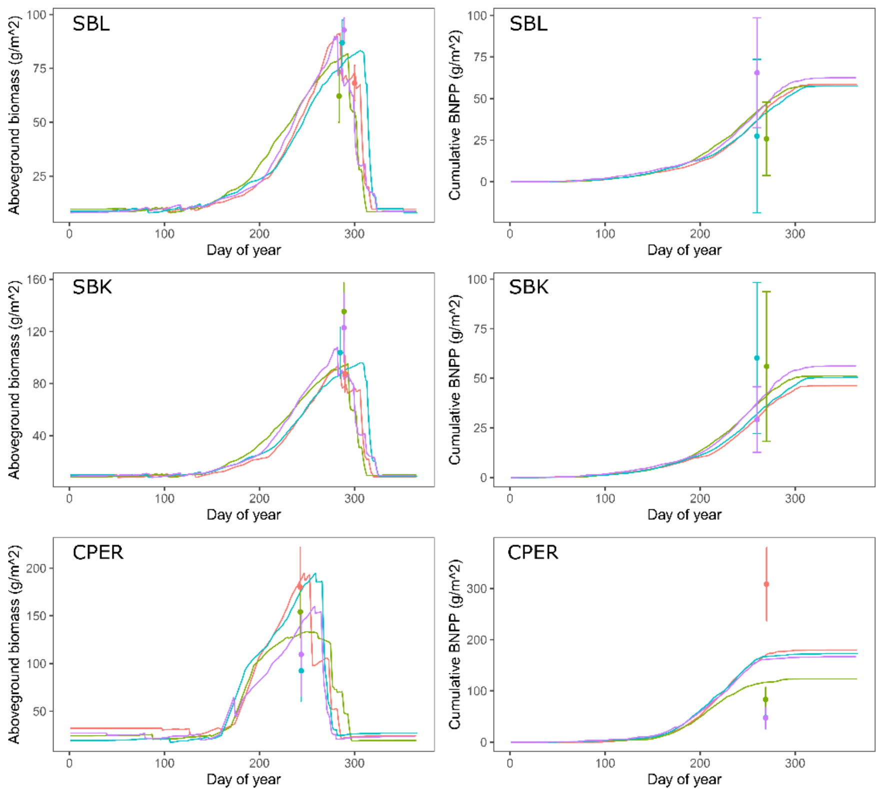

Figure S12. Within year patterns of simulated aboveground biomass and BNPP for SBL, SBK, and CPER, compared with empirical observations. Bars represent one standard deviation from the mean of the 10 replicate measurements. Years are represented as colors using the scale from Fig. 1.

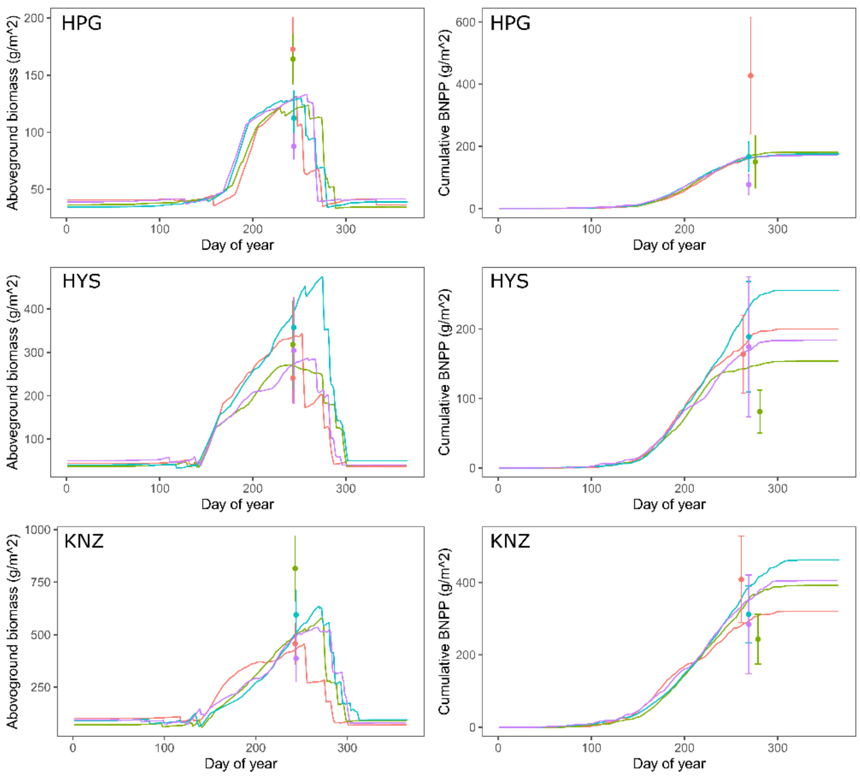

Figure S13. Within year patterns of simulated aboveground biomass and BNPP for HPG, HYS, and KNZ, compared with empirical observations. Bars represent one standard deviation from the mean of the 10 replicate measurements. Years are represented as colors using the scale from Fig. 1.

S5. Land use history of study sites

Here, we outline the recent land use history starting with the establishment of the current associations responsible for managing these areas.

SBL, SBK: The Sevilleta National Wildlife Refuge in central New Mexico, USA, was established in 1973. Prior to that time the land was lightly to moderately grazed by domestic herbivores (mostly cattle along with some horses and sheep) for about three centuries as part of a collective land grant to settlers from the King of Spain. All domestic herbivores were removed from the site when the refuge was established, and the vegetation has recovered from grazing (Gosz and Gosz 1996, Collins and Xia 2015). The refuge sits at the intersection of several biomes (Gosz and Gosz 1996) including Great Plains grassland dominated by blue grama (Bouteloua gracilis)(SBL site in this study) and Chihuahuan Desert grassland dominated by black grama (B. eriopoda)(SBK site in this study). Chihuahuan Desert grassland is advancing northward into Great Plains grassland (Collins et al. 2020) in response to increasing aridity throughout the southwestern US (Rudgers et al. 2018, Maurer et al. 2020).

CPER: The Central Plains Experimental Range is a shortgrass prairie dominated by B. gracilis (Hazlett 1998). The experimental station was established in the 1930s to better understand how to manage lands to avoid catastrophic occurrences such as the Dust Bowl. A number of climatic and management effects occurred at CPER, including a severe blizzard in 1949, an extreme flood in 1965, and sever droughts in 1939, 1954, 1964 (Shoop et al. 1989), and 2012 (Knapp et al. 2015). The specific area where our plots were located have been ungrazed for 14 years prior to the start of measurements. Before then, grazing occurred in the area but fire was largely absent at the site.

HPG: The High Plains Grassland Research Station was authorized by congress in 1928 to experiment with various horticultural crops in arid lands, which was begun in 1930. In 1974, the station shifted focus to rangeland management, water conservation, and land reclamation. The area where the plots were located was ungrazed since 2004 (Dijkstra et al. 2010) and has little to no history of fire.

HAR: Kansas State University began management of The Agricultural Research Center-Hays in 1994 and was managed for cattle grazing. The plots where our plots were located were ungrazed and unburned since 2005 (Heisler-White et al. 2009).

KNZ: The land where Konza Prairie Biological Station resides was purchased by the Nature Conservancy in 1971 and deeded to Kansas State University to establish a watershed-scale experiment to assess the impacts of fire and grazing on tallgrass ecological processes (Knapp et al. 1998). The watershed where our measurements took place has been burned annually in the spring since 1988 and was ungrazed by large ungulates since the early 1980s.