



*Supplement of*

## **Multi-scale assessment of a grassland productivity model**

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The PhenoGrass model from Hufkens et al. 2016 has the following form:

$$W_{t+1} = W_t + P_t - (1 - V_t)(D_t/(W_{cap} - W_p))^2 E_t - gb_3 D_t V_t \quad (1)$$

$$V_{t+1} = V_t + gS_t b_1 D_{t-L}(1 - V_t/V_{max}) - db_2(1 - V_t)V_t \quad (2)$$

$$D_t = \max(0, W_t - W_p) \quad (3)$$

$$W_t = \max(0, \min(W_{cap}, W_t)) \quad (4)$$

$$V_t = \max(0, \min(V_{max}, V_t)) \quad (5)$$

$$\begin{cases} D_{t-L} > D_{t-L-1}; & d = 0 \\ D_{t-L} \leq D_{t-L-1}; & d = 1 \end{cases} \quad (6)$$

$$S_t = (TOA_t - Phmin)/(Phmax - Phmin) \quad (7)$$

$$\begin{cases} S_{t-1} > S_t; & d = 1 \\ S_{t-1} \leq S_t; & d = 0 \end{cases} \quad (8)$$

$$g = \left(\frac{T_{max} - T_m}{T_{max} - T_{opt}}\right) \left(\frac{T_m}{T_{opt}}\right)^{\left(\frac{T_{opt}}{T_{max} - T_{opt}}\right)} \quad (9)$$

The vegetation parameter  $V$  corresponds to the fCover, which is mapped to PhenoCam  $G_{cc}$  using the transfer function based on the relationship between annual precipitation and fractional vegetation cover (Donohue et al. 2013):

$$S_c = MAP/(MAP + h) \quad (10)$$

where:

$$fCover = G_{cc} * S_c \quad (11)$$

MAP is the site level mean annual precipitation, and  $h$  is an estimated parameter.  $G_{cc}$  is a ratio of the green band within the daily image ROI:

$$G_{cc} = \frac{G_{dn}}{G_{dn} + R_{dn} + B_{dn}} \quad (12)$$

Where  $G_{dn}$ ,  $R_{dn}$ , and  $B_{dn}$  are the mean digital numbers for green, red, and blue channels, respectively. See Richardson et al. 2018 for further  $G_{cc}$  processing details.

	Parameter	Description
<b>State Variables</b>	W	Soil Water Content (mm)
	V	Fractional Cover (fCover)
	D	Plant available water (mm)
<b>Input Variables</b>	g	Plant temperature response function
	P	Precipitation (mm)
	MAP	Mean annual precipitation (mm)
	$W_{cap}$	Soil Field Capacity (mm)
	$W_p$	Soil Wilting Point (mm)
	$V_{max}$	Maximum vegetation cover (1.0)
	E	Evapotranspiration (mm)
	$T_m$	Running 15 day mean temperature (C)
	TOA	Top of atmosphere radiation
	$T_{max}$	Maximum temperature for growth (45 C)
<b>Estimated Parameters</b>	$T_{min}$	Minimum temperature for growth (0 C)
	b1	Vegetation growth parameter
	b2	Senescence parameter
	b3	Soil water extraction rate
	$T_{opt}$	Optimal vegetation growth temperature
	Phmin	Lower bound of optimal daily solar radiation
	Phmax	Upper bound of optimal daily solar radiation
	L	Lag (days)
	h	fCover Transfer function parameter

parameter	Great Plains Grasslands	E. Temperate Forests Grasslands
b1	0.0021756	0.0143214
b2	0.0607134	0.0269089
b3	0.2630305	9.8632117
Phmax	48.1106340	49.6940973
Phmin	25.5471298	33.1345876
Topt	29.7376494	35.6335041
L	3.0685254	3.1769617
h	10.3601586	949.5914722

Table S1. Final parameters for the two models which met the minimum NSE threshold.

name	lat	lon	vegetation	roi_id	first_date	last_date	site_years	ecoregion
ahwahnee	37.75	-119.58	GR	3000	2015-07-28	2020-03-05	4.6	NWForests
archboldavir	27.18	-81.22	AG	1000	2016-11-18	2020-03-05	3.1	ETempForests
archboldavirx	27.17	-81.22	AG	1000	2016-05-16	2020-03-05	3.6	ETempForests
archboldpnot	27.19	-81.20	AG	1000	2016-05-13	2020-03-05	3.6	ETempForests
archboldpnotx	27.18	-81.20	AG	1000	2016-05-16	2020-03-05	3.6	ETempForests
arsgacp1	31.51	-83.62	AG	1000	2016-05-10	2020-03-05	3.8	ETempForests
arshmnswanlake1	45.68	-95.80	AG	1000	2015-10-02	2020-03-05	4.4	GrPlains
bullshoals	36.56	-93.07	GR	1000	2013-11-19	2020-03-05	5.8	ETempForests
burnssagebrush	43.47	-119.69	SH	1000	2012-10-13	2020-03-05	7.3	NADeserts
butte*	45.95	-112.48	GR	1000	2009-01-11	2020-03-05	10.7	NWForests
cperagm	40.84	-104.77	AG	1000	2016-05-19	2020-03-05	3.8	GrPlains
cperagm	40.84	-104.77	GR	1000	2016-05-19	2020-03-05	3.8	GrPlains
cpertgm	40.83	-104.76	GR	1000	2016-05-04	2020-03-05	3.8	GrPlains
cperuvb	40.81	-104.76	GR	1000	2015-07-16	2020-03-05	4.7	GrPlains
gatesofthemountains	46.83	-111.71	GR	2000	2011-08-12	2019-02-01	7.1	NWForests
glacier	48.50	-113.99	GR	1000	2009-02-07	2020-03-05	11.0	NWForests
goodwater	39.23	-92.12	AG	1001	2015-09-26	2020-03-05	4.5	GrPlains
grandteton	43.92	-110.58	SH	1000	2015-07-28	2020-02-04	3.5	NWForests
harvardfarmnorth	42.52	-72.18	AG	1000	2015-11-07	2020-03-05	4.3	NForest
harvardfarmsouth	42.52	-72.18	AG	1000	2015-11-07	2020-03-05	4.3	NForest
harvardgarden	42.53	-72.19	AG	1000	2016-06-12	2020-03-05	3.7	NForest
hawbeckeredy	40.66	-77.85	AG	1000	2015-09-23	2019-05-14	3.4	ETempForests
humnokericea	34.59	-91.75	AG	1000	2015-06-25	2020-03-05	4.2	ETempForests
humnokericec	34.59	-91.75	AG	1000	2015-06-25	2020-03-05	4.5	ETempForests
ibp*	32.59	-106.85	GR	1000	2014-02-16	2020-03-05	6.0	NADeserts
ibp*	32.59	-106.85	SH	1001	2014-02-16	2020-03-02	6.0	NADeserts
jasperridge*	37.40	-122.22	GR	1000	2012-03-08	2017-03-09	5.0	MWCoastForests
jerbajada	32.58	-106.63	SH	1000	2014-04-20	2020-03-05	5.9	NADeserts
jernort	32.62	-106.79	SH	2000	2016-10-28	2020-03-05	3.3	NADeserts
jersand	32.52	-106.80	SH	1000	2014-02-28	2020-03-05	6.0	NADeserts
kansas*	39.06	-95.19	GR	1000	2012-12-03	2019-12-31	6.7	GrPlains
kawah	36.44	-118.91	SH	1000	2011-07-13	2019-09-20	8.2	MedCA
kelloggcorn	42.44	-85.32	AG	1000	2014-05-23	2019-10-05	4.9	ETempForests

Table S2. Sites used in analysis. A \* indicates the site was also used in Hufkins et al. 2016.

name	lat	lon	vegetation	roi id	first date	last date	site years	ecoregion
kelloggcorn2	42.40	-85.38	AG	1000	2015-07-16	2019-04-11	3.2	ETempForests
kelloggcorn3	42.40	-85.37	AG	1000	2015-07-16	2020-03-05	3.7	ETempForests
kelloggcornsoy2	42.40	-85.37	AG	1000	2015-07-16	2020-03-05	3.7	ETempForests
kelloggmiscanthus	42.40	-85.38	AG	1000	2015-07-16	2020-03-05	3.7	ETempForests
kellogggoldfield	42.40	-85.37	AG	1000	2015-07-16	2020-03-05	4.2	ETempForests
kendall*	31.74	-109.94	GR	1000	2012-07-06	2020-03-05	7.6	SouthAridHighlands
kendall*	31.74	-109.94	SH	1000	2012-08-08	2019-11-07	7.2	SouthAridHighlands
konza*	39.08	-96.56	GR	1000	2012-03-17	2019-12-19	6.2	GrPlains
lethbridge*	49.71	-112.94	GR	1000	2011-12-07	2020-03-05	8.3	GrPlains
luckyhills	31.74	-110.05	SH	2000	2015-01-26	2018-06-04	3.4	SouthAridHighlands
mandanh5	46.78	-100.95	AG	1000	2015-09-17	2020-03-05	4.5	GrPlains
mandani2	46.76	-100.93	AG	1000	2016-04-22	2020-03-05	3.7	GrPlains
manilacotton	35.89	-90.14	AG	1000	2016-06-21	2020-03-05	3.6	ETempForests
marena*	36.06	-97.21	GR	1000	2012-06-12	2018-06-19	5.8	GrPlains
mead1	41.17	-96.48	AG	1000	2016-07-12	2020-03-05	3.7	GrPlains
mead2	41.16	-96.47	AG	1000	2016-07-12	2020-03-05	3.6	GrPlains
mead3	41.18	-96.44	AG	1000	2016-07-12	2020-03-05	3.7	GrPlains
meadpasture	41.14	-96.46	AG	1000	2016-07-15	2020-03-05	3.7	GrPlains
monture*	47.02	-113.13	GR	2000	2010-11-04	2019-02-01	8.0	NWForests
mtrobson	53.03	-119.20	GR	1000	2015-02-16	2020-03-05	4.8	NWForests
nationalelkrefuge	43.49	-110.74	GR	1000	2015-08-12	2020-03-05	4.5	NWForests
NEON.D03.DSNY.	28.13	-81.44	GR	1000	2016-12-15	2020-03-05	3.2	ETempForests
NEON.D06.KONA.	39.11	-96.61	AG	1000	2016-05-07	2020-03-05	3.7	GrPlains
NEON.D06.KONZ.	39.10	-96.56	GR	1000	2017-02-25	2020-03-05	3.0	GrPlains
NEON.D09.WOOD.	47.13	-99.24	GR	1000	2016-12-18	2020-03-05	3.2	GrPlains
NEON.D10.ARIK.	39.76	-102.45	GR	1000	2016-12-18	2020-03-05	3.1	GrPlains
NEON.D10.CPER.	40.82	-104.75	GR	1000	2016-06-30	2020-03-05	3.7	GrPlains
NEON.D10.STER.	40.46	-103.03	AG	1000	2016-12-18	2020-03-05	3.2	GrPlains
NEON.D11.OAES.	35.41	-99.06	GR	1000	2017-02-28	2020-03-05	3.0	GrPlains
NEON.D13.MOAB.	38.25	-109.39	GR	1000	2017-02-25	2020-03-05	3.0	NADeserts
NEON.D14.JORN.	32.59	-106.84	GR	1000	2017-02-25	2020-03-05	3.0	NADeserts
NEON.D14.SRER.	31.91	-110.84	SH	1000	2017-02-25	2020-03-05	3.0	NADeserts
NEON.D15.ONAQ.	40.18	-112.45	GR	1000	2016-12-18	2020-03-05	3.2	NADeserts
NEON.D15.ONAQ.	40.18	-112.45	SH	1001	2016-12-18	2020-03-05	3.2	NADeserts
oakville	47.90	-97.32	GR	1000	2014-08-06	2020-03-05	4.6	GrPlains

name	lat	lon	vegetation	roi id	first date	last date	site years	ecoregion
rosemountnprs	44.68	-93.07	AG	1000	2015-10-29	2020-03-05	4.3	GrPlains
sevilletagrass	34.36	-106.70	GR	1000	2014-11-07	2020-03-05	5.1	NADeserts
sevilletashrub	34.33	-106.74	SH	1000	2014-10-29	2020-03-05	5.0	NADeserts
silverton	45.00	-122.69	AG	1000	2013-07-22	2020-02-10	5.9	NWForests
smokypurchase	35.59	-83.07	GR	2000	2016-01-02	2020-03-05	4.0	ETempForests
southerngreatplains	36.61	-97.49	AG	1000	2012-05-16	2020-03-05	7.5	GrPlains
spruceT6P16E	47.51	-93.45	SH	1000	2015-08-24	2020-03-05	4.6	NForest
stjones	39.09	-75.44	GR	1000	2015-09-20	2020-03-05	4.4	ETempForests
sweetbriargrass	37.56	-79.09	AG	1000	2016-03-23	2020-03-05	3.8	ETempForests
teddy	46.89	-103.38	GR	1000	2010-01-02	2019-03-27	8.5	GrPlains
teddy	46.89	-103.38	SH	1000	2003-05-11	2019-03-27	14.4	GrPlains
tonzi*	38.43	-120.97	GR	1000	2011-10-26	2020-02-13	7.3	MedCA
turkeypointenf02	42.66	-80.56	AG	1000	2012-05-01	2020-03-05	7.5	ETempForests
twitchell	38.11	-121.65	AG	1000	2011-11-16	2017-04-05	4.0	MedCA
uiefmaize	40.06	-88.20	AG	1000	2008-11-06	2020-03-02	11.3	ETempForests
uiefmiscanthus	40.06	-88.20	AG	1000	2008-11-12	2018-04-29	9.2	ETempForests
uiefprairie*	40.06	-88.20	GR	1000	2008-10-22	2020-03-02	11.3	ETempForests
uiefswitchgrass	40.06	-88.20	AG	1000	2008-10-22	2020-03-02	10.6	ETempForests
usgseros	43.73	-96.62	GR	1000	2014-09-11	2017-10-02	3.1	GrPlains
uwmfieldsta	43.39	-88.02	GR	1000	2013-03-15	2020-03-05	7.0	ETempForests
vaira*	38.41	-120.95	GR	1000	2011-10-17	2020-02-28	7.7	MedCA

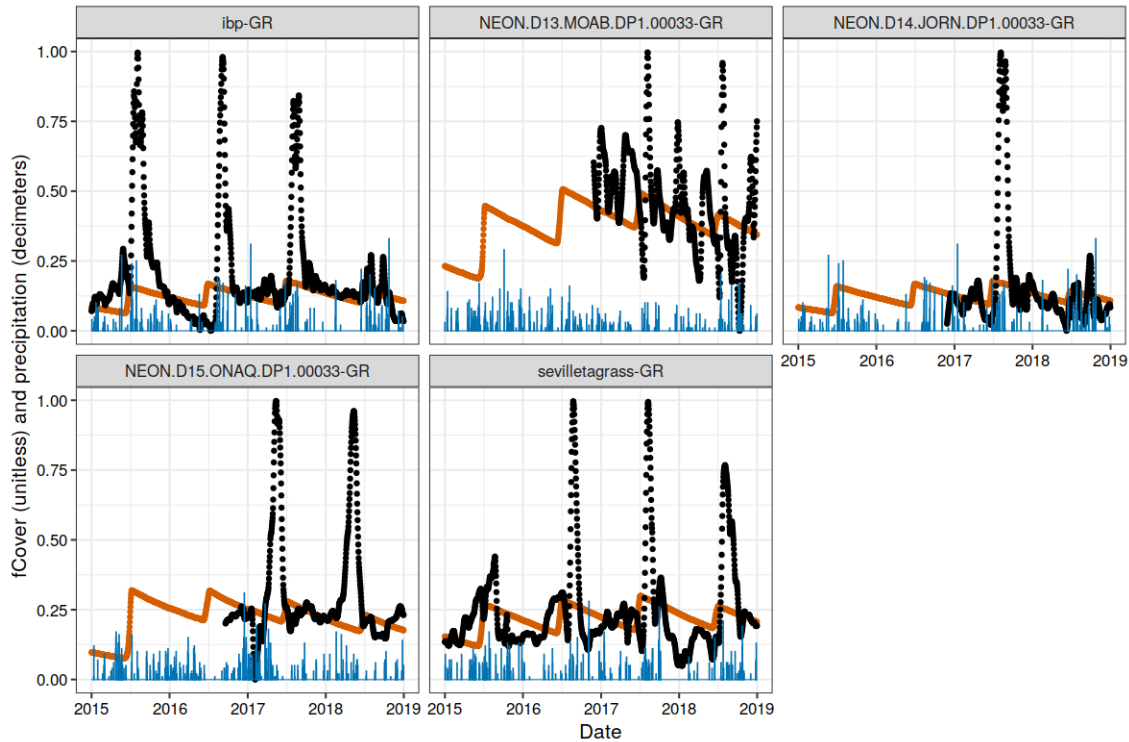


Figure S1. Predicted (red) and observed (black) fCover values at five grassland sites in the North American Deserts ecoregion for the years 2015-2018. Blue bars represent precipitation in decimeters.

## References

Richardson, Andrew D., Koen Hufkens, Tom Milliman, Donald M. Aubrecht, Min Chen, Josh M. Gray, Miriam R. Johnston, et al. 2018. “Tracking Vegetation Phenology across Diverse North American Biomes Using PhenoCam Imagery.” *Scientific Data* 5 (1): 180028. <https://doi.org/10.1038/sdata.2018.28>.

Donohue, Randall J., Michael L. Roderick, Tim R. McVicar, and Graham D. Farquhar. 2013. “Impact of CO<sub>2</sub> Fertilization on Maximum Foliage Cover across the Globe’s Warm, Arid Environments.” *Geophysical Research Letters* 40 (12): 3031–35. <https://doi.org/10.1002/grl.50563>.

Hufkens, Koen, Trevor F. Keenan, Lawrence B. Flanagan, Russell L. Scott, Carl J. Bernacchi, Eva Joo, Nathaniel A. Brunsell, Joseph Verfaillie, and Andrew D. Richardson. 2016. “Productivity of North American Grasslands Is Increased under Future Climate Scenarios despite Rising Aridity.” *Nature Climate Change* 6 (7): 710–14. <https://doi.org/10.1038/nclimate2942>.