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:

\[ W_{t+1} = W_t + P_t - (1 - V_t)(D_t/(W_{cap} - W_p))^2E_t - gb_3D_tV_t \]  
(1)

\[ V_{t+1} = V_t + gS_t b_t D_{t-L}(1 - V_t/V_{max}) - db_2(1 - V_t)V_t \]  
(2)

\[ D_t = max(0, W_t - W_p) \]  
(3)

\[ W_t = max(0, min(W_{cap}, W_t)) \]  
(4)

\[ V_t = max(0, min(V_{max}, V_t)) \]  
(5)

\[ \{ D_{t-L} > D_{t-L-1}; \quad d = 0 \} \]
\[ \{ D_{t-L} \leq D_{t-L-1}; \quad d = 1 \} \]  
(6)

\[ S_t = (TOA_t - Phmin)/(Phmax - Phmin) \]  
(7)

\[ \{ S_{t-1} > S_t; \quad d = 1 \} \]
\[ \{ S_{t-1} \leq S_t; \quad d = 0 \} \]  
(8)

\[ g = \left( \frac{T_{max} - T_m}{T_{max} - T_{opt}} \right) \left( \frac{T_m}{T_{opt}} \right) \left( \frac{x_{opt}}{x_{max} - x_{opt}} \right) \]  
(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):

\[ S_c = MAP/(MAP + h) \]  
(10)

where:

\[ fCover = G_{cc} \ast S_c \]  
(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:

\[ G_{cc} = \frac{G_{dn}}{G_{dn} + R_{dn} + B_{dn}} \]  
(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.
### State Variables

- **W**: Soil Water Content (mm)
- **V**: Fractional Cover (fCover)
- **D**: Plant available water (mm)
- **g**: Plant temperature response function

### Input Variables

- **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)
- **T_{min}**: Minimum temperature for growth (0 C)

### Estimated Parameters

- **b1**: Vegetation growth parameter
- **b2**: Senescence parameter
- **b3**: Soil water extraction rate
- **T_{opt}**: Optimal vegetation growth temperature
- **P_{h_{min}}**: Lower bound of optimal daily solar radiation
- **P_{h_{max}}**: 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                       |
| Ph_{max}  | 48.1106340              | 49.6940973                      |
| Ph_{min}  | 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     |
| archboldpuot          | 27.19   | -81.20  | AG         | 1000   | 2016-05-13       | 2020-03-05      | 3.6        | ETempForests     |
| archboldpuotx         | 27.18   | -81.20  | AG         | 1000   | 2016-05-16       | 2020-03-05      | 3.6        | ETempForests     |
| arsgacpl              | 31.51   | -83.62  | AG         | 1000   | 2016-05-10       | 2020-03-05      | 3.8        | ETempForests     |
| arsmonswanlake1       | 45.68   | -95.80  | AG         | 1000   | 2015-10-02       | 2020-03-05      | 4.4        | GrPlains         |
| bullshoals            | 36.36   | -93.07  | AG         | 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         |
| 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         |
| grandtetons           | 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          |
| hawbeckereddy         | 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         |
| kaweah                | 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       |
| kelloggoldfield    | 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      | 7.2        | 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           |
| mandanm2           | 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.CFER.     | 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      |
| sevilletaggrass       | 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 | AG         | 1000   | 2014-09-20   | 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   | 2014-01-02   | 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

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