Supporting Information for "Representing grasslands using dynamic prognostic phenology based on biological growth stages: Part 1. Implementation in the Simple Biosphere Model (SiB4)"

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S1. Running Mean Length Selection

To determine an appropriate running mean length for the environmental and weather potentials used in identifying the phenology stage, we performed sensitivity tests at two contrasting grassland sites in the United States. The first site is US-Seg (34.36° N, 106.70° W), a desert grassland with a mean annual temperature (MAT) of 13.7° C and a mean annual precipitation (MAP) of 275 mm. At this site, we show results for four years, from 2000 through 2003. The second site is US-Kon (39.08° N, 96.56° W), a tall grass prairie with an MAT of 12.8° C and an MAP of 870 mm. For this site, we show results for a drought year (2012) and a productive year (2013).

At both sites, we investigate the impact of three different running mean lengths on the phenology stage. In these experiments, we kept all model parameters the same except for changing the averaging length to 1 day, 10 days, and 21 days. The results are shown in Figure S3. Starting with the average environmental potential (Figures S3A and S3B), the daily mean values (orange) are quite noisy from day-to-day variability. With jumps > 0.5 between days, this does not seem ideal for phenology, since it is supposed to be representing seasonal variability, not daily changes. On the other extreme, 21 days (blue) shows smoothed out behavior highlighting seasonality; however, the timing is delayed and the potential value is considerably lower than the daily mean. Looking at the value we used in this study of 10 days (teal), this figure illustrates that it captures both the timing and the magnitude similar to the daily mean; however, the day-to-day variability is removed with daily changes now < 0.05. This illustrates our assertion that a 10-day mean captures the dominant temporal variability of synoptic and seasonal events without the disruption of day-to-day variability.

Following through the implications of this choice, we next investigate the resulting phenology index (Figures S3C and S3D). These figures show that changes in the index are driven by changes in the environmental potential. Again, using daily values is noisier, while both 10-day and 21-day means appear to have very similar values in most cases. At US-Kon, the index jumps up to unity show the growing season being reset to allow the phenology stage to return to leaf-out. Using daily averages prevents this from happening several times at both sites because the potentials are too noisy to coincide with the other circumstances required to start a growing season.

Finally, the resulting phenology stage is shown in Figures S3E and S3F. As expected, using daily potentials creates very disjointed phenology stages, jumping back and forth between stages rapidly. This is inconsistent with the method's goal of capturing seasonal behavior. Using 21-days shows a much clearer seasonal cycle at both sites, progressing from 1 (leaf-out) to 5 (dormant). Using 10-day means results in similar seasonal patterns as the 21-day means, but with the additional response to synoptic-scale events. For example, at US-Seg, we see leaf-out ending earlier in 2001 with what the daily mean suggests is a dry or cold event that causes higher stress to the vegetation. As another example, at US-Kon, the 10-day mean is able to capture the stress from the drought (mid-year 2012) earlier.

In this study, we selected a running mean length of 10 days, and this sequence of figures justifies this selection. At two very distinct grassland sites, 10-day running means represent phenology optimally by providing a reasonable compromise between over-reacting to daily conditions and responding timely to interannual events impacting seasonality (drought). Note that the user can adjust this parameter as they see fit.

S2. Grazing

SiB4 includes a simple grazing scheme that is described in this section, with the variables and constants listed in Tables S5 and S6, respectively. The methodology is based on a climatological daily loss of carbon from the canopy pools ($ClimGrz$) to represent the amount of grazing on appropriate days. All user-specified values related to grazing are constant across all PFTs rather than being PFT-specific parameters. If desired, rather than calculating daily grazing amounts, SiB4 has the capability to read in this information (i.e. user-specified $ClimGrz$).

To calculate $ClimGrz$, the daily loss of carbon for each canopy pool cp can be determined by:

$$ClimGrz_{cp} = \frac{E_{Grz} \cdot TNPP_{cp}}{TGrzD} \tag{1}$$

where E_{Grz} specifies the fraction of biomass that is removed by grazing, $TNPP_{cp}$ is a multi-year total of the daily net primary productivity (NPP) per canopy pool, and $TGrzD$ is the total number of days grazing occurred during the same time period. These are calculated as:

$$E_{Grz} = \begin{cases} E_{GrzP} & LAI_{Max} \geq LAI_{GrzE} \\ E_{GrzS} & LAI_{Max} < LAI_{GrzE} \end{cases} \tag{2}$$

$$TNPP_{cp} = \sum_{yr=1}^{nyr} \sum_{d=1}^{365} NPP_{d,yr,cp} \tag{3}$$

$$NPP_{cp} = Gain_{A,cp} - Loss_{AR,cp} \tag{4}$$

$$TGrzD = \sum_{yr=1}^{nyr} \sum_{d=1}^{365} F_{Grz,d,yr} \tag{5}$$

$$F_{Grz} = \begin{cases} 1 & \text{LAI} \geq LAI_{GrzM} \\ 0 & \text{LAI} < LAI_{GrzM} \end{cases} \tag{6}$$

where E_{Grz} incorporates two different grazing intensities based on ecosystem productivity, E_{GrzP} is a grazing intensity parameter for productive ecosystems, E_{GrzS} is a grazing intensity parameter for sparse ecosystems, and LAI_{GrzE} is a distinguishing threshold applied to the maximum LAI that occurs during the entire time period simulated (LAI_{Max}). For *TNPP* and *TGrzD*, *nyr* is the number of years, *d* is the number of days in a year, NPP is the daily increment in biomass, F_{Grz} is a daily grazing suitability factor, and the parameter LAI_{GrzM} is the minimum LAI required for grazing. During a SiB4 simulation that includes herbivory, grazing occurs on days when the LAI $\geq LAI_{GrzM}$, and the daily carbon loss in canopy pool *cp* due to grazing ($Loss_{Grz,cp}$) is simply equal to the grazed carbon amount ($ClimGrz_{cp}$).

Grazed carbon removed daily can either be respired (R_{Grz}) or transferred to the dead carbon pools ($Gain_{Grz,dp}$). For the portion of carbon that is respired, it is released at a constant rate the day the grazing occurs:

$$R_{Grz} = E_{GrzR}\left(\frac{\sum_{cp=1}^{ncpools} Loss_{Grz,cp}}{86400 \text{ s}}\right) \tag{7}$$

where E_{GrzR} is the fraction depicting the relative amount of carbon respired. For the portion of carbon transferred, a dead carbon pool *dp* receives the carbon:

$$Gain_{Grz,dp} = E_{GrzT,dp}\left(\sum_{cp=1}^{ncpools} Loss_{Grz,cp}\right) \tag{8}$$

where E_{GrzT} is the relative fraction of carbon transferred to dead pool *dp*. The sum of E_{GrzR} and E_{GrzT} is 1.

S3. SiB4 Calculation Sequence

The timing sequence for the SiB4 carbon cycle is illustrated in Figure S8, and here we provide a step-by-step outline of the calculation sequence.

Using LAI converted from the aboveground biomass, SiB4 simulates a day. At the beginning of the day, SiB4 calculates the solar declination and the day length. Every time-step throughout the day, SiB4 performs all of the steps required for predicting fluxes:

1. Update driver meteorology, including zenith angle.

2. Calculate heterotrophic respiration.

3. Update the land surface vegetation and snow cover and calculate albedo via a two-stream radiation approximation.

4. Calculate the radiation budget, including the absorption of radiation by the surface and the total net radiation.

5. Determine the resistances: aerodynamic, leaf-to-CAS, PFT-to-CAS, and ground-to-CAS.

6. Calculate canopy conductance, photosynthesis, autotrophic respiration, and live pool transfers.

7. Update daily holder variables for phenology.

8. Update the prognostic variables (CAS, ground, and soil temperatures, CAS water vapor mixing ratio and pressure, CAS turbulent kinetic energy, CAS CO_2 partial pressure, and CAS COS partial pressure).

9. Calculate the latent and sensible heat fluxes.

10. Update the model hydrology, including the prognostic canopy and ground surface water stores, the prognostic soil and snow column water and ice, and the snow layer thickness.

At the end of the modeled day, the SiB4 performs all of the steps required for updating the carbon pools:

1. Calculate daily totals of the carbon gains and losses.

2. Update running means of all the meteorological, hydrological, and stress variables.

3. Update the growing season flags. If the flag is switched to true, the appropriate seasonal variables are reset.

4. Calculate the phenological factors.

5. Determine the phenology stage.

6. Allocate the assimilated carbon to the live carbon pools, updating live pool gains.

7. Calculate pool losses and/or gains resulting from disturbance (grassland grazing).

8. Sum total gains and losses and update all carbon pools.

9. Update carbon pools, including the growth respiration from the change in live carbon pools.

10. Prepare for the next day by updating the vegetation state. For grasslands, the LAI uses the sum of all canopy carbon pools, such that

$$\mathrm{LAI} = (\mathrm{Leaf} + \mathrm{Stwd} + \mathrm{Prod}) \cdot SLA \tag{9}$$

where the parameter SLA is the specific leaf area set to global-mean values. From LAI, the fraction of photosynthetically active radiation (FPAR) is calculated as

$$FPAR = 1 - e^{\frac{ln(1-FPAR_{Sat})\mathrm{LAI}}{LAI_{Sat}}} \tag{10}$$

where the parameter LAI_{Sat} indicates the saturation LAI and $FPAR_{Sat}$ is the saturation value of FPAR.

Table S1: Dynamic Phenology Variables.

Name	**Diagnostic Variables**	**Units**	**Min**	**Max**
$AssimD$	Daily Mean Carbon Assimilation Rate	$mol\ C/m^2/s$	0	
$AssimD_{RM}$	10-Day Running-Mean of $AssimD$	$mol\ C/m^2/s$	0	
$AssimD_{SM}$	Seasonal Max of $AssimD_{RM}$	$mol\ C/m^2/s$	0	
$ClimLAI_{Min}$	Minimum Climatological LAI	m^2/m^2	0	
$ClimLAI_{Max}$	Maximum Climatological LAI	m^2/m^2	0	
$ClimP$	Climatological Suitability	-	CP_{Min}	CP_{Max}
$ClimW$	Climtological Water Availability	-	0	1
$FlagA$	Assimilation Flag	T or F		
$FlagG$	Growing Season Flag	T or F		
F_A	Assimilation Potential	-	0	1
F_E	Environmental Potential	-	0	1
$F_{E,RM}$	Running-Mean of F_E	-	0	1
F_{LH}	Leaf Humidity Potential	-	0	1
F_{RZ}	Root-Zone Soil Moisture Potential	-	0	1
F_T	Temperature Potential	-	0	1
$F_{WA,RM}$	Running-Mean Water Availability Potential	-	0	1
$F_{Wx,RM}$	Running-Mean Combined Weather Potential	-	0	1
$F_{Wx,SM}$	Seasonal Maximum of $F_{Wx,RM}$	-	0	1
PI	Phenology Index	-	0	PSG_{Max}
PS_{DayL}	Phenology Stage Day Length Potential	-	0	1
PS_{GI}	Phenology Stage Growth Index	-	PSG_{Min}	PSG_{Max}
PS_{Wx}	Phenology Stage Weather Potential	-	0	1
Name	**Environmental Variables**	**Units**	**Min**	**Max**
$DayL$	Daylength	hr	0	24
$DayL_{dt}$	Change in Daylength	hr	0	0.1
$DayL_{Max}$	Maximum Daylength	hr	0	24
$DayL_O$	Daylength Offset	hr		
TM_D	Daily Mean Temperature	K		
Name	**Soil Variables**	**Units**	**Min**	**Max**
FC	Field Capacity	m^{-3}	0	1
PAW	Root-Weighted Plant Available Water	-	0	1
PAW_{Top}	Root-Weighted PAW in Top Three Layers	-	0	1
$RootF$ $(nsoil)$	Root Vertical Distribution (Fractional) (nsoil = 10)	-	0	1
$RootF_3$	Root Fraction in Top Three Layers	-	0	1
TAW_{Top}	Root-Weighted Total Available Water in Top Three Layers	-	0	1
VI $(nsoil)$	Soil Ice Water Volume (nsoil = 10)	kg/m^3	0	
VL $(nsoil)$	Soil Liquid Water Volume (nsoil = 10)	kg/m^3	0	
WP	Wilting Point	m^{-3}	0	1

Table S2: Dynamic Phenology Parameters.

Name	**PFT-Specific Parameters**	**C3A**	**C3G**	**C4G**
$AllocP$ $(nlpool, nstage)$	Phenology-specific allocation fractions (nlpool=5, nstage=5)			
CL_C	$ClimP$ coefficient to calculate $ClimLAI$	1.6	1.0	1.2
CL_L	$ClimLAI_{Min}$ offset	0	0	0
CL_G	$ClimLAI_{Max}$ offset	0.7	1.2	1.0
CP_A	$ClimP$ exponential adjustment coefficient	0	0	0.15
CP_B	$ClimP$ exponential adjustment base	0	0	130
CP_C	$ClimP$ linear adjustment coefficient	4.4	2	0
CP_D	$ClimP$ linear adjustment offset	0.1 0	0	0
CP_{Min}	$ClimP$ minimum value	0.4	0.2	0.2
CP_{Max}	$ClimP$ maximum value	1	2	2
$FlagA_{Thresh}$	Threshold value for assimilation factor	0.1	0.2	0.3
FGD_{MinD}	Daylength (decreasing) requirement for $FlagG$	14	14	12
FGD_{MinI}	Daylength (increasing) requirement for $FlagG$	8.4	8.4	8.6
FGT_{Len}	Temperature length requirement for $FlagG$	4	5	5
FGT_{Min}	Temperature minimum requirement for $FlagG$	270	280	286
FGW_{Len}	Soil moisture length requirement for $FlagG$	4	4	4
FGW_{Min}	Soil moisture minimum requirement for $FlagG$	0.12	0.12	0.12
PI_{Thresh} $(nstage - 1)$	Phenology Stage Thresholds (nstage−1 = 4)			
PSD_{Min}	Photoperiod potential minimum	0.6	0.6	0.4
PSD_{Mul}	Photoperiod potential daily change	0.06	0.08	0.14
PSD_{Ref}	Photoperiod reference	24	20	20
PSG_{Min}	Growth potential minimum	0.6	0.2	0.5
PSG_{Max}	Growth potential maximum	1.5	1.5	1.5
V_{Max} $(nstage)$	Rubisco velocity (nstage=5 , $mol\ C\ m^{-2}\ s^{-1}$)			

Table S3: Senescence Variables

Name	**Pool Variables**	**Units**	—
C *(nlpool)*	Pool Carbon (nlpool=5)	$mol\ C\ m^{-2}$	
$Loss_L$ *(ncpool)*	Carbon Pool Loss from Litterfall (ncpool = 3)	$mol\ C/m^2$	
$Loss_T$ *(nlpool)*	Carbon Pool Loss from Turnover (nlpool = 5)	$mol\ C/m^2$	
Name	**Scaling Coefficients**	**Min**	**Max**
$M_{A,cp}$	Canopy Pool Assimilation Scalar	CA_{Min}	CA_{Max}
$M_{A,rp}$	Root Pool Assimilation Scalar	RA_{Min}	RA_{Max}
$M_{F,cp}$	Canopy Pool Frost Inhibition Scalar	CF_{Min}	1
$M_{F,rp}$	Root Pool Frost Inhibition Scalar	RF_{Min}	1
$M_{H,cp}$	Canopy Pool High Temperature Scalar	1	CT_{Max}
$M_{H,rp}$	Root Pool High Temperature Scalar	1	RT_{Max}
T_{DL}	Canopy Pool Day Length Transfer Fraction	0	LTD_{Max}
T_F	Canopy Pool Freezing Temperature Transfer Fraction	0	LTF_{Max}
T_W	Canopy Pool Water Deprivation Transfer Fraction	0	LTW_{Max}

Table S4: Senescence Parameters

Name	**Description**	**C3A**	**C3G**	**C4G**
E_{cp}	Canopy Pool Respiration Efficiency	0.95	0.95	0.95
E_{rp}	Root Pool Respiration Efficiency	0.6	0.65	0.45
CA_H	Canopy Pool Assim Scalar High Multiplier	1	2.5	1
CA_L	Canopy Pool Assim Scalar Low Multiplier	1	0.5	1
CA_{Max}	Canopy Pool Assim Scalar Maximum	1	2	1
CA_{Min}	Canopy Pool Assim Scalar Minimum	1	1	1
CF_{Min}	Canopy Freeze Scalar Minimum	0.1	0.1	0.1
CF_{Mul}	Canopy Freeze Scalar Multiplier	0.1	0.1	0.1
CF_{Ref}	Canopy Freeze Scalar Ref Temperature (K)	274	274	274
CT_{Max}	Canopy High Temperature Maximum	1.4	3	3
CT_{Q10}	Canopy High Temperature Q10	2	2	2
CT_{Ref}	Canopy High Temperature Ref Temperature (K)	306	306	311
LTD_C	Canopy Day Length Transfer Coefficient	0.003	0.005	0.008
LTD_R	Canopy Day Length Transfer Reference	-3	-6	-0.4
LTD_{Max}	Canopy Day Length Transfer Maximum	0.02	0.08	0.08
LTF_{Max}	Canopy Freeze Transfer Maximum	0.08	0.08	0.08
LTF_{Q10}	Canopy Freeze Transfer Q10	2.2	2.2	2.2
LTF_{Ref}	Canopy Freeze Transfer Reference Temperature (K)	274	274	274
LTW_B	Canopy Water Deficit Base	0.07	0.07	0.07
LTW_C	Canopy Water Deficit Coefficient	0.005	0.005	0.005
LTW_{Max}	Canopy Water Deficit Maximum	0.1	0.1	0.1
LTW_R	Canopy Water Deficit Transfer Reference	0.12	0.12	0.12
RA_H	Root Pool Assim Scalar High Multiplier	2	2	1
RA_L	Root Pool Assim Scalar Low Multiplier	0.6	0.6	1
RA_{Max}	Root Pool Assim Scalar Maximum	1.2	1.2	1
RA_{Min}	Root Pool Assim Scalar Minimum	0.6	0.6	1
RF_{Min}	Root Freeze Scalar Minimum	0.1	0.1	0.4
RF_{Mul}	Root Freeze Scalar Multiplier	0.1	0.1	0.1
RF_{Ref} hline RT_{Max}	Root Freeze Scalar Ref Temperature (K) Root High Temperature Maximum	272 3	274 3	274 3
RT_{Q10}	Root High Temperature Q10	1.8	1.8	1.8
RT_{Ref}	Root High Temperature Ref Temperature (K)	300	311	311
τ *(nlpool)*	Pool Turnover Time (yr) (nlpool = 5)			

Table S5: Grazing Variables.

Name	**Diagnostic Variables**	**Units**
ClimGrz (ncpool)	Climatological Daily Grazing Carbon Loss (ncpool = 3)	$mol\ C/m^2$
E_{Grz}	Biomass Fraction Removed via Grazing	-
F_{Grz}	Grazing Suitability Factor	0 or 1
$TGrzD$	Total Number of Grazed Days	*days*
TNPP (ncpool)	Total Daily Net Primary Productivity (ncpool = 3)	$mol\ C/m^2$
Name	**Pool Variables**	**Units**
$Gain_A$ *(nlpool)*	Daily Carbon Pool Gain from Assimilation (nlpool = 5)	$mol\ C/m^2/day$
$Gain_{Grz}$ *(ndpool)*	Daily Carbon Pool Gain from Grazing (ndpool = 6)	$mol\ C/m^2/day$
$Loss_{AR}$ *(nlpool)*	Daily Carbon Pool Loss from Autototrophic Respiration (nlpool = 5)	$mol\ C/m^2/day$
$Loss_{Grz}$ *(ncpool)*	Daily Carbon Pool Loss from Grazing (ncpool = 3)	$mol\ C/m^2/day$

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Table S6: Grazing Constants.

Name	**Constant**	**Value**
E_{GrzP}	Fraction of Canopy Grazed (productive)	0.4
E_{GrzS}	Fraction of Canopy Grazed (sparse)	0.1
E_{GrzR}	Fraction of Grazed Carbon Respired	0.3
E_{GrzT} *(ndpool)*	Fraction of Grazed Carbon Transferred (ndpool = 6)	0 to 0.3
LAI_{GrzE}	Sparse/Productive $ClimLAI_{Max}$ Threshold	1.0
LAI_{GrzM}	Minimum LAI for Grazing	0.7

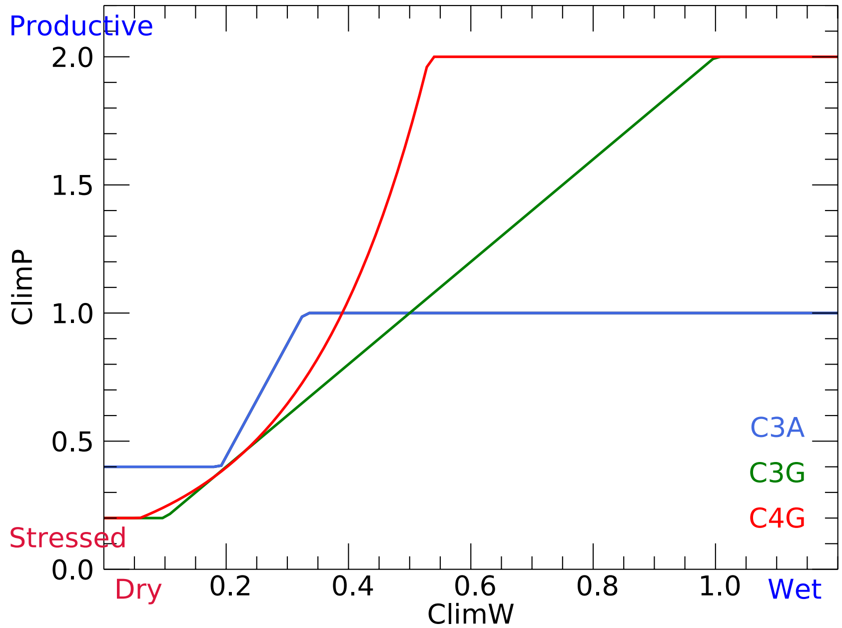

Figure S1. Relationships between *ClimP* and *ClimW* for C3 artic (blue), C3 non-arctic (green), and C4 (red) grasslands.

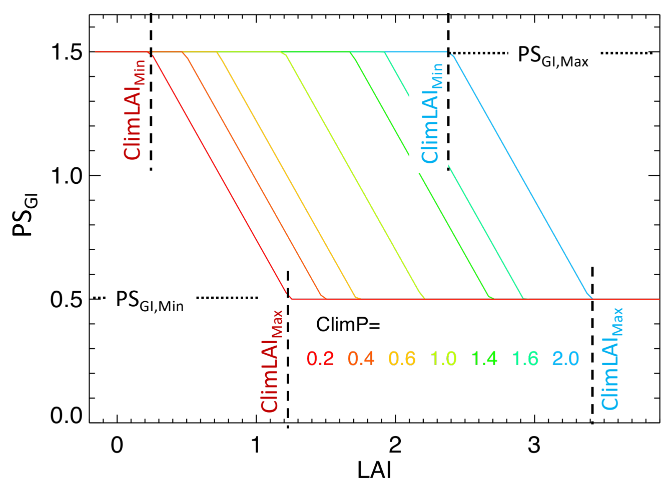

Figure S2. Sample phenology growth index (PS_{GI}) and LAI relationships. The colors show different climates as indicated by *ClimP* and the corresponding *ClimLAI* values. This example uses the parameters for C4G, which are $PS_{GI,Min}$=0.5, $PS_{GI,Max}$=1.5, $CLAI_C$=1.2, $CLAI_{OL}$=0.0, and $CLAI_{OG}$=1.

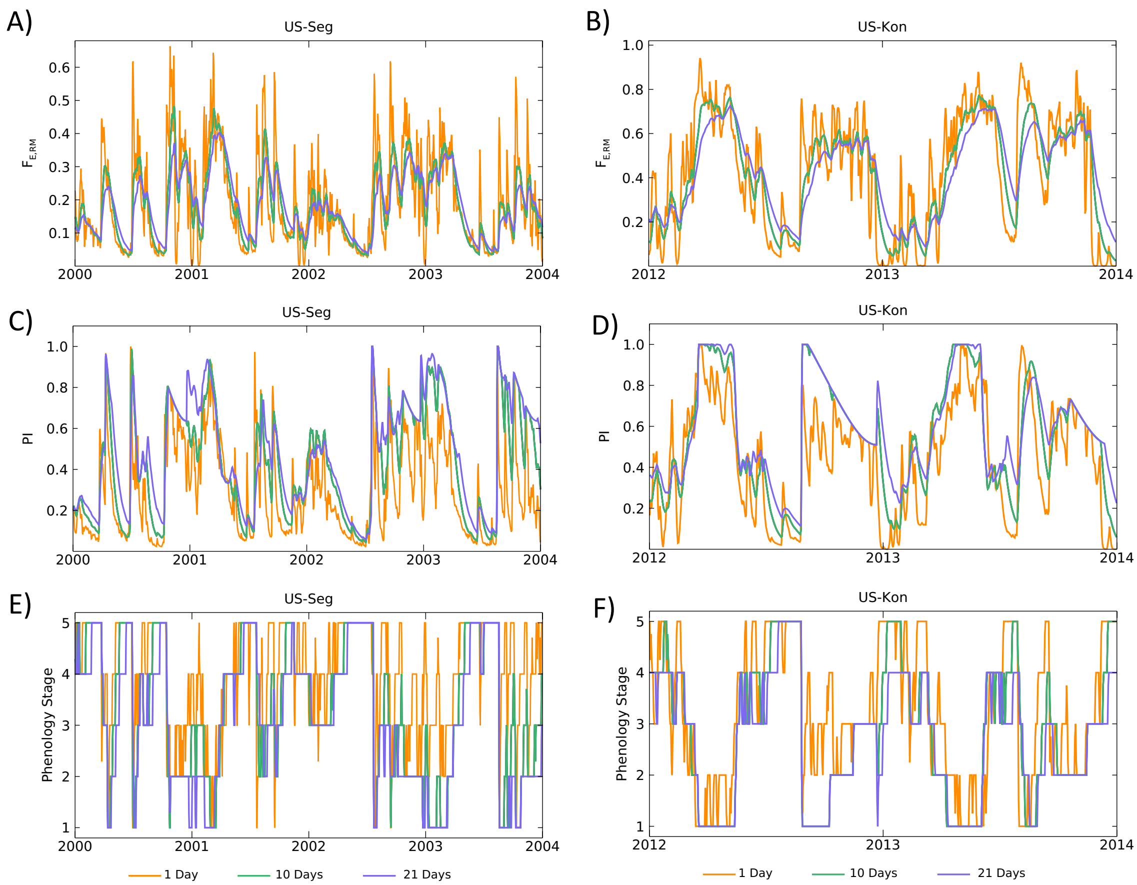

Figure S3. Phenology stage sensitivity to three different running mean lengths: 1 day (orange), 10 days (teal) and 21 days (blue). The left column shows results at US-Seg and the right column shows results at US-Kon. The top row shows the running mean environmental potential ($F_{E,RM}$), the middle row shows the phenology index (PI), and the bottom row shows the phenology stage.

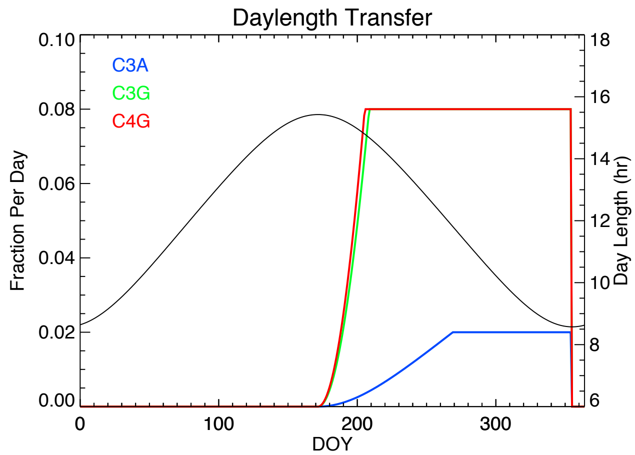

Figure S4. Sample phenology day length potential (PS_{DayL}) and day length relationships. The black line shows the day length throughout the year at 45^{o}N. The colors show the parameter values for C3A (blue), C3G (green), and C4G (red).

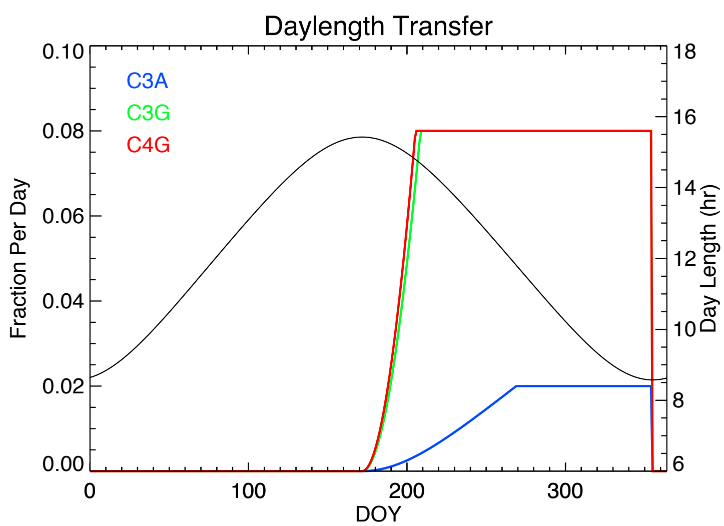

Figure S5. Litterfall day length transfer fractions at 45^{o}N. The black line shows the day length throughout the year, and the colors show the T_{DayL} values for C3A (blue), C3G (green), and C4G (red) grasslands.

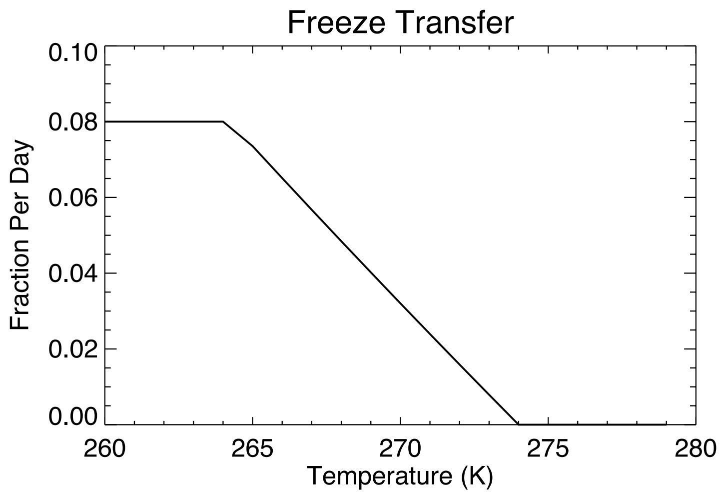

Figure S6. Freezing temperature litterfall transfer fractions for all grasslands ($LT_{Fmax} = 0.08$, $LT_{Fq10} = 2.2$, $LT_{Fref} = 274$, .

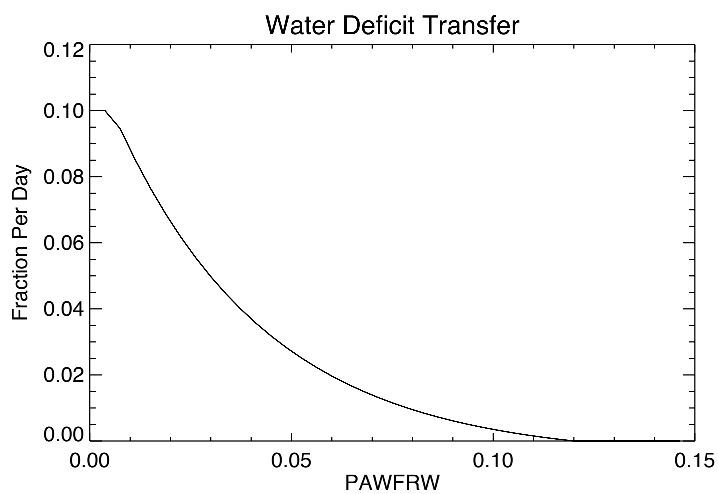

Figure S7. Water deficit litterfall transfer fractions for all grasslands (LT_{Wbase}=0.007, LT_{Wcoef}=0.005, LT_{Wmax}=0.1, LT_{Wref}=0.12

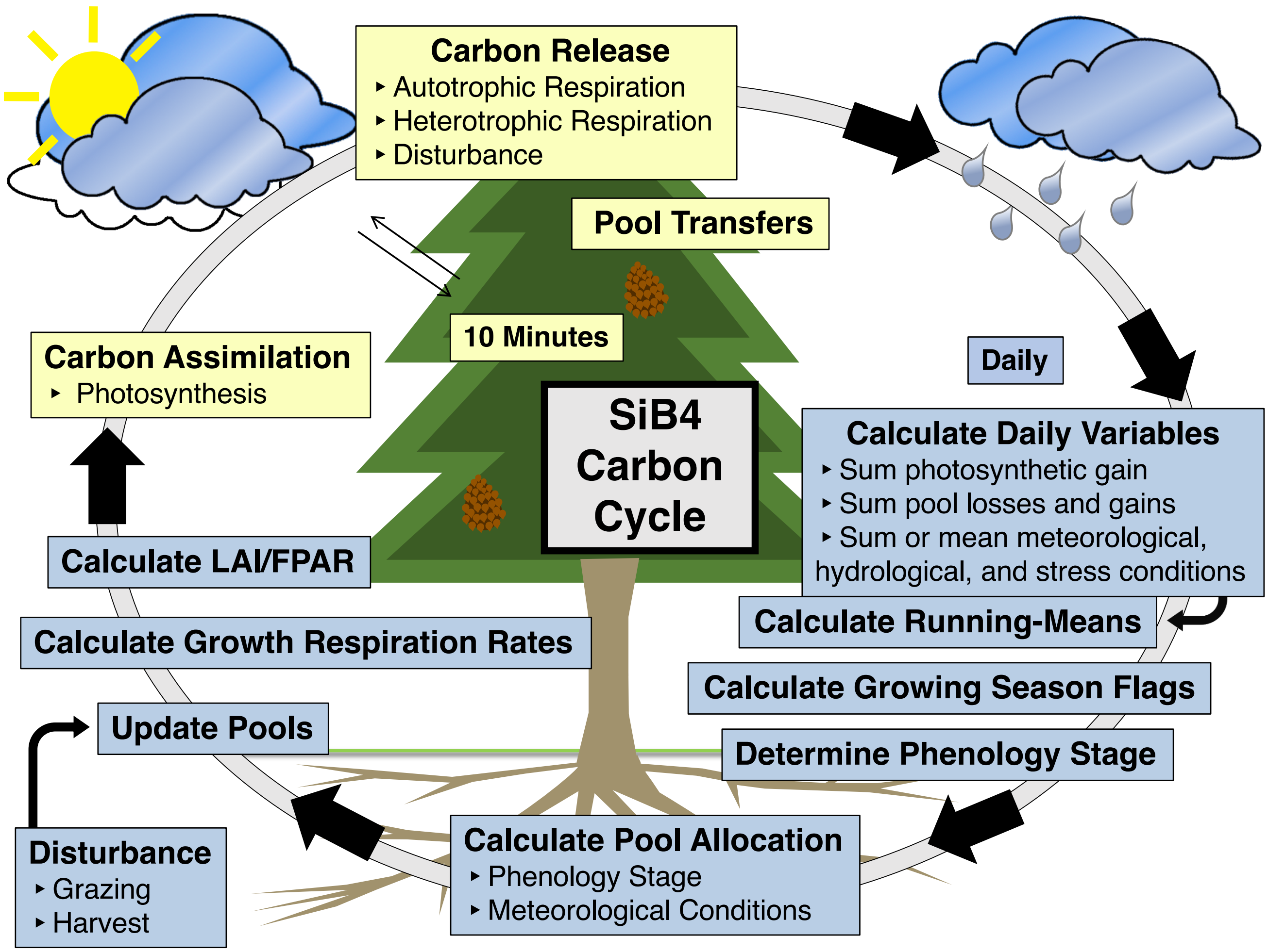

Figure S8. SiB4 Carbon Cycle Progression. Carbon fluxes calculated every model time-step are shown in the yellow boxes. Phenology and carbon pool updates calculated daily are shown in the blue boxes.