Appendix A. Multiple Element Limitation (MEL) model as applied to arctic tundra.

The full Multiple Element Limitation (MEL) model used in the paper is described in the electronic appendix to Rastetter et al. (2013). Here we describe only the modifications we made to the model for application to arctic tundra (MELIVarc). Parameters and variables and their values are defined in Table A1. All citations to equations in the text are equations in the electronic appendix to Rastetter et al. (2013).

Allometry (replaces Eq. A35)
To calculate the allometry of active biomass as a function of total biomass, we now use a simple linear relation with a correction to insure that active biomass never exceeds total biomass (Fig. A1):

$$B_A = \min\left(B_{T*},\ \alpha_B + \gamma_B\, B_{T*}\right)$$

Organic soil depth index
We calculate an organic soil depth index that is proportion to the amount of phase I plus phase II soil organic carbon. This index is used in the soil water and soil temperature models:

$$z_p = a_p\left(D_{C1} + D_{C2}\right)$$

Soil heat budget and soil temperature
We calculate the soil heat budget based on heat exchange with the underlying permafrost and the overlying air, and on the radiative heating. The soil heat budget is calculated on discrete daily time steps:

$$\begin{aligned} S_Q(t) &= S_Q(t-1) + k_{pf}\,\frac{T_{pf} - T_{so}}{z\left(z_{pf} + z_T\right)} + \frac{T_a - T_{so}}{z\, z_s\left(1/k_s + 0.01\, W_{snow}/k_{snow}\right)} + \frac{b_I(1-\alpha)I}{z}; \text{if } W_{snow} > 0 \\ &= S_Q(t-1) + k_{pf}\,\frac{T_{pf} - T_{so}}{z\left(z_{pf} + z_T\right)} + k_s\,\frac{T_a - T_{so}}{z\, z_s} + \frac{b_I\, I\, e^{-k_I L}}{z} \qquad ; \text{if } W_{snow} = 0 \end{aligned}$$

$$k_{sT} = \frac{W}{1000\, z}k_w + (1-\rho_s)\min\left(\frac{z_p}{z}, 1\right)k_{so} + (1-\rho_s)\max\left(1 - \frac{z_p}{z}, 0\right)k_{sm}$$

$$k_{sF} = 1.06\, k_{sT} + 0.0121$$

$$\begin{aligned} k_s &= k_{sT}\ ; \text{if } T_{so} > 0 \\ &= k_{sF}\ ; \text{otherwise} \end{aligned}$$

where k_{sT}, k_{sF}, and k_s are the thawed, frozen and actual soil thermal conductivity. We now use soil temperature for all temperature-sensitive processes below ground. We calculate soil temperature based on the soil heat content and the heat capacity of thawed and frozen soil:

$$T_{so} = \frac{S_Q - S_{QT}}{c_{sT}}; \text{if } S_Q > S_{QT}$$
$$= \frac{S_Q - S_{QF}}{c_{sF}}; \text{if } S_Q < S_{QF}$$
$$= 0 \quad ; \text{otherwise}$$

$$c_{sT} = \frac{W}{1000\,z} c_w + (1-\rho_s)\min\left(\frac{z_p}{z}, 1\right) c_{so} + (1-\rho_s)\max\left(1 - \frac{z_p}{z}, 0\right) c_{sm}$$

$$c_{sF} = 0.88\,c_{sT} - 0.139$$

where c_{sT} and c_{sF} are the thawed and frozen soil heat capacities. Soil temperature (T_{so}) replaces air temperature (T_a) in all the following processes and equations in Rastetter et al. (2013): (1) root portion of plant respiration in Eq. A61, (2) uptake for NH_4^+, NO_3^-, and PO_4^{3-} in Eqs. A66-A68, (3) the temperature/moisture response of general microbial metabolism in Eq. A96, and (4) denitrification in Eq. A124. T_{so} is also used to calculate non-symbiotic N fixation, which is described below.

Recalcitrant dissolved organic matter
We now simulate both labile and recalcitrant forms of dissolved organic matter and associated N (DOM and DON). The equations for recalcitrant DOM and DON production and for recalcitrant DOM leaching are identical to those for labile DOM in Rastetter et al. (2013; respectively, Eqs. A115, A116, and A132), but with different parameters. The differential equation for recalcitrant DOM is the same as that for labile DOM (Eq. A5), but without uptake by either plants or microbes.

Hydrologically active soil fraction
We restrict hydrologic runoff and plant water uptake to the fraction of the active soil layer that was thawed. In addition, because the hydraulic conductivity of the underlying silt mineral soil is low, we scale runoff and water uptake to the organic soil depth index (z_p). The scaling factor is calculated as the minimum of the thawed or organic depth fractions or one:

$$f_A = \min\left(1, \frac{z_T}{z}, \frac{z_p}{z}\right)$$

Hydrologic runoff (modified from Eq. A128)
We scale the runoff equation by the f_A to limit runoff to only that volume of the soil that is thawed:

$$R_O = D_W\, f_A\left(W - 1000\,z\,\theta_f\right) + \max\left(0, I_{rain} - f_A\left(1000\rho_s z - W\right)\right) + \max\left(0, T_{SM} - f_A\left(1000\rho_s z - W\right)\right)$$

In addition, we limited infiltration from rainfall (A134) and snow melt (A137) to the pore volume within the thawed soil; we add any excess to the runoff.

Snowmelt critical temperature (modification of Eq. A137)
We now use separate critical temperatures for determining when precipitation is as snow (T_{crt}) and the critical temperature of melting the snow pack (T_{crts}).

Water uptake by plants (modified from Eq. A52)
We scale water uptake by the f_A to limit water extraction by roots to the thawed soil:

$$U_{Ws} = g_W \, f_A U_{Wp} \left(1 - e^{-k_E R_L \frac{(V_W - V_{min})}{V_R}} \right) (\psi_s - \psi_w)$$

Canopy light photosynthesis (modified from Eq. A48)
We modified the photosynthesis-light equation to be more responsive to changes in allocated effort at low light levels:

$$U_{CI} = 1.6 \, D_L \, f_{PT} \left(\frac{C_a - 60}{C_a + 120} \right) \frac{P_{Imax}}{k_I} \ln \left(\frac{k_{PI} + I / D_L}{k_{PI} + I \, e^{-k_I L} / D_L} \right)$$

Water uptake and transpiration (modified from Eqs. A51 and A58)
To facilitate automated calibration, we added a constant (S_{cET}) to scale from hourly to daily water uptake and transpiration:

$$U_{Wp} = 7.775 \, S_{cET} \, D_L \, c_{cmax} \, \Delta_e \quad \text{and} \quad U_W = 7.775 \, S_{cET} \, D_L \, c_c \, \Delta_e$$

Note: the 7.775 is a combination of the air density, air specific heat, latent heat of vaporization for water, and psychrometer constant.

Carboxylation-diffusion (modified from Eqs. A54 and A57)
To facilitate automated calibration, we added a constant (S_{Ucc}) to scale from hourly to daily carboxylation and diffusion:

$$P_{sC} = D_L \frac{P_{Cmax} \, C_{i*}}{k_C + C_{i*}} = 0.000335 \; S_{Ucc} \; D_L \, c_{cs} \left(C_a - C_{i*} \right) \text{ and } c_c = \frac{U_C}{0.000335 \, S_{Ucc} \; D_L \left(C_a - C_i \right)}$$

Note: the 0.000335 is a combination of the ratio of diffusivity of water to CO_2, the molar weight of C, and the moles m^{-3} for an ideal gas.

CO_2- and H_2O-limited photosynthesis (modified from Eqs. A59 and A60)
To facilitate calibration, we changed the weighting on the differential term in the CO_2-limited and H_2O-limited photosynthesis to a parameter (β):

$$U_{CC} = P_{sC} + \beta\left(\frac{dP_{sC}}{dV_W} - \frac{dP_{sC}}{dV_C}\right) \text{ and } U_{CW} = P_{sC} - \beta\left(\frac{dP_{sC}}{dV_W} - \frac{dP_{sC}}{dV_C}\right)$$

Plant uptake of dissolved organic N
We allow plants to take up labile DON. The uptake equation is analogous to the other nutrient uptake equations in the model (Eqs. A66-A68). The two uptake equations for labile DOM uptake have to be solved simultaneously to calculate uptake and the concentration of DOM at the root surface (C_{aqDOMs}) and the DON uptake is then calculated based on the C:N ratio of labile DOM:

$$U_{DOM} = g_{DOM}\left(\frac{V_{DON} - V_{min}}{V_R}\right) R_L\, Q_{10v}^{T_{SO}/10}\left(\frac{C_{aqDOMs}}{k_{DOM} + C_{aqDOMs}}\right)$$
$$= \frac{D_{DOM} R_L 12 \times 10^{-3}}{\beta_{NRD}}\left(C_{aqDOMs} - C_{aqDOM}\right)$$

$$U_{DON} = U_{DOM} / q_{DOM}$$

The uptake rates of DOM and DON are added to differential equations for biomass C and N (Eqs. A1 and A6) and the uptake of DOM is subtracted from the differential equation for labile DOM (Eq. A5).

Symbiotic N fixation
We calculate symbiotic N fixation as proportional to the effort allocated to support N fixation and the root length available to host the symbionts, and modified by a Q10 function of soil temperature:

$$U_{Nfix} = g_{Nfix}\left(\frac{V_{Nfix} - V_{min}}{V_R}\right) R_L\, Q_{10v}^{T_{SO}/10}$$

The associated N gain is added to the plant biomass N in the differential equation for B_N (Eq. A6).

Allocation of uptake effort among substitutable sources of N (modified from Eqs. A82 and A83 plus adds equations for DON and symbiotic N fixation)
For the Arctic we allow plant N requirements to be filled by four substitutable sources of N, NH_4^+, NO_3^-, dissolved organic N (DON), and symbiotic N fixation. Incremental allocation of uptake effort is to the N source with the highest marginal yield. We calculate the marginal yield as the incremental increase in uptake per incremental increase in allocated effort, including the effort needed to supply the C cost of assimilating each of the N sources:

for k = NH4, NO3, DON, or Nfix

$$y_k = \frac{\frac{dU_k}{dV_k}}{1 + \frac{dU_k}{dV_k}\frac{\phi_k}{\Theta_C}}$$

We extended Eqs. A84 - A86, A94 and A95 to include all four N sources and added equations analogous to A91 and A92 for DON and symbiotic N fixation.

Temperature responses of plant metabolic respiration (replaces Eq. 61)
We implemented three changes to the equation for metabolic respiration. First we calculated root metabolic respiration based on soil temperature. Second, we modified the Q_{10} formulation so that respiration increases more linearly for air temperatures between 15 and 20 ºC (in our simulations, air temperatures rarely exceed 15 ºC and never above 20 ºC). Third, we modified the wood respiration term to account for difference between wood and rhizome respiration.

$$R_a = r_m \left(q_{LN} B_L + q_{WN} B_W e^{-k_{rmW} B_W} \right) \left(m_{Q10V} + b_{Q10V} T_a \right)^{T_a/10} + r_m q_{RN} B_R \left(m_{Q10V} + b_{Q10V} T_a \right)^{T_{SO}/10}$$

Plant respiration associated with N uptake and assimilation (modified from Eq. A62)
We now assess a respiration cost to the uptake and assimilation of all four forms of N acquisition:

$$R_u = \phi_{NH4} U_{NH4} + \phi_{NO3} U_{NO3} + \phi_{DON} U_{DON} + \phi_{Nfix} U_{Nfix}$$

Non-symbiotic N fixation
The rate of non-symbiotic N fixation in the model is proportional to the deviation of the phase I soil C:N ratio above the specified critical C:N ratio and is modified by the same temperature/moisture function as all microbial processes (R_m, Eq. A96):

$$\begin{aligned} U_{NNSfix} &= R_m \gamma_{Sfix} \left(\frac{D_{C1}}{D_{N1}} - q_{Sfix} \right) D_{C1} ; \text{ if } \frac{D_{C1}}{D_{N1}} > q_{Sfix} \\ &= 0 \qquad ; \text{otherwise} \end{aligned}$$

The fixed N is added to the differential equation for phase I soil organic matter (Eq. A8) and to the total microbial N acquisition (Eq. A106).

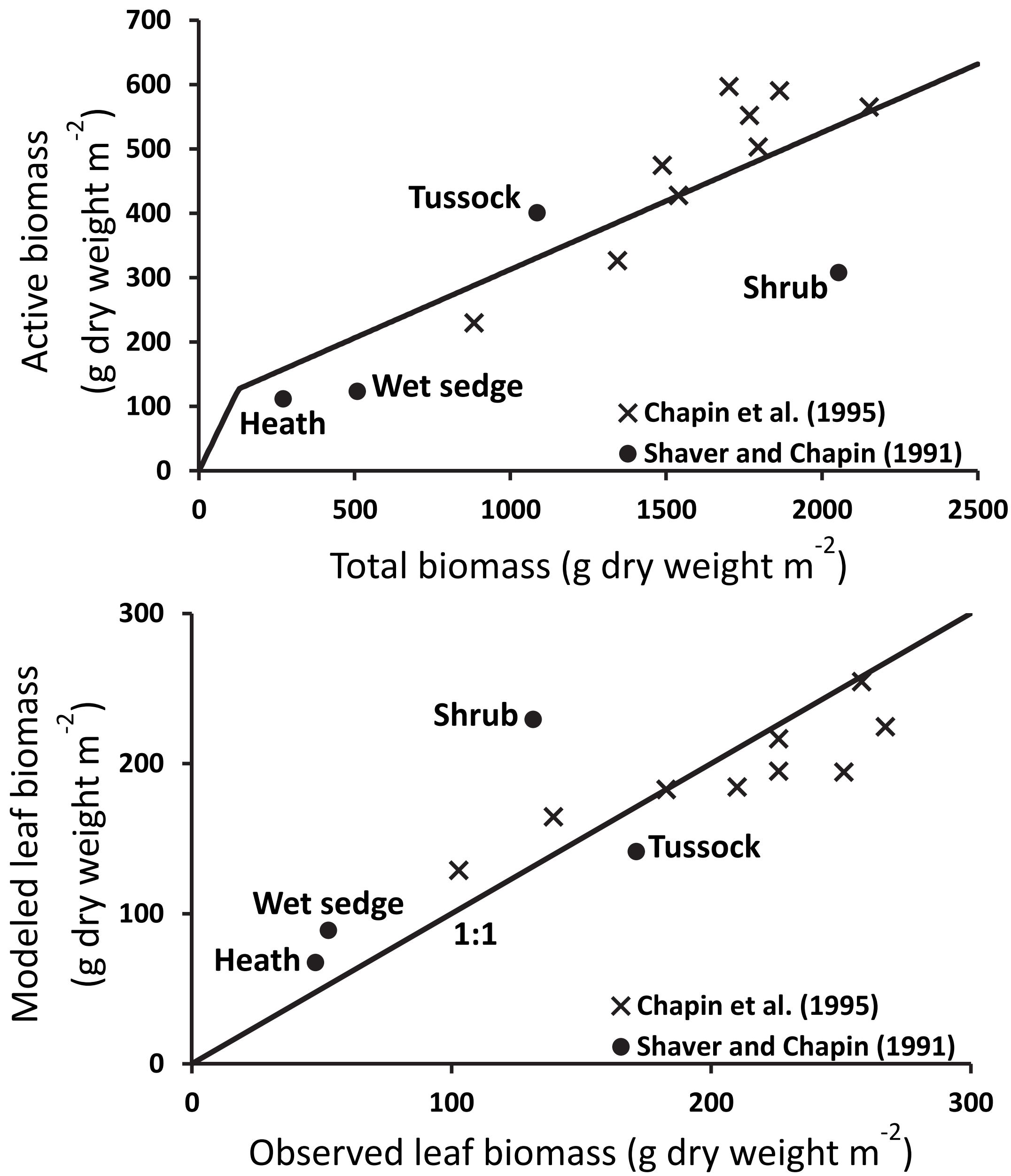

Figure A1: Allometric equation used to calculate active biomass (leaf + fine roots) from total biomass. Solid black line in the upper panel is the relationship used in the MEL model. x's are for tussock tundra after undergoing 3 and 9 years of experimental manipulations of nitrogen and phosphorus fertilization, enclosures in green houses, or enclosure in shade houses (see Fig. 3 in main text). Because only leaf and woody data were available, root mass was estimated based on the root:active ratio predicted by the MEL model. Dots are for the four major vegetation types on the North Slope of Alaska. Because the root biomass reported by Shaver and Chapin (1991) were thought to be over estimates (Shaver pers. Com.) we estimated root biomass assuming that the roots: active ratio of 0.57 used in the tussock-tundra calibration applied to all four vegetation types. Lower panel shows the modeled versus observed leaf biomass for the same data.

Table A1: State variables, drivers, processes and parameters for the Multiple Element Limitation (MEL) model. Variables are grouped into sections by type and then within each section values are arranged in the same categories used in Rastetter et al. (2013)

State Variables	Symbol	Value	Units	Notes
Jan 1 biomass C	B_C	654	g C m^{-2}	$B_C(peak)$ - L_{CWC} - L_C
Jan 1 biomass N	B_N	15.2	g N m^{-2}	$B_N(peak)$ - L_{CWCN} - L_N
Jan 1 biomass P	B_P	1.52	g P m^{-2}	$B_P(peak)$ - L_{CWCP} - L_P
Peak season biomass C	B_C	878	g C m^{-2}	Aboveground biomass (Mack et al. 2004 - Fig. 2a) + Fine roots (Sullivan et al. 2007)
Peak season biomass N	B_N	20.6	g N m^{-2}	B_C*%N (Shaver et al. 2006)
Peak season biomass P	B_P	2.06	g P m^{-2}	Shaver and Chapin, 1991 - Table 5
Soil organic C	D_{C1}	5049	g C m^{-2}	Mack et al. 2004 - Supplementary Table 1
Soil organic N	D_{N1}	178	g N m^{-2}	Calibrated, initial value from Mack et al. 2004 - Supplementary Table 1
Soil organic P	D_{P1}	17.8	g P m^{-2}	D_{N1}/N:P ratio for O horizon (Hobbie & Gough 2002 - Table 2)
Woody debris C	D_{Cc}	517.9	g C m^{-2}	Dead rhizomes (Dennis 1997, Shaver et al. 2006) + standing dead (Gough et al. 2009)
Woody debris N	D_{Nc}	6.73	g N m^{-2}	D_{Cc}*%N (Shaver et al. 2006)
Woody debris P	D_{Pc}	0.67	g P m^{-2}	$D_{Nc}/B_N{:}B_P$ (Shaver and Chapin 1991 - Table 5)
Phase II SOM C	D_{C2}	13885	g C m^{-2}	Mack et al. 2004 - Supplementary Table 1, mineral soil extrapolated to depth of thaw
Phase II SOM N	D_{N2}	646	g N m^{-2}	
Phase II SOM P	D_{P2}	79.4	g P m^{-2}	D_{N2}*P:N (Kirkby et al. 2011)
NH_4	E_{NH4}	0.26651	g N m^{-2}	Giblin et al. 1991 - Fig 5

NO_3	E_{NO3}	0.00194	g N m^{-2}	Giblin et al. 1991 - Fig 5
PO_4	E_{PO4}	0.00465	g P m^{-2}	Giblin et al. 1991 - Fig 5
P Prim min	P_A	25.11	g P m^{-2}	Chapin et al. 1978 Non-exchangeable inorganic P (lower 10cm extrapolated to depth of thaw); 64% as PA, 36% as P2nd (Yanai 1992)
P non-Occluded	P_{2nd}	14.12	g P m^{-2}	
g labile DOM C	E_{DOM}	2.3	g C m^{-2}	Total E_{DOM} = mobile (Whittinghill 2010) + sorbed (Oosterwoud 2010), split 10% labile 90% recalcitrant (Whittinghill 2010; McDowell 2006)
g recalcitrant DOM C	E_{DOMR}	20.7	g C m^{-2}	
CO_2 effort	V_c	0.383	effort g DW^{-1}	Total root effort calculated from leaf:root ratio. Effort to water uptake assumed to be 0.1. Effort assumed equal between N and P. Effort to NH_4 versus DON allowed to adjust to calibration conditions.
NH_4 Effort	V_{NH4}	0.134	effort g DW^{-1}	
PO_4 effort	V_{PO4}	0.239	effort g DW^{-1}	
Light effort	V_I	0.0367	effort g DW^{-1}	
DON effort	V_{DON}	0.105	effort g DW^{-1}	
Water effort	V_{H2O}	0.010	effort g DW^{-1}	
NO_3 effort	V_{NO3}	0.001	effort g DW^{-1}	Set to minimum effort
Nfix effort	V_{nfix}	0.001	effort g DW^{-1}	
Soil water	W	136.5	mm	Spun up based on the representative year used for control calibration.
Snow pack	W_{snow}	64.6	mm H_2O	
Soil Heat	SQ	359.6	arbitrary	

Steady State Fluxes	**Symbol**	**Value**	**Notes**
Carbon, g C/m²/yr			
Photosynthesis	U_c	430	=2 * Net Primary Production (Waring et al. 1998)
Plant maintenance respiration	R_a	146.7	$R_a = R_{cpt} - R_g - R_u$
Plant growth respiration	R_g	53.75	0.25 * NPP

N uptake respiration	R_u	14.5	Sum of N uptake * cost
DOC uptake	U_{DOM}	8.95	$U_{DON}*q_{DOM}$
Total plant respiration	R_{cpt}	215	U_c - Net primary production
Net primary production	NPP	215	Shaver & Chapin 1991 - Table 11
Coarse woody litter	L_{CWC}	49.45	23% of total litter (Shaver & Chapin 1991 - Fig. 5)
Fine litter	L_C	174.5	Net primary production - $L_{CWC}+U_{dom}$
D_{Cc} to D_{c1} transition	T_{CWC}	49.45	Steady state for W_C
Phase I respiration	R_{Cm1}	168.3	Steady state for D_{C1}
D_{C1} to D_{C2} transition	T_{DC12}	44.79	0.2 * $L_C + L_{CWC}$ (Mellilo et al. 1989 - Fig. 1)
Phase II respiration	R_{Cm2}	44.79	Steady state for D_{C2}
DOC production	P_{DOM}	13.97	$P_{don}*q_{dom}$
Microbial DOC uptake	U_{DOMm}	5	Calibrated to D_C
DOC inputs	I_{DOM}	0	Assumed equal to 0
DOC leaching	L_{DOM}	0.0243	Steady state for E_{dom}
DOMR production	P_{DOMR}	1.91	$P_{DOMR}*q_{DOMR}$
DOMR leaching	L_{DOMR}	1.91	Steady state for E_{DOMR}
DOMR deposition	I_{DOMR}	0	Assumed equal to 0
Nitrogen, g N/m^2/yr			
NH_4 deposition	I_{NH4}	0.0147	Year 2000 data in Shaver and Laundre 2006a
NO_3 deposition	I_{NO3}	0.0203	
DON deposition	----	0	I_{DOM}/q_{DOM}

NH_4 leaching	L_{NH4}	0.0013	Yano 2010: Table 6 concentration*R_O
NO_3 leaching	L_{NO3}	0.0003	Steady state E_{NO3}
DON leaching	L_{DON}	0.00657	$L_{don} = L_{donT} - L_{donR}$
Nitrification	T_{Ntr}	0	Negligible in control calibration
Denitrification	T_{DNtr}	0	Negligible in control calibration
Plant NH_4 uptake	U_{NH4}	2.96	$U_{NTotal} - U_{DON} - U_{NO3} - U_{Nfix}$
Plant NO_3 uptake	U_{NO3}	0	NO_3 often below detection in tundra
Plant DON uptake	U_{DON}	2.42	Approximately 0.45 * U_{NTotal} (Schimel & Chapin 1996)
Plant N-fixation	U_{nfix}	0	Negligible in control calibration
Coarse woody litter	L_{CWN}	0.643	$L_{CWC}*q_{WNwl}/q_C$
Fine litter	L_N	4.73	Steady state for B_n
D_{Nc} to D_{N1} transition	T_{CWN}	0.643	Steady state for D_{Nc}
Microbial NH_4 uptake	U_{NH4m}	13	U_{NH4} * 4.4 (Nadelhoffer et al. 1999 - Figure 1).
Microbial NO_3 uptake	U_{NO3m}	0.02	Assumes nearly all I_{NO3} is taken up by microbes
Microbial DON uptake	U_{DONm}	1.351	U_{domm}/q_{DOM}
Nonsymbiotic N Fixation	U_{NNSFix}	0.098	Hobara et al. 2006 - Table 3
Phase I N mineralization	R_{Nm1}	13.87	Steady state for E_{NH4}
D_{N1} to D_{N2} transition	T_{DN12}	2.084	$T_{DC12}/(D_{C2}/D_{N2})$
Phase II N mineralization	R_{Nm2}	2.084	Steady state for D_{N2}
DON production	----	3.777	Steady state for E_{dom}
Total N uptake	----	5.375	NPP C:N = 40 (Hobbie and Chapin 1998, Nadelhoffer et al. 2002)
DONR production	----	0.1248	Steady state E_{domr}

DONR deposition	----	0	Assumed = 0
DONR leaching	----	0.1248	Assuming 95% DON loss is recalcitrant
Total DON leaching	----	0.1314	Steady state: Total N budget
Phosphorus, g P/m^2/yr			
PO_4 deposition	I_{PO4}	0.002	Year 2000 data in Shaver and Laundre, 2006a
PO_4 leaching	L_{PO4}	0.0044	Steady state: Total P budget.
^{o}1 mineral weathering	T_{PAw}	0.0024	Steady state for P_a
^{o}2 mineral weathering	T_{P2w}	0.0012	Assumed half of primary mineral weathering.
^{o}2 mineral formation	*TPO4s*	0.0012	Steady state for E_{PO4}
Plant PO_4 uptake	U_{PO4}	0.5375	NPP-P ~ 10% NPP-N (Shaver and Chapin 1991 - Table 10)
coarse woody litter	L_{CWP}	0.0643	$L_{CWC}*q_{WPwl}/q_C$
fine litter	L_P	0.4732	Steady state for B_p
D_{Pc} to D_{P1} transition	T_{CWP}	0.0643	Steady state for D_{Pc}
Microbial PO_4 uptake	U_{PO4m}	1.784	Assume an approximate 7.3:1 N:P mass ratio for microbial uptake (Redfield, 1958).
Phase I P mineralization	R_{Pm1}	2.066	Steady state for D_{P1}
D_{P1} to D_{P2} transition	T_{DP12}	0.2561	$T_{DC12}/(D_{C2}:D_{P2})$
D_{P2} mineralization	R_{Pm2}	0.2561	Steady state with T_{DP2}
^{o}1 mineral deposition		0.0024	A constant rate to reflect exposure of new parent material.
Water, mm/yr			

Precipitation	I_{ppt}	327.8	Year 2000 daily temperature maximum, minimum pyranometer, and precipitation from Toolik Field Station's main weather station. Shaver and Laundre 2002
Interception	I_{nt}	32.78	Estimated as 0.1*I_{ppt}
Runoff	R_O	118	I_{ppt} - I_{nt} - *Transpiration*
Transpiration/ water uptake	U_W	144.2	I_{ppt} - R_o - I_{nt}
Evapotranspiration	-----	177	Estimated as 0.54*I_{ppt} (Kane 1997 - Table 3.1)

Description	Symbol	Value	Units	Notes
Driving Variables:				
Daily minimum temperature	T_{min}	variable	°C	Year 2000 daily temperature maximum, minimum pyranometer, and precipitation from Toolik Field Station's main weather station. Shaver and Laundre 2002
Daily maximum temperature	T_{max}	variable	°C	
Daily total short-wave radiation	I	variable	MJ m^{-2} day^{-1}	
Precipitation	I_{ppt}	variable	mm day^{-1}	
Depth of thaw	z_T	variable	m	Shaver and Laundre 2006
Atmospheric CO_2	C_a	360	mmol mol^{-1}	Assumed constant at 360 mmol mol^{-1}
NH_4 input	I_{NH4}	variable	g N m^{-2} day^{-1}	Model runs on daily values. Annual totals are reported with model fluxes, daily values are calculated from precipitation and average nutrient concentration Shaver and Laundre 2006a)
NO_3 input	I_{NO3}	variable	g N m^{-2} day^{-1}	
PO_4 input	I_{PO4}	variable	g N m^{-2} day^{-1}	
DOM input	I_{DOM}	variable	g N m^{-2} day^{-1}	
DOMR input	I_{DOMR}	variable	g N m^{-2} day^{-1}	
Apatite input	$I_{apatite}$	0.00000664	g P m^{-2} day^{-1}	A constant rate to reflect exposure of new parent material.
Environment:				
Soil depth	z	0.35	m	Shaver and Laundre 2006b

Soil porosity	ρ_s	0.85	mm mm^{-1}	Bridgham et al. 2001
Bulk density	D_{Bs}	0.343	Mg m^{-3}	Average value (Giblin et al. 1991, Nadelhoffer et al. 1995, Mack et al. 2004)
NH_4 sorption capacity	S_{NH4}	402	g NH_4-N Mg^{-1} dry soil	Fit to data in Mikolajkow 2003 - Fig. 3
NH_4 affinity constant	ε_{NH4}	786	umol NH_4 L^{-1}	
DOM sorption capacity	S_{DOM}	805	g DOM-C Mg^{-1} dry soil	Fit to Vandenbruwane et al. 2007 - Fig. 1
DOM affinity constant	ε_{DOM}	2130	umol DOM L^{-1}	
PO4 sorption capacity	S_{PO4}	62	g PO_4 -P Mg^{-1} dry soil	Fit to Vincent, 2006 - Fig. 2.2
PO4 affinity constant	ε_{PO4}	150	umol PO_4 L $^{-1}$	
DOMR sorption capacity	S_{DOMR}	600	g DOM-C Mg^{-1} dry soil	Calculated from E_{DOMR} and dissolved DOM concentration (Whittinghill 2010, Oosterwoud 2010)
DOMR affinity constant	ε_{DOMR}	2130	umol DOM L^{-1}	Same as DOM
field capacity	θ_f	0.39	mm mm^{-1}	Bridgham et al. 2001
Wilting point	θ_w	0.15	mm mm^{-1}	Assume range of 5-20% H_20 by volume @wilting point. Organic soil at high end.
Field potential	ψ_f	-0.01	MPa	Dunne and Leopold 1978, p 176
Wilting potential	ψ_w	-1.5	MPa	Dunne and Leopold 1978, p 176
Initial SOM	S_{OM0}	18934	g C m^{-2}	$D_C + S_C$
initial DOP	z_{po}	0.35	m	Shaver and Laundre 2006b
Radiation term	b_I	0.03	heat m^2 day MJ^{-1}	Calibrated to observed soil temperatures
Thermal conductivity to permafrost	k_{pf}	0.08	MJ m^{-1} day^{-1} $^oC^{-1}$	Calibrated, but in the same relative proportion to the thermal conductivity values in Biesinger et al. 2007. We had to calibrate these values because we are simulating one soil layer rather than a continuous profile of small discrete layers.

Organic soil thermal conductivity	k_{so}	0.012	MJ m^{-1} day^{-1} $^{o}C^{-1}$	Calibrated to observed soil temperatures
Mineral soil thermal conductivity	k_{sm}	0.024	MJ m^{-1} day^{-1} $^{o}C^{-1}$	Calibrated to observed soil temperatures
Water thermal conductivity	k_{w}	0.005	MJ m^{-1} day^{-1} $^{o}C^{-1}$	Calibrated to observed soil temperatures
Snow thermal conductivity	k_{snow}	0.0014	MJ m^{-1} day^{-1} $^{o}C^{-1}$	Biesinger et al. 2007, assumes 10:1 snow:water volume
Organic Soil Heat Capacity	c_{so}	0.58	MJ m^{-3} $^{o}C^{-1}$	Adapted from Biesinger et al. 2007. Relative values are proportional to each other, but smaller because they are applied to a single profile here rather than a series of discrete depths.
Mineral Soil Heat Capacity	c_{sm}	3.28	MJ m^{-3} $^{o}C^{-1}$	
Water Heat Capacity	c_{w}	4.2	MJ m^{-3} $^{o}C^{-1}$	
Zero low limit	S_{QF}	373.15	MJ m^{-3} $^{o}C^{-1}$	Amount of heat contained in the soil when it warms to freezing, calibrated to soil temp data from Toolik
Zero high limit	S_{QT}	400	MJ m^{-3} $^{o}C^{-1}$	Amount of heat contained in the soil as it cools to freezing
Permafrost temperature	T_{pf}	-7	^{o}C	1994-2003 average, Shaver and Laundre 2002
Snow albedo	α	0.8	----	Biesinger et al. 2007
Depth to permafrost	z_{pf}	1.8	m	This is assumed to be deep enough to serve as a constant temperature boundary for the soil temperature model.
Depth to surface	z_{s}	0.2	m	Representative depth for soil temperature
Organic soil index slope	a_{p}	1.85E-05	m^{3} g^{-1} C	active layer depth/initial SOM at calibration site
Allometry:				
C:dry weight ratio	q_{C}	0.5	g C g^{-1} DW	Shaver et al. 2006
Ba intercept	α_{B}	100	g C m^{-2}	Fit to Shaver and Chapin, 1991 and Chapin et al, 1995
B_{A}:B_{T} slope	γ_{B}	0.212676	none	
Specific leaf area	a_{sla}	0.006528	m^{2} g^{-1} DW	Shaver et al. 2001 - Table 5
Specific root length	a_{srl}	27.5	m g^{-1} DW	Average of estimates for *E. Vaginatum*, deciduous, and evergreen plants (Bjork et al. 2007, Ostonen et al. 2007)

Leaf N fraction	q_{LN}	0.0163	g N g^{-1} DW	Shaver et al. 1989
Wood N fraction	q_{WN}	0.00867	g N g^{-1} DW	
Root N fraction	q_{RN}	0.0112	g N g^{-1} DW	
Leaf P fraction	q_{LP}	0.00163	g P g^{-1} DW	Calculated from biomass data (Shaver et al. 1989)/N:P (Shaver & Chapin 1991 - Table 5 Tussock Site)
Wood P fraction	q_{WP}	0.000867	g P g^{-1} DW	
Root P fraction	q_{RP}	0.00112	g P g^{-1} DW	
Stoichiometric feedback	k_q	0.3	unitless	calibrated to response to changes in nutrient availability
Leaf Area Index	LAI	1.33	m^2 m^{-2}	B_L*a_{sla}
Active biomass (leaves and roots)	B_a	487.49	g DW m^{-2}	Shaver et al. 2006
Leaf Biomass	B_L	203.46	g DW m^{-2}	Shaver et al. 2006
Canopy Phenology:				
Minimum canopy fraction	f_{cmin}	0.4	none	Shaver and Chapin 1991 - Figure 2
Start Deg day sum	J_{D1}	10	Julian Day	Calibrated to phenology in Markon 2001, NDVI data for north slope
Deg day bud open	D_{bud}	10	Degree day	
Deg day full canopy	D_{full}	160	Degree day	
Day fall starts	J_{start}	250	Julian day	
Day fall ends	J_{end}	270	Julian day	
Time offset	T_{ly}	0	days	Simulation start relative to Jan 1
Latitude	l_{at}	68.5	degrees	Shaver and Laundre 2002
Jday divisor	J_{dayD}	365	days	Assuming a 365 day year
Photosynthesis/Transpiration:				
Temperature response parameters for light capture	T_{maxL}	100	^oC	Values approximated from Johnson and Tieszen (1976, Figure 6), and Chapin and Shaver (1996, Figure 10),

	T_{OL}	25	°C	refined by calibrating to arctic LTER experimental plots (Chapin et al. 1995). Data were unavailable to use separate values for light capture and carboxylation. The approximate temperature range at Toolik (-46 to 27 oC, between 1994-2003) indicates that we will never use the high end of the curve.
	a_L	0.3	°C^{-1}	
Ps light constant	g_I	35.64	g C m^{-2} leaf hr^{-1}	Calibrated to U_I
Light extinction	k_I	0.5	m^2 m^{-2}	Shaver et al. 2007
Light 1/2 saturation constant	k_{PI}	4	MJ m^{-2} day^{-1}	Calibrated to photosynthesis light curves (Shaver et al. 2007)
Ps CO_2 rate constant	g_C	0.1095	g C m^{-2} leaf hr^{-1}	Calibrated to U_C
CO_2 1/2 saturation constant	k_C	720	ppm	McMurtrie et al. 1992
Temperature response parameters for carboxylation	T_{maxC}	100	°C	Values approximated from Johnson and Tieszen (1976, Figure 6), and Chapin and Shaver (1996, Figure 10), refined by calibrating to arctic LTER experimental plots (Chapin et al. 1995)
	T_{OC}	25	°C	
	a_C	0.3	°C^{-1}	
Maximum leaf conductance	c_{smax}	20	m hr-1	Williams et al. 1996 - Fig. 9
H_2O uptake constant	g_W	0.5443	MPa^{-1}	Calibrated to U_W
Water uptake factor	k_E	0.0001	m^2 m^{-1}	Rastetter et al. 2013
Ca H2O weighting	β	0.01	unitless	Calibrated to match allocation of effort for CO_2 and H_2O
scaler UCc	s_{Ucc}	17.15	unitless	Calibrated to U_C
scaler ET	s_{cEt}	25.91	unitless	Calibrated to water uptake and transpiration
Plant Respiration:				
Respiration constant	r_{mA}	0.0369	gC g^{-1} N day^{-1}	Calibrated to NPP
NH4 C cost	ϕ_{NH4}	0.01	g C g^{-1} N	Assumed to be negligible relative to other forms of nitrogen

NO_3 C cost	ϕ_{NO3}	4.6	g C g^{-1} N	Gutschick 1981 (p 617) 1/4 to 1/2 N fixation cost
DON C cost	ϕ_{DON}	6	g C g^{-1} N	Not known, assuming value is between NO_3 and N-fixation C costs.
Nfix C cost	ϕ_{Nfix}	9.12	g C g^{-1} N	Gutschick 1981
Growth respiration	r_g	0.25	fraction	Waring and Schlesinger, 1985 - Table 2.3
Woody respiration constant	r_{mW}	0.0369	gC g^{-1} N day^{-1}	Calibrated to NPP
Sapwood:hardwood partial exponent	k_{rmW}	1.61E-05	m^2g^{-1} DW	Assume no heartwood
Respiration Q10 slope	m_{Q10R}	-0.0411		Fit to data in Tjoelker 2001 - Table 2
Respiration Q10 intercept	b_{Q10R}	3.202	unitless	
Plant nutrient uptake:				
Root radius	r_r	0.0005	m	Fahey et al. 2005 - definition of fine root
NH_4 uptake constant	g_{NH4}	8.843E-06	g N m^{-1} root day^{-1}	Calibrated to U_{NH4}
Plant NH_4 1/2 saturation constant	k_{NH4}	3.84	umol L^{-1}	Calibrated to arctic LTER experimental plots (Chapin et al. 1995)
NO_3 uptake const	g_{NO3}	0	g N m^{-1} root day^{-1}	Calibrated to U_{NO3}
Plant NO_3 1/2 saturation constant	k_{NO3}	3.84	umol L^{-1}	Calibrated to arctic LTER experimental plots (Chapin et al. 1995)
PO_4 uptake constant	g_{PO4}	8.17E-07	g P m^{-1} root day^{-1}	Calibrated to U_{PO4}
Plant PO_4 1/2 saturation constant	k_{PO4}	1.6	umol L^{-1}	Calibrated to arctic LTER experimental plots (Chapin et al. 1995)
DOM uptake constant	g_{DOM}	2.94E-05	g C m^{-1} root day^{-1}	Calibrated to U_{DOM}
Plant DOM 1/2 saturation constant	k_{DOM}	14.208	umol L^{-1}	$=q_{DOM}*k_{NH4}$
Diffusion constant NH_4	D_{NH4}	8.46E-05	m^2 d^{-1}	Raynaud and Leadley 2004 - Table 3
Diffusion constant NO_3	D_{NO3}	4.03E-05	m^2 d^{-1}	Raynaud and Leadley 2004 - Table 3

Diffusion constant DON	D_{DOM}	8.46E-05	$m^2\ d^{-1}$	Leadley et al. 1997 -Table 2: Diffusive supply of Glycine = NH4)
Diffusion constant PO_4	D_{PO4}	0.0000239	$m^2\ d^{-1}$	Raynaud and Leadley 2004 - Table 3
Q_{10} vegetation	Q_{10V}	1.5	unitless	Calibrated to the warming response in Chapin et al 1995; Q10 for all plant uptake processes are assumed to be the same.
Nfix inhibition	N_{fixI}	2	unitless	N fixation turned off for these simulations
N fixation rate constant	g_{Nfix}	0	g N m^{-1} root day^{-1}	
Litter losses:				
Evergreen leaf turnover	m_{AL}	0.001358	day^{-1}	Calibrated to L_C+L_{CWC}
Wood turnover	m_W	0.0003446	day^{-1}	
Root turnover	m_{AR}	0.0009921	day^{-1}	
Leaf litter N fraction	q_{LNl}	0.008174	g N g^{-1} DW	Calibrated to L_N+L_{CWN}
Wood litter N fraction	q_{WNl}	0.009358	g N g^{-1} DW	
Root litter N fraction	q_{RNl}	0.02286	g N g^{-1} DW	
Leaf litter P fraction	q_{LPl}	0.0007489	g P g^{-1} DW	Calibrated to L_P+L_{CWP}
Wood litter P fraction	q_{WPl}	0.001104	g P g^{-1} DW	
Root litter P fraction	q_{RPl}	0.002211	g P g^{-1} DW	
Coarse woody turnover	m_{CW}	0.0002738	day^{-1}	Calibrated to L_{CWC}
Canopy closure woody litter parameters	m_{CWx}	0	day^{-1}	Assuming no canopy closure
	k_{WL}	NA	$m^{-2}\ g^{-1}$ C	
Coarse litter N fraction	q_{WNwl}	6.5E-03	g N g^{-1} DW	$q_c\ D_{Nc}/D_{Cc}$
Coarse litter P fraction	q_{WPwl}	6.5E-04	g P g^{-1} DW	$q_c\ D_{Pc}/D_{Cc}$

Plant acclimation:				
Gain C	C_{gain}	0.8470	none	Calibrated to steady state allocation of effort
Gain N	N_{gain}	0.7593	none	
Gain P	P_{gain}	0.7551	none	
Requirement turnover	τ	0.003	day^{-1}	assumed ~ 1 yr (Rastetter et al. 2013)
N-yield range	σ_y	0.15	none	Assumed yield must be within 15% before alternate N source used.
Acclimation rate	a	0.003	day^{-1}	assumed ~ 1 yr (Rastetter et al. 2013)
Minimum effort	V_{min}	0.001	effort g^{-1} DW	This is set small enough to have little effect on effort budget but large enough for uptake to turn on in timely manner.
Soil processes:				
Microbial moisture response parameters	ω_o	0.377	pore fraction	Fit to McKane et al. 1997, Figure A1
	J_m	1.95	none	
	ω_{min}	0.0431	pore fraction	
Microbial Q_{10}	Q_{10m}	4	none	assumes Q_{10} of ~4 (Davidson et al 1998)
Coarse Woody turnover	r_{CW}	0.0003976	day^{-1}	Calibrated to W_C
Microbial DOM uptake rate	α_{DOM}	5.995E-06	day^{-1}	Calibrated to U_{DOMm}
Microbial DOM 1/2 saturation constant	k_{DOMm}	37	umol C L^{-1}	$=q_{DOM}*k_{NH4m}$
C:N DOM	q_{DOM}	3.7	g C g^{-1} N	Average of C:N of all amino acids (Brooker et al. 2008)
C:N DOMR	q_{DOMR}	15.32	g C g^{-1} N	Whittinghill 2010
Microbial NH_4 uptake rate	α_{NH4}	2.703E-05	g N m^{-2} day^{-1}	Calibrated to U_{NH4m}
Maximum microbial C efficiency	ε_C	0.6	none	Hunt et al. 1991 - Table 2
Microbe return C:N	ϕ_N	21.5	g C g^{-1} N	Calculated from steady state S_C/S_N

Phase II soil C:N	ϕ_{NII}	21.5	g C g^{-1} N	Calculated from steady state S_C/S_N
Microbial NH_4 1/2 saturation constant	k_{NH4m}	10	umol N L^{-1}	Raynaud et al. 2006 - Table 2. Assumes soil water at field capacity.
Microbial NO_3 uptake rate	α_{NO3}	1.616E-07	g N m^{-2} day^{-1}	Calibrated to U_{NO3m}
Microbial NO_3 1/2 saturation constant	k_{NO3m}	80	umol N L^{-1}	Raynaud et al. 2006 - Table 2. Assumes soil water at field capacity
Microbial PO_4 uptake rate	α_{PO4}	5.746E-06	g P m^{-2} day^{-1}	Calibrated to U_{PO4m}
Microbial PO_4 1/2 saturation constant	k_{PO4m}	4.15	umol P L^{-1}	Assumes same ratio of NH_4^+:PO_4^{3-} half-saturation constants as for plants
Microbe return C:P	ϕ_P	174.9	g C g^{-1} P	Calculated from steady state S_C/S_P
Phase II soil C:P	ϕ_{PII}	174.9	g C g^{-1} P	Calculated from steady state S_C/S_P
C mineralization constant	ψ_m	0.00020548	day^{-1}	Calibrated to R_m
N mineralization constant	ψ_{Nm}	7.813E-05	day^{-1}	Calibrated to R_{Nm}
P mineralization constant	ψ_{Pm}	0.000179624	day^{-1}	Calibrated to R_{Pm}
DOM production rate	r_{DOM}	6.515E-08	m^2 g^{-1} N	Calibrated to P_{DOM}
DOMR production rate	r_{DOMR}	8.92E-09	m^2 g^{-1} N	Calibrated to P_{DOMR}
Phase I to phase II transition rate	ξ_{12}	3.711E-05	day^{-1}	Calibrated to T_{DC12}
Phase II mineralize rate	ρ_{m2}	1.345E-05	day^{-1}	Calibrated to R_{Cm2}
Nitrification rate	r_{Nitr}	0	g N m^{-2}	Calibrated to T_{Ntr}
Nitrification 1/2 saturation constant	k_{Nitr}	8	umol N L^{-1}	Raynaud et al. 2006 - Table 2. Assumes soil water at field capacity.
Denitrification rate	r_{DNtr}	0	g N m^{-2} day^{-1}	Calibrated to T_{DNtr}
Denitrification 1/2 saturation constant	k_{DNtr}	80	umol NO_3 L^{-1}	Tian et al. 2010 - Table 5. Assumes soil water at field capacity.
Denitrification minimum soil moisture	θ_0	0.39	fraction soil volume	assumed = field capacity
Soil Nfix rate constant	γ_{Sfix}	4.484E-09	g^2 N g^{-2} C day^{-1}	Calibrated to U_{NNSFix}

Soil Nfix critical C:N	q_{Sfix}	21.5	g C g N^{-1}	Assume that N-fixation stops if C:N of Ph I soil drops below C:N of ph II soil
Soil P transformations:				
°1 mineral weathering rate	r_{PAw}	2.644E-07	day^{-1}	Calibrated to P_A
°2 mineral formation rate	r_{PO4s}	0.0000225	day^{-1}	Calibrated to T_{PO4s}
°2 mineral weathering rate	r_{P2w}	2.351E-07	day^{-1}	Calibrated to P_{no}
Hydrology and material loss:				
soil drain rate	D_w	1	day^{-1}	sandy loam, Heath 1983
Loss fraction NH_4	η_{NH4}	0.0946	none	Calibrated to L_{NH4}
Loss fraction NO_3	η_{NO3}	0.1345	none	Calibrated to L_{NO3}
Loss fraction PO_4	η_{PO4}	1.280	none	Calibrated to L_{PO4}
Loss fraction DOM	η_{DOM}	0.2673	none	Calibrated to L_{DOM}
Loss fraction DOMR	η_{DOMR}	1.188	none	Calibrated to L_{DOMR}
Interception volume	v_{int}	0.394	mm m^{-2}	Calibrated to I_{nt}
Non-leaf surface area	β_{int}	0	m^2 m^{-2}	Assumes all interception is on leaves
Branch exponent	η_{br}	0.4	none	
Mid-wood biomass	B_{MW}	100	g DW m^{-2}	Not used; interception on stems turned off
Snowfall critical temp	T_{crt}	0.76	°C	Brubaker et al. 1996
Snowmelt critical temp	T_{crts}	2	°C	Calibrated to timing of snow melt
Latent heat of fusion H_2O	C_{NR}	0.334	MJ L^{-1}	Physical constant
Short wave absorption	C_{SW}	0.1	none	Dunne and Leopold 1978 - Fig. 13.5
Long wave absorption	C_{LW}	18	none	Calibrated to observed snowmelt
Convective coefficient	C_C	2	mm $°C^{-1}$ day^{-1}	Brubaker et al. 1996

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