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Supplement of

CO_2 fluxes and ecosystem dynamics at five European treeless peatlands – merging data and process oriented modelling

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Supplemental material

Calibration procedure

A stepwise approach was used to calibrate model parameter: (I) Parameter ranges of 45 parameters were constrained by applying a Monte Carlo based calibration by multiple runs with randomized parameter values in a defined range, similar to the Generalized Likelihood Uncertainty Estimation by Beven and Binley (1992) and Beven (2006). Ranges were selected according to experiences from previous model runs, in most cases a certain range around the default values. The list of parameters and their tested ranges are displayed in Table S3. The output of these runs was compared with several different variables derived from measurements. A number of performance indicators were considered to define the behavioural models with an acceptable fit in step I a. Parameter ensembles of accepted behavioural models were further analysed to identify covariance between parameters and also to understand the importance and effect of multiple criteria (I b).

350'000 runs were executed for each site, except for Hor, for which 700’000 runs were performed. The higher amount of runs at Hor was motivated by the observed discrepancy in chamber versus EC derived R_{eco} values and a wider range for some parameters due to the relatively high ratio of biomass to GPP.

(I a) From these runs, around 75 behavioural models per site were selected according to an acceptable fit (Tab. S7) to measurement derived R_{eco} and GPP respectively in case of Hor net ecosystem exchange (NEE) and plant biomass. Due to their relatively small amplitude, winter fluxes hardly affect performance indices of the whole year. However they have a high proportion of soil to plant respiration and are therefore of special interest. Hence, performance in modelling R_{eco} and GPP during winter, respectively late autumn in case of Lom (see Tab. 4) were additionally taken into account. As the ability to constrain parameter values and the model performance depend on quality and frequency of the available measurement data, different criteria (Tab. S7) had to be applied for each site.

(I b) Performance (R^2, ME and NSE) of the 75 accepted runs on each variable was plotted against values for each parameter as well as values for each parameter against values for each other parameter. These plots were visually analysed to detect covariance between parameters which were further analysed in step III and between parameters and performance which were further analysed in step I c.

(I c) The best fit for one variable does not necessarily lead to the best fit for another variable. Therefore, a further constraint was achieved by selecting each best 10 out of the 75 runs independently for each of the variables and each parameter as listed in Table S9. According the results from I b, different performance indices were used depending on the variable: R^2 was chosen in case of R_{eco} and GPP as effect on ME can be compensated by radiation use efficiency (ϵ_L) in case of GPP and decomposition rate for the fast SOC pool (k_l) in case of R_{eco}. Mean error was chosen in case of temperature, NSE for all other variables, including winter R_{eco} and winter GPP. This procedure leads to several ranges for each parameter producing the best performance depending on the variable and the site.

(I d) The ranges were merged together to a new range for each parameter, starting with the highest value of the lower ends of all ranges and lasts to the lowest of the upper ends. These ranges will be called “overlapping ranges” in the following, even though they did not overlap in some few cases.

(II) Parameters might interact with one or more other parameters and counteract or even compensate the effect of other parameters. Ranges for such parameters could be same or overlapping between the sites, but the application of a single set of parameter values might reveal that only site specific values for one or several of these parameters lead to acceptable performance. To test this, for each site one of the 75 runs with the highest performance in R^2 of R_{eco} selected and ϵ_L and k_l adjusted until ME in GPP and R_{eco} was smaller than $|0.1|$ g C m^{-2} day^{-1}. Afterwards, stepwise each parameter was set to the rounded mean value of the overlapping range from I d and again ϵ_L and k_l adjusted until ME in GPP and R_{eco} was smaller than $|0.1|$ g C m^{-2} day^{-1}. If then the performance in R^2 of R_{eco} and GPP was not reduced by more than 0.05 the modified parameter was kept at this value. Otherwise it was set back to the previous value and further investigated in III. This procedure was repeated for all parameters except ϵ_L and k_l.

(III) Parameters showing strong interactions or showing different valid ranges for the different sites or variables were investigated by further multiple calibrations with 2500 to 5000 runs. For each parameter only this particular parameter and very few other parameters which are directly related to it were calibrated, while all others were kept constant to the values from step II. Criteria for accepted runs were a mean error of max $|0.3|$ g C m^{-2} day^{-1} in R_{eco} and

GPP, respectively in GPP and uppermost temperature case of p_{ck}, to accept 60 to 150 runs. Such additional multiple calibrations were also performed if the previous results indicated an optimal range outside the tested range. In this case the calibration range of the parameter was increased.

Then steps I c, d and II were repeated for these additional calibration. If the performance in R^2 of R_{eco} and GPP was reduced by more than 0.05 the parameter was considered to be site specific. Again, ϵ_L and k_l were adjusted until ME in GPP and R_{eco} was smaller than |0.1| g C m^{-2} day^{-1}. This set of parameter values will be called common configuration (C1) in the following.

(IV) Different combination of parameter values might lead to similar good results, which is called equifinality (Beven, 2006). In those cases were step I to III indicated covariance between parameters, several different combinations of parameter values leading to similar good results (ME in GPP and R_{eco} smaller than |0.1| g C m^{-2} day^{-1}) were tested. Such runs with a single set of parameter values are called single runs in the following and numbered with C1 to C7 (Tab. S8).

Beven, K.: A manifesto for the equifinality thesis, Journal of Hydrology, 320, 18–36, doi:10.1016/j.jhydrol.2005.07.007, 2006.

Beven, K. and Binley, A.: The future of distributed models: Model calibration and uncertainty prediction, Hydrological processes, 6, 279–298, 1992.

Tables

Table S1. Dynamic forcing data

Site	Variable	Period	Resolution of measurement / as used for calibration	number of replicates
Lom	water table	mid 2006-2010	half-hourly/hourly	1
	meteorology (temperature, global radiation, precipitation, wind speed, relative humidity)	mid 2006-2010	half-hourly/hourly	1
Amo	water table	April 2007-2010	half-hourly/hourly	1
	meteorology (temperature, global radiation, precipitation, wind speed, relative humidity)	mid 2006-2010	half-hourly/hourly	1
Hor	water table	2004-2006	half-hourly/hourly	2
	meteorology (temperature, global radiation, precipitation, wind speed, relative humidity)	2004-2011	half-hourly/hourly	1
FsA and FsB	water table	2007-2011	biweekly, since April 2010 half hourly / hourly	1
	meteorology (temperature, global radiation, precipitation, wind speed, relative humidity)	2007-2011	half-hourly/hourly	1

Table S2. Dynamic data for calibrations and comparisons – methods and instruments

Site	Variable	Period	Resolution of measurement / as used for calibration	Method	replicates	Described in	number of data points
Lom	NEE	mid 2006-10	half-hourly/hourly	EC	1	Aurela et al., 2009)	34895
	R_{eco}	2007, 2009, 2010	half-hourly/hourly, summer only	automatic opaque chamber	2	Lohila et al., 2010	27853
	R_{eco}, GPP	mid 2006-10	half-hourly/hourly	empirical modelling from EC data	1	Aurela et al., 2009	15236
	winter R_{eco}	2006-2010	half-hourly/hourly	empirical modelling from night NEE EC data during Sept.-Nov.	1		6356
	soil temperature at −7 cm	mid 2006-10	half-hourly/hourly	automatic temperature sensors	1		34318
	soil temperature at −60 cm	mid 2006-10	half-hourly/hourly	automatic temperature sensors	1		34318
	LAI	2007-10	4-10 times each summer	optical canopy analyser	9-19		41
	Snow depth	mid 2006-10	hourly	automatic sensor	1		34316
Amo	NEE	mid 2006-10	half-hourly/hourly	EC	1	Drewer et al., 2010	38710
	R_{eco}	mid 2006-10	biweekly	manual opaque chamber	9	Dinsmore et al., 2010	57
	R_{eco}, GPP	mid 2006-10	half-hourly/hourly	empirical model from EC data	1	Drewer et al., 2010	43475
	winter R_{eco}	mid 2006-10	half-hourly/hourly	empirical modelling from night NEE EC data during Nov. -Apr.	1		5348
	soil temperature at −10 cm	mid 2006-10	half-hourly/hourly	automatic temperature sensors	1		35808
	soil temperature at −40 cm	mid 2006-10	half-hourly/hourly	automatic temperature sensors	1		35808
	LAI	2004	11 times	optical canopy analyser	2		11
Hor	NEE	2004-10, except 2007	half-hourly/hourly	EC	1	Hendriks et al., 2007	49611
	R_{eco}	2003-06	biweekly	manual opaque chamber	6		53
	R_{eco}, GPP	2004-10, except 07,09	half-hourly/hourly	empirical model from EC data	1	Reichstein et al., 2005, Papale et al., 2006	39420

	winter R_{eco}	2004-10, except 07,09	half-hourly/hourly	empirical modelling from night NEE EC data during Nov. -Apr.	1		3966
	soil temperature at −8 cm	mid 2004-mid 2011	half-hourly/hourly	automatic temperature sensors	1		48881
	soil temperature at −11 cm	mid 2004-mid 2011	half-hourly/hourly	automatic temperature sensors	1		48881
	LAI	2006-07	4 times a year	optical canopy analyser, weighted mean from 7 vegetation types	3	Hendriks, 2009	8
	above ground biomass	2005-07	4 times a year	$0.16m^2$ clipped, dead leaves removed, weighted mean from 7 vegetation types	3	Hendriks, 2009	12
	Root biomass	2006-07	4 times a year	sieved soil cores of $1.15\cdot10^{-4}$ m^3, dead roots manually removed, weighted mean from 7 vegetation types	2	Hendriks, 2009	8
FsA and FsB	NEE	2007-2011	3-4 weekly several measurements per day	manual transparent chamber	3	Drösler, 2005; Beetz et al., 2013; Leiber-Sauheitl et al., 2013	1161
	R_{eco}	2007-2011	3-4 weekly several measurements per day	manual opaque chamber	3	Drösler, 2005; Beetz et al., 2013; Leiber-Sauheitl et al., 2013	1161
	GPP	2007-2011	3-4 weekly several measurements per day	empirical model from chamber data	3	Drösler, 2005; Beetz et al., 2013; Leiber-Sauheitl et al., 2013	1161
	winter R_{eco}	2007-2011	3-4 weekly several measurements per day	manual opaque chamber during Nov.-Apr.	3		357
	soil temperature at −2 cm	2007	half-hourly/hourly	automatic temperature sensors	1		36447
	soil temperature at −50 cm	2007	half-hourly/hourly	automatic temperature sensors	1		36447
	LAI	summer 2011-summer 2012	~3 weekly	optical canopy analyser	3		26
	Above ground biomass	2007-2011	4 weekly	0.04 m^2, since 2011 0.16 m^2, clipped and sorted into living and dead	3		43

Table S3. List of main equations used in this study

Equation	No.	Definition
Plant biotic processes		
$C_{Atm\rightarrow a} = \varepsilon_L \cdot \eta \cdot f(T_l)\cdot f(T_{sum})\cdot f(CN_l)\cdot f(E_{ta}/E_{tp})\cdot R_{s,pl}$ where ε_L is the radiation use efficiency and η is the conversion factor from biomass to carbon	(1)	Rate of photosynthesis (g C m^{-2} day^{-1})
$f(T_l) = \begin{cases} 0 & T_l < p_{mn} \\ (T_l - p_{mn})/(p_{o1} - p_{mn}) & p_{mn} \le T_l \le p_{o1} \\ 1 & p_{o1} < T_l < p_{o2} \\ 1-(T_l - p_{o2})/(p_{mx} - p_{o2}) & p_{o2} \le T_l \le p_{mx} \\ 0 & T_l > p_{mx} \end{cases}$ where p_{mn}, p_{o1}, p_{o2} and p_{mx} are parameters.	(2)	Response function for leaf temperature
$f(CN_l) = p_{fixedN}$ Where p_{fixedN} is a parameter.	(3)	Response function for fixed leaf C:N ratio
$f(E_{ta}/E_{tp}) = \dfrac{E_{ta}}{E_{tp}}$	(4)	Response function for transpiration
$C_{a\rightarrow Leaf} = l_{c1}\cdot C_a$ where l_{c1}, is a parameter.	(5)	Allocation of new assimilates to the leaves
$C_{a\rightarrow Root} = (1-l_{c1})\cdot C_a$	(6)	Allocation of new assimilates to the roots
$C_{respleaf} = k_{mrespleaf}\cdot f(T)\cdot C_{leaf} + k_{gresp}\cdot C_{a\rightarrow Leaf}$ where $k_{mrespleaf}$ is the maintenance respiration coefficient for leaves, k_{gresp} is the growth respiration coefficient, and $f(T_a)$ is the temperature. The equation calculates respiration from stem, roots, and grains by exchanging $k_{mrespleaf}$ to $k_{mrespstem}$, $k_{mresproot}$, $k_{mrespgrain}$, and using the corresponding storage pools. Respiration from the old carbon pools is estimated with the same maintenance respiration coefficients as for respiration from new carbon pools.	(7)	Plant growth and maintenance respiration from leaves (g C m^{-2} day^{-1})
$f(T) = t_{Q10}^{(T-t_{Q10bas})/10}$ where t_{Q10} and t_{Q10bas} are parameters.	(8)	Temperature response function for maintenance respiration (–)
$C_{Leaf\rightarrow Stem} = l_{LS}\cdot C_{Leaf}$ where l_{LS} is a parameter	(9)	Reallocation of C from leaf pool to stem pool – here used as pool for senescent leaves.
$C_{Leaf\rightarrow LitterSurface} = f(T_{Sum})\cdot f(A_l)\cdot s_{newleaf}\cdot C_{Leaf}$ where $s_{newleaf}$ is a scaling factor. Stem C is calculated analogously with $s_{newstem}$.	(10)	Leaf C entering the surface litter pool
$f(T_{Sum}) = l_{Lc1} + (l_{Lc2} - l_{Lc1})\cdot \min\left(1, \dfrac{\max(0, T_{Sum} - t_{L1})}{\max(1, t_{L2} - t_{L1})}\right)$ where *tL1*, *tL2*, *lLc1* and *lLc2* are parameters and *TSum* is the so called “dorming” temperature sum, *TDormSum*. *TDormSum* is calculated at the end to the growing season when the air temperature is below the	(11)	leaf litter fall dependence of temperature sum

threshold temperature $T_{DormTth}$, as the accumulated difference between $T_{DormTth}$ and Ta. $T_{DormTth}$ is a parameter. The stem litter rate is calculated analogously with the parameters *tS1*, *tS2*, *lSc1* and *lSc2*.		
$f(A_l) = e^{l_{LaiEnh} \cdot A_l}$ where l_{LaiEnh} is a parameter and A_l the leaf area index	(12)	Litter fall dependency of LAI
$C_{Root \rightarrow Litter} = f(l_{Rc}) \cdot C_{Root} \cdot s_{newroot}$ where $s_{newroot}$ is a scaling factor. The root litter rate function, *f(lRc)*, can be calculated with Eq. (11) by exchanging the parameters *tL1*, *tL2*, *lLc1* and *lLc2* to *tR1*, *tR2*, *lRc1* and *lRc2*.	(13)	Root C entering the soil litter pool
$C_{OldLeaf \rightarrow LitterSurface} = f(l_{Lc}) \cdot (C_{OldLeaf} - C_{RemainLeaf}) s_{oldleaf}$ where or *soldleaf* is a scaling factor. The litter fall for stems and roots is calculated analogously.	(14)	Litter fall from roots, leaves and stems in the “old” biomass in perennial plants are calculated similarly to the “new” biomass but with the important exception that some of the old leaves may be retained
$C_{RemainLeaf} = C_{OldLeaf} (1 - \frac{1}{l_{life} - 1})$ where l_{life} is a parameter	(15)	fraction of the whole $C_{OldLeaf}$ pool that will be excluded from the calculation of the litterfall from the old leaves
$C_{Leaf \rightarrow Harvest} = f_{leafharvest} \cdot C_{Leaf}$ where $f_{leafharvest}$ is a parameter. Harvest from the stem pool is calculated analogously by exchanging $f_{leafharvest}$ with $f_{stemharvest}$. These parameters are also used to calculate the harvest fractions from the old stem and leaves perennials.	(16)	amount of harvested carbon, removed from the system
$C_{Leaf \rightarrow LitterSurface} = f_{leaflittharv} \cdot (C_{Leaf} - C_{Leaf \rightarrow Harvest})$ where $f_{leaflittharv}$ is a parameter. Similar flows are calculated for stem and roots by exchanging $f_{leaflittharv}$ to $f_{stemlittharv}$	(17)	amount of plant parts, which are removed from the plant and enter the surface litter pool at harvest
$C_{Mobile} = (C_{Leaf \rightarrow LitterSurface} + C_{OldLeaf \rightarrow LitterSurface}) \cdot m_{retain}$ where m_{retain} is an allocation coefficient.	(18)	Allocation to the mobile C pool for developing new leaves during litter fall
$C_{Mobile \rightarrow Leaf} = C_{Mobile} \cdot m_{shoot}$ where *mshoot* is an allocation coefficient.	(19)	Allocation from the mobile C pool at leafing (between GSI 1 and 2) as an additional supply. This process goes on as long as there is carbon left in the mobile pool.
$C_{Roots \rightarrow Leaf} = m_{Root} \cdot (C_{Roots} - C_{Leaf} \cdot r_{rl})$ where m_{Root} and r_{rl} are parameters	(20)	Allocation of C in the roots to leaves, taking place after a harvest event as long as root:leaf ratio is smaller than the value of the parameter r_{rl} or until the plant goes to dormancy.
Plant abiotic processes		
$R_{s,pl} = (1 - e^{-k_{rn} \frac{A_l}{f_{cc}}}) \cdot f_{cc} \left(1 - a_{pl}\right) R_{is}$ where k_{rn} is the light use extinction coefficient given as a single parameter common for all plants, f_{cc} is the surface canopy cover, and a_{pl} is the plant albedo.	(21)	Plant interception of global radiation (MJ m^{-2} day^{-1})
$f_{cc} = p_{c\max} (1 - e^{-p_{ck} A_l})$ Where p_{cmax} is a parameter that determines the maximum surface	(22)	Surface canopy cover (m^2 m^{-2})

cover and p_{ck} is a parameter that governs the speed at which the maximum surface cover is reached. A_l is the leaf area index of the plant.		
$A_l = \frac{B_l}{p_{l,sp}}$ Where $p_{l,sp}$ is a parameter and B_l is the total mass of leaf.	(23)	Leaf area index ($\mathrm{m}^2\ \mathrm{m}^{-2}$)
$L_\upsilon E_{tp} = \frac{\Delta R_n + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma \left(1 + \frac{r_s}{r_a}\right)}$ where R_n is net radiation available for transpiration, e_s is the vapour pressure at saturation, e_a is the actual vapour pressure, ρ_a is air density, c_p is the specific heat of air at constant pressure, L_v is the latent heat of vaporisation, $\varDelta$ is the slope of saturated vapour pressure versus temperature curve, γ is the psychrometer 'constant', r_s is 'effective' surface resistance and r_a is the aerodynamic resistance.	(24)	Potential transpiration (mm day^{-1})
$r_s = \frac{1}{\max(A_l\, g_l, 0.001)}$ where g_l is the leaf conductance.	(25)	Stomatal resistance (s m^{-1})
$g_l = \frac{R_{is}}{R_{is} + g_{ris}} \frac{g_{\max}}{1 + \frac{(e_s - e_a)}{g_{vpd}}}$ where g_{ris}, g_{max} and g_{vpd} are parameter values, g_{maxwin} corresponds to g_{vpd} in winter.	(26)	Stomatal conductance per leaf area (m s^{-1})
Soil carbon and nitrogen processes		
$C_{DecompL} = k_l \cdot f(T) \cdot f(\theta) \cdot C_{Litter}$ Where k_l is a parameter.	(27)	Decomposition of the fast C pool (g C m^{-2} day^{-1})
$C_{DecompH} = k_h \cdot f(T) \cdot f(\theta) \cdot C_{Humus}$ Where k_h is a parameter.	(28)	Decomposition of the slow C pool (g C m^{-2} day^{-1})
$C_{LitterSurface \rightarrow Litter1} = l_{l1} \cdot C_{LitterSurface}$ where $ll1$ is a parameter.	(29)	Litter from inactive surface litter pool, entering the fast SOC pool at a continuous rate.
$f(T) = t_{Q10}^{(T - t_{Q10bas})/10}$ Where t_{Q10} and t_{Q10bas} are parameters. Where t_{max} and t_{min} are parameters.	(30)	Response function for soil temperature (–)
$f(\theta) = \begin{cases} p_{\theta satact} & \theta = \theta_s \\ \min\left(\left(\frac{\theta_s - \theta}{p_{\theta Upp}}\right)^{p_{\theta p}} (1 - p_{\theta satact}) + p_{\theta satact},\ \left(\frac{\theta - \theta_{wilt}}{p_{\theta Low}}\right)^{p_{\theta p}} \right) & \theta_{wilt} \le \theta \le \theta_s \\ 0 & \theta < \theta_{wilt} \end{cases}$	(31)	Response function for soil moisture (–)

where $p_{\theta Upp}$, $p_{\theta Low}$, $p_{\theta Satact}$, and $p_{\theta p}$ are parameters and the variables, θ_s, θ_{wilt}, and θ, are the soil moisture content at saturation, the soil moisture content at the wilting point, and the actual soil moisture content, respectively.		
Soil heat processes		
$q_h(0) = k_{ho}\frac{(T_s - T_1)}{\Delta z/2} + C_w\left(T_a - \Delta T_{Pa}\right)q_{\text{in}} + L_v q_{vo}$	(32)	Soil surface heat flow (J m^{-2} day^{-1})
where k_{ho} is the conductivity of the organic material at the surface, T_s is the surface temperature, T_1 is the temperature in the uppermost soil layer, ΔT_{Pa} is a parameter that represents the temperature difference between the air and the precipitation, q_{in}, is the water infiltration rate, q_{vo} is the water vapour flow, and L_v is the latent heat. The temperature difference, $T_a - \Delta T_{Pa}$, can optionally be exchanged to surface temperature, T_s.		
$k_{ho} = h_1 + h_2\theta$	(33)	Heat conductivity of the organic material at the surface
where *h1* and *h2* are empirical constants		

Table S4. Calibrated parameters

Symbol	Name	unit	Eq.	Definition	Min	Max
g_{maxwin}	CondMaxWinter	m s^{-1}	(26)	maximal conductance of fully open stomata	0.002	1
g_{ph}	GSI Post Harvest(1)	-		growth stage to which plant is set back after harvest	1.3	3
k_{gresp}	GrowthCoef(1)	day^{-1}	(7)	growth respiration coefficient	0.13	0.25
k_l	RateCoefLitter1	a^{-1}	(27)	rate coefficient for the decay of C in the fast pool		0.003
$k_{mrespleaf}$	MCoefLeaf(1)	day^{-1}	(7)	maintenance respiration coefficient for leaves	0.015	0.035
$k_{mresproot}$	MCoefRoot(1)	day^{-1}	(7)	maintenance respiration coefficient for root		0.003
$k_{mrespstem}$	MCoefStem(1)	day^{-1}	(7)	maintenance respiration coefficient for stem		0.013
k_{rn}	RntLAI	-	(21)	extinction coefficient in the Beer law used to calculate the partitioning of net radiation between canopy and soil surface	0.52	1
l_{cl}	Leaf c1(1)	g C^{-1}	(5)	allocation fraction to the leaves	0.52	0.55
l_{l1}	RateCoefSurf L1	day^{-1}	(29)	fraction of the above ground residues that enter the litter 1 pool of the uppermost soil layer	0.002	0.008
l_{LaiEnh}	LAI Enh Coef(1)	-	(12)	scaling factor for enhanced litter fall rates from leaf with higher LAI values	0.0016	0.6
l_{Lc1}	LeafRate1(1)	day^{-1}	(11)	rate coefficient for the litter fall from leaves before the first threshold temperature sum is reached		0.05
l_{Lc2}	LeafRate2(1)	day^{-1}	(11)	rate coefficient for the litter fall from leaves after the second threshold temperature sum is reached	0.1	0.3
l_{LS}	C Leaf to Stem(1)	-	(9)	scaling factor for reallocation of C from leaf to stem	0.015	0.025
l_{Rc1}	RootRate1(1)	day^{-1}	(13)	rate coefficient for the litter fall from roots before the first threshold temperature sum is reached		0.015
l_{Rc2}	RootRate2(1)	day^{-1}	(13)	rate coefficient for the litter fall from roots after the second threshold temperature sum is reached	0.01	0.05
l_{Sc1}	StemRate1(1)	day^{-1}	(11)	rate coefficient for the litter fall from leaves before the first threshold temperature sum is reached	0.003	0.1
l_{Sc2}	StemRate2(1)	day^{-1}	(11)	rate coefficient for the litter fall from leaves after the second threshold temperature sum is reached	0.03	0.2
m_{retain}	Mobile Allo Coef	-	(18)	coefficient for determining allocation to mobile internal storage pool	0.4^{a}, 0.05^{bc},	0.8^{ab}, 0.5^{c}, 0.45^{d}

					0.01[d]	
m_{Root}	RateCoef_fRoot(1)	-	(20)	speed at which reallocation from roots to leaves after harvest take place	0.005	0.04
m_{shoot}	Shoot Coef	-	(19)	coefficient for determining allocation from the mobile pool to the leaf at leafing	0.05	0.15
p_{ck}	Area kExp(1)	-	(22)	speed at which the maximum surface cover is reached	0.5	1
$p_{l,sp}$	Specific LeafArea	g C m^{-2}	(23)	the inverse of specific leaf area, i.e. leaf mass per unit leaf	44	49
p_{mn}	T LMin(1)	°C	(2)	minimum mean air temperature for photosynthesis	0.001	0.5
p_{θ}	ThetaPowerCoef	vol %	(31)	coefficient in the soil moisture response function	0.65	4.5
$p_{\theta Satact}$	Saturation activity	vol %	(31)	saturation activity in soil moisture response function	0.001	0.252, 1[f]
$p_{\theta Upp}$	ThetaUpperRange	vol %	(31)	water content interval in the soil moisture response function for microbial activity, mineralisation−immobilisation, nitrification and denitrification	20, 8[f]	77
r_{rl}	Root Leaf Ratio(1)	-	(20)	threshold value for root:leaf ratio for reallocation of C from roots to leaves after harvest	5	6.5
$s_{newleaf}$	New Leaf(1)	-	(10)	scaling factor for litter fall of new leaf	0.15	0.25
$s_{newroot}$	New Roots(1)	-	(13)	scaling factor for litter fall of new roots	0.1	0.25
$s_{newstem}$	New Stem(1)	-	(10)	scaling factor for litter fall of new stem	0.1	0.15
T_{amean}	TempAirMean	°C		assumed value of mean air temperature for the lower boundary condition for heat conduction.	5.5[a], 10.5[b,d], 13[c]	6.2[a], 15.5[b,c], 13[d]
$T_{DormTth}$	Dormancy Tth	°C	(11)	threshold temperature for plant dormancy	0.1	2.5, 5[f]
$T_{EmergeSum}$	TempSumStart	°C		air temperature sum that is the threshold for start of plant development	0.5	10
$T_{EmergeTh}$	TempSumCrit	°C		critical air temperature that must be exceeded for temperature sum calculation	0.15	1
t_{L1}	LeafTsum1(1)	day°C	(11)	threshold temperature sum for the lower leaf litter rate	10	20
t_{L2}	LeafTsum2(1)	day°C	(11)	threshold temperature sum for the higher leaf litter rate	20	50
$T_{MatureSum}$	Mature Tsum	°C		temperature sum beginning from grain filling stage for plant reaching maturity stage	80[a], 320[b], 750[c], 1050[d]	115[a],450[b] , 850[c], 1350[d]
t_{Q10}	TemQ10	-	(8), (30)	response to a 10 °C soil temperature change on the microbial activity, mineralisation-immobilisation, nitrification and denitrification and plant maintenance respiration	1.95	3.5

t_{Q10bas}	TemQ10Bas	°C	(8), (30)	base temperature for the microbial activity, mineralisation-immobilisation, nitrification and denitrification at which the response is 1	15	26
t_{R1}	RootTsum1(1)	day°C	(13)	threshold temperature sum for the lower root litter rate	10	20
t_{R2}	RootTsum2(1)	day°C	(13)	threshold temperature sum for the higher root litter rate	20	50
t_{S1}	StemTsum1(1)	day°C	(11)	threshold temperature sum for the lower stem litter rate	10	20
t_{S2}	StemTsum2(1)	day°C	(11)	threshold temperature sum for the higher stem litter rate	20	50
ε_L	PhoRadEfficiency	gDw MJ^{-1}	(1)	radiation use efficiency for photosynthesis at optimum temperature, moisture and C-N ratio	1.5[a], 2.3[b], 1.8[c], 2.5[d]	2.6[ab], 3.2[cd]

[a] at Lom

[b] at Amo

[c] at Hor

[d] at FsA and FsB

[e] Parameter uses opposite values to the linked parameter

[f] range tested in additional multiple runs

Table S5. Most important parameters with constant values

Symbol	Name	unit	Eq.	Definition	Value
ΔT_{Pa}	TempDiffPrec_Air	°C	(32)	difference between air temperature and infiltrating precipitation that will be considered for calculation in convective heat transport by precipitation to the soil	-2
Δz_{humus}	OrganicLayerThick	m	(33)	thickness of the humus layer as used as a thermal property	3[abd]; 2.5[c]
a_{pl}	AlbedoLeaf	%	(21)	plant albedo	25
$f_{leafharvest}$	FHarvest Leaf	-	(16)	the fraction of leaves that is harvested	0.85
$f_{leaflittharv}$	FLitter Leaf	-	(17)	fraction of the remaining leaves after harvest that enters the fast SOC pool	0.1
$f_{stemharvest}$	FHarvest Stem	-	(16)	the fraction of stem that is harvested	0.85
$f_{stemlittharv}$	FLitter Stem	-	(17)	fraction of the remaining stem after harvest that enters the fast C pool	0.1
g_{max}	CondMax	$m^2 s^{-1}$	(26)	the maximal conductance of fully open stomata	0.02
g_{ris}	CondRis	$J m^{-2} day^{-1}$	(26)	the global radiation intensity that represents half-light saturation in the light response	
g_{vpd}	CondVPD	Pa	(26)	the vapour pressure deficit that corresponds to a 50 % reduction of stomata conductance	100
h_1	OrganicC1	-	(33)	empirical constant in the heat conductivity of the organic material at the surface	0.06
h_2	OrganicC2	-	(33)	empirical constant in the heat conductivity of the organic material at the surface	0.005
k_h	RateCoefHumus	day^{-1}	(28)	rate coefficient for the decay of C in the slow pool	
l_{life}	Max Leaf Lifetime	a	(15)	maximum leaf lifetime	1
p_{cmax}	Max Cover	$m^2 m^{-2}$	(22)	maximum surface cover of plant	1
p_{fixedN}	FixedN	-	(3)	response for leaf C:N ratio	1
p_{mx}	PhoTempResMax	°C	(2)	maximum mean air temperature for photosynthesis	35
p_{o1}	PhoTempResOpt1	°C	(2)	lower limit mean air temperature for optimum photosynthesis	15
p_{o2}	PhoTempResOpt2	°C	(2)	upper limit mean air temperature for optimum photosynthesis	25
$p_{\theta Low}$	ThetaLowerRange	vol %	(31)	water content interval in the soil moisture response function for microbial activity, mineralisation−immobilisation, nitrification and denitrification.	13
$s_{oldleaf}$	Old Leaf(1)	-	(14)	scaling factor for litter fall of old leaf	1
$s_{oldroot}$	Old Roots(1)	-	(14)	scaling factor for litter fall of old roots	1
$s_{oldstem}$	Old Stem(1)	-	(14)	scaling factor for litter fall of old stem	1
η	Biomass to carbon	$mol C g^{-1} dw$	(1)	conversion factor from biomass to carbon	0.45

[a] at Lom

[b] at Amo

[c] at Hor

[d] at FsA and FsB

Table S6. CoupModel switches - differences to default configuration

Modules	Options	Value
Abiotic driving variables	SoilDrainageInput	Simulated
Abiotic driving variables	SoilInfilInput	Simulated
Abiotic driving variables	SoilTempInput	Simulated
Abiotic driving variables	SoilWaterFlowInput	Simulated
Abiotic driving variables	SoilWaterInput	Simulated
Abiotic driving variables	WaterStressInput	Simulated
Drainage and deep percolation	DriveDrainLevel	Driving File
Drainage and deep percolation	PhysicalDrainEq	Linear Model
External N inputs	N Deposition	on
Gas processes	Methane Model	Detailed
Gas processes	Methane emission by plants	on
Gas processes	Methane oxidation by plants	on
Gas processes	Trace Gas Emissions	Direct Loss
Hidden	AboveTable	No
Hidden	TAirGlobRad	Used
Hidden	TimeResolution	Hourly
Hidden	TypeOfDrivingFile	Standard driving file
Interception	PrecInterception	on
Meteorological Data	CloudInput	Estimated(sunshine)
Meteorological Data	HumRelInput	Read from PG-file (first position)
Meteorological Data	PrecInput	Read from PG-file (first position)
Meteorological Data	TempAirInput	Read from PG-file (first position)
Meteorological Data	VapourAirInput	As relative humidity
Model Structure	Evaporation	Radiation input style
Model Structure	GroundWaterFlow	on
Model Structure	LateralInput	WaterShed approach
Model Structure	Nitrogen and Carbon	Dynamic interaction with abiotics
Model Structure	PlantType	Explicit big leafes
Model Structure	SnowPack	on
Model Structure	WaterEq	On with complete soil profile
Numerical	NitrogenCarbonStep	Independent
Plant	AlbedoVeg	Simulated
Plant	CanopyHeightInput	Simulated
Plant	LaiInput	Simulated
Plant	PlantDevelopment	Start=f(TempSum)
Plant	RootInput	Simulated
Plant Growth	Growth	Radiation use efficiency

Plant Growth	Harvest Day	PG File specified
Plant Growth	Litter fall dynamics	f(DormingTempSum)
Plant Growth	N ReAllocation	On
Plant Growth	N fixed Supply	on
Plant Growth	PlantRespiration	Growth and Maintenance
Plant Growth	ReAllocationToLeaf	On
Plant Growth	Winter regulation	On
Soil evaporation	Evaporation Method	Iterative Energy Balance
Soil evaporation	Surface Temperature	f(E-balance Solution)
Soil frost	FrostSwelling	Off
Soil heat flows	Convection flow	Not accounted for
Soil mineral N processes	Denitrification	Microbial based
Soil mineral N processes	Nitrification	Microbial based
Soil organic processes	Initial Soil Organic	Table

Table S7. Criteria for accepted runs in the basic calibration (I a). Lower and upper limits are separated by fore slash. In case of R^2, the upper limit corresponds to the highest value achieved for this site. The criteria were selected to fit for around 75 runs and depend on the different performances achieved for the different sites.

Site	Accepted runs	R_{eco} ME	$R_{eco}R^2$	GPP ME	GPP R^2	LAI ME	LAI R^2	Winter R_{eco} ME	Winter GPP ME	NEE R^2	Root biomass ME
Lom	74	−0.15/0.15	0.72/0.79	−0.15/0.15	0.65/0.70	−0.2/0.2		−0.25/0.25	−0.25/0.25		
Amo	64	−0.2/0.2	0.65/0.71	−0.2/0.2	0.65/0.68	−0.5/0.5		−0.4/0.4	−0.4/0.4		
Hor	74	−0.5/0.5		−0.5/0.5					−2/2	0.48/0.53	−150/150
FsA	68	−0.85/0.85	0.5/0.73	−0.85/0.85	0.32	−0.3/0.3	0.58/0.75	−3/3	−1/1		
FsB	67	−0.8/0.8	0.65/0.87	−0.8/0.8	0.35/0.40	−0.25/0.25	0.65/0.82	−2/2	−1/1		

Table S8. Configurations of the selected single value representations C1-C7. Resulting values for k_{l1} and ε_L can be found in Figure 6.

Identifier	Description	t_{Q10} [-]	t_{Q10bas} [°C]	$p_{\theta Satact}$ [-]	$k_{mrespleaf}$ [day^{-1}]	C:N fast pool [-]	p_{ck} [-]
C1_basic	selected basic common configuration	2.7	18.5	0.05	0.017	27.5	0.42[a], 0.2[b], 0.9[c], 1[d]
C2_↑plant_resp	higher ratio of plant to soil respiration	2.7	18.5	0.05	0.022	27.5	0.42[a], 0.2[b], 0.9[c], 1[d]
C3_↑$p_{\theta Satact}$	higher saturation activity	2.7	18.5	0.40	0.017	27.5	0.42[a], 0.2[b], 0.9[c], 1[d]
C4_↑temp_response	steeper temperature response function	4.0	12.0	0.05	0.008	27.5	0.42[a], 0.2[b], 0.9[c], 1[d]
C5_C3&C4	higher saturation activity and steeper temperature response	4.0	12.0	0.40	0.008	27.5	0.42[a], 0.2[b], 0.9[c], 1[d]
C6_C:N_60	C:N of 60 for the fast decomposition pool	2.7	18.5	0.05	0.017	60	0.42[a], 0.2[b], 0.9[c], 1[d]
C7_common_p_{ck}	same p_{ck} value for all sites	2.7	18.5	0.05	0.017	27.5	1

[a] at Lom

[b] at Amo

[c] at Hor

[d] at FsA and FsB

Table S9. Variables and related parameter as used for further parameter constraint in step I c and III

Variable	Site	Parameter
R_{eco}	Lom, Amo, Hor, FsA, FsB	$l_{cl}, l_{Sc1}, l_{Sc2}, l_{Lc1}, l_{Lc2}, l_{LaiEnh}, T_{MatureSum}, T_{DormTth}, t_{R1}, t_{R2}, t_{S1}, t_{S2}, g_{maxwin}, k_{mrespstem}, k_{mresproot}, p_{\theta Satact}, p_{\theta Upp}, l_{l1}, p_{\theta}, k_{l}, T_{EmergeSum}, t_{Q10}, t_{Q10bas}$
GPP	Lom, Amo, Hor, FsA, FsB	$k_{rn}, p_{ck}, \varepsilon_{L}, p_{l,sp}, l_{cl}, s_{newroot}, s_{newleaf}, s_{newstem}, l_{Rc1}, l_{Rc2}, l_{Sc1}, l_{Sc2}, l_{Lc1}, l_{Lc2}, l_{LaiEnh}, T_{MatureSum}, l_{LS}, T_{DormTth}, t_{L1}, t_{L2}, t_{R1}, t_{R2}, t_{S1}, t_{S2}, m_{shoot}, m_{retain}, T_{EmergeTh}, T_{EmergeSum}, p_{mn}, g_{maxwin}, g_{ph}, k_{mrespstem}, k_{mresproot}, k_{gresp}, k_{mrespleaf}, t_{Q10}, t_{Q10bas}$
winter R_{eco}	Lom, Amo, Hor, FsA, FsB	$t_{R1}, t_{R2}, t_{S1}, t_{S2}, k_{gresp}, p_{\theta Satact}, p_{\theta Upp}, l_{l1}, p_{\theta}, k_{l}, T_{EmergeSum}, t_{Q10}, t_{Q10bas}$
winter GPP	Lom, Amo, Hor, FsA, FsB	$l_{cl}, s_{newstem}, l_{Sc2}, l_{Lc1}, T_{MatureSum}, l_{LS}, T_{DormTth}, t_{L1}, t_{L2}, t_{R1}, t_{R2}, t_{S1}, t_{S2}, p_{mn}, g_{maxwin}, g_{ph}, k_{gresp}, k_{mrespleaf}$
upper most soil temperature	Lom, Amo, Hor, FsA, FsB	$k_{rn}, p_{ck}, \varepsilon_{L}$
lowest soil temperature	Lom, Amo, Hor, FsA, FsB	T_{amean}
LAI	Lom, Hor, FsA, FsB	$k_{rn}, p_{ck}, \varepsilon_{L}, p_{l,sp}, l_{cl}, s_{newleaf}, l_{LaiEnh}, T_{MatureSum}, T_{DormTth}, t_{L1}, t_{L2}, m_{shoot}, m_{retain}, T_{EmergeTh}, T_{EmergeSum}, m_{Root}, , k_{mrespleaf}\, r_{rl}, g_{ph}$
snow depth	Lom	
green above ground biomass	Hor, FsA, FsB	$\varepsilon_{L}, p_{l,sp}, s_{newroot}, s_{newleaf}, s_{newstem}, g_{ph}$
total above ground biomass	Hor, FsA, FsB	$s_{newstem}, l_{LS}, g_{ph}, k_{mrespleaf}$
root biomass	Hor	$l_{cl}, s_{newroot}, l_{Rc1}, l_{Rc2}$

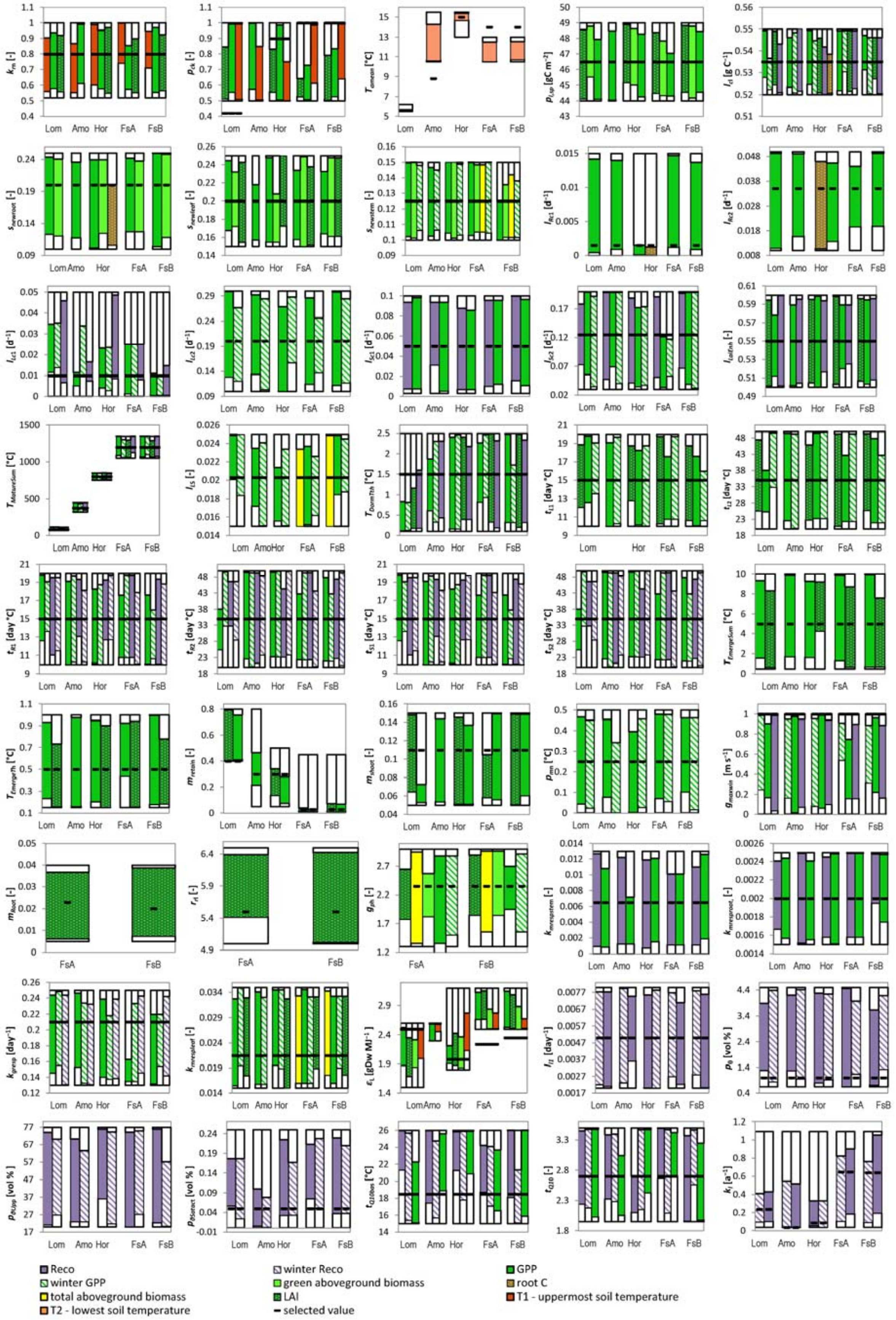
Lom
Amo
Hor
FsA
FsB
Reco
winter Reco
GPP
winter GPP
green aboveground biomass
root C
total aboveground biomass
LAI
T1 - uppermost soil temperature
T2 - lowest soil temperature
selected value

Figure S1. Tested parameters and ranges of the basic calibration and for configuration C1 selected values. Each solid bar show the range of the 10 out of 350'000 runs with the best performance index for a validation variable (x-axis). Only those bars were shown where either a covariance between the performance on this variable and the parameter were detected or expected due to model equations. Tested ranges are indicated by the grey frame around the bar.