Model description

Ecosys represents multiple canopy and soil layers and fully coupled carbon, energy, water, and nutrient cycles solved at an hourly time step. Surface energy and water exchanges drive soil heat and water transfers to determine soil temperatures and water contents. These transfers drive soil freezing and thawing and, hence, active layer depth, through the general heat flux equation. Carbon uptake is controlled by plant water status calculated from convergence solutions that equilibrate total root water uptake with transpiration. Atmospheric warming increases surface heat advection, soil heat transfers, and hence active layer depth. Canopy temperatures affect CO_2 fixation rates from their effects on carboxylation and oxygenation modeled with Arrhenius functions for light and dark reactions. Soil temperatures affect heterotrophic respiration through the same Arrhenius function as for dark reactions.

Carbon uptake is also affected by plant nitrogen uptake. The model represents fully coupled transformations of soil carbon, nitrogen, and phosphorus through microbially driven processes. Soil warming enhances carbon uptake by hastening microbial mineralization and root nitrogen uptake. Carbon uptake is affected by phenology with leafout and leafoff (deciduous plants) or dehardening and hardening (evergreen plants) being determined by accumulated exposure to temperatures above set values while day length is increasing or below set values while day length is decreasing. Senescence is driven by excess maintenance respiration and by phenology in deciduous plant functional types.

Ecosystem-Atmosphere energy exchange:

Canopy energy and water exchanges in *ecosys* are calculated through a multi-layered soil-root-canopy system. The clumping effect for each leaf and stem surface is represented by a species-specific interception fraction to simulate non-uniformity in the horizontal distribution of leaves within each canopy layer. Coupled first-order closure schemes are solved between the atmosphere and each of leaf and stem surfaces in the multi-layered canopy to achieve energy balance at each model time step. Once the system converges to the required canopy temperature, latent and sensible heat fluxes of each canopy layer are calculated based on the simulated vapor pressure deficit, canopy-atmosphere temperature gradient, aerodynamic conductance, and stomatal conductance. Canopy heat storage is calculated from changes in canopy temperature and heat capacities of leaves, twigs, and stems.

Canopy water relations:

A convergence solution is sought for the canopy water potential of each plant population at which the difference between its transpiration and total root water uptake equals the difference between its water contents at the previous and current water potentials. Canopy water potential controls transpiration and soil-root water uptake, which affects stomatal conductance and thereby all the processes (e.g., canopy temperature and vapor pressure) described in “Ecosystem-Atmosphere energy exchange”.

Canopy carbon and nutrient cycling:

Leaf carboxylation rates are adjusted from those calculated under non-limiting water potential to those under current water potential. The gross canopy CO_2 fixation is the sum of the leaf carboxylation rate of each leaf surface present on each branch of each plant species, which is then transported to a mobile pool of carbon storage. Storage carbon oxidized in excess of maintenance respiration requirements is used as growth respiration to drive the formation of new biomass. Net CO_2 fixation is calculated as the difference between gross fixation and the sum of maintenance, growth, and senescence respiration in the simulated canopy.

Nutrient (nitrogen and phosphorous) uptake is calculated for each plant species by solving for aqueous concentrations at root and mycorrhizal surfaces in each soil layer at which radial transport by mass flow and diffusion from the soil solution to the surfaces equals active uptake by the surfaces. This solution dynamically links rates of soil nutrient transformations with those of root and mycorrhizal nutrient uptake. The products of nitrogen and phosphorous uptake are transported to mobile pools of nitrogen and phosphorous stored in each root and mycorrhizal layer, which regulate vegetation growth.

Plant functional type dynamics:

The model represents prognostic vegetation dynamics with internal resource allocation and remobilization. Shifts in plant functional types are modeled through processes of plant functional type competition for light, water, and nutrients within each canopy and rooted soil layer depending on leaf area and root length. Each plant functional type competes for nutrient and water uptake from common nutrient and water stocks held across multi-layer soil profiles, calculated from algorithms for transformations and transfers of soil carbon, nitrogen, and phosphorus, and for transfers of soil water. Modeled differences in plant functional type functional traits determine the strategy of resource acquisition and allocation that drive growth, resource remobilization, and litterfall, and therefore each plant functional type dynamic competitive capacity under different environmental conditions.

Soil microbial activity:

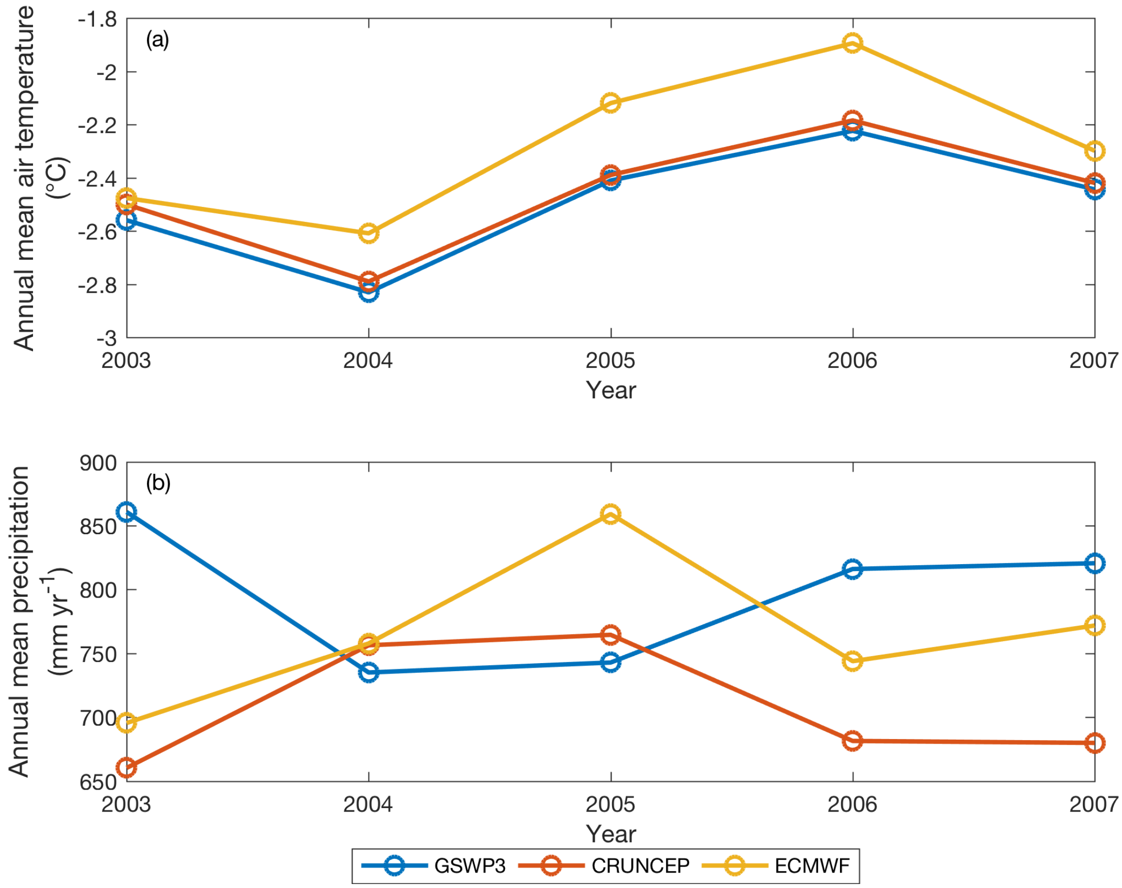
The modeling of microbial activity is based on six organic states: solid, soluble, sorbed, acetate, microbial biomass, and microbial residues. Carbon, nitrogen and phosphorous may move among these states within each of four organic matter-microbe complexes: plant litterfall, animal manure, particulate organic matter, and humus. Microbial biomass in *ecosys* is an active agent of organic matter transformation. The rate at which each component is hydrolyzed is a function of substrate concentration that approaches a first-order function at low concentrations, and a zero-order function at high concentrations. These rates are regulated by soil temperature through an Arrhenius function and by soil water content through its effect on microbial concentration. Similar to the growth and decline of vegetation biomass described above, the net change in microbial biomass is determined by the difference between heterotrophic respiration and maintenance respiration. When heterotrophic respiration is greater than maintenance respiration, the excessive amount of respiration is used as growth respiration that drives microbial growth according to the energy requirements of biosynthesis.

Supplemental Material Table 1. Key soil properties of the (a) palsa (b) bog (c) fen at Stordalen Mire used in *ecosys*.

	Depth m	BD mg m^{-3}	K_{sat} mm h^{-1}	TOC g kg^{-1}	TON g kg^{-1}	FC m^3 m^{-3}	WP m^3 m^{-3}	pH
(a) Palsa								
	0.01	0.10	100	452.04	8.88	0.4	0.15	3.9
	0.05	0.10	100	438.38	9.62	0.4	0.15	3.9
	0.1	0.12	25	388.16	10.90	0.4	0.15	3.9
	0.2	0.20	25	343.97	12.21	0.4	0.15	3.9
	0.3	0.30	25	331.83	13.86	0.4	0.15	4.1
	0.4	0.80	20	304.80	14.19	0.4	0.15	4.5
	0.5	1.20	18	208.73	10.89	0.4	0.15	4.4
	0.6	1.20	15	206.77	10.88	0.4	0.15	4.4
	0.7	1.23	13	203.92	10.77	0.4	0.15	5.1
	0.9	1.25	12	200.71	11.10	0.4	0.15	5.3
	1.1	1.25	12	150.00	8.60	0.2	0.11	5.3
	1.3	1.35	10	120.00	7.60	0.2	0.11	5.3
	1.5	1.35	10	120.00	7.60	0.2	0.11	5.3
(b) Bog								
	0.01	0.02	500	390.20	4.22	0.4	0.15	4.2
	0.05	0.02	500	407.15	5.59	0.4	0.15	4.2
	0.1	0.04	500	403.20	6.81	0.4	0.15	4.2
	0.2	0.04	500	418.90	8.83	0.4	0.15	4.2
	0.3	0.15	300	461.90	11.93	0.4	0.15	4.2
	0.4	0.35	200	466.60	13.06	0.4	0.15	4.4
	0.5	1.05	100	466.20	13.30	0.4	0.15	4.6
	0.6	1.25	60	406.20	13.30	0.4	0.15	4.7
	0.7	1.30	50	406.20	13.30	0.4	0.15	4.8
	0.9	1.33	40	406.20	13.30	0.4	0.15	4.9
	1.1	1.35	25	400.00	13.60	0.2	0.11	5.0
	1.3	1.35	15	400.00	13.60	0.2	0.11	5.0
	1.5	1.35	15	400.00	13.60	0.2	0.11	5.0
(c) Fen								
	0.01	0.02	500	436.90	13.47	0.4	0.15	5.7
	0.05	0.02	500	435.18	14.97	0.4	0.15	5.7
	0.1	0.04	500	435.14	15.55	0.4	0.15	5.7
	0.2	0.04	500	380.83	15.55	0.4	0.15	5.7
	0.3	0.15	300	340.83	14.47	0.4	0.15	5.7
	0.4	0.35	200	336.51	16.49	0.4	0.15	5.7
	0.5	0.70	100	336.51	17.65	0.4	0.15	5.7

0.6	1.10	60	430.21	22.65	0.4	0.15	5.7
0.7	1.20	50	430.21	22.65	0.4	0.15	5.8
0.9	1.25	40	430.51	22.65	0.4	0.15	5.9
1.1	1.30	25	430.51	22.60	0.2	0.11	6.0
1.3	1.35	15	380.00	20.60	0.2	0.11	6.0
1.5	1.35	15	380.00	20.60	0.2	0.11	6.0

Abbreviations BD: bulk density, K_{sat}: saturated hydraulic conductivity, TOC: total organic carbon, TON: total organic nitrogen, FC: field capacity, WP: wilting point.



Supplemental Material Figure 1. Annual mean air temperature (a) and precipitation (b) extracted from GSWP3 (blue), CRUNCEP (red), and ECMWF (yellow) at the Stordalen Mire.