The Cryosphere

Supplement of

Large carbon cycle sensitivities to climate across a permafrost thaw gradient in subarctic Sweden

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1   **Model description**

2   *Ecosys* represents multiple canopy and soil layers and fully coupled carbon, energy,

3   water, and nutrient cycles solved at an hourly time step. Surface energy and water exchanges

4   drive soil heat and water transfers to determine soil temperatures and water contents. These

5   transfers drive soil freezing and thawing and, hence, active layer depth, through the general heat

6   flux equation. Carbon uptake is controlled by plant water status calculated from convergence

7   solutions that equilibrate total root water uptake with transpiration. Atmospheric warming

8   increases surface heat advection, soil heat transfers, and hence active layer depth. Canopy

9   temperatures affect CO_2 fixation rates from their effects on carboxylation and oxygenation

10   modeled with Arrhenius functions for light and dark reactions. Soil temperatures affect

11   heterotrophic respiration through the same Arrhenius function as for dark reactions.

12   Carbon uptake is also affected by plant nitrogen uptake. The model represents fully

13   coupled transformations of soil carbon, nitrogen, and phosphorus through microbially driven

14   processes. Soil warming enhances carbon uptake by hastening microbial mineralization and root

15   nitrogen uptake. Carbon uptake is affected by phenology with leafout and leafoff (deciduous

16   plants) or dehardening and hardening (evergreen plants) being determined by accumulated

17   exposure to temperatures above set values while day length is increasing or below set values

18   while day length is decreasing. Senescence is driven by excess maintenance respiration and by

19   phenology in deciduous plant functional types.

20

21   *Ecosystem-Atmosphere energy exchange:*

22   Canopy energy and water exchanges in *ecosys* are calculated through a multi-layered

23   soil-root-canopy system. The clumping effect for each leaf and stem surface is represented by a

24 species-specific interception fraction to simulate non-uniformity in the horizontal distribution of

25 leaves within each canopy layer. Coupled first-order closure schemes are solved between the

26 atmosphere and each of leaf and stem surfaces in the multi-layered canopy to achieve energy

27 balance at each model time step. Once the system converges to the required canopy temperature,

28 latent and sensible heat fluxes of each canopy layer are calculated based on the simulated vapor

29 pressure deficit, canopy-atmosphere temperature gradient, aerodynamic conductance, and

30 stomatal conductance. Canopy heat storage is calculated from changes in canopy temperature

31 and heat capacities of leaves, twigs, and stems.

32

33 *Canopy water relations:*

34   A convergence solution is sought for the canopy water potential of each plant population

35 at which the difference between its transpiration and total root water uptake equals the difference

36 between its water contents at the previous and current water potentials. Canopy water potential

37 controls transpiration and soil-root water uptake, which affects stomatal conductance and thereby

38 all the processes (e.g., canopy temperature and vapor pressure) described in "Ecosystem-

39 Atmosphere energy exchange". The water table depth in *ecosys* is calculated at the end of each

40 time step as the depth to the top of the saturated zone below which air-filled porosity is zero.

41 Changes in the simulated water table depth were driven by dynamical interactions among

42 precipitation, evapotranspiration, vertical water transport, and lateral water transport.

43

44 *Canopy carbon and nutrient cycling:*

45   Leaf carboxylation rates are adjusted from those calculated under non-limiting water

46 potential to those under current water potential. The gross canopy CO_2 fixation is the sum of the

47   leaf carboxylation rate of each leaf surface present on each branch of each plant species, which is

48   then transported to a mobile pool of carbon storage. Storage carbon oxidized in excess of

49   maintenance respiration requirements is used as growth respiration to drive the formation of new

50   biomass. Net CO_2 fixation is calculated as the difference between gross fixation and the sum of

51   maintenance, growth, and senescence respiration in the simulated canopy.

52   Nutrient (nitrogen and phosphorous) uptake is calculated for each plant species by

53   solving for aqueous concentrations at root and mycorrhizal surfaces in each soil layer at which

54   radial transport by mass flow and diffusion from the soil solution to the surfaces equals active

55   uptake by the surfaces. This solution dynamically links rates of soil nutrient transformations with

56   those of root and mycorrhizal nutrient uptake. The products of nitrogen and phosphorous uptake

57   are transported to mobile pools of nitrogen and phosphorous stored in each root and mycorrhizal

58   layer, which regulate vegetation growth.

59

60   *Plant functional type dynamics:*

61   The model represents prognostic vegetation dynamics with internal resource allocation

62   and remobilization. Shifts in plant functional types are modeled through processes of plant

63   functional type competition for light, water, and nutrients within each canopy and rooted soil

64   layer depending on leaf area and root length. Each plant functional type competes for nutrient

65   and water uptake from common nutrient and water stocks held across multi-layer soil profiles,

66   calculated from algorithms for transformations and transfers of soil carbon, nitrogen, and

67   phosphorus, and for transfers of soil water. Modeled differences in plant functional type

68   functional traits determine the strategy of resource acquisition and allocation that drive growth,

69   resource remobilization, and litterfall, and therefore each plant functional type dynamic

70   competitive capacity under different environmental conditions.

71

72   *Soil microbial activity:*

73   The modeling of microbial activity is based on six organic states: solid, soluble, sorbed,

74   acetate, microbial biomass, and microbial residues. Carbon, nitrogen and phosphorous may move

75   among these states within each of four organic matter-microbe complexes: plant litterfall, animal

76   manure, particulate organic matter, and humus. Microbial biomass in *ecosys* is an active agent of

77   organic matter transformation. The rate at which each component is hydrolyzed is a function of

78   substrate concentration that approaches a first-order function at low concentrations, and a zero-

79   order function at high concentrations. These rates are regulated by soil temperature through an

80   Arrhenius function and by soil water content through its effect on microbial concentration.

81   Similar to the growth and decline of vegetation biomass described above, the net change in

82   microbial biomass is determined by the difference between heterotrophic respiration and

83   maintenance respiration. When heterotrophic respiration is greater than maintenance respiration,

84   the excessive amount of respiration is used as growth respiration that drives microbial growth

85   according to the energy requirements of biosynthesis.

86

87   Supplemental Material Table 1. Key soil properties of the (a) palsa (b) bog (c) fen at the

88   Stordalen Mire used in *ecosys*.

	Depth	BD	K_{sat}	TOC	TON	FC	WP	pH
	m	mg m^{-3}	mm h^{-1}	g kg^{-1}	g kg^{-1}	m^3 m^{-3}	m^3 m^{-3}	
(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

89 Abbreviations BD: bulk density, K_{sat}: saturated hydraulic conductivity, TOC: total organic

90 carbon, TON: total organic nitrogen, FC: field capacity, WP: wilting point.

91

92   Supplemental Material Table 2. Key vegetation parameters of the (a) palsa (b) bog (c) fen at the

93   Stordalen Mire used in *ecosys*.

		$V_{c, max}$	$C_i:C_a$	SLA	Leaf N:C	Root N:C	Leaf P:C	Root P:C	Planting density
		$\mu mol\ g^{-1}s^{-1}$		$m^2/g\ C$	g N/g C	g N/g C	g P/g C	g P/g C	m^{-2}
(a) Palsa									
	Shrub	45	0.7	4.50E-03	7.00E-02	1.75E-02	7.00E-03	1.75E-03	1.00E+00
	Lichen	45	0.7	1.67E-03	4.00E-02	2.00E-02	4.00E-03	2.00E-03	1.00E+02
	Moss	45	0.7	1.67E-03	8.00E-02	4.00E-02	8.00E-03	4.00E-03	1.00E+03
	Sedge	45	0.7	3.33E-03	1.00E-01	2.50E-02	1.00E-02	2.50E-03	1.00E+00
(b) Bog									
	Moss	45	0.7	1.67E-03	4.00E-02	2.00E-02	4.00E-03	2.00E-03	6.00E+03
	Sedge	45	0.7	3.33E-03	1.00E-01	2.50E-02	1.00E-02	2.50E-03	2.00E+01
(c) Fen									
	Sedge	45	0.7	3.33E-03	3.00E-02	7.50E-03	3.00E-03	7.50E-04	1.00E+01

94

95   Abbreviations Vc, max: Rubisco Carboxylation Activity, Ci:Ca: Ratio of CO2 concentration
96   across stomata, SLA: Specific Leaf Area, Leaf N:C: Leaf Nitrogen:Carbon ratio, Root N:C: Root
97   Nitrogen:Carbon ratio, Leaf P:C: Leaf Phosphorus:Carbon ratio, Root P:C: Root
98   Phosphorus:Carbon ratio
99
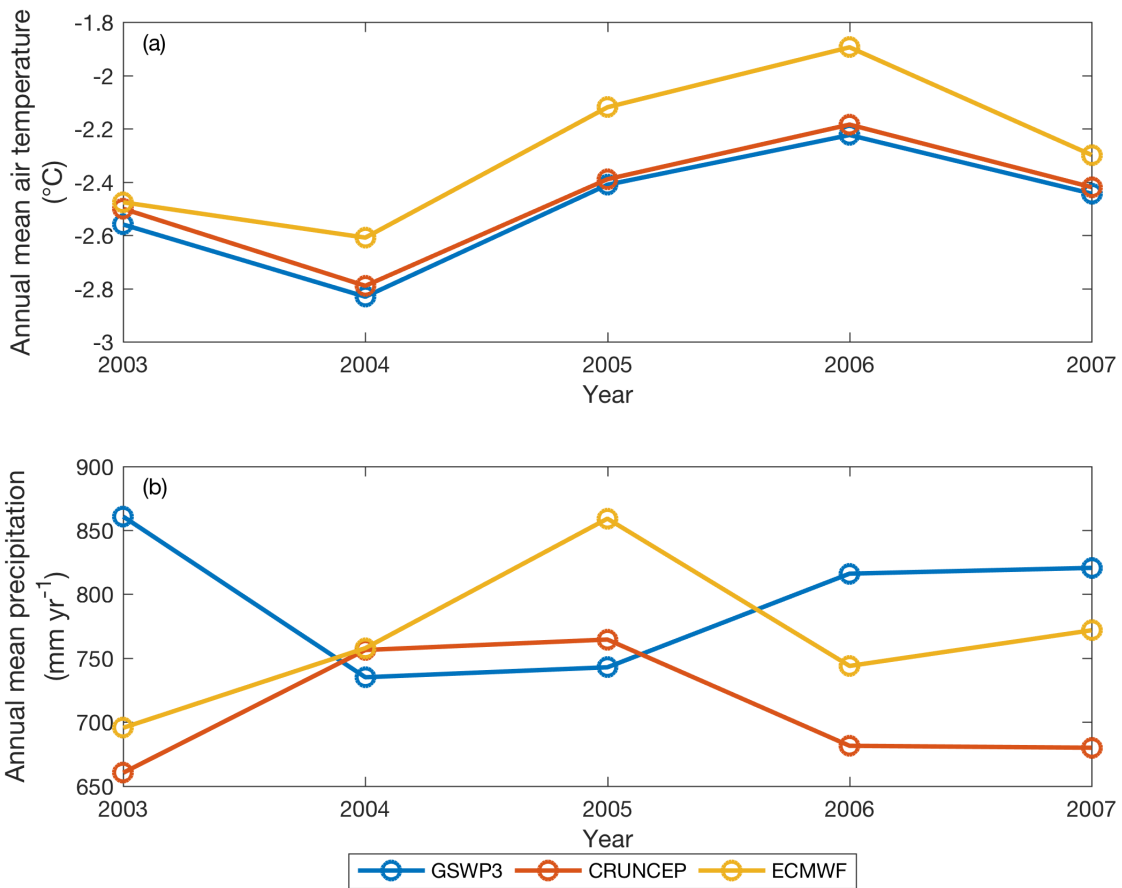
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101   Supplemental Material Figure 1. Annual mean air temperature (a) and precipitation (b) extracted

102   from GSWP3 (blue), CRUNCEP (red), and ECMWF (yellow) at the Stordalen Mire.

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