



Supplement of

Ecosystem respiration during snowmelt and soil thaw leads to a rare annual CO₂ net loss in a boreal fen

Karoliina Särkelä et al.

Correspondence to: Karoliina Särkelä (karoliina.sarkela@oulu.fi)

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Table S1. Non-productive and productive seasons: duration and mean NEE and air temperature during each period.

Non-productive season					Productive season				
Year	Non-productive season	Duration (days)	Mean NEE (g C/m ² /day)	Mean Air T (°C)	Year	Productive season	Duration (days)	Mean NEE (g C/m ² /day)	Mean Air T (°C)
2005-2006	07.10. – 18.03.	162	0.22	-3.76	2006	19.03. – 23.08.	158	-0.32	10.9
2006-2007	24.08. – 26.04.	245	0.19	1.51	2007	27.04. – 20.09.	147	-0.61	12.7
2007-2008	21.09. – 28.04.	220	0.14	-0.07	2008	29.04. – 13.09.	138	-0.88	12.0
2008-2009	14.09. – 26.04.	223	0.20	-0.44	2009	27.04. – 20.09.	147	-0.62	13.2
2009-2010	21.09. – 03.05.	224	0.17	-4.31	2010	04.05. – 10.09.	130	-0.77	14.9
2010-2011	11.09. – 26.04.	227	0.19	-3.22	2011	27.04. – 25.10.	182	-0.66	12.7
2011-2012	26.10. – 28.04.	185	0.14	-2.50	2012	29.04. – 26.09.	152	-0.97	12.2
2012-2013	27.09. – 30.04.	214	0.24	-2.78	2013	01.05. – 17.09.	140	-1.04	14.8
2013-2014	18.09. – 21.04.	215	0.22	0.06	2014	22.04. – 20.09.	152	-0.92	13.5
2014-2015	21.09. – 29.04.	220	0.24	0.30	2015	30.04. – 15.09.	139	-0.88	12.7
2015-2016	16.09. – 01.06.	259	0.33	1.43	2016	02.06. – 21.09.	112	-0.51	14.2
2016-2017	22.09. – 19.05.	238	0.18	-0.66	2017	20.05. – 29.09.	133	-0.69	12.4
2017-2018	30.09. – 07.05.	219	0.23	-1.57	2018	08.05. – 29.07.	83	-0.65	16.7
2018-2019	30.07. – 04.05.	278	0.25	3.09	2019	05.05. – 03.09.	122	-0.62	14.3
2019-2020	04.09. – 11.05.	250	0.22	1.43	2020	12.05. – 02.09.	114	-0.74	14.6
2020-2021	03.09. – 26.04.	234	0.27	0.11	2021	27.4. – 10.9	136	-0.85	14.3

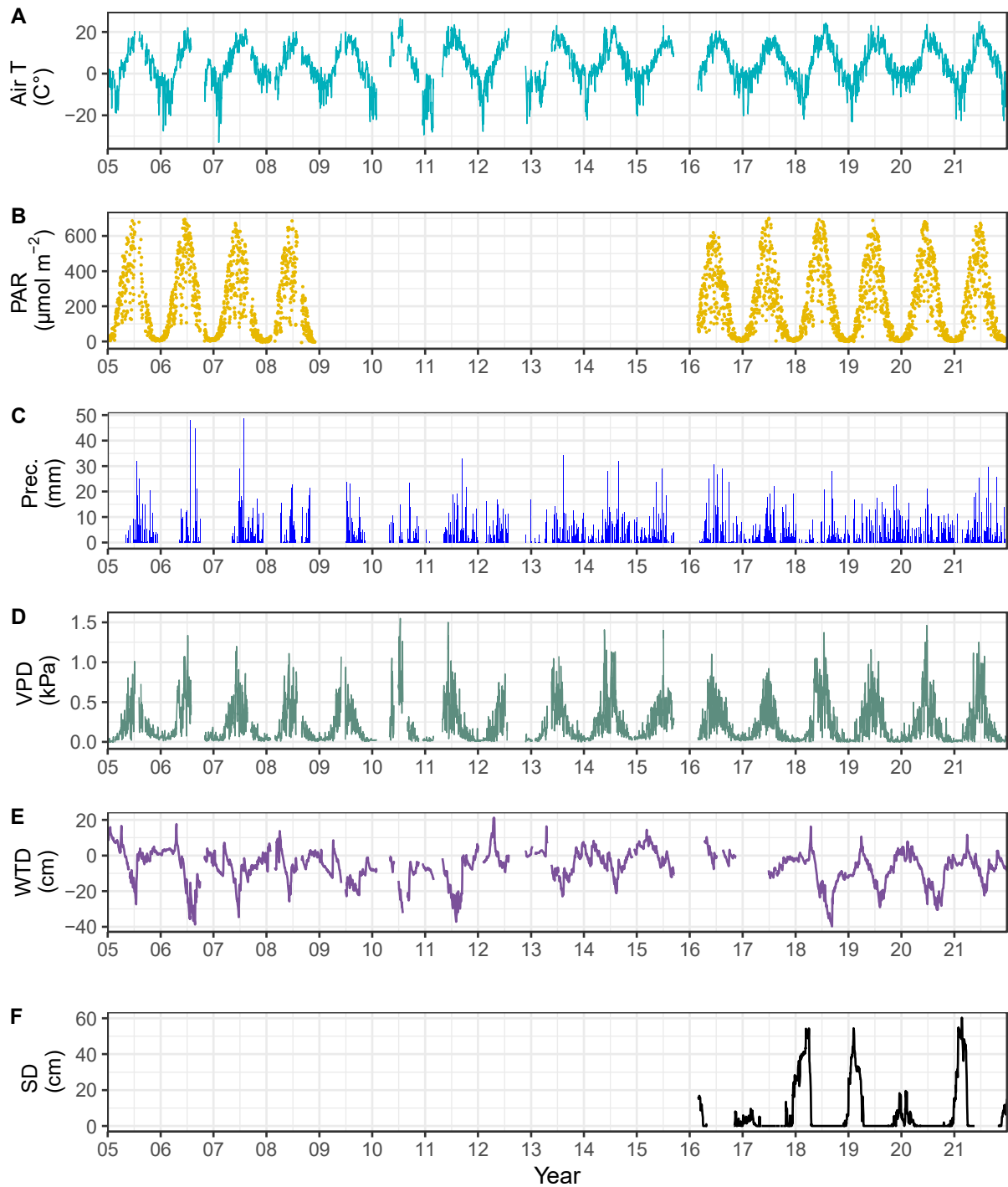


Figure S1. Time series of air temperature (A), precipitation (B), photosynthetically active radiation (C), vapor pressure deficit (D), water table depth (E) and snow depth (F) in 2005-2021. Precipitation is expressed as daily sums and is calculated from the hourly summed data. The other variables are expressed as daily means and are

calculated from hourly averaged data. Data for PAR in 2009-2015 was not used due to instrument malfunction. Snow depth measurements started at spring 2016. Precipitation data shown in the figure is measured with ARG-100 tipping bucket rain gauge in 2006-2016 and with OTT Pluvio2S weighing rain gauge in 2017-2021.

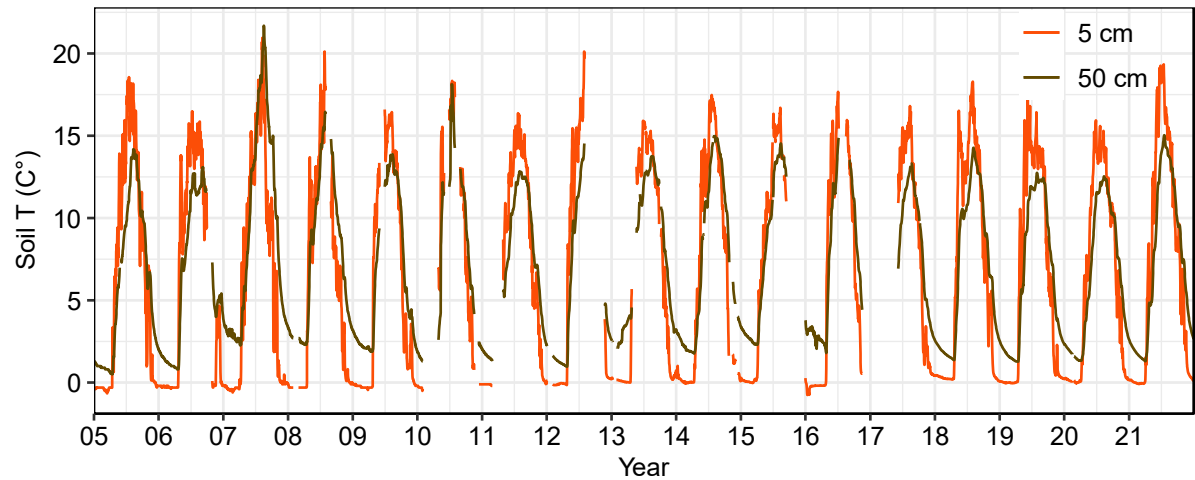
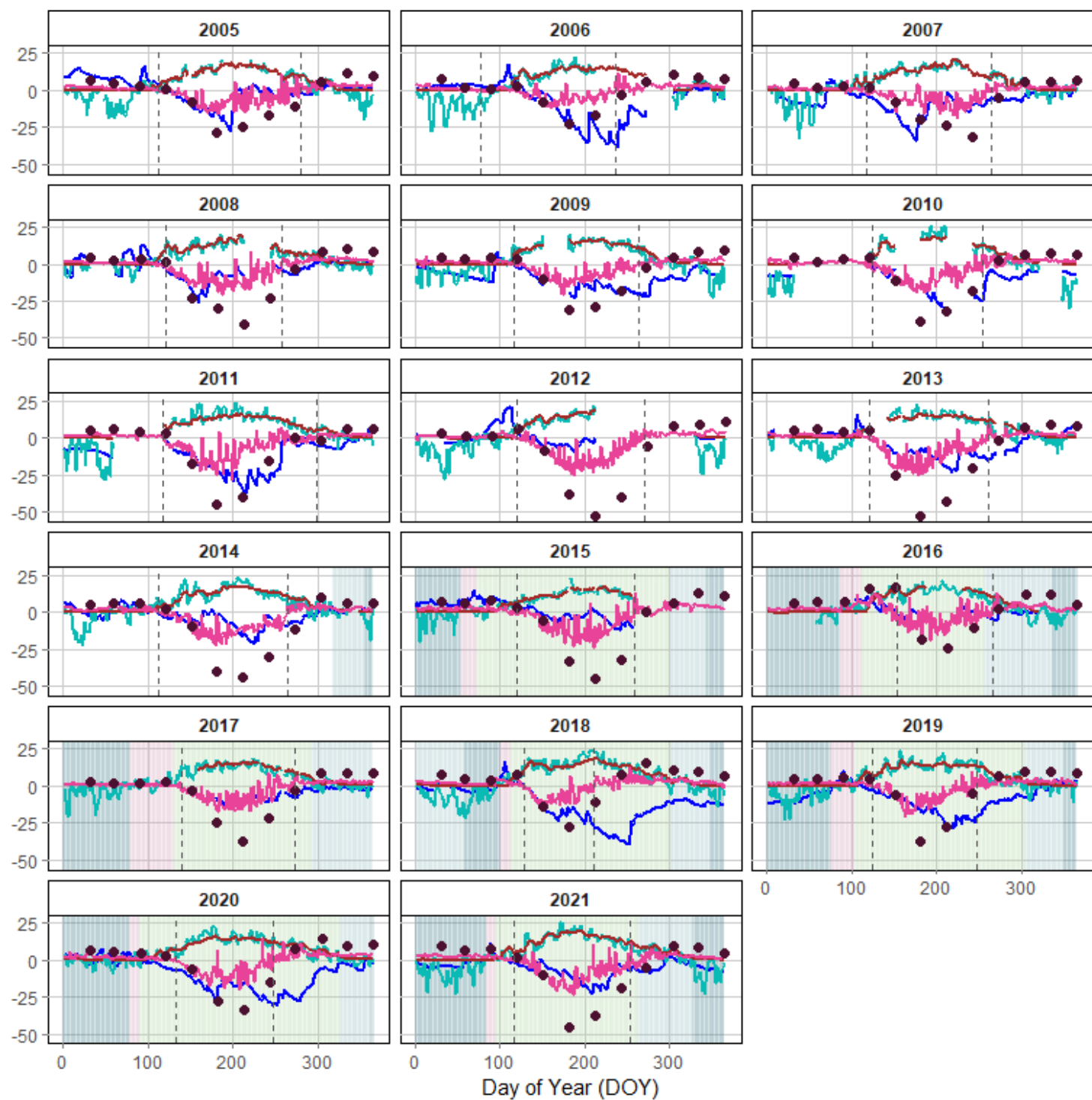


Figure S2. Time series of daily means of soil temperature at 5 cm depth (red line) and 50 cm depth (brown line). Daily means are calculated from hourly averaged data. The measurement practices changed in 2017, including the measurement depth. The figure of the time series of soil temperature at 50 cm depth includes the temperature measured at 50 cm depth for 2005-2016 and temperature measured at 45 cm depth for 2017-2021. The data for both measuring depths is from lawn microsite for 2005-2016 and an average of five microsites for 2017-2021.



Freeze/Thaw State freezing frozen thawed thawing

Variable Air Temperature (celsius) NEE g C/day x 10 NEE g C/month Soil Temperature Water Table Depth

Figure S3. Daily sums of te Net ecosystem exchange of CO₂ (NEE), air and soil temperature and water table depth during each year 2005-2021. The end and start of the productive season are marked with vertical dashed lines - first three days of negative NEE marked the end of the productive season and first three consecutive days of positive NEE marked the start of productive season. Freeze-thaw status is marked with the background colour for the years 2014-2021. The status is determined for a 200meter radius from the Eddy Covariance mast and determined from Sentinel-1 IW GRD radar backscatter time series. Monthly sums of NEE are marked with a brown scatter. The daily values of NEE are multiplied by 10 for visibility.

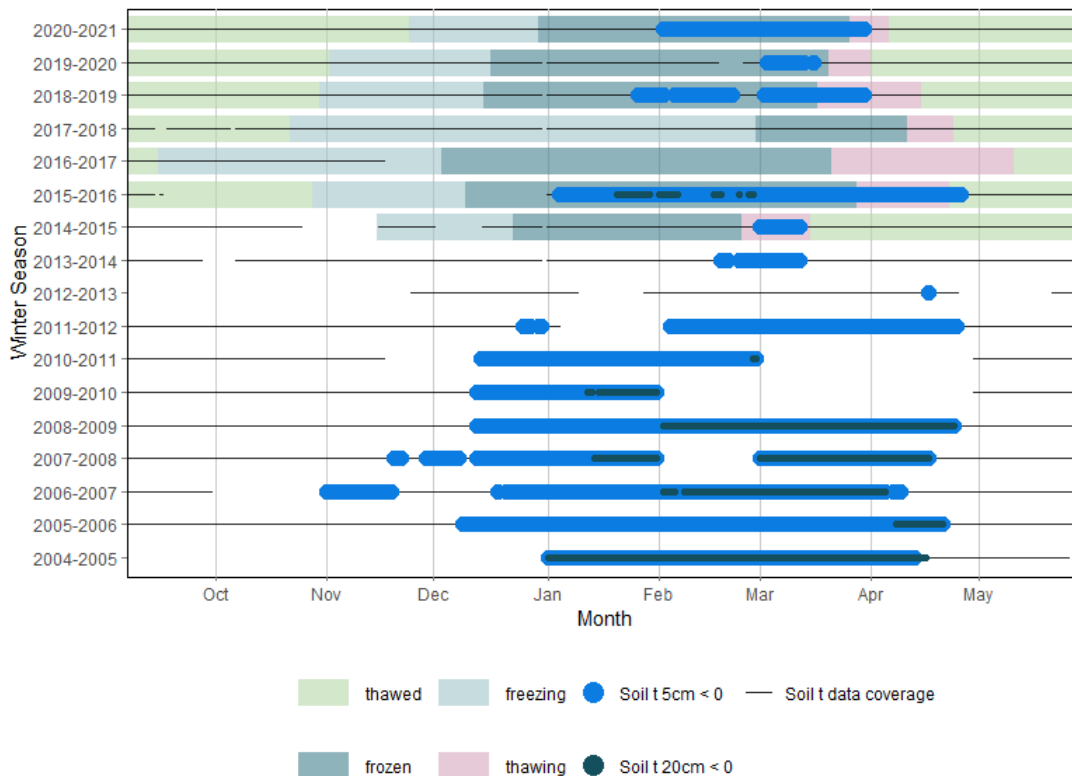


Figure S4. Freeze-thaw status and site-measured soil temperature (Soil t) below freezing temperatures during winter. The freeze-thaw status has been assigned for 200m radius around the eddy-Scovariance (EC) mas, and is determined from Sentinel-1 IW GRD radar backscatter time series. Soil temperature is measured on site. Daily mean soil temperature below 0°C at 5 cm (light blue) and 20 cm (dark blue) depth are marked as thick lines. Horizontal line shows the data coverage for the soil temperature.

Table S2. Freezing, frozen and thawing periods for 2014-2021. The status is determined for a 200meter radius from EC mast. The freezing and thawing periods were determined from Sentinel-1 IW GRD radar backscatter time series (2014–2021) using visual inspection of median VV, VH, and VH/VV ratio trends from both orbit directions, supported by ground measurements of temperature, soil moisture, and snow depth.

Winter-Spring	Freezing Period	Frozen Period	Thawing Period	Freezing Duration (days)	Frozen Duration (days)	Thawing Duration (days)
2014-2015	15.11 – 22.12	23.12 – 23.02	24.02 – 14.03	38	63	19
2015-2016	28.10 – 09.12	10.12 – 26.03	27.03 – 21.04	43	108	26
2016-2017	14.09 – 01.12	02.12 – 20.03	21.03 – 10.05	79	109	51
2017-2018	22.10 – 27.02	28.02 – 10.04	11.04 – 23.04	129	42	13
2018-2019	30.10 – 14.12	15.12 – 16.03	17.03 – 14.04	46	92	29
2019-2020	02.11 – 16.12	17.12 – 18.03	19.03 – 30.03	45	93	12
2020-2021	23.11 – 28.12	29.12 – 25.03	26.03 – 05.04	36	87	11
2021-2022	21.09 – 24.11	-	-	65	-	-

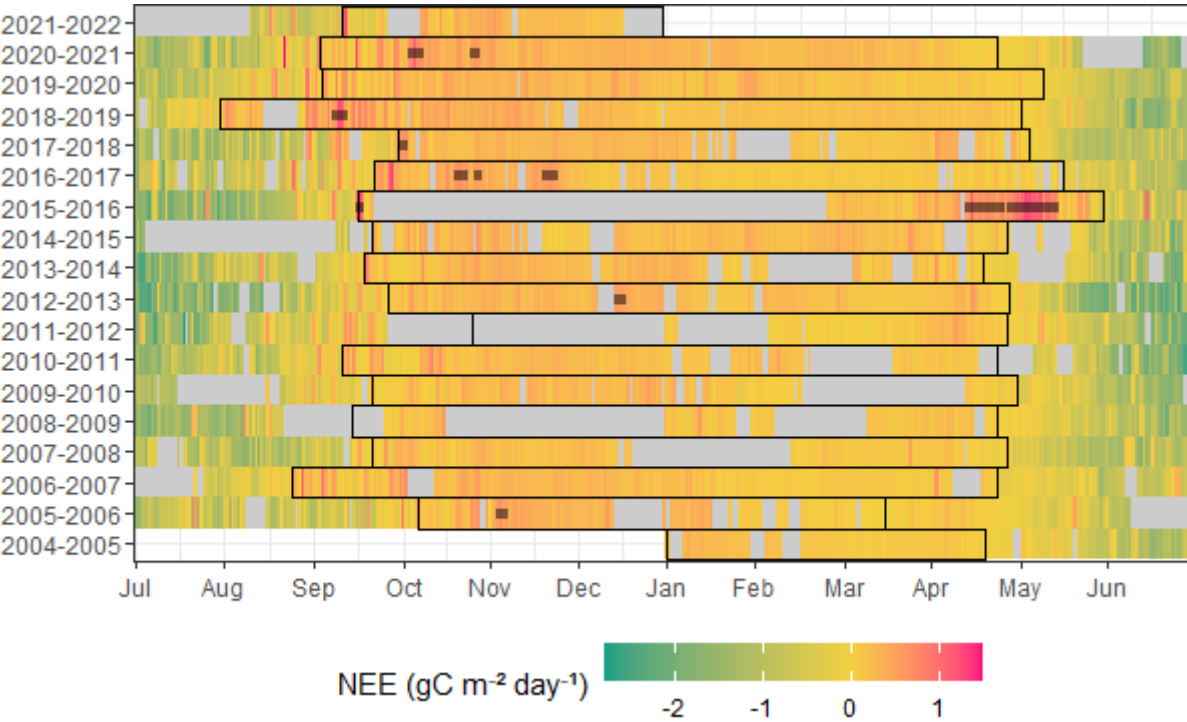
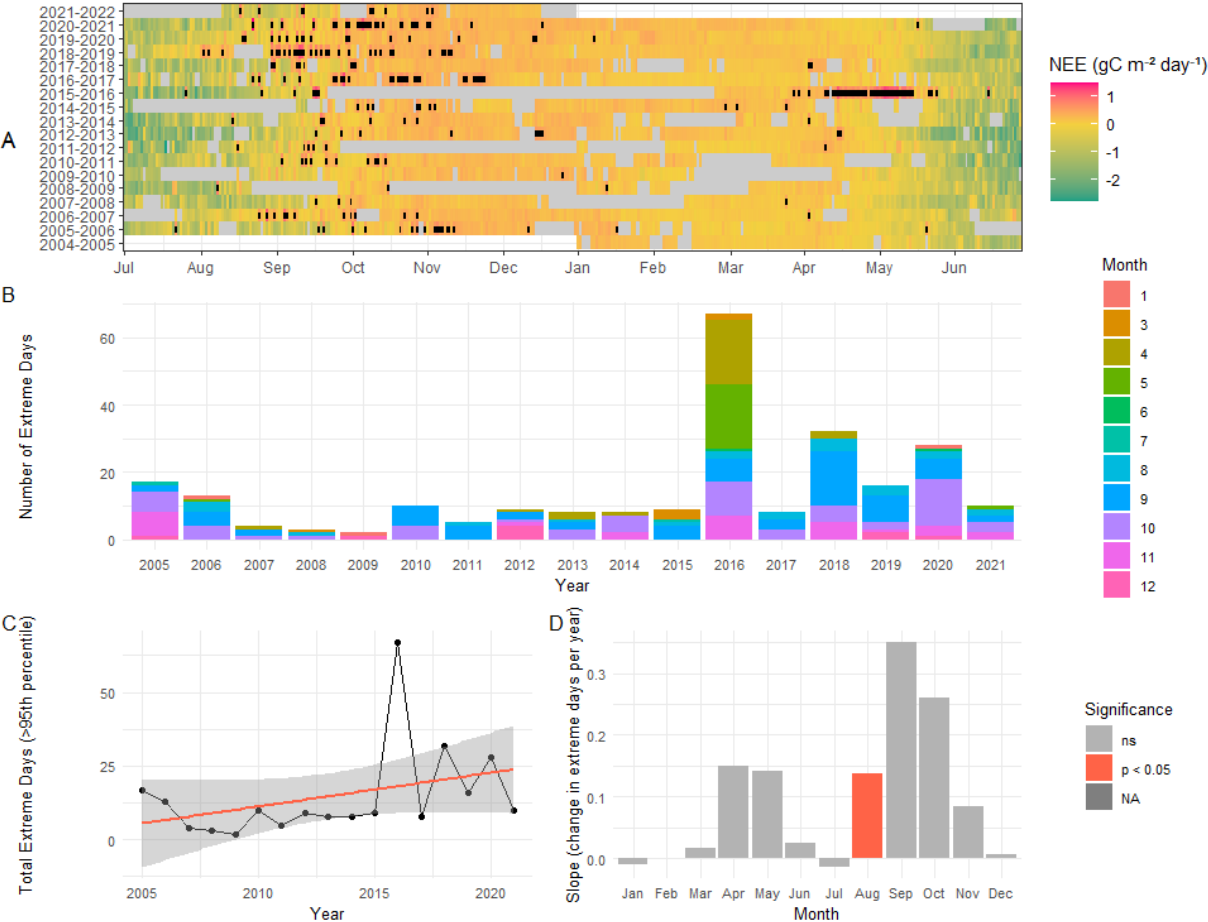


Figure S5. Daily net ecosystem exchange (NEE; gC m⁻² day⁻¹) in 2005-2021 and the non-growing season (NGS) periods centered in the winter. Each row represents one year beginning in July and ending in June of the following year. Colors indicate daily mean NEE values, where yellow - green gradient reflects negative values (net carbon sink) and yellow - pink gradient reflects positive values (net carbon release). Black rectangular outlines mark the non-productive season periods, defined as the period beginning after the first three consecutive days of positive NEE and ending after the first three consecutive days of negative NEE. Black vertical lines mark the periods with three or more consecutive days with daily mean flux values exceeding the upper 95th percentile.

45 The grey tiles mark the days with less than 12 hourly observations, meaning that more than 12 of the hourly values are gapfilled.



50 **Figure S6.** A) Daily net ecosystem exchange (NEE; $\text{gC m}^{-2} \text{ day}^{-1}$) in 2005-2021 and the daily values exceeding
the 95th percentile (black). Each row represents one year beginning in July and ending in June of the following
year. Colors indicate daily mean NEE values, where yellow - green gradient reflects negative values (net carbon
sink) and yellow - pink gradient reflects positive values (net carbon release). The grey tiles mark the days with
less than 12 hourly observations, meaning that more than 12 of the hourly values are gapfilled. B) The Amount of
55 days of daily NEE exceeding the 95th percentile by year, coloured by month. C) The amount of days of daily NEE
exceeding the 95th percentile with a linear regression line fitted (red) and standard deviation marked as grey
shading. D) The slope of change in extreme days per year aggregated by month. The colour of the bar indicates
the significance of the change (grey=insignificant and red: significant).

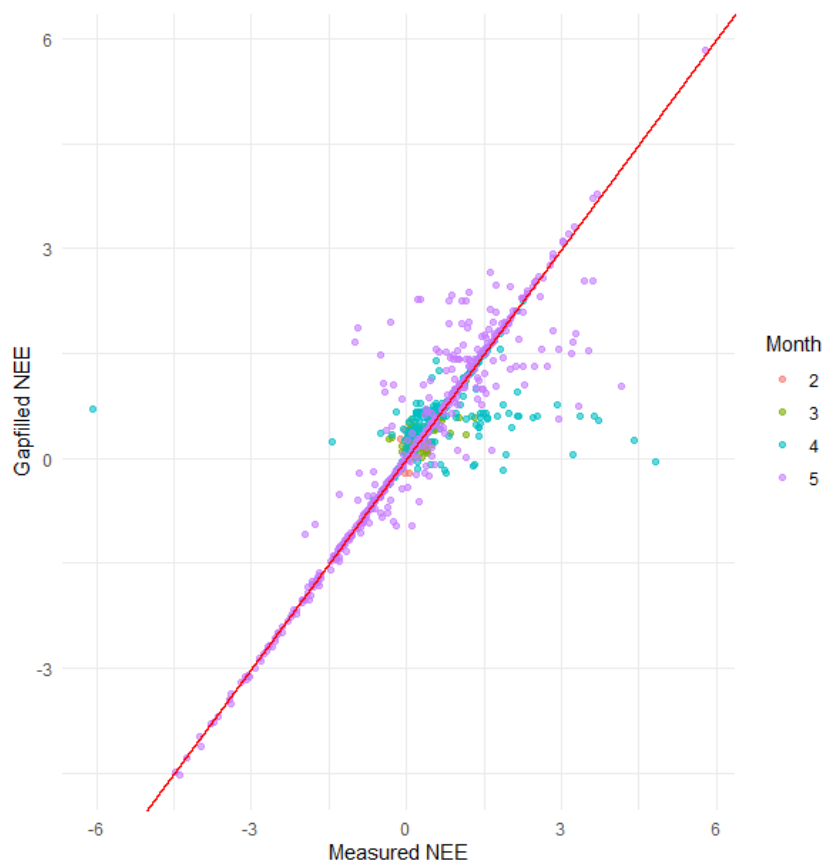


Figure S7. Half-hourly NEE observations plotted against gap-filled NEE values during spring 2016. Only the highest-quality measurements from the period 26 February to 31 May were included. This period corresponds to the time after the data gap until the end of the anomalous emission event. Colours indicate the month of observation.



Figure S8. Daily CH₄ and NEE of CO₂ during spring 2016 (February–June). Solid lines show the observed daily fluxes in 2016, while the semi-transparent lines represent the long-term (2005–2021) mean. Mean fluxes were calculated by averaging fluxes for each calendar day across the full dataset and is shown to illustrate how the 2016 flux dynamics compare with the typical seasonal pattern.

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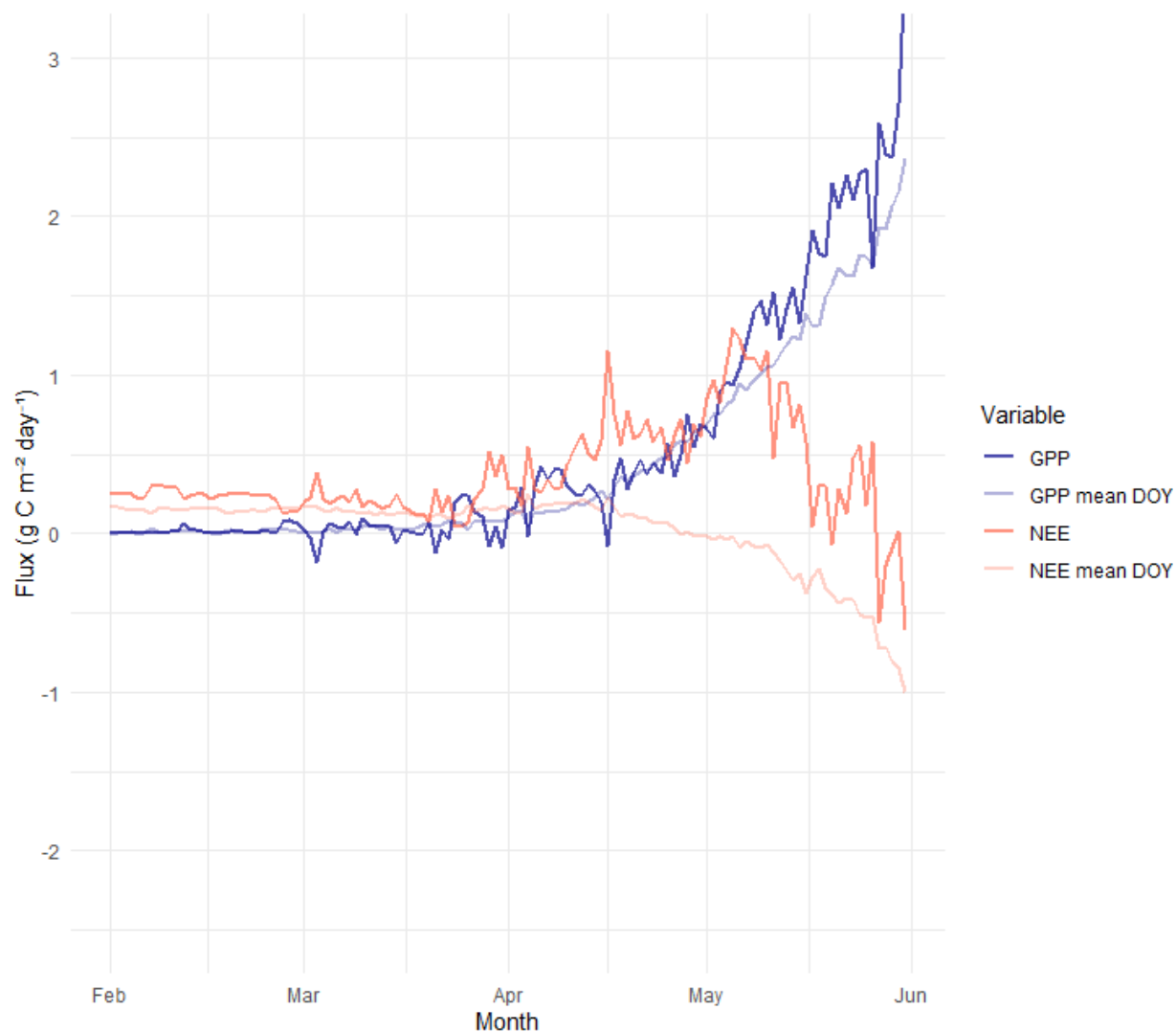


Figure S9. Daily GPP and NEE during spring 2016 (February–June). Solid lines show the observed daily fluxes in 2016, while the semi-transparent lines represent the long-term mean. Mean fluxes mean were calculated by averaging fluxes for each calendar day across the full dataset and is shown to illustrate how the 2016 flux dynamics compare with the typical seasonal pattern.

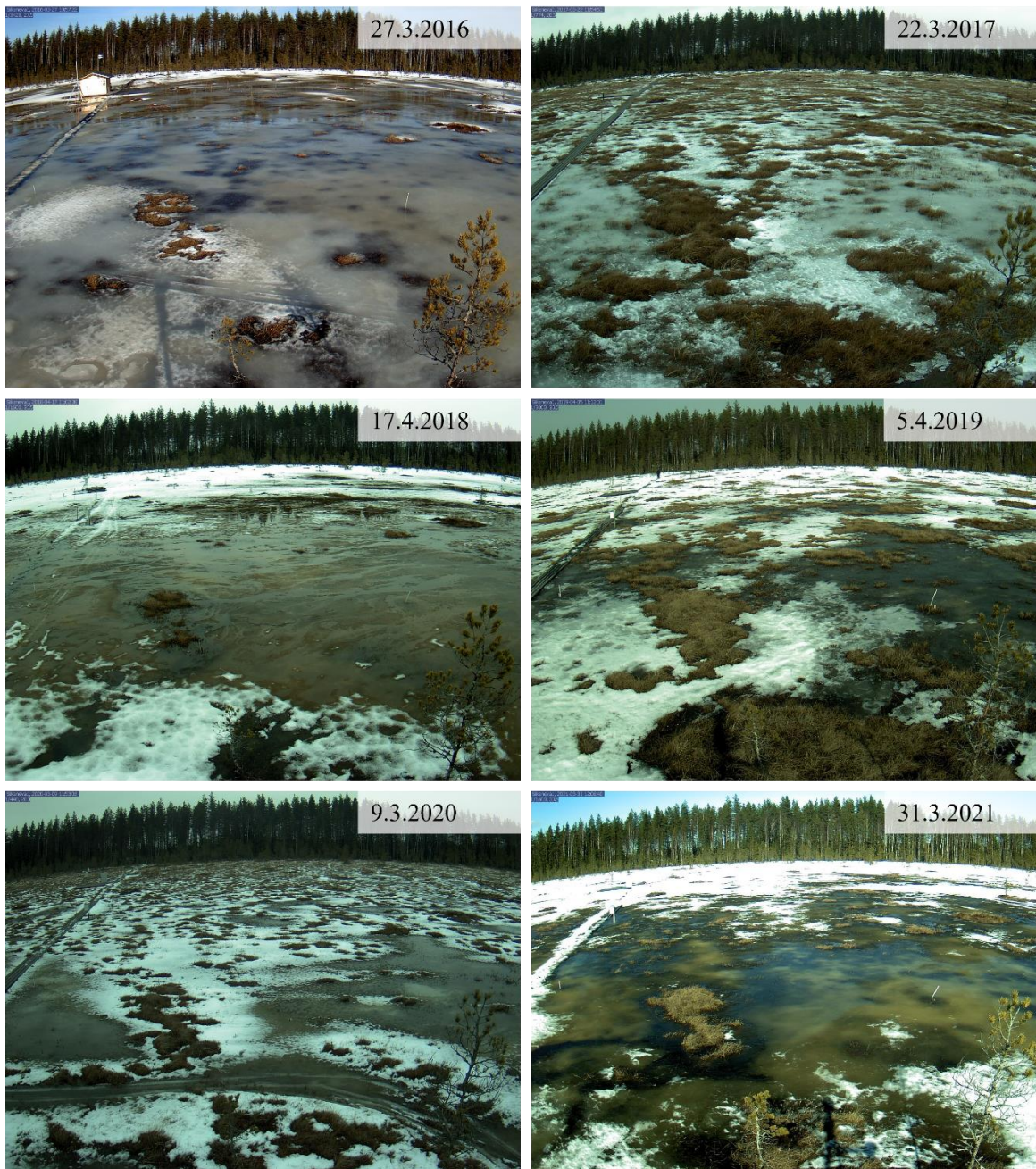


Figure S10. Phenocamera images of the Siikaneva fen following snowmelt for the years 2016–2021. Images were available from 2016 onward, and for each year, the first image in which the ground beneath the snow became visible was selected.

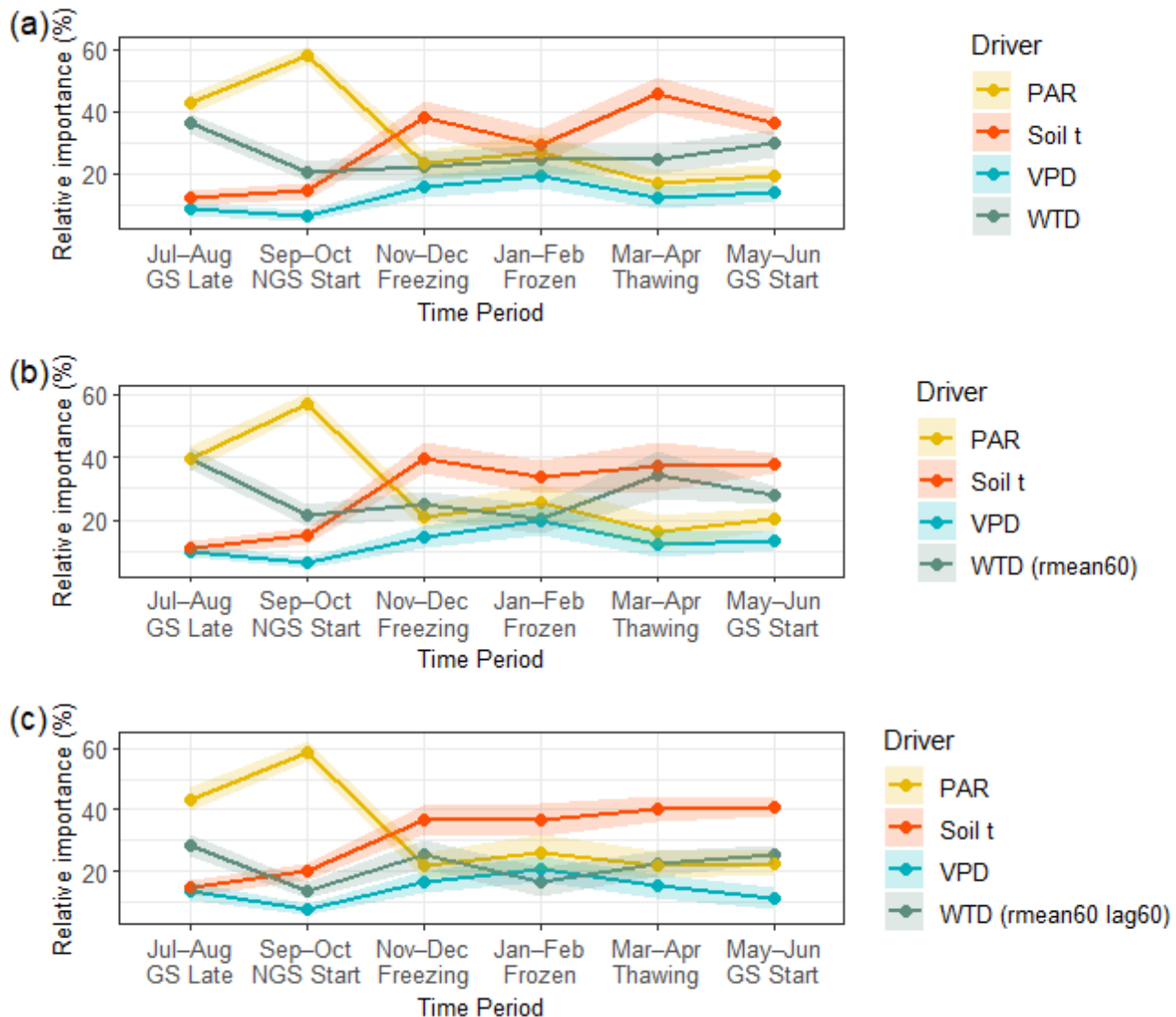


Figure S11. Relative importance of photosynthetically active radiation (PAR), vapor pressure deficit (VPD), water table depth (WTD), and soil temperature at 5 cm in predicting daily net ecosystem exchange (NEE), based on random forest models. All variables and NEE were aggregated to daily means. Shading represents standard deviation. Due to incomplete PAR records at the Siikanen site, data from the Hyytiälä Forest Station were used for 2009–2015. Subplots differ in the soil temperature aggregation used: a) Daily mean WTD; b) Mean WTD, averaged over the two months preceding each flux measurement; c) Mean WTD, averaged over a two-month window and lagged by 60 days (i.e., a lagged two-month mean).