The Cryosphere

Supplement of

Review article: Terrestrial dissolved organic carbon in northern permafrost

Liam Heffernan et al.

Correspondence to: Liam Heffernan (w.heffernan@vu.nl)

Table S1. Categorical variables included in the database for analysis

Permafrost Zone	EcoRegion	Permafrost Conditions	Thermal Horizon	Disturbance Type	Soil Class	Ecosystem Type	Extraction Method	Measurement Method
Continuous	Arctic tundra	Present	Active layer	Fire	Histosol	Coastal tundra	Centrifugation	
Discontinuous	Sub-arctic tundra	Absent	Permafrost lens	Active layer thickening	Histel	Forest	Leaching	
Sporadic	Sub-arctic boreal		Permafrost free	Thermokarst terrestrial	Orthel	Peatland	Dry leaching	
Permafrost free	Continental boreal		Water	Thermokarst aquatic	Turbel	Permafrost bog	Dialysis	
			Thaw stream			Permafrost wetland	Grab	
						Retrogressive thaw slump	Ice core	
						Upland tundra	Potassium sulphate	
						Yedoma	Lysimeter	
							Piezometer	
							Pump	
							Rhizon	

Table S2. Number of studies, DOC concentrations, and country location for each ecosystem type. Total number of studies in table is greater than number of studies in the database as some studies have sites at multiple ecosystem types

Ecosystem	No. of studies	No. of DOC measurements	Study location
Peatland	7	48	Can, Swe, USA
Permafrost bog	37	721	Can, Fin, Rus, Swe, USA
Permafrost wetland	20	478	Can, Gre, Rus, USA
Forest	20	332	Can, Rus, Swe, USA
Upland tundra	22	527	Can, Gre, Rus, Sva, Swe, USA
Retrogressive thaw slump	7	175	Can, USA
Coastal tundra	9	414	Can, USA
Yedoma	9	145	Can, Rus, USA

Can = Canada; Fin = Finland; Gre = Greenland; Rus = Russia; Sva = Svalbard; Swe = Sweden; USA = USA (Alaska)

Table S3. Dissolved organic carbon concentrations (DOC) and number of DOC measurements and number of studies they were taken from using the three main filter sizes used (0.22, 0.45, and 0.7 µm) to determine DOC concentrations corresponding to the violin plots from permafrost zones, ecoregions, soil class, and thermal horizon from Figure 2 in main text. DOC = median DOC concentration (mg L^{-1}) ± the interquartile range. N = the number outside the parentheses represents DOC measurements and the number inside the parentheses represents the number of studies.

	0.22 µm		0.45 µm		0.7 µm	
	DOC	N	DOC	N	DOC	N
Permafrost zone						
Continuous	42.9 ± 52.3	322 (8)	38.6 ± 82.5	710 (32)	15.1 ± 86.6	562 (16)
Discontinuous	22.6 ± 47.8	28 (6)	57.1 ± 58.0	578 (30)	42.1 ± 59.7	68 (10)
Sporadic			66.2 ± 146.8	81 (3)	29.6 ± 5.0	2 (1)
EcoRegion						
Arctic Tundra	30.9 ± 36.5	130 (4)	39.6 ± 89.1	501 (22)	15.8 ± 89.4	466 (10)
Sub-Arctic Tundra	51.7 ± 42.2	154 (5)	41.0 ± 72.1	209 (10)	11.4 ± 20.1	76 (5)
Continental Boreal	38.6 ± 161.6	55 (3)	56.8 ± 43.6	319 (15)	16.6 ± 15.1	15 (4)
Sub-Arctic Boreal	19.9 ±48.4	11 (2)	59.7 ± 89.8	340 (18)	46.1 ± 63.3	75 (8)
Soil Class						
Turbel	46.2 ± 52.1	287 (6)	52.8 ± 87.2	294 (15)	8.3 ± 9.8	237 (11)
Othel	19.1 ± 24.4	31 (2)	26.7 ± 66.3	388 (18)	84.6 ± 128.2	259 (9)
Histel	23.2 ± 34.2	32 (7)	59.2 ± 76.6	652 (27)	9.7 ± 51.8	134 (8)
Histosol			61.6 ± 39.4	35 (4)	34.3 ± 3.5	2 (1)
Thermal Horizon						
Active Layer	42.7 ± 58.1	188 (12)	53.7 ± 78.2	858 (45)	28.3 ± 85.9	186 (12)
Permafrost Lens	63.6 ± 80.4	78 (7)	24.4 ± 110.2	372 (18)	18.6 ± 122.4	279 (5)
Thaw Stream	25.6 ± 19.3	78 (1)			10.4 ± 10.9	122 (7)
Permafrost Free	67.6 ± 65.8	6 (2)	56.8 ± 14.7	139 (7)	41.6 ± 54.7	45 (7)

Table S4. Dissolved organic carbon concentrations (DOC; mg L^{-1}) and number of DOC measurements and number of studies they were taken from using the three main filter sizes used (0.22, 0.45, and 0.7 μm) to determine DOC concentrations corresponding to the boxplots showing DOC concentrations found across ecosystems in Figure 3 in main text. DOC = median DOC concentration (mg L^{-1}) ± the interquartile range. N = the number outside the parentheses represents DOC measurements and the number inside the parentheses represents the number of studies.

Ecosystem	0.22 μm		0.45 μm		0.7 μm	
	DOC	N	DOC	N	DOC	N
Yedoma			20.8 ± 40.8	22 (5)	8.2 ± 10.8	96 (4)
Coastal tundra	52.0 ± 123.1	13 (2)	37.7 ± 79.5	232 (5)	109.6 ± 95.5	154 (3)
RTS	25.6 ± 19.3	78 (1)	23.4 ± 21.4	4 (1)	7.8 ± 8.6	113 (7)
Upland tundra	50.8 ± 39.5	147 (2)	21.1 ± 67.3	275 (9)	10.8 ± 8.2	49 (6)
Forest	41.6 ± 183.1	51 (3)	54.8 ± 63.7	138 (12)	27.4 ± 51.9	9 (4)
Permafrost wetland	64.1 ± 109.7	33 (2)	45.2 ± 54.8	109 (10)	16.6 ± 71.9	154 (4)
Permafrost bog	22.7 ± 53.6	21 (6)	64.1 ± 81.8	554 (19)	48.1 ± 53.9	55 (6)
Peatland	8.9	1 (1)	61.6 ± 39.4	35 (4)	34.3 ± 3.5	2 (1)

Table S5. Dissolved organic carbon concentrations (DOC) and number of DOC measurements and number of studies they were taken from using the three main DOC extraction methods (Leaching, Suction, and Grab) corresponding to the violin plots from permafrost zones, ecoregions, soil class, and thermal horizon from Figure 2 in main text. DOC = median DOC concentration (mg L^{-1}) ± the interquartile range. N = the number outside the parentheses represents DOC measurements and the number inside the parentheses represents the number of studies. Type identifies whether DOC was extracted from either soil or water samples, and both represents all DOC concentrations using that extraction approach.

	Type	Leaching		Suction		Grab	
		DOC	N	DOC	N	DOC	N
Permafrost Zone							
Continuous	Both			41.6 ± 73.3	676 (21)		
	Soil	41.0 ± 103.7	635 (27)	75.8 ± 86.2	304 (5)		
	Water			20.8 ± 32.9	372 (16)	11.4 ± 18.2	311 (13)
Dis-continuous	Both			56.6 ± 52.3	383 (15)		
	Soil	57.7 ± 107.4	222 (19)	65.0 ± 13.4	36 (1)		
	Water			55.3 ± 59.9	347 (14)	39.4 ± 47.1	32 (7)
Sporadic	Both						
	Soil	66.2 ± 146.8	81 (3)				
	Water					29.6 ± 5.0	2 (1)
EcoRegion							
Arctic Tundra	Both			26.4 ± 80.6	555 (16)		
	Soil	41.7 ± 99.2	395 (18)	114.8 ± 97.4	155 (3)		
	Water			11.9 ± 30.7	400 (13)	11.2 ± 19.9	249 (6)
Sub-Arctic Tundra	Both			57.5 ± 35.9	194 (5)		
	Soil	34.9 ± 96.4	193 (9)	55.6 ± 35.9	185 (3)		
	Water			97.9 ± 149.7	9 (2)	10.9 ± 9.9	52 (5)
Continental Boreal	Both						
	Soil	63.0 ± 152.9	185 (10)				
	Water			55.0 ± 21.7	182 (8)	31.6 ± 44.6	22 (4)
Sub-Arctic Boreal	Both						
	Soil	57.3 ± 102.1	165 (11)				
	Water			70.7 ± 62.0	128 (8)	64.0 ± 138.8	22 (6)
Soil Class							
Turbel	Both			45.5 ± 57.2	323 (7)		
	Soil	50.6 ± 102.0	259 (13)	53.5 ± 40.1	152 (3)		

	Water			31.0 ± 65.4	171 (4)	8.9 ± 9.7	225 (11)
Orthel	Both			55.0 ± 94.8	280 (12)		
	Soil	23.2 ± 80.8	353 (16)	106.1 ± 92.8	157 (3)		
	Water			21.8 ± 29.6	123 (9)	37.3 ± 93.6	97 (4)
Histel	Both			49.1 ± 58.1	428 (20)		
	Soil	74.9 ± 125.1	321 (18)	64.3 ± 13.4	31 (2)		
	Water			47.1 ± 57.5	397 (18)	64.0 ± 35.8	19 (4)
Histosol	Both						
	Soil	72.5 ± 36.3	5 (2)				
	Water			62.2 ± 23.7	28 (2)	7.2 ± 2.6	4 (1)

Thermal Horizon

Active Layer	Both			36.5 ± 59.4	735 (29)		
	Soil	61.0 ± 107.1	545 (36)	63.1 ± 43	205 (5)		
	Water			21.0 ± 48.6	530 (24)	62.3 ± 34.6	25 (5)
Permafrost Lens	Both			113.1 ± 108.2	139 (5)		
	Soil	33.4 ± 134.1	303 (14)	115.7 ± 102.3	135 (3)		
	Water			16.3 ± 10.0	4 (2)	12.9 ± 24.1	198 (5)
Thaw Stream	Both						
	Soil	24.6 ± 19.7	84 (2)				
	Water					10.5 ± 12.3	118 (7)
Permafrost Free	Both						
	Soil	55.1 ± 41.1	6 (3)				
	Water			57.4 ± 20.3	185 (10)	7.2 ± 2.6	4 (1)

Table S6. Dissolved organic carbon concentrations (DOC; mg L^{-1}) and number of DOC measurements and number of studies they were taken from using the three main DOC extraction methods (Leaching, Suction, and Grab) corresponding to the boxplots showing DOC concentrations found across ecosystems in Figure 3 in main text. DOC = median DOC concentration (mg L^{-1}) ± the interquartile range. N = the number outside the parentheses represents DOC measurements and the number inside the parentheses represents the number of studies. Type identifies whether DOC was extracted from either soil or water samples, and both represents all DOC concentrations using that extraction approach.

Ecosystem	Phase	Leaching		Suction		Grab	
		DOC	N	DOC	N	DOC	N
	Both						
Yedoma	Soil	9.1 ± 15.4	14 (1)				
	Water					8.8 ± 11.9	91 (5)
	Both			66.7 ± 105.1	345 (5)		
Coastal tundra	Soil	105.7 ± 230.0	45 (5)	115.7 ± 97.7	153 (2)		
	Water			35.3 ± 56.9	192 (3)	0.7 ± 1.6	9 (1)
	Both						
RTS	Soil	24.0 ± 20.6	97 (3)				
	Water					8.0 ± 7.8	98 (7)
	Both			41.9 ± 50.7	219 (8)		
Upland tundra	Soil	22.2 ± 80.9	263 (8)	51.0 ± 38.8	163 (4)		
	Water			6.7 ± 7.2	56 (4)	10.8 ± 7.9	47 (4)
	Both						
Forest	Soil	65.5 ± 103.1	143 (11)				
	Water			25.4 ± 29.7	50 (6)	48.1 ± 30.1	5 (2)
	Both						
Permafrost wetland	Soil	72.6 ± 108.2	84 (7)				
	Water			7.3 ± 11.3	183 (8)	51.6 ± 133.7	74 (3)
	Both			61.4 ± 25.7	234 (11)		
Permafrost bog	Soil	81.9 ± 133.7	286 (14)	65.9 ± 10.5	24 (1)		
	Water			59.6 ± 29.8	210 (10)	64.0 ± 22.2	17 (3)
	Both						
Peatland	Soil	55.1 ± 41.1	6 (3)				
	Water			62.2 ± 23.7	28 (2)	7.2 ± 2.6	4 (1)

Table S7. Dissolved organic carbon concentrations (DOC) and number of DOC measurements and number of studies they were taken from using the three main DOC analysis methods used (Combustion, Persulphate, Photometric) to determine DOC concentrations corresponding to the violin plots from permafrost zones, ecoregions, soil class, and thermal horizon from Figure 2 in main text. DOC = median DOC concentration (mg L^{-1}) ± the interquartile range. N = the number outside the parentheses represents DOC measurements and the number inside the parentheses represents the number of studies.

	Combustion		Persulphate		Photometric	
	DOC	N	DOC	N	DOC	N
Permafrost zone						
Continuous	27.3 ± 68.2	1372 (56)	116.1 ± 94.5	143 (1)	47.7 ± 28.4	31 (4)
Discontinuous	52.9 ± 59.6	709 (41)	66.8 ±71.2	87 (8)		
Sporadic	62.0 ± 143.9	83 (4)				
EcoRegion						
Arctic Tundra	19.3 ± 57.6	954 (36)	116.1 ± 94.5	143 (1)	71.5 ± 54.4	10 (1)
Sub-Arctic Tundra	42.5 ±49.7	489 (24)	105.6 ± 1.6	4 (1)	40.1 ± 25.3	21 (3)
Continental Boreal	56.9 ± 58.5	360 (17)	14.8 ± 7.7	4 (1)		
Sub-Arctic Boreal	56.7 ± 86.2	361 (24)	66.8 ± 69.2	79 (6)		
Soil Class						
Turbel	34.5 ± 68.8	708 (30)	19.6 ± 38.1	11 (2)		
Othel	22.8 ± 64.7	556 (26)	110.9 ± 94.9	152 (4)	47.7 ± 28.4	31 (4)
Histel	50.4 ± 69.2	863 (45)	76.6 ± 61.4	67 (4)		
Histosol	60.9 ± 38.7	37 (5)				
Thermal Horizon						
Active Layer	41.7 ± 74.3	1122 (65)	79.4 ± 61.4	139 (8)	47.7 ± 28.4	31 (4)
Permafrost Lens	22.2 ± 90.5	641 (27)	135.6 ± 95.7	88 (3)		
Thaw Stream	15.6 ± 20.5	202 (9)				
Permafrost Free	56.8 ± 21.9	199 (15)	27.4 ± 39.4	3 (2)		

Table S8. Dissolved organic carbon concentrations (DOC; mg L^{-1}) and number of DOC measurements and number of studies they were taken from using the three main DOC analysis methods used (Combustion, Persulphate, Photometric) to determine DOC concentrations corresponding to the boxplots showing DOC concentrations found across ecosystems in Figure 3 in main text. DOC = median DOC concentration (mg L^{-1}) ± the interquartile range. N = the number outside the parentheses represents DOC measurements and the number inside the parentheses represents the number of studies.

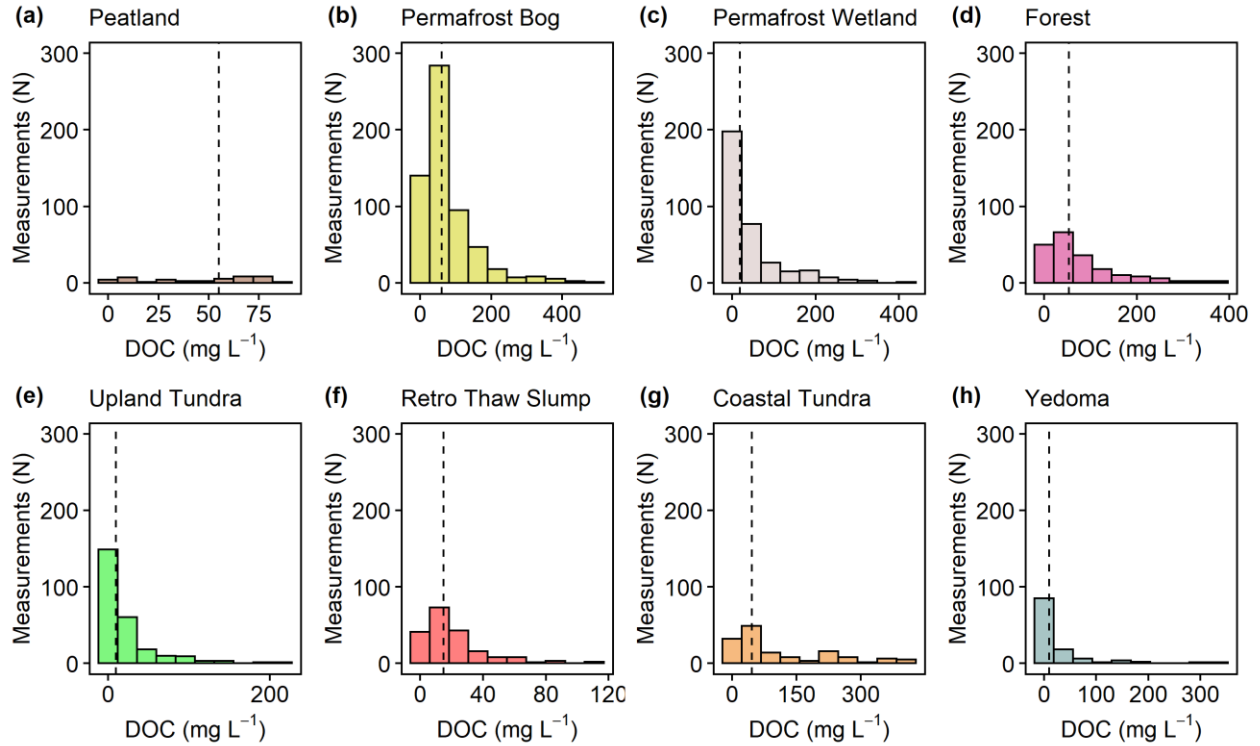| Ecosystem	Combustion		Persulphate		Photometric	
	DOC	N	DOC	N	DOC	N
Yedoma	8.9 ± 13.1	107 (7)	19.6 ± 38.1	11 (2)		
Coastal tundra	46.6 ± 172.3	155 (8)	116.1 ± 94.5	143 (1)		
RTS	14.8 ± 19.1	195 (9)				
Upland tundra	28.3 ± 59.4	523 (22)			71.5 ± 54.5	10 (1)
Forest	58.9 ± 104.5	168 (13)	27.4 ± 31.5	9 (3)	40.1 ± 25.3	21 (3)
Permafrost wetland	17.6 ± 53.6	346 (20)	60.9 ± 35.6	30 (1)		
Permafrost bog	62.5 ± 73.1	632 (29)	99.9 ± 60.3	37 (4)		
Peatland	58.6 ± 39.1	38 (6)				

Figure S1. Histograms for the number of DOC measurements (N) at various DOC concentrations (mg L^{-1}) included in the dataset in the top 3 m for each ecosystem type. DOC concentrations binned into 10 groups for each. (f) Retro Thaw Slump = Retrogressive thaw slump. Black dotted vertical lines in each panel represents the median DOC concentration (mg L^{-1}) for that ecosystem. Note different scales of DOC concentrations on *x*-axis.
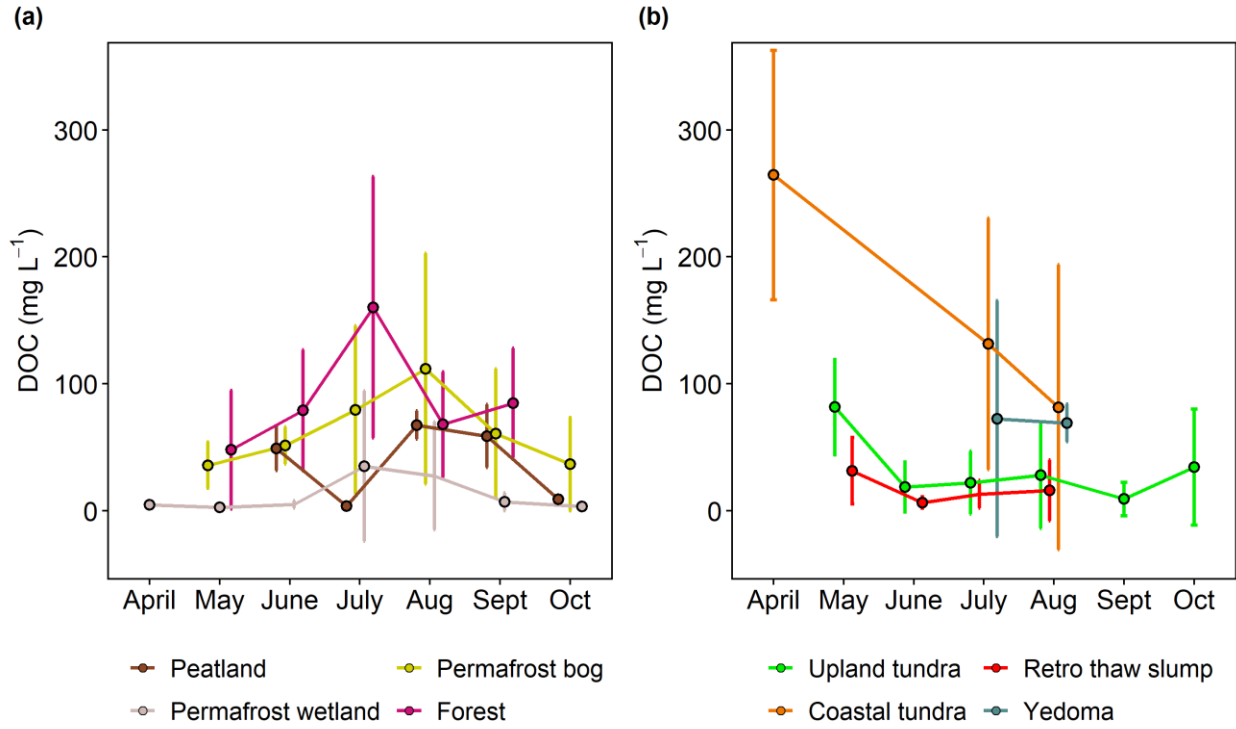
Figure S2. Seasonality in DOC concentrations (mg L^{-1}) in the top 3 m for each ecosystem type. (a) Organic rich ecosystems. (b) Mineral soil dominated ecosystems. Error bars represent ± 1 standard deviation.
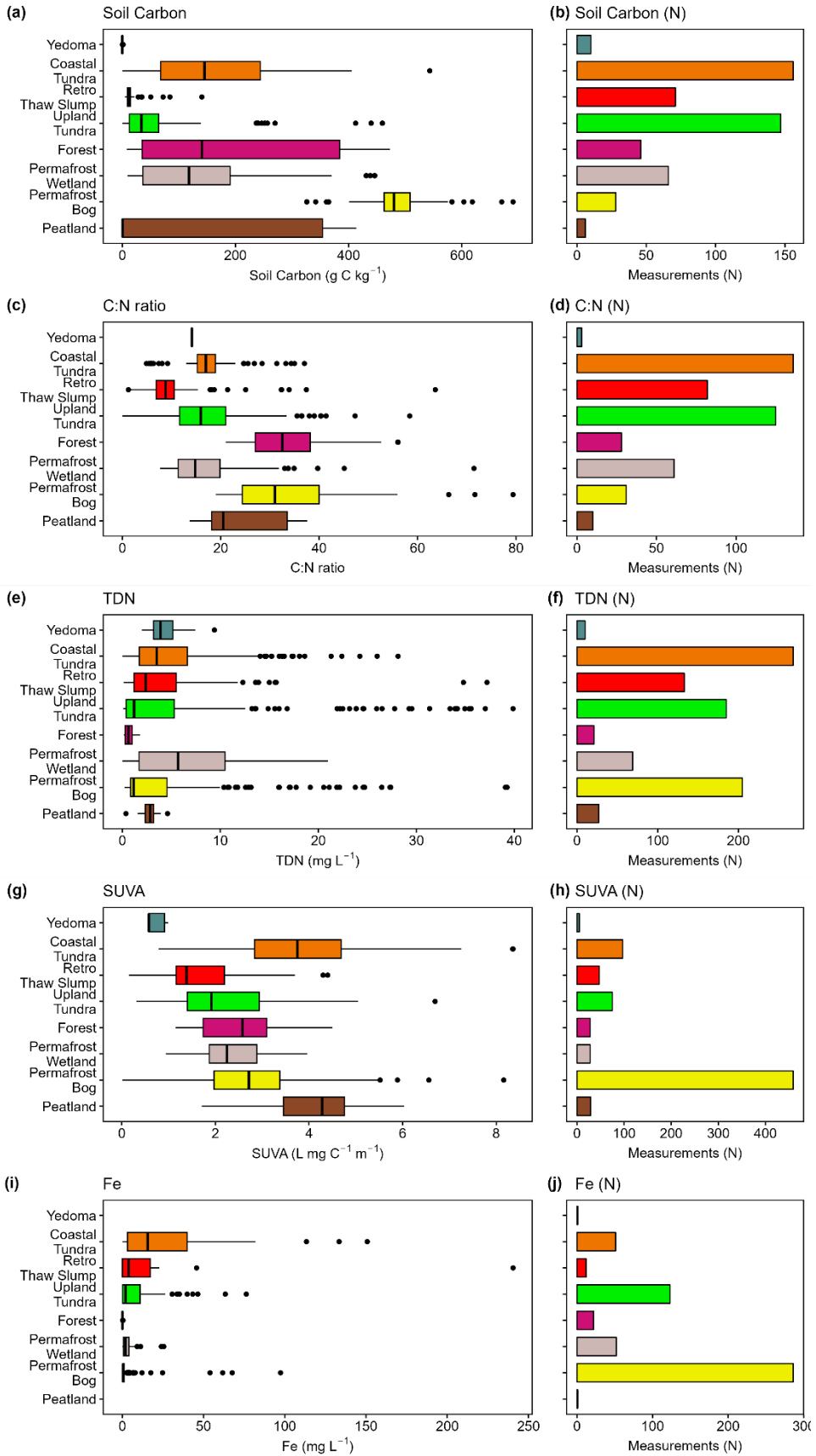
(a) Soil Carbon

(b) Soil Carbon (N)

(c) C:N ratio

(d) C:N (N)

(e) TDN

(f) TDN (N)

(g) SUVA

(h) SUVA (N)

(i) Fe

(j) Fe (N)

Figure S3. Boxplot of (a, c, e, g, i) continuous variables used in analysis, and bar plots of (b, d, f, h, j) the number of measurements of each continuous variable taken from the top 3 m for each ecosystem type. Boxes represents the interquartile range (25 – 75%), with median shown as black horizontal line. Whiskers extend to 1.5 times the interquartile range (distance between first and third quartile) in each direction. Soil Carbon = carbon content of soil (g C kg^{-1}). C:N ratio = carbon:nitrogen ratio. TDN = total dissolved nitrogen (mg L^{-1}). SUVA = the specific UV absorbance at 254 nm (L mg C^{-1} m^{-1}). Fe = dissolved iron ((mg L^{-1}).
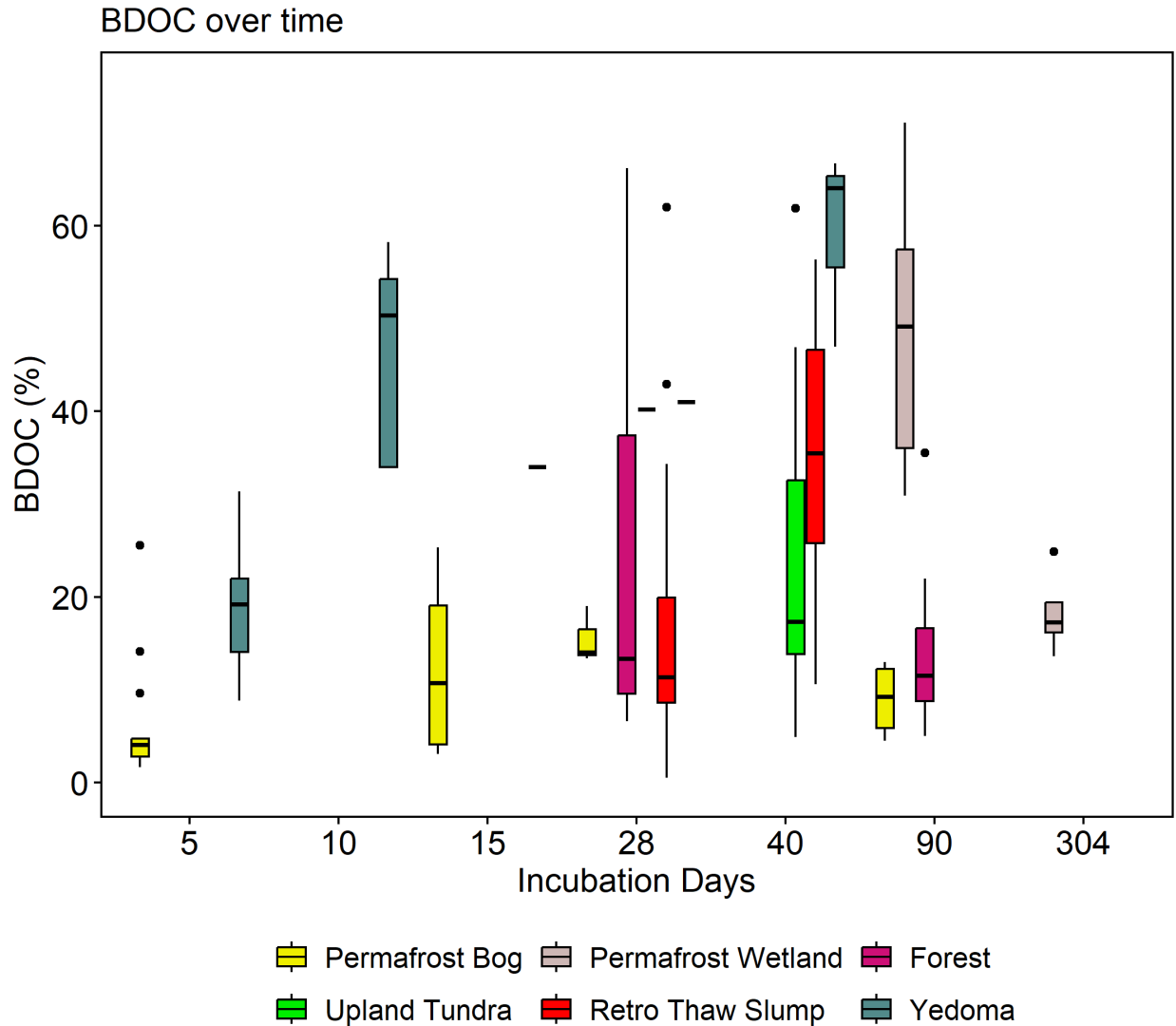
BDOC over time

Figure S4. Change in biodegradable DOC (BDOC; %) from the top 3 m over time during incubations for each ecosystem type where data was available. BDOC loss was determined following 3 – 304 days of incubation. Time points were binned into 5, 10, 15, 28, 40, 90, and 304 incubations days for improved clarity of presentation. Data from different incubation lengths was combined due to low sample size. Retro Thaw Slump = Retrogressive Thaw Slump. Boxes represents the interquartile range (25 – 75%), with median shown as black horizontal line. Whiskers extend to 1.5 times the interquartile range (distance between first and third quartile) in each direction, with outlier data plotted individually as black dots.
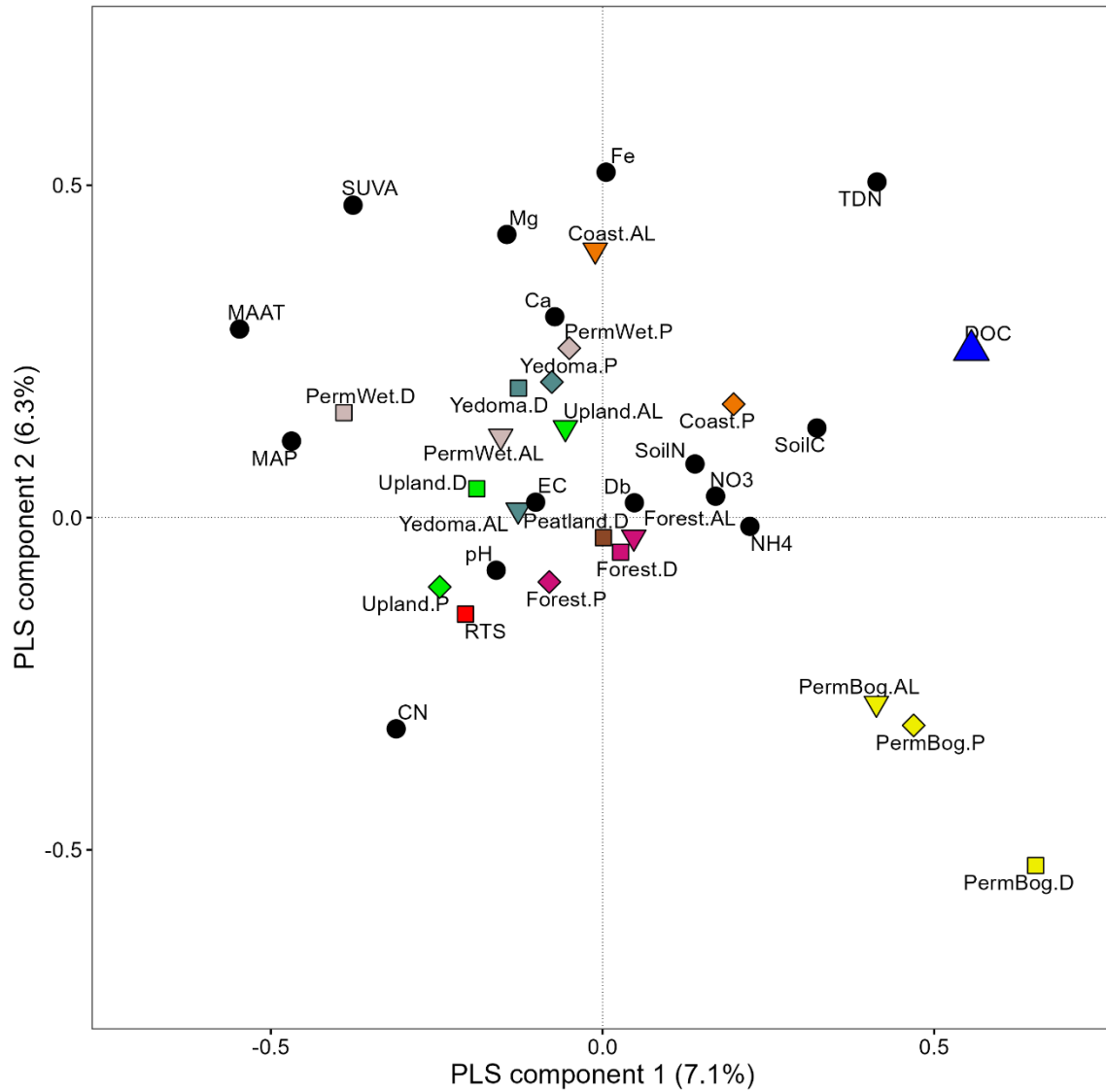
Figure S5. Partial least squares regression (PLS) with loadings plot containing all continuous and categorical variables considered when attempting to explain the variance in DOC concentrations (blue triangle). Black circles in the loadings plot represent continuous environmental data that had at lest 20% coverage of DOC data. All continuous data was log transformed, mean centered, and standardized. CN = carbon:nitrogen ratio. SUVA = the specific UV absorbance at 254 nm. MAP = mean annal precipitation. MAAT = mean annual temperature. SoilC = carbon content of. TDN = total dissolved nitrogen. Fe = dissolved iron. Ca = dissolved calcium. Mg = dissolve d magnesium. Db = bulk density of soil. pH = soil or pore water pH. EC = electrical conductivity of soil pore water. SoilN = soil nitrogen content. NO3 = dissolved nitrate. NH4 = dissolved ammonium. PermWet = permafrost wetland ecosystem class. Yedoma= Yedoma ecosystem class. RTS = retrogressive thaw slump ecosystem class. Coast = coastal tundra ecosystem class. PermBog = permafrost bog ecosystem class. Forest = forest ecosystem class. Upland = upland tundra ecosystem class. Peatland = peatland tundra ecosystem class. Measurements from the active layer of each ecosystem class are shown as downward pointing triangle icons and labelled ".AL" after the ecosystem label. Measurement s

from the permafrost lens of each ecosystem class are shown as diamond icons and labelled ".P" after the ecosystem label. Measurements from disturbed sites of each ecosystem class are shown as square icons and labelled ".D" after the ecosystem label.