

Supplementary Material

The current state of CO₂ flux chamber studies in the Arctic tundra: a review

Supplementary Material I. List of articles in the review.

- Arens SJT, Sullivan PF and Welker JM (2008) Nonlinear responses to nitrogen and strong interactions with nitrogen and phosphorus additions drastically alter the structure and function of a high arctic ecosystem. *Journal of Geophysical Research-Biogeosciences* 113(G3): 10.
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Supplementary Material 2. Methods in the systematic review.

I. Data collection

This article is based on a literature review of chamber-derived CO₂ flux studies during the growing season in the Arctic tundra. The survey was conducted via ISI Web of Science (WoS) for articles published in the years 2000-2016. The search was carried out using a query that accounted for the region, scale, flux terminology, and different vegetation types: (tundra or arctic) and ecosystem and (“CO₂ flux” or “carbon dioxide emissions” or “greenhouse gas exchange” or “CO₂ exchange” or “carbon exchange” or “carbon flux”) and (meadow or sedge or tussock or hummock or heath or herb or grass or grassland or graminoid or forb or moss or bryophyte or lichen or "cushion plant" or shrub or tree). The query resulted in 242 articles out of which we included approximately 20 % of the studies. Firstly, we wanted to focus on soil chamber measurements and, therefore, excluded studies with eddy covariance or leaf cuvette measurements only. Secondly, only studies that included growing season measurements were taken into account. Studies with GPP, ER, and/or NEE measurements were included. Boreal regions were excluded from the review as we wanted to focus on tundra patterns and processes only, although they are usually included in the carbon balance assessments of Arctic regions (Belshe et al., 2013; McGuire et al., 2010; Treat et al., 2015). However, we included studies with sub-Arctic and Arctic peatlands and fens due to their importance in tundra carbon cycling. Additional articles were derived from the references of the selected publications.

The final 93 publications were read through systematically in order to collect data on the 1) measurement information, 2) study design and location, and 3) environmental variables used to explain the CO₂ fluxes. All the environmental variables measured and described were taken into account, also derived from the study design descriptions (e.g. organic layer depth). The variables were further divided into the following categories and their classes: climate (air temperature, photosynthetically active radiation, soil microclimate), vegetation (biomass, plant traits, growth & phenology), soils (nutrients, physical properties, microbes) and disturbance (geomorphology, herbivory, disease). To our knowledge, at least seven articles were partly using the same CO₂ flux data, but the other environmental variables used in these studies was variable.

Information on the dominant and secondary species was also collected, and the vegetation data was further classified into Circumpolar Arctic Vegetation Map (CAVM) physiognomic units (Walker et al., 2005). CAVM was developed for landscape-scale analysis and does not consider fine-scale variation but we wanted to classify the vegetation data according to a widely-used vegetation classification. Furthermore, we recognize that classification was sometimes subjective and based on limited data on the species cover. Principally, we defined plots that were described to have only limited vegetation cover, or were described as barren or polar desert, to physiognomic unit B; plots that had tussocks and were mainly dominated by *Eriophorum*, *Carex*, and mosses to unit G; plots with a dominance of *Dryas*, *Cassiope*, and other prostrate-dwarf shrubs, such as *Salix arctica* and *S. polaris*, to unit P; erect-shrubs such as *Betula nana*, *Salix glauca*, *Rhododendron tomentosum*, *Vaccinium vitis-idaea* to unit S; and, plots described to be on wetland (bog, fen, palsa) to unit W.

2. Other data sets used in the figures

The data for Figure 2 was acquired from WorldClimv2 1970-2000 (average temperature and yearly cumulative precipitation at 2.5 minutes resolution; Fick & Hijmans, 2017), Soilgrid (topsoil pH at approx. 1 km resolution; Hengl et al., 2017), NCSCDv2 (soil organic carbon content at approx. 10 km resolution; Hugelius et al., 2013), TERRA/MODIS NDVI-product (from 1st of July, 2015 at approx. 10 km resolution; NASA, 2017) and GTOPO DEM (elevation at approx. 1 km resolution; USGS, 2004). The data was processed with the *raster* package (Hijmans et al. 2016) in R program. The values from the circumpolar data sets were extracted to the observation points. Raster extent varied and, therefore, 10-25 observation sites did not receive any values given they were outside the extent (e.g. soil pH map in southern Svalbard). The tundra area for describing the entire Arctic variation was defined by Ecoregions (Dinerstein et al., 2017). The entire Arctic variation data was rescaled to 10 km resolution for the plots.

Supplementary Material 3. Table with 20 most cited publications. Citations were derived from Web of Science, 16th of March 2017. Fluxes describe the CO₂ fluxes measured in the study (SR= soil respiration), manipulation defines whether the study is based on manipulative observations (e.g. experimental warming) and region defines study location(s) of the observations.

Authors	Year	Title	Journal	Citations	Fluxes	Manipulation	Region
Schuur et al.	2009	The effect of permafrost thaw on old carbon release and net carbon exchange from tundra	NATURE	423	GPP, ER, NEE	0	Alaska
Welker et al.	2000	Annual CO ₂ flux in dry and moist arctic tundra: Field responses to increases in summer temperatures and winter snow depth	CLIMATIC CHANGE	131	NEE	1	Alaska
Oberbauer et al.	2007	Tundra CO ₂ fluxes in response to experimental warming across latitudinal and moisture gradients	ECOLOGICAL MONOGRAPHS	124	GPP, ER, NEE	1	Canada
Welker et al.	2004	CO ₂ exchange in three Canadian High Arctic ecosystems: response to long-term experimental warming	GLOBAL CHANGE BIOLOGY	117	GPP, ER, NEE	1	Canada
Kurzbach et al.	2007	CO ₂ flux determination by closed-chamber methods can be seriously biased by inappropriate application of linear regression	BIOGEOSCIENCES	109	NEE	0	Fennoscandia, Russia
Christensen et al.	2000	Trace gas exchange in a high-arctic valley 1. Variations in CO ₂ and CH ₄ flux between tundra vegetation types	GLOBAL BIOGEOCHEMICAL CYCLES	107	GPP, ER, NEE	0	Greenland
Johansson et al.	2006	Decadal vegetation changes in a northern peatland, greenhouse gas fluxes and net radiative forcing	GLOBAL CHANGE BIOLOGY	106	NEE	1	Fennoscandia
Boelman et al.	2003	Response of NDVI, biomass, and ecosystem gas exchange to long-term warming and fertilization in wet sedge tundra	OECOLOGIA	104	GPP, ER, NEE	1	Alaska
Shaver et al.	2007	Functional convergence in regulation of net CO ₂ flux in heterogeneous tundra landscapes in Alaska and Sweden	JOURNAL OF ECOLOGY	92	GPP, ER, NEE	0	Fennoscandia
Street et al.	2007	What is the relationship between changes in canopy leaf area and changes in photosynthetic CO ₂ flux in arctic ecosystems?	JOURNAL OF ECOLOGY	87	GPP	0	Fennoscandia, Alaska
Johnson et al.	2000	Plant carbon-nutrient interactions control CO ₂ exchange in Alaskan wet sedge tundra ecosystems	ECOLOGY	81	GPP, ER, NEE, SR	1	Alaska
Heikkinen et al.	2004	Carbon balance in East European tundra	GLOBAL BIOGEOCHEMICAL CYCLES	59	GPP, ER, NEE, SR	0	Russia
Blasi et al.	2008	Initial effects of experimental warming on carbon exchange rates, plant growth and microbial dynamics of a lichen-rich dwarf shrub tundra in Siberia	PLANT AND SOIL	59	GPP, ER, NEE	1	Siberia
Bokhorst et al.	2011	Impacts of multiple extreme winter warming events on sub-Arctic heathland: phenology, reproduction, growth, and CO ₂ flux responses	GLOBAL CHANGE BIOLOGY	56	GPP, ER, NEE, SR	1	Fennoscandia
Sullivan et al.	2008	Temperature and microtopography interact to control carbon cycling in a high arctic fen	ECOSYSTEMS	54	GPP, ER, NEE	1	Greenland
Grogan & Jonasson	2005	Temperature and substrate controls on intra-annual variation in ecosystem respiration in two subarctic vegetation types	GLOBAL CHANGE BIOLOGY	54	ER	1	Fennoscandia
Grogan & Chapin	2000	Initial effects of experimental warming on above- and belowground components of net ecosystem CO ₂ exchange in arctic tundra	OECOLOGIA	54	GPP, ER, NEE, SR	1	Alaska
Natali et al.	2011	Effects of experimental warming of air, soil and permafrost on carbon balance in Alaskan tundra	GLOBAL CHANGE BIOLOGY	53	GPP, ER, NEE, SR	1	Alaska
Bäckstrand et al.	2010	Annual carbon gas budget for a subarctic peatland, Northern Sweden	BIOGEOSCIENCES	51	NEE	0	Fennoscandia
Larsen et al.	2007	Significance of cold-season respiration and photosynthesis in a subarctic heath ecosystem in Northern Sweden	GLOBAL CHANGE BIOLOGY	47	GPP, ER, NEE	1	Fennoscandia

Supplementary Material 4. Table with descriptive data from the 93 articles included in this review. The different columns indicate studies with GPP, ER, and NEE measurements, and an average of all CO₂ flux studies. The row names are different classifications of the data which describe information of the studies, study designs, methods, measurements, vegetation, and climatological, soil, and disturbance variables. Cells indicate the number of the studies (except for average number of citations). In the spatial study designs, the focus is on understanding the CO₂ fluxes in the landscape (related to e.g. different vegetation types or topographic positions) whereas in the temporal study designs, the focus is to understand CO₂ dynamics. In manipulative studies, environmental conditions have been modified. In some cases, no data was available (e.g. chamber size).

Studies with measurements of		GPP	ER	NEE	All fluxes
General information		Number of	studies with	observations	of
Arctic	Oroarctic	31	33	36	39
	Low Arctic	28	29	29	32
	High Arctic	27	30	29	33
Region	Alaska	26	29	27	32
	Canada	7	7	7	8
	Fennoscandia	20	22	24	27
	Russia	12	12	13	13
	Greenland	16	15	17	18
	Svalbard	5	7	7	8
Publication year	2011-2016	40	44	42	47
	2006-2010	23	24	26	29
	2000-2005	15	16	16	17
Average number of citations		35	34	37	36
Study designs					
Spatial/temporal	Spatial	21	22	24	25
	Temporal	18	20	19	21
	Spatial and temporal	31	34	33	39
Observational/manipulati	Observational	42	46	47	53

	Manipulative	35	37	36	39
	Warming	20	20	21	21
	Nutrient addition	7	6	6	7
	Water modifications	5	5	5	5
Median number of observations	All	24	24	29	26
	Spatial	40	40	41	42
	Temporal	18	18	18	18
	Spatial and temporal	18	19	18	20
	Manipulative	20	20	20	20
	Observational	30	29	26	29
Median number of sites	All	3	3	3	3
	Observational	4	4	4	4
Study methods					
Chamber types	Manual	72	77	75	84
	Automatic	8	9	11	11
Chamber size	Edges/diameter < 25 cm	18	17	14	18
	Edges/diameter 25-50 cm	26	24	23	26
	Edges/diameter > 50 cm	22	18	20	22
	Height < 25 cm	12	12	10	12
	Height 25-50 cm	35	29	32	35
	Height > 50 cm	8	8	8	8
Chamber type	LI-COR	48	53	51	59
	EGM	15	15	15	16
	Vaisala	2	2	2	2
CO₂ measurements					
Fluxes	GPP	78	76	74	78

	ER	76	84	77	84
	NEE	74	77	84	84
	Soil respiration	12	14	14	15
Temporal measurements	Summer season (J-A)	58	63	62	69
	Cold-season (A, M, S, O)	14	18	20	21
	Winter	16	17	18	19
	Yearly	29	33	33	35
Other flux measurements	Eddy covariance	9	10	11	11
	Leaf cuvette	4	5	4	5
Other gas fluxes	N ₂ O	2	2	2	3
	CH ₄	20	21	23	24
Vegetation					
Peatland		21	22	23	23
Vegetation cover	Species/PFT/Total cover	44	44	44	44
Biomass	Aboveground species/PFT/Total	44	43	43	44
	Belowground biomass	10	12	12	12
	LAI	21	21	20	23
	NDVI	27	27	26	29
	(field or satellite-based)				
Any biomass (cover + biomass)		75	75	75	75
Plant traits	Leaf chemical properties	15	15	15	17
	Leaf cover	11	12	12	13
	Vegetation height	9	10	10	11
Growth & phenology		17	17	17	17

Climate					
Surface	Air temperature	74	77	78	80
	PAR	69	70	71	72
Soils	Soil temperature	64	69	66	74
	Thaw depth	37	41	42	45
	Soil moisture	39	42	39	46
	Water table height	32	33	34	35
Soils					
Nutrients	C	15	15	15	15
	N	18	18	18	18
	P	5	5	5	5
	pH	13	13	13	15
	Litter biomass	6	6	5	7
Physical	Organic layer depth	25	28	25	28
	Soil type	13	14	13	15
	Texture	25	25	25	27
Microbes	Microbial community	1	1	1	1
	Microbial biomass	4	5	4	5
	Microbial activity	4	4	3	4
Disturbance					
Geomorphology	Permafrost	10	11	12	12
	Cryoturbation	6	8	7	8
	Fluvial activity	4	4	4	4
	Hummocks & hollows	9	10	10	10
Herbivory	Reindeer	4	5	5	5
	Muskox	3	3	3	3
	Small mammals	1	1	1	1
	Goose	4	4	4	4

Supplementary Material 5. Table of dominant species as informed by the authors. From vegetation informed only at genera-level, *Carex* (30 studies), *Sphagnum* (19 studies), *Eriophorum* (12 studies), and *Salix* (7 studies), were studied the most.

Species	Functional group	Number of studies
<i>Betula nana</i>	Deciduous shrub	29
<i>Empetrum hermaphroditum/nigrum</i>	Evergreen shrub	24
<i>Eriophorum vaginatum</i>	Graminoid	23
<i>Vaccinium uliginosum</i>	Deciduous shrub	19
<i>Vaccinium vitis-idaea</i>	Deciduous shrub	17
<i>Eriophorum angustifolium</i>	Graminoid	15
<i>Cassiope tetragona</i>	Evergreen shrub	11
<i>Rubus chamaemorus</i>	Forb	11
<i>Eriophorum scheuchzeri</i>	Graminoid	10
<i>Carex aquatilis</i>	Graminoid	9
<i>Dryas octopetala</i>	Evergreen shrub	9
<i>Carex stans</i>	Graminoid	8
<i>Rhododendron tomentosum</i>	Evergreen shrub	8
<i>Salix arctica</i>	Deciduous shrub	8
<i>Salix glauca</i>	Deciduous shrub	8
<i>Salix pulchra</i>	Deciduous shrub	8
<i>Rhododendron subarcticum</i>	Evergreen shrub	7
<i>Andromeda polifolia</i>	Evergreen shrub	6
<i>Dryas integrifolia</i>	Evergreen shrub	6
<i>Dupontia psilosantha</i>	Graminoid	6
<i>Salix polaris</i>	Deciduous shrub	6

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