



Abt. Mikrometeorologie

Master's Thesis in Geoecology

# Investigation of Greenhouse-Gas Fluxes on a Grazed Wet Tussock Tundra in Northeastern Siberia

by Wolfgang Fischer

Bayreuth, May 2020

Supervisor:Prof. Dr. Christoph ThomasCo. Supervisor:Dr. Mathias Göckede (MPI Jena)

# Contents

Та	able o	of Contents	iii
A	cknov	wledgement	xi
AI	ostra	ct	xii
Ζı	usami	menfassung	xiii
1	Intr	oduction	1
	1.1	Organic Carbon in Permafrost Ecosystems and its Vulnerability to Global Warming	1
	1.2	Carbon Fluxes in Tundra Environments and Their Assessment with Flux Chambers	3
	1.3	Arctic Tundra Ecosystems and the Impact of Grazing $\hfill \ldots \hfill \hfill \ldots \hfill \hfill \ldots \hfill \ldots$	4
	1.4	Pleistocene Park - a Model for Productive and Resilient Permafrost Ecosystems	
		in the Future?	7
	1.5	Research Objectives and Limitations	8
2	Mat	terials and Methods	9
	2.1	Site Description	9
		2.1.1 Location of Study Area	9
		2.1.2 Pleistocene Park	9
		2.1.3 Ambolikha Site	11
	2.2	Instrumentation for Measuring Environmental and Soil Parameters	12
		2.2.1 Soil Moisture (SM), Thaw Depth and Soil Temperature $(T_S)$	12
		2.2.2 Radiation, Albedo and Air Temperature	12
	2.3	Flux-Chamber Setup and Instrumentation	13
	2.4	Flux-Chamber Data Processing	14
		2.4.1 Calculation of $CO_2$ and $CH_4$ Fluxes $\ldots \ldots \ldots$	14
		2.4.2 Interpolation of $CO_2$ and $CH_4$ Fluxes	15
	2.5	Statistics: Comparison of Greenhouse Gas fluxes, Soil Temperatures and Albedo	
		Between Sites	16
3	Res	ults	18
	3.1	Environmental Conditions During the Observation Period $\ldots \ldots \ldots \ldots \ldots$	18
		3.1.1 Weather, Air Temperature and Pressure	18

		6.1.1	Interpolation of Soil Temperatures	xv
	6.1	Interp	olation of Environmental Parameters	xv
6	Арр	endix		xv
Bi	bliogr	raphy		47
5	Con	clusion	5	46
		4.3.2	$CH_4$ Fluxes	44
		4.3.1	$CO_2$ Exchange: $GPP$ and $R_{eco}$	43
	4.3	How N	Aight Grazing Influence the C-Balance of Permafrost Tundra Ecosystems? .	43
		4.2.5	Flux Interpolation Based on Environmental Parameters	41
		4.2.4	Grazing Influence on Soil Moisture	40
		4.2.3	Grazing Influence on Soil Temperatures	39
		4.2.2	Evaluating the Acquisition of Environmental and Soil Parameters at Both Sites	38
		4.2.1	Vegetation and Soil Structure at Pleistocene Park and Ambolikha Site: Grazing Impacts at Pleistocene Park	37
		tocene	Park and Ambolikha Site	37
	4.2	Assess	ing Differences of Environmental Conditions and Parameters Between Pleis-	
		4.1.4	Reviewing (chamber-) Fluxes in Similar Tundra Ecosystems	36
		4.1.3	Accounting for Site Heterogeneity	35
		4.1.2	Assessment of Flux Calculations	35
		4.1.1	Assessment of Flux Chamber Measurements and Their Limitations	34
		Cham	bers	34
	4.1	C-Flux	kes in Context: Methodological and Comparability Challenges with Flux	
4	Disc	ussion		34
		3.4.3	Comparing Fluxes between PPL at AS	31
		3.4.2	Variability Between Plots at AS	30
		3.4.1	Variability Between Plots at PPL	30
	3.4	Evolut	tion of Modeled C-Fluxes Over the Course of the Observation Period	30
	3.3	Summ	ary Statistics on Flux Models	28
		3.2.4	Modeling $CH_4$ Fluxes $\ldots$	27
		3.2.3	Modeling $NEE$	26
		3.2.2	Modeling $R_{eco}$	23
		3.2.1	Modeling $GPP$	23
	3.2	Deriva	tion of Models for the Interpolation of C-Fluxes	22
		3.1.3	Soil Temperatures, Thaw Depthes and Soil Moistures	20
		3.1.2	Radiation Balance and Albedo	19

xxiv

	6.1.2	Correction and Interpolation of Soil Moistures	xix
	6.1.3	Correction of PARr-Values	xxi
6.2	Calcul	ation and Interpolation of C-Fluxes	xxii
	6.2.1	Error Calculation	xxii

## Declaration of Authorship

# List of Figures

1.1	a) thaw slump on carbon-rich permafrost (yedoma) on the riverbank of the kolyma river ("duvany jar") in northeast siberia. $b$ ) Larch taiga, northeastern siberia	
	close to duvany jar. $c$ ) wet tussock tundra close to a lake at Pleistocene Park, northeastern siberia. $d$ ) Eddy-Covariance station close on a wet tussock tundra	
	close to the Northeast Science Station in Cherskiy (2017)	2
1.2	Grazing influences in tundra ecosystems. a) Exclosure of musk ox in greenland,	
	2. July 2013 (Photograph from Falk et al.,2015). (b) Raisduoddar (69°31'29 N,	
	$21^{\circ}9'16$ E; altitude $430-570$ m a.s.l.) and (c) Cearro ( $69^{\circ}43'23$ N, $21^{\circ}37'45$ E;	
	altitude 540–570 m a.s.l.) are reindeer ranges bisected by pasture rotation fences	
	built in the 1960s. These fences separate the graminoid- dominated, heavily	
	grazed summer range (on the left in the photographs) and the shrub- dominated,	
	Nightly grazed winter range (on the right in the photographs, photographs from	F
1.0		Э
1.3	Horses, bison and musk ox in Pleistocene Park. Photograph taken from Zimov et	7
	al., 2012	1
2.1	Location of study sites. a) The study site is located near Chersky within the	
2.1	Location of study sites. a) The study site is located near Chersky within the Arctic Circle ( $66^{\circ}33'$ N). b) Satellite image of the region. c) Aerial photograph	
2.1	Location of study sites. a) The study site is located near Chersky within the Arctic Circle (66°33' N). b) Satellite image of the region. c) Aerial photograph of the ambolikha site, the location of the meteorological tower/eddy covariance	
2.1	Location of study sites. a) The study site is located near Chersky within the Arctic Circle ( $66^{\circ}33'$ N). b) Satellite image of the region. c) Aerial photograph of the ambolikha site, the location of the meteorological tower/eddy covariance system and chamber plots are indicated. Plots numer "0" and "2", which are	
2.1	Location of study sites. a) The study site is located near Chersky within the Arctic Circle ( $66^{\circ}33'$ N). b) Satellite image of the region. c) Aerial photograph of the ambolikha site, the location of the meteorological tower/eddy covariance system and chamber plots are indicated. Plots numer "0" and "2", which are used in this study, are framed in red boxes. d) Location of the two sites inside	
2.1	Location of study sites. a) The study site is located near Chersky within the Arctic Circle ( $66^{\circ}33'$ N). b) Satellite image of the region. c) Aerial photograph of the ambolikha site, the location of the meteorological tower/eddy covariance system and chamber plots are indicated. Plots numer "0" and "2", which are used in this study, are framed in red boxes. d) Location of the two sites inside pleistocene park. The area between the fences (red) is the core area with most	
2.1	Location of study sites. a) The study site is located near Chersky within the Arctic Circle (66°33' N). b) Satellite image of the region. c) Aerial photograph of the ambolikha site, the location of the meteorological tower/eddy covariance system and chamber plots are indicated. Plots numer "0" and "2", which are used in this study, are framed in red boxes. d) Location of the two sites inside pleistocene park. The area between the fences (red) is the core area with most grazing pressure. The drainage ditch (blue) was dug to drain the lake in the lower	
2.1	Location of study sites. a) The study site is located near Chersky within the Arctic Circle (66°33' N). b) Satellite image of the region. c) Aerial photograph of the ambolikha site, the location of the meteorological tower/eddy covariance system and chamber plots are indicated. Plots numer "0" and "2", which are used in this study, are framed in red boxes. d) Location of the two sites inside pleistocene park. The area between the fences (red) is the core area with most grazing pressure. The drainage ditch (blue) was dug to drain the lake in the lower corner of the picture.	10
2.1 2.2	Location of study sites. a) The study site is located near Chersky within the Arctic Circle (66°33' N). b) Satellite image of the region. c) Aerial photograph of the ambolikha site, the location of the meteorological tower/eddy covariance system and chamber plots are indicated. Plots numer "0" and "2", which are used in this study, are framed in red boxes. d) Location of the two sites inside pleistocene park. The area between the fences (red) is the core area with most grazing pressure. The drainage ditch (blue) was dug to drain the lake in the lower corner of the picture	10
2.1 2.2	Location of study sites. a) The study site is located near Chersky within the Arctic Circle (66°33' N). b) Satellite image of the region. c) Aerial photograph of the ambolikha site, the location of the meteorological tower/eddy covariance system and chamber plots are indicated. Plots numer "0" and "2", which are used in this study, are framed in red boxes. d) Location of the two sites inside pleistocene park. The area between the fences (red) is the core area with most grazing pressure. The drainage ditch (blue) was dug to drain the lake in the lower corner of the picture	10
<ul><li>2.1</li><li>2.2</li></ul>	Location of study sites. a) The study site is located near Chersky within the Arctic Circle (66°33' N). b) Satellite image of the region. c) Aerial photograph of the ambolikha site, the location of the meteorological tower/eddy covariance system and chamber plots are indicated. Plots numer "0" and "2", which are used in this study, are framed in red boxes. d) Location of the two sites inside pleistocene park. The area between the fences (red) is the core area with most grazing pressure. The drainage ditch (blue) was dug to drain the lake in the lower corner of the picture	10
2.1	Location of study sites. a) The study site is located near Chersky within the Arctic Circle (66°33' N). b) Satellite image of the region. c) Aerial photograph of the ambolikha site, the location of the meteorological tower/eddy covariance system and chamber plots are indicated. Plots numer "0" and "2", which are used in this study, are framed in red boxes. d) Location of the two sites inside pleistocene park. The area between the fences (red) is the core area with most grazing pressure. The drainage ditch (blue) was dug to drain the lake in the lower corner of the picture	10
2.1	Location of study sites. a) The study site is located near Chersky within the Arctic Circle (66°33' N). b) Satellite image of the region. c) Aerial photograph of the ambolikha site, the location of the meteorological tower/eddy covariance system and chamber plots are indicated. Plots numer "0" and "2", which are used in this study, are framed in red boxes. d) Location of the two sites inside pleistocene park. The area between the fences (red) is the core area with most grazing pressure. The drainage ditch (blue) was dug to drain the lake in the lower corner of the picture	10
2.1	Location of study sites. a) The study site is located near Chersky within the Arctic Circle (66°33' N). b) Satellite image of the region. c) Aerial photograph of the ambolikha site, the location of the meteorological tower/eddy covariance system and chamber plots are indicated. Plots numer "0" and "2", which are used in this study, are framed in red boxes. d) Location of the two sites inside pleistocene park. The area between the fences (red) is the core area with most grazing pressure. The drainage ditch (blue) was dug to drain the lake in the lower corner of the picture	10

3.1	Atmospheric conditions during the measurement period. Air pressure was measured at Ambolikha site	18
3.2	a) $R_{net}$ at both sites, diurnal cycle averaged over the observation period (07/07/2019 - 21/07/2019); b) $K_{net}$ (solid lines) and $I_{net}$ (dashed lines); c) daily means of albedo	19
3.3	Development of $T_S$ (daily means, modeled values) in all depths at each site. Boxplots show differences between mean daily $T_S$ during the whole observation period ("all time") and the first/second week ("week1 and "week2". Letters indicate significant groups	21
3.4	a) Evolution of thaw depthes, depicted in negative values indicating below-ground level; b) Development of soil moistures at PPL (daily means) over the course of the observation period. The water table at AS-0 and AS-2 was above ground, hence soil moisture there was at its maximum during the whole period. $\ldots$	22
3.5	Light use response curves (PAR vs. GPP) for all plots."*" indicates $p < 0.05$ , "****" indicates $p < 0.0001$ , ns. indicates $p > 0.05$	23
3.6	Depiction of the relationship between $T_{S,5cm}$ and $SM$ and $R_{eco}$ for PPL-1 and PPL-2. Interpolation models are formed by the equations of depicted regression curves. The graphs on the right show modeled vs. measured fluxes, respectively.	24
3.7	Depiction of the relationship between $T_{air}$ and $R_{eco}$ for PPL-3, AS-0 and AS-2 (left column). Interpolation models are formed by the equation of the depicted regression curve. The graphs on the right show modeled vs. measured fluxes, respectively.	25
3.8	Modeled vs. measued NEE at all sites	26
3.9	Depiction of influencing drivers of $CH_4$ -fluxes (PPL-1: $a, b, c$ , PPL-2: $d, e, f$ , PPL-3: $g, h, i$ ) and the following derivation of formulas for the interpolation process, showing how magnitude of fluxes is higher for high soil moistures $(a, d, g)$ , and	
	how $SM_{15cm}$ and $T_{S,25cm}$ jointly explain $CH_4$ fluxes.	27
3.10	Exponential regressions between $CH_4$ fluxes and $T_{S,15cm}$ for AS-0 (a) and AS-2 (b).	28
3.11	Evolution of C-fluxes at all plots during the observation period. $GPP(a)$ , $R_{eco}(b)$ , $NEE(c)$ and $CH_4(d)$	32
3.12	C-fluxes - boxplots. "all time, site average" shows C-flux daily means averaged over the plots at each site over the whole observation period. On the right side, daily means of $GPP$ , $R_{eco}$ , $NEE$ and $CH_4$ -fluxes during the whole period, the first week and second week for each single plot are shown. Letters indicate significant groups. Shared letters between plots indicate $p > 0.05$	33

4.1	a) Tussock decaying close to a drainage ditch. Almost all tussocks close to PPL are
	in a state of decay, also those far away from the drainage. b) Tussock decaying
	close to a yak stable, away from drainage ditch. c) Trail along fence used by
	grazers. Note that grazing occurs on both sides of the fence, while being a lot
	more intense on the right side. d) Cows grazing. Note the damage at willow
	shrubs caused by browsing. PPL site is located around 400m further along the
	electricity line in a depressed plain
6.1	Procedure to model and interpolate soil Temperatures for the study period based
	on chamber point measurements (PP lowland). a) to c): procedure for $T_S$ in 5cm.
	d) for $T_S$ in 15cm. e) to h) plots showing both modeled and measured values for
	each depth
6.2	Procedure to model and interpolate soil Temperatures for the study period based
	on chamber point measurements (AS-0) and continuous $T_{air}$ measurements xvii
6.3	Procedure to model and interpolate soil Temperatures for the study period based
	on chamber point measurements (AS-2) and continuous $T_{air}$ measurements xviii
6.4	Correction of Soil Moisture values (PP lowland). Data noise has been removed by
	choosing continuous, low fluctuating intervals as reliable data. Systematic offsets
	were corrected by adding a constant number on 8th of July for SM in $7.5 \mathrm{cm}$
	and 15cm. When two series of values with different magnitudes were present the
	relatively higher values were identified to be correct for logical reasons
6.5	Interpolation of Soil Moisture values (PP lowland). For each day and each depth,
	one average value (corrected SM values) was calculated and included into the
	continuous dataset from the CNR-1 measurements and the gaps were linearly
	interpolated.
6.6	Correction of par-values. Values from chamber measurements that lie visibly far
	below the values from the CNR-1 were replaced by those values

## List of Tables

2.1	Number of utilisable light $(NEE)$ and dark $(R_{eco})$ measurements for each chamber	
	site and total numer of Measurement days.	14
3.1	Radiation components at AS and PPL.	19
3.2	Summary of the point-measurement-preceeding time intervals of $T_{air}$ ( $T_{air} - MA$ , $MA =$ "moving average" unit = hours) which explain $T_{a}$ in the various depths	
	$MA = MOVING average , unit = nours) which explain TS in the various depths(and statistical parameters for the applied linear regression - i.e. T_{i} - MA vs$	
	(and statistical parameters for the applied linear regression - i.e. $T_{air}$ - MA vs. $T_{c}$ ) A more detailed version of this table is found in the Appendix	20
3.3	$R^2$ and <i>p</i> -values for linear regressions between final modeled fluxes and measured	20
	fluxes. ****, ***, **, **, * , ns. indicate $p < 0.0001, p < 0.001, p < 0.01, p < 0.05, p > 0.001, p < 0.01, p < 0.000, p < 0.0$	
	0.05, respectively. $\ldots$	29
3.4	Mean daily C-Fluxes for each chamber site (total SE in brackets). Values in	
	$\mu molC * m^{-}2 * s^{-}1$	29
3.5	Coefficients of variance $(CV)$ for modeled fluxes between the single chamber plots	
	at PPL and AS. NEE is left out since it is constructed from $R_{eco}$ and $GPP$	30
4.1	Comparison of mean growing season fluxes ( chamber measurements) in different	
	studies. Values in $\mu molC * m^- 2 * s^- 1$ . (*) indicates sites in the same area as AS	
	in this study.	36
6.1	Summary of time intervals $(T_{air} - MA, [h], MA = "moving average")$ inside which	
	$T_{air}$ explains $T_S$ in the various depths (and statistical parameters for the applied	
	linear model), statistical parameters of a logarithmic model between residuals	
	from the first linear model $(T_{S,5cm}$ vs. $T_{air}movarg)$ vs. a moving average of	
	PAR (only for $T_{S,5cm}$ , [h]), the same for the linear model between the resulting	
	residuals from the logarithmic model (residual-2) and $T_{S,35cm}$ , as well as the the	
	final resulting statistics and RMSE (°C, linear regression: modeled vs. measured).	xix
6.2	Error range of C-fluxes. Values in $\mu mol(C) * m^- 2 * s^- 1$ . $Err_{abs}$ describes the	
	final cumulative error that is also used in the results section. $\ldots$ $\ldots$ $\ldots$ $\ldots$	xxiii

## Acknowledgement

I am thankful that I was given the opportunity to write my Master's Thesis about this special environment. I am therefore most grateful for Mathias Göckede, my first supervisor, who gave me great guidance from beginning to the end during fieldwork and paper work. I also thank Prof. Christoph Thomas, my second assessor, who set up the contact in the first place. Further I want to thank Martin Heimann and Olaf Kolle, the technicians from the Max Planck Institute in Jena, for their effort and help to set up and maintain the instrumentation. I give thanks to the Zimov family together with all the people sparing no effort for our well-being and for our work to run smoothly. Not to forget I want to thank the horses, the bison, the cows, the sheep, the musk oxen and reindeers who animate this remote piece of land.

I really want to show my deep respect for the Zimovs and all the staff from Pleistocene Park. This experiment is outstanding and, whether the pleistocene fauna will return or not, or whether the claims about its effect will be as powerful as assumed or not, invites us to expand our thinking about what is "natural" and what is not.

Finally, I want to dedicate this piece of work to the big scientific stream of understanding. May the insights contribute to a good future for all beings on our planet.

## Abstract

The northern permafrost regions cover around 24% of the land surface on the northern hemisphere and account for almost 50% of the belowground organic carbon stocks on earth. Global warming affects these regions around twice as much compared to the global mean, causing deeper thaw and retreat of permafrost. This makes the massive carbon stocks vulnerable to mineralization and raises the question how different ecosystems in the tundra and taiga regions, particularly their carbon balance, react to this warming. Environmental conditions like soil moisture, air and soil temperatures or nutrient availability modulate the carbon fluxes, which vary on a very fine scale. Grazing was shown to be of big importance in altering soil or vegetation properties and carbon fluxes in tundra ecosystems. In this study, we investigate main growing season  $CO_2$  and  $CH_4$  fluxes on a wet tussock tundra with a 25 year history of grazing by various big herbivores (Musk ox, bison, reindeer, horse, sheep, cow) at pleistocene park in northeastern siberia and on a nearby undisturbed wet tussock tundra, using flux chambers. Further, we measured soil temperatures, soil moistures and net radiation. Soil temperatures at pleistocene park reacted one order of magnitude faster to changes in air temperatures compared to the ungrazed site. Soil temperatures in 5cm at pleistocene park were continuously higher compared to the undisturbed site, while deep soil temperatures at 35cm were lower in the beginning of the measurement period, though were higher after four days into the observations. This indicates continuously lower deep soil temperatures at the pleistocene park lowland before the observation period compared to the undisturbed site. Overall, both GPP and  $R_{eco}$  were significantly higher at pleistocene park compared to the undisturbed site, showing considerable variations between plots at each site. NEE stayed at comparable levels at both sites throughout the measurement period. This results indicate a promoting effect of grazing on topsoil warming and drying, and paralelly a promoting effect on both productivity and ecosystem respiration during the growing season. Differences in annual NEE need to be assessed considering autumn and winter fluxes, which are highly important at tundra ecosystems. Both soil moisture and  $CH_4$  fluxes at pleisto cere park decreased throughot the observation period, while  $CH_4$  fluxes at the undisturbed site were significantly higher and stayed at high levels, while soils remained saturated. Grazing therefore might distinctly alter soil hydrology, leading to lower  $CH_4$  emissions.

## Zusammenfassung

Die nördliche Permafrostregion erstreckt sich über 24% der Landfläche der Nordhalbkugel und speichert etwa 50% des organischen Kohlenstoffs, der in den Böden und bodennahen Schichten unseres Planeten gebunden ist. Da die rezente Erderwärmung diese Region etwa doppelt so stark betrifft wie im globalen Durchschnitt, taut der Permafrost langsam auf und ist im Rückgang begriffen. Gleichzeitig wird der gespeicherte organische Kohlenstoff verwundbarer für die Mineralisierung durch Mikroorganismen. Das wirft die Frage auf, wie verschiedene Ökosysteme in Tundra und Taiga auf die Erwärmung reagieren, im besonderen ihre Kohlenstoffbilanz. Luft- und Bodentemperatur, Einstrahlung, Bodenfeuchte, Vegetationstyp oder Nährstoffverfügbarkeit modulieren die, feinskalig variablen, Kohlenstoffflüsse. Die Beweidung mit großen Pflanzenfressern hat einen großen Einfluss auf Boden und Vegetation in Tundra-Ökosystemen und damit auf die Kohlenstoffbilanz. In dieser Studie untersuchen wir mit Kammer-Flussmessungen die  $CO_2$ und  $CH_4$ -Bilanz einer nassen Horstgras-Tundra mit einer 25-jährigen Beweidungsgeschichte im nordost-sibirischen Pleistozän Park während der Hauptvegetationszeit. Diese werden mit den Flüssen auf einer nahegelegenen, ungestörten nassen Horstgras-Tundra verglichen. Begleitend wurden Luft- und Bodentemperaturen, Bodenfeuchte und Ein/Ausstrahlung gemessen. Die Bodentemperaturen in 5cm Tiefe im Park waren durchgehend höher im Vergleich zur ungestörten Fläche, während die Temperaturen in 35cm zunächst niedriger waren und dann wärmer wurden. Die Bodentemperaturen im Park haben eine Größenordnung schneller auf Lufttemperaturänderungen reagiert. Die Ergebnisse weisen darauf hin, dass durch die Beweidung Bodentemperaturen, vor allem flache, im Sommer erhöht werden. Sie deuten auch darauf hin, dass die tiefen Bodentemperaturen im Park vor Beginn der Messperiode durchgehend niedriger waren. Sowohl Photosyntheseleistung als auch Respiration im Park waren signifikant höher im Vergleich zur ungestörten Fläche, gleichzeitig variierten sie an den verschiedenen Standorten merklich. Die Nettobilanz der  $CO_2$  Flüsse zeigte keine signifikanten Unterschiede. Es ist anzunehmen, dass dies durch die Beweidung bewirkt wurde. Der Effekt der Beweidung auf die jährliche Netto-Kohlenstoffbilanz könnte daher von den Herbst- und Winterflüssen abhängen, die in der Tundra eine hohe Bedeutung haben. Gleichzeitig weist der Standort im Park einen kontinuierlichen Abfall der Bodenfeuchten auf, während die ungestörte Fläche durchgehend gesättigt war. Dies schlägt sich auf die  $CH_4$  Flüsse nieder, welche im Park ständig sanken während sie am ungestörten Standort hoch blieben. Diese bodenhydrologischen Veränderungen wurden möglicherweise von der Beweidung beeinflusst.

## **1** Introduction

# 1.1 Organic Carbon in Permafrost Ecosystems and its Vulnerability to Global Warming

The northern permafrost region covers approximately 24% of the terrestrial area on the northern hemisphere. Permafrost occurs in the parts of the circum-arctic region that are not covered by ice sheets and glaciers. These areas are characterized by cold winter temperatures and low snow depth, that lead to a long-term negative annual heat balance of the land surface, which in turn cause a permanently frozen layer in the ground (Brown et al., 1998). Apart from polar deserts, ecosystems on permafrost are generally segmented into tundra, a biome of treeless vegetation and their adjacent tree-line areas in the arctic and oro-arctic regions (R. Virtanen et al., 2016), and boreal forest (or taiga), which are defined as forests growing in high-latitude environments where freezing temperatures occur for 6 to 8 months and in which trees are capable of reaching a minimum height of 5 m and a canopy cover of 10% (Agricultural Organization, 2010). The arctic permafrost region might account for almost 50% of the belowground organic carbon stocks on earth(Hugelius et al., 2014). The known pool of organic C in the arctic Permafrost is estimated to be between 1307 Gt (Hugelius et al., 2014), and 1672 Gt (previously estimated by Tarnocai et al. (2009)). From this 1307 Gt, 1035 Gt are stored in the upper layer and 272 Gt in deposits below 3m (Hugelius et al., 2014), namely deltaic alluvial deposits (91 Gt) and yedoma/thermokarst deposits (181 Gt), which mostly formed during the Pleistocene. Tarnocai et al., 2009 estimated the C content in these deposits to be higher (241 Gt/407 Gt), while arriving at similar results (1024 Gt) for soils between 0 and 3m. For comparison, the atmospheric C-pool is estimated to be 830 Gt C. With the current global warming, surface air temperatures in polar regions are rising about twice as fast as the global mean (Overland et al., 2015). Therefore, understanding the current state and future evolution of permafrost and its ecosystems, particularly their interactions with the atmosphere, is crucial. The present and future warming will most likely continue to cause a deeper than of these regions and further retreat of permafrost (Lindgren et al., 2016). Simultaneously, these large pools of soil organic carbon (SOC) that were previousy frozen may become available for mineralization, leading to increased greenhouse gas fluxes to the atmosphere in the future, possibly turning the permafrost region from a sink to a source of atmospheric C (Schuur et al., 2008) - which in turn leads to a positive feedback to global warming.



Figure 1.1: a) thaw slump on carbon-rich permafrost (yedoma) on the riverbank of the kolyma river ("duvany jar") in northeast siberia. b) Larch taiga, northeastern siberia close to duvany jar. c) wet tussock tundra close to a lake at Pleistocene Park, northeastern siberia. d) Eddy-Covariance station close on a wet tussock tundra close to the Northeast Science Station in Cherskiy (2017).

Accumulating evidence from direct flux measurements shows, that arctic tundra ecosystems could already act as a source in the present (Natali, Watts, et al., 2019; E S Euskirchen et al., 2012; Oechel, Laskowski, et al., 2014) and will do so in the future. Other studies show, that arctic tundra ecosystems might act both as a sink (Kutzbach et al., 2007; Kittler et al., 2017) or a source, when certain environmental parameters are experimentally altered (Kittler et al., 2017). However, because of the remoteness of large parts of the Arctic, these ecosystems are difficult to access. The harsh climatic conditions and logistical challenges make it difficult to install durable long-term monitoring sites. For that reason, there is a sparse data coverage of carbon flux measurements for the Arctic (Oechel, Laskowski, et al., 2014; Donatella Zona et al., 2016). There have been a number of studies aiming to quantify the potential responses of permafrost ecosystems to global warming (with reference to C-exchange). These responses have typically been assessed combining estimates of soil thermal changes with those of simplified soil carbon

decomposition (Burke et al., 2012; C D Koven et al., 2015; Schneider Von Deimling et al., 2012). Results gathered by Schuur et al. (2015) integrates many of these studies and showed that the potential carbon release from today's permafrost zone would be between 37 and 174 Gt carbon until 2100 under a "business-as-usual" scenario (RCP 8.5). Koven et al. (2015) estimated a permafrost carbon response of 28–113 Gt C for the same time period, which is comparable. Their scenario was based on a soil carbon decomposition model in which the response of soil carbon to warming was calibrated by the results of laboratory incubation experiments(Schädel et al., 2014). Modelled carbon emissions from permafrost projected under various warming scenarios translate into a range of 0.13–0.27 °C additional global warming by 2100 (E. A.G. Schuur et al., 2015). However, commonly used models lack certainty, for example by not accounting for abrupt thaw processes and the importance of deep carbon pools - a survey filled out by a group of 40 international scientists revealed, that experts intimately familiar with permafrost hypothesize carbon emissions from permafrost by 2100 to be much higher (234-380 Gt C in CO<sub>2</sub>-equivalents) assuming the "business as usual" pathway RCP8.5 (**ippc3013**; Edward A.G. Schuur, Abbott, 2013).

# 1.2 Carbon Fluxes in Tundra Environments and Their Assessment with Flux Chambers

To determine whether a ecosystem is a sink or a source of atmospheric  $CO_2$ , the carbon balance of the ecosystem can be assessed by measuring C-fluxes. There are two fluxes that dominate the biosphere-atmosphere exchange:  $CO_2$  uptake by ecosystems by photosynthesis (GPP: gross primary production) and carbon release to the atmosphere by plant and microbial respiratory losses ( $R_{eco}$ : ecosystem respiration). The net exchange of C between the atmosphere and the ecosystem is called NEE (net ecosystem exchange) (Callaghan et al., 2004). While magnitudes and feedbacks of GPP and  $R_{eco}$  generally are climatically controlled, they are highly ecosystemand scale dependent (Oberbauer et al., 2007; Paré, Bedard-Haughn, 2012). Tundra landscape is heterogeneous at multiple scales (Fletcher et al., 2012; Post et al., 2009; T. Virtanen, Ek, 2014). At the landscape scale, there is a high diversity of environmental conditions and vegetation types, creating a mosaic of ecosystems like bogs or barrens. These ecosystems, then again, are composed of diverse plant-communities, such as heaths, tussocks, or hummocks. Even at a very fine scale, environmental conditions vary strongly within only a few meters (Aalto et al., 2013), making a representative assessment of fluxes difficult.

The two most prevalent methods to measure C-Fluxes are the eddy-covariance (EC) method and chamber-measurement techniques. EC measures fluxes continuously at an ecosystem scale, thus averaging over fine-scale heterogeneity (Kade et al., 2012), while chambers can be used for studying individual plant communities or fine scale variations in ecosystems. Furthermore, chambers can directly measure all components of the flux (*GPP*,  $R_{eco}$  and *NEE*), for example by shading the chamber with a opaque hood to determine  $R_{eco}$  (Kwon, Heimann, et al., 2016), while EC measures only NEE directly. Both approaches have disadvantages, for example, EC requires more electricity, technical knowledge, and understanding of surface-layer meteorology, while chambers are relatively cheap and simple to operate - but for all that very labour intensive. Generally, these flux chamber measurements exhibit typical issues by nature and depending on their individual designs, which will be discussed in the context of the measurements conducted in this study in section 4.1. There are a number of studies in permafrost regions, where flux chambers were used (Cassidy et al., 2016; Falk et al., 2015; Kwon, Heimann, et al., 2016; Natali, Edward A G Schuur, et al., 2015a; C. Corradi et al., 2005; Göckede et al., 2017; Väisänen et al., 2014). Notably, these studies focus on growing season fluxes. Chamber measurements are not only useful to supplement EC-measurements (Cassidy et al., 2016; Kade et al., 2012). By themselves, they provide important data on the various, especially small scale, processes regulating biosphere-atmosphere interactions (McGuire et al., 2012), for example water table depth, that depth and vegetation structure(Kwon, Heimann, et al., 2016; Kade et al., 2012), effects of rapid thaw processes (Cassidy et al., 2016), effects of artificial warming or fertilizing (Väisänen et al., 2014; Natali, Edward A G Schuur, et al., 2015a) or the influence of grazing (Falk et al., 2015; Väisänen et al., 2014).

## 1.3 Arctic Tundra Ecosystems and the Impact of Grazing

Nowadays throughout the arctic, there is a relatively low abundance of herbivores, particularily big herbivores (S. A. Zimov et al., 2012). Of the present ones, impacts from reindeer or caribou and in some cases musk ox are studied the most. Herbivores are an important factor influencing boreal and arctic ecosystems. Through grazing, trampling and fecal deposition, for example reindeers in the scandinavian tundra can cause an almost complete change in the species composition of whole communities (Manseau et al., 1996; Johan Olofsson, 2006; Ylänne et al., 2018). Their grazing is shown to significantly decrease height, abundance and C-Storage in shrubs, decrease moss layer thickness and increase the abundance of graminoids (Kitti et al., 2009; Manseau et al., 1996; Johan Olofsson, 2006). Similarly, excluding musk ox from a high arctic mire in greenland leads to a decrease of total vascular plant tillars and an increase in the amounts of moss and litter (Falk et al., 2015). Because shrub dominated tundra ecosystems have a lower albedo than grass-dominated ones, reindeer-grazing showed to increase surface albedo and therefore decrease net radiation in an order of magnitude comparable to the increase by a doubling of atmospheric  $CO_2$  (Te Beest et al., 2016; Chapin et al., 2005). In this way, grazing counteracts shrub encroachment (i.e. the northward expansion and magnification of shrubs and dwarf shrubs) and its positive effects on albedo (Chapin et al., 2005; Cohen et al., 2013; Betts, Ball, 1997), which has been a common feature in (sub-)arctic ecosystems for decades due to rising air temperatures (Myers-Smith et al., 2011; Chapin et al., 2005). Moderate to heavy grazing in tundra ecosystems leads to significantly higher soil temperatures in summer (J. Olofsson et al., 2004; Te Beest et al., 2016) and colder soil temperatures in winter (Sergei A Zimov et al., 1995; S. A. Zimov et al., 2012; Beer et al., 2020). Among various types of grazing regimes, this is attributed to a decrease in the abundance of shrubs (less shading) and/or bryophytes (less insulation) (Van der Wal et al., 2001) or snow trampling by animals (Sergei A Zimov et al., 1995; S. A. Zimov et al., 2012; Beer et al., 2020). Intensive grazing by reindeer also influences the distribution of the Carbon (C) and Nitrogen(N) pools in the ecosystem, promoting higher Soil N pools and belowground biomass (J. Olofsson et al., 2004) and increased primary productivity, which is attributed to enhanced nutrient cycling and respiration (Johan Olofsson et al., 2001).



Figure 1.2: Grazing influences in tundra ecosystems. a) Exclosure of musk ox in greenland, 2. July 2013 (Photograph from Falk et al.,2015). (b) Raisduoddar (69°31'29 N, 21°9'16 E; altitude 430–570 m a.s.l.) and (c) Čearro (69°43'23 N, 21°37'45 E; altitude 540–570 m a.s.l.) are reindeer ranges bisected by pasture rotation fences built in the 1960s. These fences separate the graminoid- dominated, heavily grazed summer range (on the left in the photographs) and the shrub- dominated, lightly grazed winter range (on the right in the photographs, photographs from Ylänne et al., 2018.

Similarily, exclusion of musk ox from a high arctic mire (dominated by sedges) in greenland lead to a strong decrease of NEE along a decrease of both GPP and  $R_{eco}$  (Ecosystem Respiration) (Falk et al., 2015), indicating a strong positive influence on ecosystem productivity by grazing. This supports related findings on this subject, where musk ox are shown to graze almost 50% of available shoots in an arctic wet tundra in greenland while considerably increasing primary production, or, in the authors words: "Indeed, Sverdrup Pass is like a lush, self sustaining oasis, surrounded by hostile icefields and relatively isolated from other lowlands. Musk ox apparently have maintained a well-fertilized, highly productive ecosystem, that in their absence would degenerate to a nutrient starved, overgrown grassland." (Raillard, Svoboda, 2000). However, other studies found, that heavy grazing in arctic tundra (dominated by shrubs, when not grazed) decreased main growing season GPP while not decreasing  $R_{eco}$ , leading to decreased NEE (Metcalfe, Johan Olofsson, 2015; Väisänen et al., 2014; Cahoon, Sullivan, Post, et al., 2012). Hereby, an increase of shrub abundance in grazing exclosures lead to an increase of LAI (Leaf area index), what mediated the increase of GPP. This effect however, can be counteracted by higher canopy temperatures of shrubs and low soil moistures (caused by increased transpiration by woody vegetation), leading to higher VPD, hence drought stress and strongly reduced GPP (Cahoon, Sullivan, Shaver, et al., 2012). However, since all studies cited here only investigated growing season fluxes, the annual NEE is not fully identified. Winter, especially early winter, respiration plays a big role in the annual carbon balance of arctic ecsosystems (Grogan, 2012; E S Euskirchen et al., 2012; Kittler et al., 2017), and therefore needs more attention. In summary, C-Flux responses to grazing are still unclear, might not be uniform, and dependent on ecosystem type, soil and climatic conditions, herbivore density and other, maybe unidentified variables.

The northern latitude ecosystems had a different face during the Pleistocene. Zimov et al., 2012 projected an average total biomass of animals of 10.5 tons per square km roaming the landscape in these times, including bison, horses, reindeer, wolves, lions and mammoths among various less abundant species. During the Late Pleistocene and early Holocene, most of these animals went extinct and all regions around the world suffered losses of megafauna species of a magnitude not seen for many millions of years (Prescott et al., 2012; Barnosky et al., 2016). Initially, climate change after the Pleistocene was believed to be the main trigger for these events(Barnosky et al., 2016), while nowadays the evidence that early humans were the main factor is getting predominant (Barnosky et al., 2016; S. A. Zimov et al., 2012; Sandom et al., 2014; Araujo et al., 2017; Prescott et al., 2012). These ecological changes had profound effects on terrestrial ecosystems. Big animals are disproportionately important for the movement of nutrients away from a concentration gradient (Doughty, Wolf, et al., 2013; Wolf et al., 2013). Extinctions and hunting pressures over the past 12,000 years decreased nutrient diffusivity by large animals to less than 10% of its former value (Doughty, Roman, et al., 2016), leading to strong hypothesized decreases in nutrient concentrations at a continental scale, and therefore a decrease in productivity(Doughty, Wolf, et al., 2013; Wolf et al., 2013), which leads us back to the positive effects reindeers and musk ox for productivity. A relatively higher fertility is correspondingly attributed to the prehistoric ecosystems on permafrost regions - available phosphorus in yedoma (paleo-soils, also containing a big amount of preserved animal bones) is an order of magnitude higher than in modern soils (S. A. Zimov et al., 2012). One can speculate that also the currently observable grazing influences of herbivores in the tundra described in the paragraph before have been much stronger under a higher density of herbivores, moreover featuring massive ones like mammoths.

## 1.4 Pleistocene Park - a Model for Productive and Resilient Permafrost Ecosystems in the Future?



Figure 1.3: Horses, bison and musk ox in Pleistocene Park. Photograph taken from Zimov et al., 2012.

As a research pioneer in the field of permafrost ecosystems, Sergey Zimov initiated the formation of "Pleistocene Park" in the nineties. "Pleistocene Park" is an ecological experiment aiming to reestablish the extinct ecosystems described in the previous section based on the assumption that they could potentially exist in todays climate (S. A. Zimov et al., 2012). The park is situated in north-eastern Siberia near Chersky, Sakha Republik, 100km south of the arctic ocean. While initially designed to reestablish the "mammoth steppe fauna" with all its features, this experiment also claims to mitigate global warming by several reasons (Source: pleistocenepark.ru): a) Increased Carbon sequestration by simultaniously increasing productivity and root formation during the growing season and decreasing permafrost temperature by trampling the snow in the winter - thereby limiting permafrost that and respiration. b) Increasing the surface albedo by decreasing shrub and tree cover, c) Decreasing Methane emissions by decreasing soil moisture through increased evapotranspiration by a more active vegetation. These claims are in accordance with some of the findings described in chapter 1.3. However, until today no quantitative research has been conducted to investigate the influence of grazing on the C-fluxes inside Pleistocene Park and their drivers, despite the obvious changes of the landscape that occur there (own observation).

## 1.5 Research Objectives and Limitations

The main objective of this research is to take a "snapshot" of growing season C-fluxes (measured with chambers), soil parameters (temperature and moisture) and the radiation balance of a grazed area in Pleistocene Park and compare it to those from a nearby undisturbed site. Hereby, we limit ourselves on a small number study sites, which are selected to represent the particular ecosystems, grazed and ungrazed, in the best possible way. By that, we want to collect insights if and how the park management influences these parameters. Furthermore, we want to discuss how the park management generally influences the face and stability of this ecosystem and provide insights to examine the credibility of the statements from the previous section (1.4). This study is limited in its scope due to the remoteness of the study site, as well as reasonable working period and financial resources. Therefore, it can not be sufficient to cover the entirety of the investigations neccessary to make a comprehensive comparison (i.e. missing out spring, autumn and winter period, and limitations in the number of chamber sites). Hereby we hypothesize, that the grazed area inside Pleistocene Park acts as a stronger sink of Carbon (higher NEE) compared to the undisturbed site during the month of July. In that context we assume that both  $R_{eco}$  and GPP are higher inside the Park. At the same time, we hypothesize, that the area inside Pleistocene Park dries out more quickly and emits less  $CH_4$ . Finally, we hypothesize that the albedo on the grazed site is slightly higher than at the undisturbed site. We hope to help further investigations focus on the most important drivers that determine whether grazing on arctic ecosystems is an effective phenomenon to sequester atmospheric  $CO_2$ , decrease  $CH_4$  - emissions and preserve permafrost - and how effective it could be.

## 2 Materials and Methods

## 2.1 Site Description

#### 2.1.1 Location of Study Area

The study area is located in northeastern Siberia near the Northeast Science Station in Chersky, Sakha Republic, Russia, around 100km south of the arctic Ocean. The weather patterns typically vary from arctic cold and moist air masses reaching the region in winter when the main wind direction is from N to NW to the continental warm and dry air masses in summer when the main wind direction is from S to SE. The mean daily air temperature can remain at or below -40°C for days at a time from december to february, while the mean daily temperature in the summer is warm, approximately 11°C. The total amount of precipitation each year is 200-215mm, with 80-110mm of this as rain(Corradi et al., 2005). Snowmelt leads to an annual spring flood in the river basin starting in late may that increases the water level significantly above the soil surface in a big area. Around the beginning of July the water level gradually decreases(Kwon, Heimann, et al., 2016). To attain insight about the grazing influence on Carbon Fluxes, we chose two measurement sites, one that hosts a variety of grazing herbivores (sheep, yaks, cows, horses; also in the past: bison, musk ox, reindeer) in Pleistocene Park (PP) and one non-grazed tussock tundra several kilometers from the park for comparison.

### 2.1.2 Pleistocene Park

At the first measurement site, inside PP, measurements on two different places have been conducted. Both lie in the longest and most intensively grazed area (starting 1996) and were installed next to a power line that runs through the park for access to electricity. The first subsite("PP Lowland Site", "PPL") is located inside the lowland wet tussock tundra and is flooded every year in spring during snowmelt. In 60m distance, there is a drainage channel to drain a nearby lake into another one, which was dug by the park operators. The vegetation around this site consists of Salix spp. and Betula exilis on moist soils, with an understory composed of mosses, grasses, and sedges, including Calamagrostis langsdorfii, Carex appendiculata, and Eriophorum spp. with a thick soil organic horizon. The lake shore is dominated by carex spec. (Eugénie S. Euskirchen et al., 2017). Precisely, our site was a moist-wet meadow without shrubs and featuring decaying tussocks - that used to be dominated by tussocks and saturated with water during the whole year (Sergey Zimov).



Figure 2.1: Location of study sites. a) The study site is located near Chersky within the Arctic Circle (66°33' N). b) Satellite image of the region. c) Aerial photograph of the ambolikha site, the location of the meteorological tower/eddy covariance system and chamber plots are indicated. Plots numer "0" and "2", which are used in this study, are framed in red boxes. d) Location of the two sites inside pleistocene park. The area between the fences (red) is the core area with most grazing pressure. The drainage ditch (blue) was dug to drain the lake in the lower corner of the picture.

The second sub-site lies in the never-flooded upland ("PP upland site"). In this commu-

nity, larch are sparsely distributed and are mixed with taller shrubs, including Salix spp. and Betula middendorffi. The understory is dominated by Vaccinium vitis-idaea, V. uliginosum, and Rhododendron subarcticum Harmaja (formerly known as Ledum decumbens) and mosses (Eugénie S. Euskirchen et al., 2017). At our location however, graminoids, herbs and willows dominate the vegetation due to the park management and a past forest fire (qt. Nikita Zimov). However, due to methodological and interpretational issues we collected little amount of data and excluded the upland site from further analysis.



Figure 2.2: a) Site "AS-0". b) Site "AS-2". c) PPL site during NEE measurement. d) Scheme of the setup in the lowland site. In the area depicted by the red frame soil temperatures and soil moistures were measured. Fluxes at the three chamber plots (1/2/3) were measured in a circular pattern, leaving the UGGA and the CR-1000 stationary at one place, controling measurements with the laptop on a small table.

## 2.1.3 Ambolikha Site

The second site, outside PP, lies on an extensive wet-tussock tundra plain along the ambolikha river, a small tributary of the kolyma river ("Ambolikha site", "AS"). Here a long-term drainage experiment site is installed. It features two Eddy covariance measurement systems for each of two transects (drained/control) endowed for flux-chamber measurements. The dominant vegetation

species are tussock-forming Carex appendiculata and lugens, and Eriophorum angustifolium, with betula nana and willow spec. growing on evevated areas with a lower water table. An organic peat layer (15–20 cm deep) has accumulated on top of alluvial material soils (silty clay) (Kwon, Beulig, et al., 2017). We assumed that the control transect of this experiment might be an approximation to the initial state of the lowland site inside PP before the ecosystem was altered through the park management. We chose two of the existing plots ("ambolikha 0" and "ambolikha 2"; from now "AS-0" and "AS-2") to cover some of the variability concerning vegetation structure and soil properties.

## 2.2 Instrumentation for Measuring Environmental and Soil Parameters

### 2.2.1 Soil Moisture (SM), Thaw Depth and Soil Temperature( $T_S$ )

At each sub site inside PP, one Th3-s Soil Temperature Profile Probe (UMS GmbH München) was installed, measuring soil temperatures at 5cm, 15cm, 25cm and 35cm depth. To create a gapless dataset for the period of measurement,  $T_{S,25cm}$  and  $T_{S,35cm}$  were interpolated linearly (PP lowland site) or modeled based on a moving average of  $T_{air}$ .  $T_{S,5cm}$  and  $T_{S,15cm}$  have been modeled based on air temperature, and in the case of  $T_{S,5cm}$  incoming shortwave radiation and corresponding  $T_{S,35cm}$  were used additionaly in the course of stepwise linear regressions to improve the prediction. For soil moisture(SM) measurements, one TDR-Sonde (time-domain reflectometry soil moisture sensors; CS 640, 630, and 605, Campbell Scientific, USA) for each depth (7.5cm, 15cm and 30cm) was installed next to the Th3-s. At the Ambolikha site, the same, permanently installed, setup was used - hereby, SM values were not used, since the water table was above groud during the whole period. SM values were flagged based on plausibility limits, and systematic errors partly corrected. Only trustworthy values have been used for further analysis. The detailed procedure of the interpolation and correction process for both ST and SM can be found in the Appendix. That depths were measured with a metal pole that was stuck into the ground, right next to the chamber plot, to avoid disturbance, until it hit the frozen surface of the permafrost. The measured thaw depth was defined as the distance between this point and the ground surface, which for his part was defined including the organic layer on top, while loose material was softly pressed down until more or less stable ground was touched. Consequently, standing water and tussock structures at AS-0 and AS-2 were not integrated into the thaw depth. Issues arising with this approach are taken up in the discussion.

#### 2.2.2 Radiation, Albedo and Air Temperature

To determine the radiation balance and its components, a CNR1 net radiometer was installed at a electricity pole next to the lowland-sub-site in PP at 4m height. At the ambolikha site, a CNR4 radiometer is permanently installed and the data was provided by the MPI Jena. Both radiometers measure the energy balance between incoming short-wave and long-wave radiation versus surface-reflected short-wave and outgoing long-wave radiation and air temperature(Source: Campbell Scientific). Measurements were taken in 10 minute averaging intervals. The following formula shows the calculation of the net radiation:

$$R_{net} = K \uparrow -K \downarrow +I \uparrow -I \downarrow \tag{1}$$

 $R_{net}$  is the net radiation.  $K \uparrow$  and  $K \downarrow$  are the outgoing and the incoming shortwave radiation,  $I \uparrow$  and  $I \downarrow$  the outgoing and the incoming longwave radiation, respectively. We could not measure sensible and latent heat fluxes, nor soil heat fluxes. Therefore, no quantitative assessment of the whole energy balance could be conducted. Albedo was calculated by dividing the average  $K \uparrow$  by the average  $K \downarrow$  at each site. To compare the sites, mean albedo was calculated after first averaging  $K \uparrow$  and  $K \downarrow$  for both sites over the whole observation period. To attain continuous values for PAR,  $K \downarrow$  was converted based on the approach of Britton, Dodd, 1976.

## 2.3 Flux-Chamber Setup and Instrumentation

Directly prior to measurements, inside PP wooden fences have been constructed to protect the sites from grazing animals during chamber operation. We placed walking boards around our setup to prevent damaging plants and minimize influences on measurements by disturbing the soil. On each sub-site inside PP, three Flux-Chamber plots were installed to determine  $CO_2$ and  $CH_4$  fluxes. At the ambolikha site, as described earlier, two of the existing plots were used. To prevent leaching of air at the edges, 60cm\*60cm PVC collars, which have a socket at the top for the chamber, were tucked into the ground at each plot. The chamber was made by a 4mm thick,  $60cm^3$  Plexiglass box (open at the bottom). It has an opening value on the top to avoid pressure effects when the chamber is placed onto the collars. Inside the chamber, fans were installed at three different heights to mix the air. Sensors for  $T_{air}$ , relative air humidity,  $P_{air}$ , and photosynthetically active radiation (PAR) were attached to one side of the chamber. For measurements, the chamber was oriented in a way to minimize shading the vegetation with the instruments.  $CO_2$  and  $CH_4$  fluxes were determined with a non-steady-state flow-through method using an Ultra-Portable Greenhouse Gas Analyzer (UGGA, Los Gatos Research, USA), measuring gas concentrations at 1 Hz. The measurement technology of the UGGA is based on off-axis integrated cavity output spectroscopy (OA-ICOS), an improved method of CRDS for

field usage. The chamber inside and gas analyser were connected via 6 mm plastic tubes.

Air was sucked in from three different tubes in three heights. Ecosystem respiration( $R_{eco}$ ) was determined by using a white PE-Tarp as an additional hood to shield radiation. While measuring, the instruments in the chamber were connected to a logger box (CR-1000) and a laptop for control. Each flux measurement was restricted to a maximum of two minutes to minimize saturation effects (i.e., warming and pressurized effects) within the chamber. After

	AS-0	AS-2	PPL-1	PPL-2	PPL-3
light	77	40	77	71	68
$\operatorname{dark}$	45	27	46	42	41
days	4	4	9	9	9

**Table 2.1:** Number of utilisable light (*NEE*) and dark ( $R_{eco}$ ) measurements for each chamber site and total numer of Measurement days.

completing one measurement, the chamber was ventilated until ambient  $CO_2$  concentrations were reached. For each plot, one measurement iteration consisted of three NEE measurements and two  $R_{eco}$  measurements. In PP, chamber plots were measured rotating between them. At Ambolikha site, plots were dealt with for longer continuous intervals to minimize time losses, since they were too far apart from each other to just move the chamber without relocating the whole setup. On each day, only one of the two main sites were adressed. The total quantity of measurements is shown in Tab.2.1.

## 2.4 Flux-Chamber Data Processing

## **2.4.1 Calculation of** $CO_2$ and $CH_4$ Fluxes

As described, every single chamber measurement resulted in a 1Hz time series of  $CO_2$  and  $CH_4$  concentrations.



Figure 2.3: Example: Depiction of the process from raw data to a median slope and its RMSE.

A number of slopes was calculated after choosing a sensible interval with a gradient as linear and outlier-free as possible, using a bootstrapping approach (Fig.2.3). Hereby, inside this interval, start and endpoints of linear fits are defined randomly (and manually evaluated and sometimes adjusted) to generate a big number of slopes (dependent on the length of the interval). Then a median value is generated for a final resulting slope. Unplausible or disturbed signals have been flagged and excluded from further analysis. These include unstable signals without a distinctly discernable slope (making the calculation of an explicit slope impossible) or signals obviously disturbed by leakage (i.e. unusually muffeled and noisy signals). From these slopes a median slope was calculated. This median value was transformed to a flux using the following formula:

$$Flux = slope * \frac{\frac{V_{ch}}{A_{ch}} * p_{air}}{R * T_{air}}$$
(2)

 $V_{ch}$  and  $A_{ch}$  are the volume and surface area of the chamber. R is the ideal gas constant (8.3144621J/mol \* kg),  $T_{air}$  and  $p_{air}$  are the mean air temperature (K) and pressure (Pa) inside the chosen interval. Fluxes return in  $[\mu molC - CO_2m^{-2}s^{-1}]$  and  $[\mu molC - CH_4m^{-2}s^{-1}]$ . The photosynthesis portion of the flux (GPP) is calculated from the difference between measured NEE and the mean of measured  $R_{eco}$  during one measurement iteration. The standard error (RMSE)of each flux measurement was calculated using all bootstrapped slopes, distinguishing between  $R_{eco}$  and NEE measurements. The slope error for GPP is the summed up error of  $R_{eco}$  and NEE measurements. Error values are given in Tab. 6.2 (Appendix). Calculations were conducted using R.

### 2.4.2 Interpolation of CO<sub>2</sub> and CH<sub>4</sub> Fluxes

To compare flux variability among study sites induced by temporal discrepancies in sampling and to visualize the implications of these differences for net  $CO_2$  exchange,  $CO_2$  and  $CH_4$  fluxes for each chamber plot on each study site were interpolated throughout the measurement period. GPP is modelled as a function of PAR, using a rectangular hyperbola function (Runkle et al., 2013).

$$GPP = -\frac{P_{max} * \alpha * PAR}{P_{max} + \alpha * PAR}$$
(3)

The fit parameters  $\alpha$  and  $P_{max}$  represent, respectively, the initial canopy quantum efficiency (that is, the initial slope of the GPP-PAR curve at PAR= 0) and the maximum canopy photosynthetic potential, which is the hypothetical maximum of GPP at infinite PAR; GPP is the modelled  $CO_2$  uptake using this approach. Both  $\alpha$  and Pmax are assumed to have positive values, necessitating the negative sign on the equation's right-hand side to allow GPP to fit the NEE sign convention. Hereby, upward fluxes imply carbon losses from the ecosystem (hence  $R_{eco}$ ) and are expressed in positive, downward fluxes, implying carbon uptake, (hence, GPP) in negative values. This model contains the explicit assumption that the gross productivity flux is not influenced by light stress or temperature effects (Runkle et al., 2013). For each site  $\alpha$ and  $P_{max}$  were determined by fitting PAR against the GPP-Fluxes from chamber measurements and applying a Non-linear-least-squares (nls) model in R. Unplausible PAR values from chamber measurements have been replaced by PAR derived from the CNR1 and CNR4 measurements (See Appendix A for precise information). With these parameters, a GPP could be modeled for the entire observation period.

 $R_{eco}$  and the  $CH_4$  - fluxes were interpolated by an empirical approach using consequently applied linear models based on environmental drivers and their evolution in correlation with  $R_{eco}$  and  $CH_4$  - fluxes, respectively. This was done separately for each single chamber, since driver combinations that generate the best fit were not uniform (see discussion section for more details). The following formulas were derived to interpolate  $R_{eco}$  and  $CH_4$  fluxes for all single plots:

$$R_{eco}(PPL-1, PPL-2) = exp(a_0 * T_{Soil,5cm} + b_0) + a_1 * SM_{7.5cm} + b_1$$
(4)

$$R_{eco}(PPL - 3, AS - 0, AS - 2) = exp(a_0 * T_{air} + b_0)$$
(5)

$$F_{CH_4}(AS) = exp(a_0 * T_{Soil,15cm} + b_0)$$
(6)

$$F_{CH_4}(PPL) = a_0 * T_{Soil,25cm} + b_0 + a_1 * SM_{15cm} + b_1$$
(7)

In each formula,  $a_0$  is the slope of the first applied model,  $a_1$  for the second.  $b_0$  and  $b_1$  are corresponding intercepts. Derivations of formulas and resulting depictions of the correlations between environmental drivers and  $R_{eco}$  and  $CH_4$  - fluxes, as well es total errors, are shown in the results section.

Total errors for all fluxes were derived considering the standard error from the final model compared to observed values (linear regression), further considering the standard error from the bootstrapping approach used to transfer measured concentration slopes into fluxes (see 2.3.1) and the standard error from modeled  $T_S$  (for  $R_{eco}$  and  $CH_4$  fluxes). A detailed error calculation is shown in the Appendix.

## 2.5 Statistics: Comparison of Greenhouse Gas fluxes, Soil Temperatures and Albedo Between Sites

To visualize and compare C-fluxes between plots and study sites, daily means for GPP,  $R_{eco}$ , NEE and  $CH_4$ -fluxes were calculated. Due to the changing meteorological conditions (See chapter 3.1) during the study period, measurements were subdivided into two phases, namely "Week 1" and "Week 2". Daily average  $T_S$  and C-fluxes were compared using Tukey's post-hoc test. Mean daily albedo and  $R_{net}$  were compared using a two-sample t-test.

## **3** Results

## 3.1 Environmental Conditions During the Observation Period

### 3.1.1 Weather, Air Temperature and Pressure

Mean air temperatures were insignificantly higher at PP lowland site. Both sites showed a strong decline of daily average  $T_{air}$  between 14.3°C and 26.9°C in the first week (from July 7th until July 15th, max.  $T_{air}$  35.9°C at July 12th, pleistocene park) down to 6.9°C to 10.9°C during the second week (until July 22nd) (Fig. 3.1). Weather conditions changed from sunny to lightly clouded in the first week to changeable weather with little precipitation over the course of the second week. There are no recordings available that quantify precipitation.



Figure 3.1: Atmospheric conditions during the measurement period. Air pressure was measured at Ambolikha site.

### 3.1.2 Radiation Balance and Albedo

Incoming shortwave-radiation  $(K \downarrow)$  differed slightly between sites, when averaged over the observation period, reasoned by the slight differences in weather. Mean daily  $K \downarrow$  was insignificantly (p = 0.91) higher at PPL  $(234.79W/m^2)$  compared to AS  $(230.18W/m^2)$ . However, albedo was significantly higher at PPL, with an average value of 0.217, compared to the AS, with an average value of 0.192 (p < 0.0001). This is also reflected by the lower  $K_{net}$  at PPL  $(183.73W/m^2)$  compared to AS  $(185.75W/m^2)$ , despite  $K \downarrow$  being higher at PPL, resulting in a insignificantly lower energy input of  $2.02 W/m^2$  at PPL.  $I \downarrow$  showed strong differences between sites, and the signal at PPL was very wavery and uneven. This did not seem logically explainable , therefore  $I \downarrow$  at PPL was replaced by the  $I \downarrow$  from AS. Overall, mean daily  $R_{net}$  was higher at AS  $(134.77W/m^2)$  compared to PP  $(132.61W/m^2)$ , however, this diffenence was insignificant (p = 0.85). Radiation data is summarized in Tab.3.1 and Fig.3.2.

 Table 3.1: Radiation components at AS and PPL.

	$R_{net}$	$K\downarrow$	$K\uparrow$	$I\downarrow$	$I\uparrow$	albedo
PPL	132.61	234.79	51.04	391.1	340.0*	0.217
AS	134.77	230.18	44.42	391.0	340.0	0.192



Figure 3.2: a)  $R_{net}$  at both sites, diurnal cycle averaged over the observation period (07/07/2019 - 21/07/2019); b)  $K_{net}$ (solid lines) and  $I_{net}$  (dashed lines); c) daily means of albedo

#### 3.1.3 Soil Temperatures, Thaw Depthes and Soil Moistures

 $T_S$  generally were lowest at AS-2 and highest at PPL (Fig.3.3), were mainly governed by air temperatures and showed, in the case of  $T_{S,5cm}$ , a distinct diurnal cycle depending on  $K \downarrow$  at all sites. For  $T_{S,5cm}$  at PPL also  $T_{S,35}$  was an important factor modulating  $T_{S,5cm}$  (see Appendix for a detailed description). At PPL, the deeper  $T_S$  showed no noticeable diurnal cycle, except  $T_{S,15cm}$  (which however could not be resolved by the interpolation model). Moving average (MA) time intervals of  $T_{air}$ , which explain  $T_S$  in all depths, and their significance are shown in Tab 3.1.  $T_{S,5cm}$  at PPL reacted one order of magnitude faster to changes in  $T_{air}$  compared to AS-0 and AS-2, while for  $T_{S,15cm}$  AS-0 reacted faster compared to PPL. Since at PPL no MA interval could be identified for  $T_{S,25cm}$  and  $T_{S,35cm}$  (due to limited data availability), those could not be compared between PPL and AS. For AS-2,  $T_{S,35cm}$  as well could not be interpolated based on moving averages of  $T_{air}$ .

**Table 3.2:** Summary of the point-measurement-preceeding time intervals of  $T_{air}$  ( $T_{air} - MA$ , MA = "moving average", unit = hours) which explain  $T_S$  in the various depths (and statistical parameters for the applied linear regression - i.e.  $T_{air}$  - MA vs.  $T_S$ ). A more detailed version of this table is found in the Appendix.

	AS-0	AS-2	PPL
$T_{S,5cm} \\ T_{air} - MA \\ R^2/p$	<b>40.7</b> 0.98****	<b>86.7</b> 0.99****	<b>4.3</b> 0.77****
$T_{S,15cm} \\ T_{air} - MA \\ R^2/p$	<b>67.5</b> 1****	<b>108.3</b> 1****	<b>100</b> 0.96****
$T_{S,25cm} \\ T_{air} - MA \\ R^2/p$	<b>113.0</b> 0.99****	<b>204.8</b> 0.97****	-
$     T_{S,35cm} \\     T_{air} - MA \\     R^2/p $	<b>281.7</b> 0.71****	<b>288.3</b> 0.073 <sup>ns</sup>	-



Figure 3.3: Development of  $T_S$  (daily means, modeled values) in all depths at each site. Boxplots show differences between mean daily  $T_S$  during the whole observation period ("all time") and the first/second week ("week1 and "week2". Letters indicate significant groups.

Thaw depths were continously deeper at PPL compared to AS-0 and AS-2, while they showed distinct differences among themselves (Fig.3.4 a). Soil thaw progressed continuously at both sites, while at PPL thaw depthes increased faster compared to AS-0 and AS-2.



Figure 3.4: a) Evolution of thaw depthes, depicted in negative values indicating below-ground level; b) Development of soil moistures at PPL (daily means) over the course of the observation period. The water table at AS-0 and AS-2 was above ground, hence soil moisture there was at its maximum during the whole period.

Over the observation period, thaw depth increased from 49cm to 58cm at PPL-1 and from 39cm to 50cm at PPL-2, which showed the deepest and slowest thaw at PPL, respectively. Thaw depth decreased from 31cm to 34cm at AS-0 and from 32cm to 36cm at AS-2. However,  $T_{S,35cm}$  was constantly above 0°C at AS-0 and AS-2, showing a discrepancy between thaw depthes and measured  $T_S$ . This means, that the actual thaw depth at the  $T_S$  sensor location was deeper. Soil moistures at PPL at all depths decreased continously (Fig. 3.4 b). Due to instrument issues, soil moistures could not be assessed at AS-0 and AS-2, however, soils at AS-0 and AS-2 stayed saturated during the whole time with the water table being above ground.

## 3.2 Derivation of Models for the Interpolation of C-Fluxes

In this section, the derivation and usage of the equations 3-7 in chapter 2.4.2 used to interpolate GPP,  $R_{eco}$  and  $CH_4$  fluxes, is described.

#### 3.2.1 Modeling GPP

To explain *GPP*, light use response curves were computed for each plot (Fig.3.5).  $\alpha$  and  $P_{max}$  were calculated (equation 3, chapter 2.4.2) and used to model a 10 minute resolution time series for *GPP* during the whole measurement period using PAR-values calculated from continuous  $K \downarrow$  measurements.  $P_{max}$  values at all PPL-sites are distincly higher compared to AS-0 and AS-2, while  $\alpha$  fluctuates and shows no discernable differences between sites. At AS-2,  $\alpha$  could not be calculated in a significant way, since there was too little data under low-PAR conditions. This is reflected by the max. measured *GPP* fluxes, ranging from -23.11±0.26, -27.57±0.27 and -24.06±0.33 at PPL-1, PPL-2 and PPL-3 and -22.79±0.30 and -8.92±0.24 at AS-0 and AS-2, respectively.



Figure 3.5: Light use response curves (PAR vs. GPP) for all plots."\*" indicates p < 0.05, "\*\*\*" indicates p < 0.0001, ns. indicates p > 0.05

### **3.2.2 Modeling** $R_{eco}$

Investigating the environmental drivers and their evolution in correlation with  $R_{eco}$  measurements reavealed, that there is no uniform driver (or set of drivers) that shows the best fits for regression analysis while at the same time logically describing fluxes. Since most of the time parameters like SM were not normally distributed across other variables (i.e. PAR,  $T_{air}$ ,  $T_S$  or flux measurements), data was too limited for attempting a typical stepwise regression approach
or check for causally valuable correlations without subsetting. For PPL-1 and PPL-2, in contrast to all other sites, changes in SM apparently excerted a strong influence on  $R_{eco}$  (see Fig.3.6, note distribution of  $SM_{7.5cm}$  vs.  $T_{S,5cm}$ ; see Fig.3.7 for comparing distribution of  $SM_{7.5cm}$  at PPL-3. Here however,  $R_{eco}$  was fitted against  $T_{air}$ ). In the case for PPL-1 and PPL-2, a pseudo-stepwise regression utilizing first  $T_{S,5cm}$  (exponential fit) and  $SM_{7.5cm}$  (linearly fitted against residuals) yielded the best results. Hence, these terms were used to model  $R_{eco}$ . Hereby, since SM values were not normally distributed throughout  $T_S$  regimes,  $R_{eco}$  fluxes during a moisture interval that shows a good distribution, specific for each site, was chosen in which the exponential regression  $(T_{S,5cm}\tilde{R}_{eco})$  was conducted.



Figure 3.6: Depiction of the relationship between  $T_{S,5cm}$  and SM and  $R_{eco}$  for PPL-1 and PPL-2. Interpolation models are formed by the equations of depicted regression curves. The graphs on the right show modeled vs. measured fluxes, respectively.

The residuals utilized for the second, linear regression resulted from applying the exponential formula from the first regression to  $T_{S,5cm}$  from all measurements of the respective chamber,

and afterwards subtracting these values from actual  $R_{eco}$  fluxes. Fits and modeled vs. measured values are depicted in Fig 3.6.  $R^2$  and *p*-values of linear regressions between modeled and measured fluxes are depicted in Tab.3.3.



Figure 3.7: Depiction of the relationship between  $T_{air}$  and  $R_{eco}$  for PPL-3, AS-0 and AS-2 (left column). Interpolation models are formed by the equation of the depicted regression curve. The graphs on the right show modeled vs. measured fluxes, respectively.

For  $R_{eco}$  measurements at PPL-3, AS-0 and AS-2 fits were best when utilizing air temperatures for an exponential regression, while no correlation could be found when trying to explain residuals with SM, that depth or other variables.  $K \downarrow$ /PAR was negatively correlated (significant) to the residuals at AS-0 and AS-2, with  $R^2$  being 0.59 and 0.29, respectively. Contrastingly, fitting  $R_{eco}$  at AS-0 and AS-2 against  $T_{S,5cm}$  ( $R^2 = 0.66$  and 0.64, respectively) leads to residuals that are positively correlated to  $K \downarrow$ /PAR ( $R^2 = 0.55$  and 0.45, respectively). However, since  $K \downarrow$ /PAR values were not normally distributed across  $R_{eco}$  and the respective  $T_{air}/T_{S,5cm}$ , these  $R^2$  have no validity. Notably, an exponential regression between  $(T_{air} + T_{S,5cm})/2$  and  $R_{eco}$  yielded  $R^2 = 0.92$  and  $R^2 = 0.93$  for AS-0 and AS-2, respectively. Despite these slightly better fits,  $T_{air}$  was used for modeling. Reasons are discussed in chapter 4.2.6.

## **3.2.3 Modeling** NEE

As described in section 2.3, NEE was interpolated by subtracting modeled  $R_{eco}$  from modeled GPP. Fig.3.8 depicts modeled and measured NEE at each site, which agree well to each other.



Figure 3.8: Modeled vs. measued NEE at all sites.

## **3.2.4 Modeling** $CH_4$ Fluxes

 $CH_4$  fluxes showed a strong correlation to both  $T_S$  (all sites) and SM at all depths (PPL-1, PPL-2, PPL-3). However, there was a strong colinearity between  $T_S$  and SM.



Figure 3.9: Depiction of influencing drivers of  $CH_4$ -fluxes (PPL-1: a, b, c, PPL-2: d, e, f, PPL-3: g, h, i) and the following derivation of formulas for the interpolation process, showing how magnitude of fluxes is higher for high soil moistures (a, d, g), and how  $SM_{15cm}$  and  $T_{S,25cm}$  jointly explain  $CH_4$  fluxes.

Therefore, to reach a the best possible fit for interpolating  $CH_4$  fluxes at PPL while accounting for both drivers (considering physicality), data was split up in two moisture groups ( $SM_{15cm} >$  60% and  $SM_{15cm} < 60\%$ ) to apply a pseudo-stepwise regression. Then, for each plot, a linear regression between  $CH_4$  fluxes of the lower moisture group and  $T_{S,25cm}$  was applied (Fig.3.9 b, e, h). Second, the resulting linear equation was applied to the complete dataset for each plot integrating both moisture groups. The difference between these calculated values and the measured values (hence, residuals) was fitted against  $SM_{15cm}$ , applying another linear regression, yielding in a second linear equation.



Figure 3.10: Exponential regressions between  $CH_4$  fluxes and  $T_{S,15cm}$  for AS-0 (a) and AS-2 (b).

These two resulting equations were used to interpolate  $CH_4$  fluxes for each plot. Since soil moistures did not change at AS-0 and AS-2,  $CH_4$  fluxes here were explained only by  $T_S$  ( $T_{S,15cm}$ ). Hereby, a linear regression between  $CH_4$  fluxes and  $T_{S,15cm}$  yielded the particular linear equations used to model fluxes at these sites (Fig.3.10).  $R^2$ s and *p*-values for the regression steps are shown in Fig.3.10, for the final models in Tab 3.3.

## 3.3 Summary Statistics on Flux Models

All models used to interpolate flux data show a significant fit to actual measured values (linear regressions, see Tab.3.3). The fit for GPP at AS-2 was weakest with the by far worst significance. Mean daily C-fluxes and error ranges are depicted in Tab. 3.4. Notably, the error stated for NEE values is very high, since NEE inherits both errors of GPP and  $R_{eco}$ , however, as shown in Tab 3.3. and Fig. 3.8., NEE fits very good to actual measured values.

			AS-0	AS-2	PPL-1	PPL-2	PPL-3	
		$_{TPP}$	$0.82^{****}$	0.11*	0.87***	0.73****	$0.81^{***}$	
		$R_{eco}$	$0.90^{****}$	$0.88^{***}$	$0.86^{****}$	$0.44^{****}$	$0.85^{****}$	
	Γ	VEE	$0.84^{****}$	$0.49^{****}$	$0.76^{****}$	$0.61^{****}$	$0.80^{****}$	
		$CH_4$	$0.84^{***}$	$0.93^{****}$	$0.84^{***}$	$0.93^{***}$	$0.88^{***}$	
	Lable 3.4: Mean	daily C-I	Iuxes for ea	ch chamber sit	e (total SE in br	ackets). Valu	es in $\mu mol C * m^- 2$	* s <sup>-</sup> 1
	Ambolikha Site		PP	Lowland Site		,		
	AS-0	AS	3-2	AS-avg	PPL-1	PPL-2	PPL-3	PPL-avg
Whole P.								
GPP	$-9.55(\pm 2.80)$	-4.82(	土1.44) -'	$7.19(\pm 2.12)$	$-10.3(\pm 2.03)$	$-12.6(\pm 2.94)$	) $-10.26(\pm 2.48)$	$-11.06(\pm 2.48)$
ER	$3.67(\pm 1.46)$	$2.58(\pm$	E0.58) 5	$3.13(\pm 1.02)$	$7.42(\pm 1.31)$	$7.66(\pm 1.64)$	$0.17(\pm 0.97)$	$7.09(\pm 1.31)$
NEE	$-5.88(\pm 4.26)$	-2.24(=	$\pm 2.02$ )	$4.06(\pm 3.14)$	$-2.88(\pm 3.34)$	$-4.95(\pm 4.58)$	$-4.08(\pm 3.55)$	$-3.97(\pm 3.82)$
$CH_4$	$0.15(\pm 0.014)$	$0.22(\pm$	-0.016) 0	$.18(\pm 0.015)$	$0.17(\pm 0.049)$	$0.10(\pm 0.023$	$0.018(\pm 0.008)$	$0.1(\pm 0.028)$
Week 1								
GPP	$-10.32(\pm 2.80)$	-5.10(z)	$\pm 1.44)$		$-11.18(\pm 2.03)$	$-13.55(\pm 2.94)$	1) $-11.12(\pm 2.48)$	
ER	$4.87(\pm 1.46)$	$3.14(\pm$	E0.58)		$8.57(\pm 1.31)$	$8.00(\pm 1.64)$	$7.77(\pm 0.97)$	
NEE	$-5.45(\pm 4.26)$	-1.96(=	$\pm 2.02)$		$-2.60(\pm 3.34)$	$-5.55(\pm 4.58)$	$-3.34(\pm 3.55)$	
$CH_4$	$0.17 (\pm 0.014)$	$0.23(\pm$	-0.016)		$0.25(\pm 0.049)$	$0.16(\pm 0.023$	$0.03(\pm 0.08)$	
Week 2								
GPP	$-8.67(\pm 2.80)$	-4.51(=	$\pm 1.44)$		$-9.30(\pm 2.03)$	$-11.54(\pm 2.94)$	$1) -9.29(\pm 2.48)$	
ER	$2.30(\pm 1.46)$	$1.94(\pm$	E0.58)		$6.11(\pm 1.31)$	$7.27(\pm 1.64)$	$(4.35(\pm 0.97))$	
NEE	$-6.37(\pm 4.26)$	-2.57(=	$\pm 2.02)$		$-3.19(\pm 3.34)$	$-4.27(\pm 4.58)$	() $-4.94(\pm 3.55)$	
CH	$0.12(\pm 0.014)$	0.20(+	-0.016)		$0.067(\pm 0.049)$	$0.038(\pm 0.02)$	$3) 0.0025(\pm 0.008)$	

29

# 3.4 Evolution of Modeled C-Fluxes Over the Course of the Observation Period

Flux magnitudes were distinctly varying over time and with weather and soil conditions, therefore, as with  $T_S$ , fluxes were compared covering the whole observation period, the first week (until July 15th, included), and the second week (after July 15th until July 22nd). Mean fluxes (*GPP*, *NEE*,  $R_{eco}$ , *CH*<sub>4</sub>) in all distinguished time periods are depicted in Tab. 3.4 and Figs. 3.11 and 3.12.

## 3.4.1 Variability Between Plots at PPL

Mean daily GPP was higher (significant for all plots) during the first week compared to the second week. Mean differences between the plots varied weakly over time (Fig.3.11). Overall, GPP at PPL-2 was significantly higher compared to PPL-1 and PPL-3, which showed no significant differences. During the first week, there were no significant differences between the mean  $R_{eco}$  at PPL-1, PPL-2 and PPL-3. Though, PPL-1 and PPL-2 showed a steeper rise in the beginning ("overtaking" PPL-3, which was highest in the beginning of observations) and a shallower fall, when approaching the second-cold week, compared to PPL-3 (Fig.3.11). During the second week  $R_{eco}$  significantly decreased at all sites except for PPL-2, where it decreased only insignificantly. This was explained by the positive effect of decreasing observed SM on  $R_{eco}$ at PPL, which counteracted the decrease of  $T_{S,5cm}$ . This had the strongest effect for PPL-2, less effects for PPL-1 and no effect for PPL-3. Furthermore,  $CH_4$  fluxes at PPL showed a strong significant variability between plots, despite them being less than 3m apart(See Figs. 3.11 and 3.12., CV shown in Tab. 3.5).

**Table 3.5:** Coefficients of variance (CV) for modeled fluxes between the single chamber plots at PPL and AS. NEE is left out since it is constructed from  $R_{eco}$  and GPP.

	GPP	$R_{eco}$	$CH_4$
PPL	12%	11%	77%
AS	42%	22%	32%

### 3.4.2 Variability Between Plots at AS

As for PPL, mean daily GPP at AS-0 and AS-2 was higher during the first week compared to the second week, while mean differences between the plots varied weakly over time (Fig.3.11). Overall, C-uptake at AS-0 was significantly stronger (stronger NEE and GPP). Differences in  $R_{eco}$  between AS-0 and AS-2 were not significant during the whole observation period, while they were insignificantly higher at AS-0 during the first week and converged in the second week.  $CH_4$ -fluxes were significantly higher at AS-2.

## 3.4.3 Comparing Fluxes between PPL at AS

Overall, GPP was higher at all PPL sites compared to AS, while being highest at PPL-2 and lowest at AS-2 (Fig.3.12). Differences between PPL-1, PPL-3 and AS-0 were not significant. As for GPP, during the whole measurement period,  $R_{eco}$  was highest at PPL-2 and lowest at AS-2 and reached its maximum at all sites during the hottest period at July 12th (Fig.3.11).  $R_{eco}$  was significantly higher at all PPL sites compared to AS-0 and AS-2. CV (Coefficient of Variance) between chambers is shown in Tab. 3.5. Ultimately, the differing trends of modeled  $R_{eco}$  lead to a changable trend of NEE over time. However, overall differences between the PPL sites and AS were mostly insignificant over the observation period, with PPL-2 being the strongest carbon sink in the first and AS-0 in the second week. Differences of NEE between plots (alltime, week1 and week2) and significances are depicted in Fig. 3.12, mean values displayed in Tab. 3.4.

 $CH_4$  fluxes showed a remarkably different evolution comparing PPL and AS. Generally, they were lowest at PPL-3 throughout the observation period. The strongest emitters were PPL-1 and AS-2 in the beginning, shifting to AS-2 and AS-0 in the second week. For absolute values and error ranges for fluxes see Tab. 3.4. Fluxes at PPL continuously decreased following the  $T_{air}$  peak at July 12th, which was explained by continuously decreasing SM, though slightly increasing until July 12th due to rising  $T_S$ . In contrast,  $CH_4$  fluxes at AS-0 and AS-2 stayed at relatively high levels (AS-2 significantly higher than AS-0, see Fig. 3.12) throughout the observation period, only moduled by  $T_S$ . Comparing PPL and AS during the first week,  $CH_4$ fluxes at PPL-1, acting as the strongest emitting plot at PPL, were significantly higher compared to AS-0 and insignificantly higher compared to AS-2.



**Figure 3.11:** Evolution of C-fluxes at all plots during the observation period. *GPP* (a),  $R_{eco}$  (b), NEE (c) and  $CH_4$  (d)



Figure 3.12: C-fluxes - boxplots. "all time, site average" shows C-flux daily means averaged over the plots at each site over the whole observation period. On the right side, daily means of GPP,  $R_{eco}$ , NEE and  $CH_4$ -fluxes during the whole period, the first week and second week for each single plot are shown. Letters indicate significant groups. Shared letters between plots indicate p > 0.05.

# 4 Discussion

## 4.1 C-Fluxes in Context: Methodological and Comparability Challenges with Flux Chambers

## 4.1.1 Assessment of Flux Chamber Measurements and Their Limitations

The application of flux chambers excert a hard to predict influence on the fluxes themselves, and were reviewed and summarized by Kutzbach et al., 2007. Observed effects are for example altering the underlying concentration gradients that were in effect prior to chamber deployment, changing air or soil temperature beneath the chamber or artificially promoting water vapour accumulation which depletes the CO2 concentration and might influence the stomata regulation of plants. Furthermore, closed chambers block natural turbulence and advection and therefore modify the diffusion resistance of the soil- or plant-atmosphere boundary layer. Additionally, natural pressure fluctuations are altered. The compression of the soil surrounding the chamber site disturbs pressure gradients across the soil-atmosphere interface and air might leak through soil pores below the chamber or directly at the chamber components. For calculations, when not being quantifiable, the assumption is made that these problems do not affect fluxes, though they can not be eliminated. In this study, these issues were adressed by keeping closure times short (< 2 minutes) to avoid strong temperature and gas concentration changes and condensation. There is not much one can do about locking out turbulence and advection than trying to restrict the problems. In this study, fans were used to mix the air inside the chamber, and a valve on top of the chamber was used to reduce pressure effects when placing the chamber on the collar. Walking boards were placed around the site and steps close to the chamber collars were omitted to disturb the soil as little as possible. An inaccurate calculation of the headspace volume is another source of error. Hereby, in our case, especially asymptric tussock structures at AS-0 and AS-2 made it difficult to come up with a 100% correct chamber volume.

Apart from that, we specifically observed certain issues with our chamber setup. First, installing the collars in the ground, while necessary to prevent leaching of air at the edges of the chamber, disturbs the soil and plant roots. At Pleistocene Park, we had to cut a shallow slit in the ground using a saw to be able to install the collars. Next, each chamber measurement potentially damages plants by crimping grass blades between the rim of the chamber and the collar. These factors might potentially decrease photosynthesis to a stronger extent than heterotrophic respiration. It is difficult to quantify this unknown impacts, since for this method placing collars in the ground is obligatory. In another study, using the same system, scientists waited for several weeks before conducting the first chamber measurements to leave time for regenaration (Kwon, Heimann, et al., 2016). Furthermore, they installed the collars around tussocks with little or no vegetation in between, further limiting the damage inflicted. In fact, both plots from the Ambolikha site used in this study emerged from there. Unfortunately, due to our limited temporal resources, we could not act in that way.

## 4.1.2 Assessment of Flux Calculations

Kutzbach et al., 2007 advises considering exponential models in place of linear models (as used in this study) to calculate fluxes from measured concentration changes of trace gas fluxes, because over time concentration gradients decrease and approach an equilibrium, which might lead to a underestimation of fluxes. Kutzbach et al., 2007 further argues and shows, that even short closure times, like in this study, might not fully rule out this issue. However, our chamber size was roughly 2 to 4 times larger compared to the experiments refered to by Kutzbach et al., 2007. High chamber volumes are shown to reduce this effect of a decreased concentration gradient (Pihlatie et al., 2013), and our chambers are in the range of the biggest compared by Pihlatie et al., 2013, where linear models did not lead to underestimation of, in this case,  $CH_4$ -fluxes. Furthermore, sampling intervals for gas concentrations refered to by Kutzbach et al., 2007 were 1s to 45s, while this study could sample at rates of 1Hz, simplifying the evaluation of concentration changes in the chamber.

## 4.1.3 Accounting for Site Heterogeneity

Heterogeneity exists within sites that are considered relatively homogeneous, and more than one chamber may be needed to adequately estimate the mean and variance of  $R_{eco}$  fluxes and also *GPP* (Davidson et al., 2002). These heterogeneities are observable in a scale as small as centimeters, and can be a result of disturbances by soil fauna, pockets of fine root proliferation, or remnants of decaying organic matter. In the arctic tundra, these small scale heterogeneities are common (Aalto et al., 2013; Zona et al., 2011) and are also reflected by variations in soil temperature, soil moisture and thaw depths. CVs (Coefficient of variance) of  $R_{eco}$  measurements in seemingly homogeneous ecosystems typically range around 30%, while reaching higher values for  $CH_4$  fluxes, which tend to be more localized(Davidson et al., 2002). CV for  $R_{eco}$  at PPL was 11% while reaching 20% at AS. For  $CH_4$  CVs were 77% and 32%, respectively, and therefore higher compared to CVs for  $R_{eco}$ . This is in accordance with statements from Davidson et al., 2002, though, differences in  $R_{eco}$  seem to be less pronounced in this study, which might be because of the little sample size.

## 4.1.4 Reviewing (chamber-) Fluxes in Similar Tundra Ecosystems

Values for C-flux measurements obtained by chamber measurements in this study lie in a similar range compared to other studies (see Tab. 4.1), therefore, generally, these values are feasible. Values from Kwon, Heimann, et al., 2016, estimated in 2014 at the Ambolikha site, actually come really close to the observations in this study. When comparing the results of this study with other studies, first of all one has to keep in mind interannual variabilities of C-fluxes, which are highly pronounced in tundra ecosystems (López-Blanco et al., 2017; Falk et al., 2015), with tendentially smaller fluxes during cold summers. Furthermore, different approaches how to assess and display the fluxes make it elaborate and sometimes contingent to compare fluxes from different studies one to one. For example, Kade et al., 2012, who used EC to calculate C-budgets in an Alaskan tussock tundra, utilized flux chambers to upscale plot level fluxes from the dominant vegetation types to the EC fluxes. Thereby, they measured *GPP* by adjusting the incoming light to certain levels of *PAR* (using plexiglass sheets), calculated light response curves (like in this study), but finally give chamber-derived *NEE* and *GPP* for PAR = 600  $\mu molPh*m^-2*s^-1$ , which can not be directly compared to fluxes in this study. Furthermore, many studies cover longer timescales compared to this study, making it difficult to derive comparable data from publications.

**Table 4.1:** Comparison of mean growing season fluxes ( chamber measurements) in different studies. Values in  $\mu molC * m^{-}2 * s^{-}1$ . (\*) indicates sites in the same area as AS in this study.

	,		( )		
Year	GPP	$R_{eco}$	NEE	ecotype	Reference
2019	$-11.06(\pm 2.48)$	$7.09(\pm 1.31)$	$-3.97(\pm 0.59)$	wet tussock tundra (PPL, grazed)	this study
2019	$-7.19(\pm 2.12)$	$3.13(\pm 1.02)$	$-4.06(\pm 3.14)$	wet tussock tundra (AS, ungrazed)	this study
2014	$-7.32 (\pm 0.11)$	$3.15(\pm 0.15)$	$-4.15 \ (\pm 0.17)$	wet tussock $tundra(*)$	Kwon et al. $(2016)$
2014	$-5.98 (\pm 0.03)$	$3.84(\pm 0.20)$	$-2.14 (\pm 0.17)$	wet tussock tundra(*)	Kwon et al. $(2016)$
2016	-7.17 (±0.33)	$5.54(\pm ?)$	-1.63 (±0.33)	coastal tundra wet carex meadow	Kelsey et al., 2016
2016	$-4.26 \ (\pm 0.61)$	$2.69(\pm 0.26)$	$-1.60 \ (\pm 0.56)$	high arctic tundra wet, graminoid dominated	Curasi et al., 2016
2012	$-4.67 (\pm 0.32)$	$1.91(\pm 0.1)$	$-2.73 (\pm 0.26)$	high arctic tundra (wetland, grazed)	Falk et al. $(2015)$
2012	$-4.28 (\pm 0.34)$	$1.67(\pm 0.076)$	$-2.53 (\pm 0.26)$	high arctic tundra (wetland, gr. exclosure)	Falk et al. $(2015)$
2015	$-1.47 (\pm 0.26)$	$1.14(\pm 0.15)$	$-0.33 (\pm 0.15)$	high arctic tundra (dwarf shrubs)	Cassidy et al. (2016)

# 4.2 Assessing Differences of Environmental Conditions and Parameters Between Pleistocene Park and Ambolikha Site

## 4.2.1 Vegetation and Soil Structure at Pleistocene Park and Ambolikha Site: Grazing Impacts at Pleistocene Park

Grazing by large herbivores has a number of obvious impacts at the vegetation in Pleistocene Park. However, one issue, restricting the attribution of the vegetational changes to herbivores, is the year-long human disturbance by the park operators which is impossible to quantify or deliminate from grazing.



Figure 4.1: a) Tussock decaying close to a drainage ditch. Almost all tussocks close to PPL are in a state of decay, also those far away from the drainage. b) Tussock decaying close to a yak stable, away from drainage ditch. c) Trail along fence used by grazers. Note that grazing occurs on both sides of the fence, while being a lot more intense on the right side. d) Cows grazing. Note the damage at willow shrubs caused by browsing. PPL site is located around 400m further along the electricity line in a depressed plain.

Over the park history, an unknown area of the park was frequented by vehicles. Furthermore, there is a unknown input of nutrients coming from the winter fodder for the animals or from fertilization experiments (which, however, were not hold at the PPL-site). Nevertheless, despite not being examined quantitatively, vegetation structure obviously changed dramatically (see Fig.

4.1). First, sedge-tussocks seem to decay. This might be a direct effect of grazing, trampling pressure or, additionally, as a result of drainage or other human disturbances (Fig. 4.1). There is a drainage ditch 60-70m away from the PP site. However, it's important to emphasize, that this phenomenon is observable also at non artificially drained areas at PP. However, this was not thoroughly investigated in this study. Around our chamber site at PP, almost all tussocks were in a state of decay or disappeared almost completely. In place of them or between them many single plant tillers grow. Compared to the Ambolikha site, where much plant litter was present in between thriving tussocks, there was sparse litter at the Pleistocene Park site.

While at the park the plant shoots are grazed off (to an unknown extent), at ungrazed sites the aboveground parts of the plant die of, wither and accumulate on the topsoil, where they rot slowly, leading to a thick organic layer (Kwon, Heimann, et al., 2016). Raillard, Svoboda, 2000 observed that valleys (wet tundra) in greenland, when heavily grazed, give the impression of a productive meadow, while similar ungrazed sites seem like a nutrient starved, overgrown grassland - the latter case being demonstrably less productive. Similar effects were observed by Falk et al., 2015, where excluding musk ox from an arctic mire decreased plant tillars and increased litter and moss cover. Grazing is generally shown to decrease living plant biomass and litter mass(Yan et al., 2018). This is in accordance with the observations in this study. While not quantitatevly investigated in this study, browsing by grazers obviously decreased shrub coverage in PP, as observable in Fig. 4.1.; d. This is in accordance with many studies describing that very same phenomenon in the context of reindeer grazing (Kitti et al., 2009; Manseau et al., 1996; Johan Olofsson, 2006) that also leads to a higher albedo (Te Beest et al., 2016; Chapin et al., 2005). Our results show a 13% higher albedo at PP compared to AS, indicating a comparable effect at PP. Therefore, there is a good case to believe that grazing at pleistocene park increases albedo in that area, which is in accordance with the managers claims.

# 4.2.2 Evaluating the Acquisition of Environmental and Soil Parameters at Both Sites

Before comparing environmental parameters, like  $T_S$ , SM and thaw depthes, between the study sites, there is a need to point out issues with acquisition and comparability. For example, both SM and thaw depthes at the PPL-site decreased continuously throughout the observation period, while soils at AS-0 and AS-2 stayed saturated and thawed more slowly. However, measured  $T_{S,35cm}$  at AS-0 and AS-2 were continuously higher than 0°C, though we measured thaw depthes slightly above 30cm. This means, that the actual thaw depth at the sensor location does not match the measured thaw depth. Furthermore, since thaw depth was measured directly next to the chamber, soil temperatures probably don't reflect the actual temperatures below the chamber. At PPL we found strongly varying thaw depthes in an area of a few square meters, indicating a high small-scale variability of soil parameters, which, as mentioned before, is a common feature in the arctic tundra(Aalto et al., 2013; Zona et al., 2011). Therefore, the

## 4.2 Assessing Differences of Environmental Conditions and Parameters Between Pleistocene Park and Ambolikha Site

locations of installed  $T_S$  and SM measuring devices and the thaw depth measuring locations might exhibit considerably different properties, and  $T_S$  or SM measurements do not reflect the actual conditions at the chamber locations to 100% - neither their magnitude nor their temporal development. Unfortunately, these variations can not be quantitatively estimated. As described, areas around AS-0 and AS-2 are much more structured, with big tussocks, compared to the relatively even PPL. These topographical differences could not be considered with our approach to measure thaw depthes, soil temperatures and soil moistures. These issues will be discussed further in section 4.2.3 in context with their relationship with C-fluxes. For a better comparison a more 3-dimensional approach to describe soil properties, also their evolution over the years under the impact of grazing, might be useful.

## 4.2.3 Grazing Influence on Soil Temperatures

Our results show, that soil temperatures at the grazed site (Pleistocene Park) were significantly higher compared to the ungrazed sites (Ambolikha site), especially those in 5cm depth. This is in accordance with other studies, showing that moderate to heavy grazing in tundra ecosystems significantly increases soil temperatures during the growing season (J. Olofsson et al., 2004; Te Beest et al., 2016). In addition, our results show, that  $T_{air}$  translates almost 10 times faster to an increase in  $T_{S,5cm}$  for PPL compared to AS-0, while for  $T_{S,15cm}$  both sites react similar, indicating a relatively stronger and faster surface warming at the grazed site. Noteably,  $T_{S,35cm}$ was higher at AS-0 in the beginning of observations, but was surpassed by those at PPL after a few days into observations, indicating that prior to the observations  $T_{S,35cm}$  and thaw depthes at PPL were lower compared to AS-0.  $T_S$  in all depths at AS-2 were relatively lowest during the whole period, showed the lowest fluctuations and had the greatest response time to air temperatures. One reason might be the water table, which was higher at AS-2 comapred to AS-0, however, this was not quantitatively assessed.

Drainage in a nearby wet tussock tundra ecosystem, close to the ambolikha site, has lead to warmer soil temperatures in shallow layers during daytime and colder soil temperatures in deeper layers by diminishing the heat capacity and thermal conductivity of organic soil (Kwon, Heimann, et al., 2016), so lower soil moisture at the PPL site compared to the ambolikha site might be a further explanation for the increased topsoil warming. However, since  $T_{S,35cm}$  at AS-0 was surpassed by those at PPL, loss off conductivity can not account for these differences by itself. I propose, that consolidation of the soil as well as removing the insulating litter and moss layer by trampling, might have lead to increasing conductivity, translating the increased surface warming to deeper layers. Apart from that, the PPL-site was still quite moist, therefore, soil moisture might not yet have limited heat conduction. The waterlocked sites AS-0 and AS-2 might have warmed up slower due to the high heat capacity of water and the shading and insulation provided by litter and tussock structures. However, as already mentioned, there might be other site specific conditions that limit the compareability of these sites. For example, we did not measure temperatures inside the tussock structures at AS-0 and AS-2, which stood partly above the water table, that might react as fast to  $T_{air}$  changes like  $T_{S,5cm}$  at PPL.

Despite not being in the scope of this study, several studies report from colder soil temperatures in winter as a result of grazing in arctic areas (Sergei A Zimov et al., 1995; S. A. Zimov et al., 2012; Beer et al., 2020; J. Olofsson et al., 2004), which was shown specifically for pleistocene park (Beer et al., 2020). Hereby, the removal of the insulating moss and lichen layer, the decrease of plant litter, and, most potently, the consolidation of the snow were shown to cause stronger energy transmission between soil and atmosphere. This is important, since snow conditions have a strong influence on  $T_S$  in the next growing season (Ling, Zhang, 2003). Insights go so far, that if the whole permafrost area was grazed, there could be a 37% reduced loss of permafrost area by 2100, if following mitigation RCP 8.5 (Beer et al., 2020), by stronger freezing in the winter. Consequently, conditions observed during the year our study was conducted are certainly different in other years, with more distinct differences in  $T_S$  during and after snow-rich winters. This might further explain, why  $T_{S,35cm}$  was higher at AS-0 compared to PPL in the beginning of the observation period - grazing and the abscence of litter decreased insulation, so  $T_S$  at PPL were probably lower compared to AS-0 when thawing began. However, AS-0 and AS-2 might not serve as the perfect comparison to pleistocene park considering soil temperatures, since site specific differences might restrain or even mislead interpretations. However, we can underpin the warming effect of grazing in the summer and state underlying processes, which obviously differ at AS-0 and AS-2 vs. PPL. These processes could also be important in the other seasons. Future studies need to address more different sites in and around PPL to attain reliable insights.

## 4.2.4 Grazing Influence on Soil Moisture

Grazing is shown to cause drying effects on soils by increasing evapotranspiration, surface runoff and water holding capacity while decreasing infiltration (Vandandorj et al., 2017; Yan et al., 2018). I.e., soil moistures in a semiarid eurasian steppe were around 10% higher in ungrazed sites compared to grazed sites in the beginning of the growing season(Yan et al., 2018), which, while not being representative for permafrost soils, principally supports the observations of our study. Despite both sites observed in this study being exposed to a spring flood, the PPL-site seems to dry out much quicker compared to the ambolikha site, which might therefore partially be explained by grazing. It is very important to mention the drainage ditch 60-70m away from the PPL site, which might have uncheckable effects on soil moisture dynamics. However, long term studies focused on the influnece of grazing on soil hydrology, especially in permafrost regions, are sparse. Further studies need to adress this topic to gain reliable insights.

## 4.2.5 Flux Interpolation Based on Environmental Parameters

Since interpolated (modeled) C-fluxes serve as a base for comparisons and for discussing the influence of grazing on those, the quality and physical plausibility of the interpolation process must be assessed. *GPP* was significantly higher at PPL compared to both sites at AS. This is quite clearly shown, PAR as the driving agent could be distinctly elaborated and was measured continuously, providing a solid foundation for comparisons based on model output or model parameters like  $P_{max}$  and  $\alpha$ .

In summary, our results show, that  $T_S/T_{air}$  and SM are dominating factors in regulating  $R_{eco}$ , while both,  $R_{eco}$  and  $T_{S,5cm}$  were considerably higher ( $R_{eco}$  1.60-4.56 fold, depending on which plots are compared in which timeframe;  $T_{S,5cm}$  1.41-1.74 fold) at the PPL site compared to AS-0 and AS-2 and soil moisture was lower. These observations confirm our hypotheses and will be discussed in the context of grazing in chapter 4.3. We could, however, not find one principal approach for all sites to explain  $R_{eco}$  fluxes with the same environmental parameters in a reasonable way. One intention of this study is to reflect C-fluxes in the most accurate way possible for comparability. Therefore, the models that reflect the behaviour of the fluxes at each chamber site in the best way (i.e. make sense physically and yield a reasonable fit), despite being based on different drivers, were used. It is important to note, that models can always only cover a fraction of the actual causality. Varying weather and soil conditions are not evenly covered by our flux measurements, which could lead to over- or undervaluation of certain environmental influences. Generally,  $R_{eco}$  in tundra peatlands is enhanced by warmer temperatures due to increased microbial activity (Ueyama et al., 2014; Aurela et al., 2007; Kwon, Heimann, et al., 2016).  $R_{eco}$  may increase under drying, with increased potential for aerobic respiration (Lafleur, 2009; Kittler et al., 2017). Compulsively trying to find one consistent formula using the same set of parameters, might be deluding oneself to think that processes driving the fluxes can be explained uniformly when this actually is not correct, especially when there are issues with the comparability of environmental parameters between sites. For example,  $T_{air}$  performed better to explain  $R_{eco}$  compared to  $T_{S,5cm}$  for AS-0 and AS-2, as well as for PPL-3, despite  $T_S$  being the driver for microbial activity. For AS-0 and AS-2, the topography of the tussock tundra might be one explanation, why  $T_S$  are worse applicable to model fluxes compared to  $T_{air}$ . Tussocks stand above water level, while the soil is underwater and covered by a loose organic layer. Therefore, the tussock is aerated and probably responds faster to changes in radiation and  $T_{air}$  compared to the soil. The same might be true for litter above the water table. Measuring "tussock core temperature" might therefore be a good idea in future studies.  $T_{S,5cm}$  alone, when used to explain  $R_{eco}$  fluxes, can not account for this process, while  $T_{air}$  might be involved in (i.e. as a driver for  $T_S$ ) all these processes both above and below ground and water table. Finally, combining  $T_S$  and  $T_{air}$  (added up and divided by 2) yielded the best fit to the  $R_{eco}$  flux data both for AS-0 and AS-2. Considering the preceeding arguments, this observation, which respects both temperatures, seems to be physically sound. However, since the fit was not so markedly better and  $T_{S,5cm}$  was not continously observed but modeled (facilitating a higher error potential),  $T_{air}$  was used to interpolate  $R_{eco}$  fluxes at AS-0 and AS-2.

In contrast, PPL does not show tussock structures (at the chamber sites) and is, at least visually determined, much tighter in its whole structure. There is much less litter on the topsoil and the water table is below ground. Notably,  $T_{S.5cm}$  reacts one order of magnitude faster to changes in  $T_{air}$  compared to AS-0 and AS-2. Here,  $T_S$  (in combination with  $SM_{7.5cm}$ ) was superior to  $T_{air}$  in predicting the fluxes for PPL-1 and PPL-2, while a lower SM accounts for higher  $R_{eco}$ , yielding good fits, while modeled fluxes follow the course of measured data quite well. As previously mentioned, lower soil moistures are generally shown to increase  $R_{eco}$ , making this procedure biogeochemically plausible. For PPL-3, fits in general are worse.  $T_{air}$ showed a better correlation and reflected measured values better compared to  $T_{S,5cm}$  and no physically sound relationship between SM and  $R_{eco}$  fluxes could be found. At PPL-3,  $SM_{7.5cm}$ was negatively correlated ( $R^2 = 0.23$ : p < 0.01, contrary to PPL-1 and PPL-2) with the residuals from an exponential regression between  $T_{S,5cm}$  and  $R_{eco}$  fluxes. However, the high fluctuating values of  $R_{eco}$  during intervals with relatively high soil moistures and the general limitation of flux data due to the short study period make it ambitious to trust this correlation. After all, modelling  $R_{eco}$  at PPL-3 using  $T_{S,5cm}$  leads to a consistent overestimation of fluxes during the second week of observations (which, notably, fluctuate much less compared to those at PPL-1 and PPL-2), thus affecting final flux estimations. These considerations justify the use of  $T_{air}$  for modeling  $R_{eco}$  at PPL-3. The non-uniformity at PPL might be explained by the fact, that there was only one set of instruments for SM and  $T_S$ , so data availability for possible drivers of  $R_{eco}$ is limited to this location. Therefore, actual relationships between fluxes and soil parameters are very probably confused, making it difficult to find a consistently valid interpolation forumla for all sites, that accounts for causal biogeochemical processes at the same time. The unclear relationship between  $R_{eco}$  and SM at PPL-3 indicates, that SM and  $T_S$  at PPL-3 evolved in a distinctly different way compared to PPL-1 and PPL-2, for example by being drier in the first place. This is underpinned by the low  $CH_4$ -fluxes at this site, which, as we show in this study, depend on SM and  $T_S$ . Additionally, the interpretation is aggravated by all the missing possible drivers, like vegetation properties, soil structural or other differences, that could not be assessed. Finally, these site-dependent differences are likely causes for these fine-scaled flux variations and are therefore worth to be investigated further. Understanding them might contribute to the understanding of the flure development of tundra ecosystems under grazing influence and, above all, global warming.

Concerning  $CH_4$  fluxes, we could visually recognize that i.e. PPL-1 looked much wetter and more "slushy" compared to the other two plots.  $CH_4$  fluxes, which depend strongly on soil water content (Kwon, Heimann, et al., 2016), varied strongly between these three sites, being highest at PPL-1 and lowest at PPL-3, which supports this observation. Because  $T_S$  and SMshowed a strong interlinear relationship during the whole observation period, it was difficult to disentangle their respective effect on  $CH_4$  fluxes. This was partly indebted by the weather conditions, that showed a relatively continuous trend from warm to cold, while moistures went down parallely. Due to this data limitation, the interpolation formulas for  $CH_4$  fluxes at PPL are not perfectly methodologically sound and can't mirror the fluxes perfectly. For AS-0 and AS-2, logically, the role of SM could not be evaluated at all, restricting examinable drivers in this study to  $T_S$ , in this case those in 15cm depth, since they showed the best correlation.

Nevertheless, all interpolation formulas are feasible for interpolating fluxes in the time window of this study, as their fit to the flux-data proves. Therefore, comparisons based on these models seem valid.

# 4.3 How Might Grazing Influence the C-Balance of Permafrost Tundra Ecosystems?

## **4.3.1** $CO_2$ Exchange: GPP and $R_{eco}$

Both experimental warming and reduced water table depth in tundra ecosystems have generally shown increased ecosystem respiration (Christensen et al., 2000; Huemmrich et al., 2010; McEwing et al., 2015; Oechel, Vourlitis, et al., 1998; Zona et al., 2011; Natali, Edward A.G. Schuur, et al., 2015b). These observations are reflected by our results. As described in the previous chapter, grazing by itself is a factor leading to warming and drying of ecosystems, therefore enhancing  $R_{eco}$ . In most of the cited studies, NEE was also reduced, because GPP was not or only to a less extent increased by warming or drying. These observations need to be discussed in the context of grazing, since grazing excerts a cascade of effects on tundra ecosystems (Manseau et al., 1996; Johan Olofsson, 2006; Kitti et al., 2009; Te Beest et al., 2016; Chapin et al., 2005; Cohen et al., 2013; Sergei A Zimov et al., 1995; S. A. Zimov et al., 2012) which are really complicated to explore. Our results show, that GPP was significantly higher at pleistocene park compared to the ungrazed Ambolikha site indicating that grazing enhanced both GPP and  $R_{eco}$ at pleistocene park lowland. However, as we could not compare differences in grazing intensity on site or before and after grazing started, these results need to be verified by further studies. Furthermore, we could not cover sessional variabilities with the scope of our study. NEE was higher in the most productive site at PPL (grazed) during the beginning of July when compared to the most productive site at Ambolikha (AS-0, ungrazed), while this trend changed sign approaching mid/end July, showing the importance of drying and warming to increase  $R_{eco}$ . NEE at the least productive site at Ambolikha (AS-2, ungrazed) was continuously the lowest measured in this study, promoting the "boost" on pruductivity by grazing. One issue in our study was, that we could not determine the effect of the nearby drainage ditch at PPL, which might have altered grazing effects (enhanced drying) and further increased  $R_{eco}$  to the disadvantage of NEE. However, our sample size was relatively small, so further studies are needed to dig deeper into these initial findings. Grazing by musk ox in greenland was shown to enhance both GPP and NEE (Falk et al., 2015), while hereby a decrease in density of tillers in the abscence of grazing was quoted as a driving agent. Grazing by reindeers in scandinavia enhanced nutrient cycling and respiration, leading to increased GPP under high grazing pressure (Johan Olofsson et al., 2001). These findings support our results. On the other hand, high grazing pressure by reindeers, caribou and musk ox was shown to decrease both GPP and NEE during the growing season (Sjögersten et al., 2011; Väisänen et al., 2014; Metcalfe, Johan Olofsson, 2015; Cahoon, Sullivan, Post, et al., 2012). However, these studies were conducted on shrubby upland tundra and are therefore not simply comparable to the sites in this study. Warming lead to a increase in GPP under high grazing pressure but not under low grazing pressure (Väisänen et al., 2014). All these sketchy contrasting results highlight the site specific and climate-dependent characteristics of possible ecosystem responses to grazing. Therefore, to quantify the grazing effects on (growing season) carbon fluxes at pleistocene park, areas with different grazing intensities need to be identified and observed over longer timescales.

All studies cited in this chapter exploring the effects of grazing on C-fluxes focused on growing season fluxes. However, grazing, especially heavy grazing, strongly influences the snow cover by trampling, leading to lower soil temperatures in winter (Beer et al., 2020; J. Olofsson et al., 2004) and the following summer, especially in deeper soil layers (Beer et al., 2020; Ling, Zhang, 2003), which was shown precisely for pleistocene park (Beer et al., 2020). Additionally, the faster response of soil temperatures at grazed ecosystems to changes in air temperatures, as shown by our results, might as well accelerate cooling from the autumn season on. Relevantly, autumn and winter respiration covers a substantial amount of total annual  $R_{eco}$  in arctic tundra ecosystems (Grogan, 2012; E S Euskirchen et al., 2012; Natali, Watts, et al., 2019; Kittler et al., 2017), sometimes even considerably higher than summer respiration (E S Euskirchen et al., 2012), and increasing over the years with global warming (Natali, Watts, et al., 2019). Snow depth is evidentially positively correlated to  $R_{eco}$  during winter (Grogan, 2012). Grazing in wet tundra ecosystems might therefore, while possibly not increasing or even decreasing the net carbon uptake during summer, balance or even overcompensate this loss by forcing soil temperatures to decrease by snow trampling and decreasing moss and litter, therefore possibly strongly decrease winter respiration.

### **4.3.2** *CH*<sub>4</sub> **Fluxes**

Principally our results show that  $CH_4$  fluxes at all PPL sites followed a similar, decreasing trend over time and with decreasing soil moisture, while at AS-0 and AS-2  $CH_4$  stayed at relatively high levels while the soils stayed saturated. In summary, cumulative modeled  $CH_4$  emissions were significantly higher at AS compared to PPL. These observations confirm our hypotheses, that the grazed site emits less  $CH_4$ , and are in accordance with other studies, where soil moisture was shown to have a dominating effect on  $CH_4$  flux magnitudes and drainage significantly decreased  $CH_4$  emissions (Kwon, Heimann, et al., 2016; Olefeldt et al., 2013). Generally, there are hints that grazing can decrease soil mositure (Vandandorj et al., 2017; Yan et al., 2018). If our observations can be endorsed by further studies focusing on the influence of grazing on soil hydrology in wet tundra ecosystems, it can be confidently stated that grazing might potentially decrease  $CH_4$  emissions. Yet, there are a number of factors influencing  $CH_4$  emissions, such as vegetation type or soil temperature (Olefeldt et al., 2013) so these aspects must be adressed, also in the context of grazing, to make a feasible point.

# 5 Conclusions

Grazing at Pleistocene Park has obviously altered vegetation and soil properties. Comparing a wet tussock tundra nearby and a wet meadow at PP further shows distinct differences in soil thermal and hydrological properties, which themselves are reflected by differences in C-Fluxes. Soil temperatures at the PP site react one order of magnitude faster to changes of air temperatures compared to the undisturbed tundra, while soils dry up quicker. Both GPP and  $R_{eco}$ during July are significantly higher at the grazed site in PP compared to a undisturbed wet tussock tundra, while differences in NEE are not pronounced.  $CH_4$  fluxes, following hydrological properties, are lower at PP. Soils at AS did not dry at all, therefore it is safe to say that the  $CH_4$ -fluxes at PPI will stay much lower over the rest of the season compared to AS. According to the park operators, the study site at PP used to be a wet tussock tundra, that was mainly water saturated during the whole year, similar to the undisturbed site used for comparisons. This indicates, that grazing, which was previously shown in other studies to enhance soil temperatures and both GPP ad  $R_{eco}$  during the growing season, as well as soil drainage and evapotranspiration, was the driving force to bring about the transformation of this ecosystem. The effect of grazing on nutrient availability is another question that could be assessed at pleistocene park. However, other disturbances excerted by the park operation (i.e. artificial drainage), might have further unknown influence on these properties. To be able to assess long term effects of grazing, C-Fluxes need to be investigated over longer timescales, also integrating non-growing season fluxes. Especially fluxes during autumn and early winter, which account for a significant part of the annual C-Balance, need to be studied to be able to determine the ultimate effect of grazing on carbon sequestration in the arctic tundra. Since NEE did not show distinct differences during the growing season, the cold part of the year might determine which ecosystem sequesters more atmospheric C. As already shown by other studies, soil temperatures under grazed permafrost ecosystems stay lower during the winter months. Should the soils at PPl cool as fast in autumn as they warm in the summer,  $R_{eco}$  might probably decrease faster compared to AS and stay at lower levels throughout the winter. This would lead to a higher NEE. To assess these questions, further studies need to be conducted focusing on cold season C-fluxes on grazed ecosystems.

# Bibliography

- Aalto, Juha, Le Roux, Peter C., Luoto, Miska (2013). "Vegetation mediates soil temperature and moisture in arctic-alpine environments". Arctic, Antarctic, and Alpine Research 45.4, 429–439. ISSN: 15230430. DOI: 10.1657/1938-4246-45.4.429.
- Agricultural Organization, Food a. (2010). "Global Forest Resources Assessment 2010: Terms and Definitions".
- Araujo, Bernardo B.A. et al. (2017). "Bigger kill than chill: The uneven roles of humans and climate on late Quaternary megafaunal extinctions". *Quaternary International* 431, 216–222. ISSN: 10406182. DOI: 10.1016/j.quaint.2015.10.045.
- Aurela, Mika et al. (2007). "CO2 exchange of a sedge fen in southern Finland The impact of a drought period". Tellus, Series B: Chemical and Physical Meteorology 59.5, 826–837. ISSN: 02806509. DOI: 10.1111/j.1600-0889.2007.00309.x.
- Barnosky, Anthony D et al. (2016). "Assessing the Causes of Late Pleistocene Extinctions on the Continents Published by : American Association for the Advancement of Science Stable URL : http://www.jstor.org/stable/3839254". Science 306.5693, 70–75.
- Beer, Christian et al. (2020). "Protection of Permafrost Soils from Thawing by Increasing Herbivore Density". Scientific Reports 10.1, 1–10. ISSN: 20452322. DOI: 10.1038/s41598-020-60938-y.
- Betts, Alan K, Ball, John H (1997). "Albedo over the boreal forest". Journal of Geophysical Research: Atmospheres 102.D24, 28901–28909. DOI: 10.1029/96JD03876.
- Britton, C. M, Dodd, J. D (1976). "Relationships of Photosynthetically Active Radiation". Agricultural Meteorology 17.1, 1–7. DOI: https://doi.org/10.1016/0002-1571(76)90080-7.
- Brown, J et al. (1998). "Circum-Arctic map of permafrost and ground-ice conditions. Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology". *Digital media*.
- Burke, E J, Hartley, I P, Jones, C D (2012). "Uncertainties in the global temperature change caused by carbon release from permafrost thawing". *Cryosphere* 6.5, 1063–1076. ISSN: 19940416. DOI: 10.5194/tc-6-1063-2012.
- Cahoon, Sean M.P., Sullivan, Patrick F., Post, Eric, et al. (2012). "Large herbivores limit CO 2 uptake and suppress carbon cycle responses to warming in West Greenland". *Global Change Biology* 18.2, 469–479. ISSN: 13541013. DOI: 10.1111/j.1365-2486.2011.02528.x.

- Cahoon, Sean M.P., Sullivan, Patrick F., Shaver, Gaius R., et al. (2012). "Interactions among shrub cover and the soil microclimate may determine future Arctic carbon budgets". *Ecology Letters* 15.12, 1415–1422. ISSN: 14610248. DOI: 10.1111/j.1461-0248.2012.01865.x.
- Callaghan, Terry V et al. (2004). Effects on the function of arctic ecosystems in the short- and long-term perspectives. DOI: 10.1579/0044-7447-33.7.448.
- Cassidy, Alison E, Christen, Andreas, Henry, Gregory H.R. (2016). "The effect of a permafrost disturbance on growing-season carbon-dioxide fluxes in a high Arctic tundra ecosystem". Biogeosciences 13.8, 2291–2303. ISSN: 17264189. DOI: 10.5194/bg-13-2291-2016.
- Chapin, F. S. et al. (2005). "Role of land-surface changes in arctic summer warming". *Science* 310.5748, 657–660. ISSN: 00368075. DOI: 10.1126/science.1117368.
- Christensen, T R et al. (2000). "Trace gas exchange in a high-Arctic valley: 1. Variationsin CO2 and CH4 Flux between tundra vegetation types". *Global Biogeochemical Cycles* 14.3, 701–713. ISSN: 19449224. DOI: 10.1029/1999GB001134.
- Cohen, Juval et al. (2013). "Effect of reindeer grazing on snowmelt, albedo and energy balance based on satellite data analyses". *Remote Sensing of Environment* 135, 107–117. ISSN: 00344257. DOI: 10.1016/j.rse.2013.03.029. URL: http://dx.doi.org/10.1016/j.rse. 2013.03.029.
- Corradi, C. et al. (2005). "Carbon dioxide and methane exchange of a north-east Siberian tussock tundra". *Global Change Biology* 11.11, 1910–1925. ISSN: 13541013. DOI: 10.1111/j.1365–2486.2005.01023.x.
- Corradi, C et al. (2005). "Carbon dioxide and methane exchange of a north-east Siberian tussock tundra". *Global Change Biology* 11.11, 1910–1925.
- Curasi, Salvatore R, Loranty, Michael M, Natali, Susan M (2016). "Water track distribution and effects on carbon dioxide flux in an eastern Siberian upland tundra landscape". *Environmental Research Letters* 11.4. ISSN: 17489326. DOI: 10.1088/1748-9326/11/4/045002.
- Davidson, E A et al. (2002). "Minimizing artifacts and biases in chamber-based.pdf". Agricultural and Forest Meteorology 113, 21–37.
- Doughty, Christopher E, Roman, Joe, et al. (2016). "Global nutrient transport in a world of giants". Proceedings of the National Academy of Sciences of the United States of America 113.4, 868–873. ISSN: 10916490. DOI: 10.1073/pnas.1502549112.
- Doughty, Christopher E, Wolf, Adam, Malhi, Yadvinder (2013). "The legacy of the Pleistocene megafauna extinctions on nutrient availability in Amazonia". Nature Geoscience 6.9, 761–764.
  ISSN: 17520894. DOI: 10.1038/ngeo1895. URL: http://dx.doi.org/10.1038/ngeo1895.
- Euskirchen, E S et al. (2012). "Seasonal patterns of carbon dioxide and water fluxes in three representative tundra ecosystems in northern Alaska". *Ecosphere* 3.1, art4. ISSN: 2150-8925. DOI: 10.1890/es11-00202.1.
- Euskirchen, Eugénie S. et al. (2017). "Interannual and Seasonal Patterns of Carbon Dioxide, Water, and Energy Fluxes From Ecotonal and Thermokarst-Impacted Ecosystems on Carbon-

Rich Permafrost Soils in Northeastern Siberia". Journal of Geophysical Research: Biogeosciences 122.10, 2651–2668. ISSN: 21698961. DOI: 10.1002/2017JG004070.

- Falk, Julie Maria et al. (2015). "Large herbivore grazing affects the vegetation structure and greenhouse gas balance in a high arctic mire". *Environmental Research Letters* 10.4. ISSN: 17489326. DOI: 10.1088/1748-9326/10/4/045001.
- Fletcher, Benjamin J et al. (2012). "Photosynthesis and productivity in heterogeneous arctic tundra: Consequences for ecosystem function of mixing vegetation types at stand edges". *Journal of Ecology* 100.2, 441–451. ISSN: 00220477. DOI: 10.1111/j.1365-2745.2011. 01913.x.
- Göckede, Mathias et al. (2017). "Shifted energy fluxes, increased Bowen ratios, and reduced thaw depths linked with drainage-induced changes in permafrost ecosystem structure". Cryosphere 11.6, 2975–2996. ISSN: 19940424. DOI: 10.5194/tc-11-2975-2017.
- Grogan, Paul (2012). "Cold season respiration across a low arctic landscape: The influence of vegetation type, snow depth, and interannual climatic variation". Arctic, Antarctic, and Alpine Research 44.4, 446–456. ISSN: 15230430. DOI: 10.1657/1938-4246-44.4.446.
- Huemmrich, K F et al. (2010). "Tundra carbon balance under varying temperature and moisture regimes". *Journal of Geophysical Research* 115. ISSN: 0148-0227. DOI: 10.1029/2009jg001237.
- Hugelius, Gustaf et al. (2014). "Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps". *Biogeosciences (Online)* 11.23.
- Kade, Anja et al. (2012). "Upscaling of CO2 fluxes from heterogeneous tundra plant communities in Arctic Alaska". Journal of Geophysical Research G: Biogeosciences 117.4, 1–11. ISSN: 01480227. DOI: 10.1029/2012JG002065.
- Kelsey, K. C. et al. (2016). "Interactions among vegetation, climate, and herbivory control greenhouse gas fluxes in a subarctic coastal wetland". Journal of Geophysical Research: Biogeosciences 121.12, 2960–2975. ISSN: 21698961. DOI: 10.1002/2016JG003546.
- Kitti, Heidi, Forbes, Bruce C, Oksanen, Jari (2009). "Long- and short-term effects of reindeer grazing on tundra wetland vegetation". *Polar Biology* 32.2, 253–261. ISSN: 07224060. DOI: 10.1007/s00300-008-0526-9.
- Kittler, Fanny et al. (2017). "Long-Term Drainage Reduces CO2 Uptake and CH4 Emissions in a Siberian Permafrost Ecosystem". *Global Biogeochemical Cycles* 31.12, 1704–1717. ISSN: 19449224. DOI: 10.1002/2017GB005774.
- Koven, C D et al. (2015). "A simplified, data-constrained approach to estimate the permafrost carbon-climate feedback". *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 373.2054. ISSN: 1364503X. DOI: 10.1098/rsta.2014.0423. URL: http://dx.doi.org/10.1098/rsta.2014.0423.
- Kutzbach, L et al. (2007). "CO2 flux determination by closed-chamber methods can be seriously biased by inappropriate application of linear regression". *Biogeosciences* 4.6, 1005–1025. ISSN: 17264189. DOI: 10.5194/bg-4-1005-2007.

- Kwon, Min Jung, Beulig, Felix, et al. (2017). "Plants, microorganisms, and soil temperatures contribute to a decrease in methane fluxes on a drained Arctic floodplain". *Global Change Biology* 23.6, 2396–2412. ISSN: 13652486. DOI: 10.1111/gcb.13558.
- Kwon, Min Jung, Heimann, Martin, et al. (2016). "Long-term drainage reduces CO 2 uptake and increases CO 2 emission on a Siberian floodplain due to shifts in vegetation community and soil thermal characteristics". *Biogeosciences* 13.14, 4219–4235. ISSN: 17264189. DOI: 10.5194/bg-13-4219-2016.
- Lafleur, Peter M (2009). Connecting atmosphere and wetland: Trace gas exchange. DOI: 10. 1111/j.1749-8198.2008.00212.x.
- Lindgren, Amelie et al. (2016). "Gis-based maps and area estimates of northern hemisphere permafrost extent during the last glacial maximum". *Permafrost and Periglacial Processes* 27.1, 6–16.
- Ling, Feng, Zhang, Tingjun (2003). "Impact of the timing and duration of seasonal snow cover on the active layer and permafrost in the Alaskan Arctic". *Permafrost and Periglacial Processes* 14.2, 141–150. ISSN: 10456740. DOI: 10.1002/ppp.445.
- López-Blanco, Efrén et al. (2017). "Exchange of CO2 in Arctic tundra: Impacts of meteorological variations and biological disturbance". *Biogeosciences* 14.19, 4467–4483. ISSN: 17264189. DOI: 10.5194/bg-14-4467-2017.
- Manseau, M., Huot, J., Crete, M. (1996). "Effects of Summer Grazing by Caribou on Composition and Productivity of Vegetation: Community and Landscape Level". *The Journal of Ecology* 84.4, 503. ISSN: 00220477. DOI: 10.2307/2261473.
- McEwing, Katherine Rose, Fisher, James Paul, Zona, Donatella (2015). "Environmental and vegetation controls on the spatial variability of CH4 emission from wet-sedge and tussock tundra ecosystems in the Arctic". *Plant and Soil* 388.1-2, 37–52. ISSN: 15735036. DOI: 10.1007/s11104-014-2377-1.
- McGuire, A. D. et al. (2012). "An assessment of the carbon balance of Arctic tundra: Comparisons among observations, process models, and atmospheric inversions". *Biogeosciences* 9.8, 3185–3204. ISSN: 17264170. DOI: 10.5194/bg-9-3185-2012.
- Metcalfe, Daniel B, Olofsson, Johan (2015). "Distinct impacts of different mammalian herbivore assemblages on arctic tundra CO2 exchange during the peak of the growing season". Oikos 124.12, 1632–1638. ISSN: 16000706. DOI: 10.1111/oik.02085.
- Myers-Smith, Isla H. et al. (2011). "Shrub expansion in tundra ecosystems: Dynamics, impacts and research priorities". *Environmental Research Letters* 6.4. ISSN: 17489326. DOI: 10.1088/1748-9326/6/4/045509.
- Natali, Susan M, Schuur, Edward A G, et al. (2015a). "Permafrost thaw and soil moisture driving CO2 and CH4 release from upland tundra". Journal of Geophysical Research: Biogeosciences 120.361, 1–13. ISSN: 21698953. DOI: 10.1002/2014JG002872.Received.

- Natali, Susan M, Schuur, Edward A.G., et al. (2015b). "Permafrost thaw and soil moisture driving CO2 and CH4 release from upland tundra". *Journal of Geophysical Research: Biogeo*sciences 120.3, 525–537. ISSN: 21698961. DOI: 10.1002/2014JG002872.
- Natali, Susan M, Watts, Jennifer D, et al. (2019). "Large loss of CO2 in winter observed across the northern permafrost region". *Nature Climate Change* 9.11, 852–857. ISSN: 17586798. DOI: 10.1038/s41558-019-0592-8.
- Oberbauer, Steven F. et al. (2007). "Tundra CO2 fluxes in response to experimental warming across latitudinal and moisture gradients". *Ecological Monographs* 77.2, 221–238. ISSN: 00129615. DOI: 10.1890/06-0649.
- Oechel, Walter C., Laskowski, Cheryl A., et al. (2014). "Annual patterns and budget of CO2 flux in an Arctic tussock tundra ecosystem". *Journal of Geophysical Research: Biogeosciences* 119.3, 323–339. ISSN: 21698961. DOI: 10.1002/2013JG002431.
- Oechel, Walter C., Vourlitis, George L., et al. (1998). "The effects of water table manipulation and elevated temperature on the net CO 2 flux of wet sedge tundra ecosystems". *Global Change Biology* 4.1, 77–90. ISSN: 1354-1013. DOI: 10.1046/j.1365-2486.1998.00110.x.
- Olefeldt, David et al. (2013). "Environmental and physical controls on northern terrestrial methane emissions across permafrost zones". *Global Change Biology* 19.2, 589–603. ISSN: 13541013. DOI: 10.1111/gcb.12071.
- Olofsson, J., Stark, S., Oksanen, L. (2004). "Reindeer influence on ecosystem processes in the tundra". *Oikos* 105.2, 386–396. ISSN: 00301299. DOI: 10.1111/j.0030-1299.2004.13048.x.
- Olofsson, Johan (2006). "Short- and long-term effects of changes in reindeer grazing pressure on tundra heath vegetation". *Journal of Ecology* 94.2, 431–440. ISSN: 00220477. DOI: 10.1111/j.1365-2745.2006.01100.x.
- Olofsson, Johan et al. (2001). "Effects of summer grazing by reindeer on composition of vegetation, productivity and nitrogen cycling". *Ecography* 24.1, 13–24. ISSN: 09067590. DOI: 10.1034/j.1600-0587.2001.240103.x.
- Overland, James et al. (2015). "The melting Arctic and midlatitude weather patterns: Are they connected?" *Journal of Climate* 28.20, 7917–7932.
- Paré, Maxime C, Bedard-Haughn, Angela (2012). "Landscape-scale N mineralization and greenhouse gas emissions in Canadian Cryosols". *Geoderma* 189-190, 469–479. ISSN: 00167061. DOI: 10.1016/j.geoderma.2012.06.002. URL: http://dx.doi.org/10.1016/j.geoderma.2012.06.002.
- Pihlatie, Mari K et al. (2013). "Comparison of static chambers to measure CH4 emissions from soils". Agricultural and Forest Meteorology 171-172, 124-136. ISSN: 01681923. DOI: 10.1016/ j.agrformet.2012.11.008.
- Post, Eric et al. (2009). Ecological dynamics across the arctic associated with recent climate change. DOI: 10.1126/science.1173113.
- Prescott, Graham W et al. (2012). "Quantitative global analysis of the role of climate and people in explaining late Quaternary megafaunal extinctions". *Proceedings of the National*

Academy of Sciences of the United States of America 109.12, 4527–4531. ISSN: 00278424. DOI: 10.1073/pnas.1113875109.

- Raillard, Martin, Svoboda, Josef (2000). "High Grazing Impact, Selectivity, and Local Density of Muskoxen in Central Ellesmere Island, Canadian High Arctic". Arctic, Antarctic, and Alpine Research 32.3, 278–285. ISSN: 1523-0430. DOI: 10.1080/15230430.2000.12003365.
- Runkle, B. R.K. et al. (2013). "Bulk partitioning the growing season net ecosystem exchange of CO 2 in Siberian tundra reveals the seasonality of it carbon sequestration strength". *Biogeo*sciences 10.3, 1337–1349. ISSN: 17264189. DOI: 10.5194/bg-10-1337-2013.
- Sandom, Christopher et al. (2014). "Global late Quaternary megafauna extinctions linked to humans, not climate change". Proceedings of the Royal Society B: Biological Sciences 281.1787. ISSN: 14712954. DOI: 10.1098/rspb.2013.3254.
- Schädel, Christina et al. (2014). "Circumpolar assessment of permafrost C quality and its vulnerability over time using long-term incubation data". *Global Change Biology* 20.2, 641–652. ISSN: 13541013. DOI: 10.1111/gcb.12417.
- Schneider Von Deimling, T. et al. (2012). "Estimating the near-surface permafrost-carbon feedback on global warming". *Biogeosciences* 9.2, 649–665. ISSN: 17264170. DOI: 10.5194/bg-9– 649-2012.
- Schuur, E. A.G. et al. (2015). Climate change and the permafrost carbon feedback. DOI: 10.1038/ nature14338.
- Schuur, Edward A.G., Abbott, Benjamin (2013). "Climate change: High risk of permafrost thaw". Nature 480.7375, 32–33. ISSN: 00280836. DOI: 10.1038/480032a.
- Sjögersten, Sofie et al. (2011). "Recovery of ecosystem carbon fluxes and storage from herbivory". Biogeochemistry 106.3, 357–370. ISSN: 01682563. DOI: 10.1007/s10533-010-9516-4.
- Tarnocai, Charles et al. (2009). "Soil organic carbon pools in the northern circumpolar permafrost region". *Global biogeochemical cycles* 23.2.
- Te Beest, Mariska et al. (2016). "Reindeer grazing increases summer albedo by reducing shrub abundance in Arctic tundra". Environmental Research Letters 11.12. ISSN: 17489326. DOI: 10.1088/1748-9326/aa5128.
- Ueyama, Masahito, Iwata, Hiroki, Harazono, Yoshinobu (2014). "Autumn warming reduces the CO2 sink of a black spruce forest in interior Alaska based on a nine-year eddy covariance measurement". *Global Change Biology* 20.4, 1161–1173. ISSN: 13541013. DOI: 10.1111/gcb. 12434.
- Väisänen, Maria et al. (2014). "Consequences of warming on tundra carbon balance determined by reindeer grazing history". Nature Climate Change 4.5, 384–388. ISSN: 17586798. DOI: 10. 1038/nclimate2147.
- Van der Wal, R., Van Lieshout, S. M.J., Loonen, M. J.J.E. (2001). "Herbivore impact on moss depth, soil temperature and arctic plant growth". *Polar Biology* 24.1, 29–32. ISSN: 07224060. DOI: 10.1007/s003000000170.

- Vandandorj, Sumiya et al. (2017). "Microsite and grazing intensity drive infiltration in a semiarid woodland". *Ecohydrology* 10.4. ISSN: 19360592. DOI: 10.1002/eco.1831.
- Virtanen, Risto et al. (2016). "Where do the treeless tundra areas of northern highlands fit in the global biome system: Toward an ecologically natural subdivision of the tundra biome". *Ecology and Evolution* 6.1, 143–158. ISSN: 20457758. DOI: 10.1002/ece3.1837.
- Virtanen, Tarmo, Ek, Malin (2014). "The fragmented nature of tundra landscape". International Journal of Applied Earth Observation and Geoinformation 27.PARTA, 4-12. ISSN: 15698432. DOI: 10.1016/j.jag.2013.05.010. URL: http://dx.doi.org/10.1016/j.jag.2013.05.010.
- Wolf, Adam, Doughty, Christopher E, Malhi, Yadvinder (2013). "Lateral Diffusion of Nutrients by Mammalian Herbivores in Terrestrial Ecosystems". *PLoS ONE* 8.8. ISSN: 19326203. DOI: 10.1371/journal.pone.0071352.
- Yan, Yuchun et al. (2018). "Grazing modulates soil temperature and moisture in a Eurasian steppe". Agricultural and Forest Meteorology 262.12, 157–165. ISSN: 01681923. DOI: 10.1016/ j.agrformet.2018.07.011. URL: https://doi.org/10.1016/j.agrformet.2018.07.011.
- Ylänne, Henni et al. (2018). "Consequences of grazer-induced vegetation transitions on ecosystem carbon storage in the tundra". *Functional Ecology* 32.4, 1091–1102. ISSN: 13652435. DOI: 10.1111/1365-2435.13029.
- Zimov, S. A. et al. (2012). "Mammoth steppe: A high-productivity phenomenon". Quaternary Science Reviews 57, 26-45. ISSN: 02773791. DOI: 10.1016/j.quascirev.2012.10.005. URL: http://dx.doi.org/10.1016/j.quascirev.2012.10.005.
- Zimov, Sergei A et al. (1995). Steppe-Tundra Transition: A herbivore-driven Biome shift at the end of the pleistocene. URL: http://www.jstor.org/stable/2462990.
- Zona, Donatella et al. (2016). "Cold season emissions dominate the Arctic tundra methane budget". Proceedings of the National Academy of Sciences of the United States of America 113.1, 40-45. ISSN: 10916490. DOI: 10.1073/pnas.1516017113.
- Zona, D et al. (2011). "Microtopographic controls on ecosystem functioning in the Arctic Coastal Plain". Journal of Geophysical Research: Biogeosciences 116.3, 1–12. ISSN: 01480227. DOI: 10.1029/2009JG001241.

# 6 Appendix

## 6.1 Interpolation of Environmental Parameters

## 6.1.1 Interpolation of Soil Temperatures

Because there were no continuous  $T_S$  measurements, there was a need to interpolate them based on available data (i.e. air temperature, PAR), since  $T_S$  was the basis for interpolating  $R_{eco}$ fluxes and  $CH_4$  fluxes. Hereby, multiple successively applied linear and exponential fits were used to correlate various drivers to the changes of  $T_S$  in the different depths (5cm, 15cm, 25cm, 35cm) over time.

**PP Lowland site**  $T_{S,15cm}$  was interpolated based on a linear model where  $T_{S,15cm}$  was fitted against a moving average of  $T_a ir$  (Fig 5.1.; d).  $T_{S,5cm}$  was interpolated based on a more refined model, where residuals resulting after the same approach (Fig 6.1.), were exponentially fitted against a moving average of PAR (Fig 6.1.; b) and subsequent residuals against  $T_{S,35cm}$  (Fig. 6.1.; c). A summary of statistical parameters for each step, as well as statistical parameters and the RMSE for the final model (modeled vs. measured) are given in Tab. 6.1. At the PP lowland site,  $T_{S,25cm}$  and  $T_{S,35cm}$  were interpolated linearly (Fig 5.1.; g and h) because the data didn't cover the needed time interval to explain temperatures with a moving average of  $T_{air}$ . An error for  $T_{S,35cm}$  (which was used for interpolation of  $T_{S,5cm}$ ) was not considered since it was linearly interpolated and no error could be calculated. Since the possible error in this case is most probably much lower than the modeling error for  $R_{eco}$ , we considered it to be of small concern.

**AS-0 and AS-2** The same approach was used for AS-0 and AS-2. Due to the more extensive dataset, for all soil temperatures matching moving averages of  $T_air$  could be determined, with one exception being  $T_{S,35cm}$  at AS-2, where the amount of data for  $T_{air}$  does not reach back far enough. For  $T_{S,5cm}$ , residuals resulting after the same approach as for the PP lowland site (Fig.6.2(AS-0) and Fig.6.3(AS-2); *a*), were exponentially fitted against a moving average of PAR (Fig.6.2(AS-0) and Fig.6.3(AS-2); *b*). For  $T_{S,15cm}, T_{S,25cm}$  and  $T_{S,35cm}$  linear models, where  $T_S$  was fitted against a moving average of  $T_air$ , were dervied(Fig.6.2(AS-0) and Fig.6.3(AS-2); *b*). For  $T_{S,15cm}, T_{S,25cm}$  and  $T_{S,35cm}$  linear models, where  $T_S$  was fitted against a moving average of  $T_air$ , were dervied(Fig.6.2(AS-0) and Fig.6.3(AS-2); *c*/*d*/*e*). Covered time intervals for moving averages,  $R^2$  and p-values are given in Tab.6.1. Fig.6.2(AS-0) and Fig.6.3(AS-2) *f*, *g*, *h* and *i* show interpolated and measured values. Statistical

parameters and errors from linear regressions between measured and modeled  $T_S$  in all depths are shown in Tab. 6.1.



Figure 6.1: Procedure to model and interpolate soil Temperatures for the study period based on chamber point measurements (PP lowland). a) to c): procedure for  $T_S$  in 5cm. d) for  $T_S$  in 15cm. e) to h) plots showing both modeled and measured values for each depth.



Figure 6.2: Procedure to model and interpolate soil Temperatures for the study period based on chamber point measurements (AS-0) and continuous  $T_{air}$  measurements.



Figure 6.3: Procedure to model and interpolate soil Temperatures for the study period based on chamber point measurements (AS-2) and continuous  $T_{air}$  measurements.
Table 6.1: S	ummary of time intervals $(T_{air} - MA, [h], MA = "moving average")$ inside which $T_{air}$
ez	xplains $T_S$ in the various depths (and statistical parameters for the applied linear model),
st	tatistical parameters of a logarithmic model between residuals from the first linear model
(1	$T_{S,5cm}$ vs. $T_{air}movarg$ ) vs. a moving average of PAR (only for $T_{S,5cm}$ , [h]), the same for
$\mathbf{t}$	he linear model between the resulting residuals from the logarithmic model (residual-2) and
Т	$S_{35cm}$ , as well as the final resulting statistics and RMSE (°C, linear regression: modeled
V	s. measured).

	AS-0	AS-2	$\operatorname{PPL}$
$\begin{array}{c} T_{S,5cm} \\ T_{air} - MA \\ R^2/p \end{array}$	<b>40.7</b> 0.98****	<b>86.7</b> 0.99****	<b>4.3</b> 0.77****
lm: residual - PAR PAR - MA $R^2/p$	2.2 0.70****	$1 \\ 0.64^{****}$	$1 \\ 0.42^{****}$
lm: residual-2 - $T_{S,35cm}$ $R^2/p$	-	-	0.71****
final model $R^2/p$ RMSE	$0.95^{****}$ 0.238	$0.99^{****}$ 0.2574	$0.95^{****}$ 0.6637
$     T_{S,15cm}     T_{air} - MA     R^2/p $	<b>67.5</b> $1^{****}$	<b>108.3</b> 1****	<b>100</b> 0.96****
final model $R^2/p$ RMSE	$1^{****}$ 0.073	1**** 0.101	$0.94^{****}$ 0.250
$\begin{array}{c} T_{S,25cm} \\ T_{air} - MA \\ R^2/p \end{array}$	<b>113.0</b> 0.99****	<b>204.8</b> 0.97****	-
final model $R^2/p$ RMSE	$0.99^{****}$ 0.107	$0.97^{****}$ 0.009	-
$T_{S,35cm} \\ T_{air} - MA \\ R^2/p$	<b>281.7</b> 0.71****	<b>288.3</b> 0.073 <sup>ns</sup>	-
final model $R^2/p$ RMSE	$0.96^{****}$ 0.045	-	-

## 6.1.2 Correction and Interpolation of Soil Moistures

Noisy data in the observed soil moistures in 7.5cm, 15cm and 30cm depth has been cleaned by selecting continuous intervals of little fluctuating data as trustworthy. Data points above and below visually determined plausibility limits around these intervals were removed from further analysis. When two low-fluctuating series of values with different magnitudes were measured

(at all depths), the relatively higher values were chosen to be reliable and systematic offsets for  $SM_{15cm}$  and  $SM_{7.5cm}$  at July 8th were adjusted by adding a constant number (Fig. 6.4.). This is assumed to be justified by the logical development of the values to be dropping throughout the observation period due to the dominating dry and mostly hot weather conditions (See chapter 3.1.).



Figure 6.4: Correction of Soil Moisture values (PP lowland). Data noise has been removed by choosing continuous, low fluctuating intervals as reliable data. Systematic offsets were corrected by adding a constant number on 8th of July for SM in 7.5cm and 15cm. When two series of values with different magnitudes were present the relatively higher values were identified to be correct for logical reasons.

Soil Moistures at all depths were interpolated by calculating one average value for each measurement-day using the corrected values and linearly interpolate between these values. This yields a continuous time series with a 10 minute resolution fitting the CNR1 dataset (Fig.6.5.). No error for interpolated values was calculated and the potential magnitude of the error evaluated as being of low concern.



Figure 6.5: Interpolation of Soil Moisture values (PP lowland). For each day and each depth, one average value (corrected SM values) was calculated and included into the continuous dataset from the CNR-1 measurements and the gaps were linearly interpolated.

### 6.1.3 Correction of PARr-Values

Mostly, PAR observations of chamber measurements were reliable and close to the CNR1 observations, with a little negative offset that is likely an effect caused by the plexiglass screen. As these values still represent the available amount of radiation for Photosynthesis, no systematic correction was applied. At 8th, 10th and 13th July some values were considerably lower than those measured by the CNR-1 and therefore replaced by the temporally closest CNR-1 values (Fig.6.6.).



Figure 6.6: Correction of par-values. Values from chamber measurements that lie visibly far below the values from the CNR-1 were replaced by those values.

## 6.2 Calculation and Interpolation of C-Fluxes

#### 6.2.1 Error Calculation

For the final modeled fluxes, which also serve to calculate daily average fluxes, a series of error sources was identified. First, using the bootstrapping approach to obtain a median slope of  $CO_2$  and  $CH_4$  concentration gradients explained in the methods section, leads to a number of different slopes and therefore an error range (see Fig.2.3). The standard error of the calculated slopes was transformed into a flux by the same formula like the median slope, averaged over all measurements and is called  $Err_{slope}$ . For GPP,  $Err_{slope}$  is composed by the both  $Err_{slope}$  of NEE measurements and  $R_{eco}$  measurements. Second, modeling the chamber fluxes in order to have a continuous time series results in deviations from the modeled vs. the measured fluxes. Here, a linear regression (modeled vs. measured) was applied to evaluate the model quality and to obtain a standard error. Third, to model and interpolate  $R_{eco}$  (at PPL-1 and PPL-2) and  $CH_4$  fluxes (at AS-0 and AS2), soil temperatures, by themselves also interpolated by a model, were used. Therefore, the RMSE of these models was considered by adding it to the  $T_S$  - term in the interpolation formula for  $R_{eco}(T_{S,5cm})$  and  $CH_4$  fluxes ( $T_{S,15cm}$ ; ( $T_{S,25cm}$ )). Then, the initial flux was substracted from this "enhanced" flux, the result was defined as the  $T_S$ -error

	Ambolikha Site		PP Lowland Site		
	AS-0	AS-2	PPL-1	PPL-2	PPL-3
NEE					
$Err_{abs}$ (ER)	1.46	0.58	1.31	1.64	0.97
$Err_{abs}$ (GPP)	2.80	1.44	2.03	2.94	2.48
$Err_{comp}$	4.26	2.02	3.34	4.58	3.55
ER					
$Err_{slope}$	0.16	0.13	0.15	0.13	0.13
$Err_{mod}$	0.89	0.45	0.65	1.16	0.84
$Err_{T_S}$	-	-	0.51	0.35	-
$Err_{abs}$	1.46	0.58	1.31	1.64	0.97
GPP					
$Err_{slope}$	0.30	0.24	0.26	0.27	0.33
$Err_{mod}$	2.50	1.20	1.77	2.67	2.15
$Err_{abs}$	2.80	1.44	2.03	2.94	2.48
$CH_4$					
$Err_{slope}$	0.0022	0.0033	0.0039	0.0026	0.00090
$Err_{mod}$	0.011	0.012	0.045	0.020	0.007
$Err_{T_{S,15cm}}$	0.0013	0.0014	-	-	-
$Err_{abs}$	0.014	0.016	0.049	0.027	0.008

**Table 6.2:** Error range of C-fluxes. Values in  $\mu mol(C) * m^{-}2 * s^{-}1$ .  $Err_{abs}$  describes the final cumulative error that is also used in the results section.

 $(Err_{T_s})$ . All these errors were summarized by  $Err_{abs}$  and they are depicted in Tab. 6.2. NEE errors are summed up  $Err_{abs}$  from  $R_{eco}$  and GPP.

# **Declaration of Authorship**

I hereby declare that the thesis titled "Investigation of Greenhouse-Gas Fluxes on a Grazed Wet Tussock Tundra in Northeastern Siberia" is my own unaided work. All direct or indirect sources used are acknowledged as references. This thesis was not previously presented to another examination board and has not been published.

Hiermit erkläre ich, dass ich die vorgelegte Arbeit "Investigation of Greenhouse-Gas Fluxes on a Grazed Wet Tussock Tundra in Northeastern Siberia" eigenständig verfasst und keine anderen als die im Literaturverzeichnis angegebenen Quellen und Hilfsmittel benutzt habe. Weiter wurde diese Arbeit bisher nicht veröffentlicht oder zur Erlangung eines akademischen Grades eingereicht.

Bayreuth, 15.05.2020

.....

Wolfgang Fischer