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Tundra landscape heterogeneity, not inter-annual variability, controls the decadal regional carbon balance in the Western Russian Arctic

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Abstract
Across the Arctic, the net ecosystem carbon (C) balance of tundra ecosystems is highly uncertain due to substantial temporal variability of C fluxes and to landscape heterogeneity. We modeled both carbon dioxide (CO$_2$) and methane (CH$_4$) fluxes for the dominant land cover types in a ~100 km$^2$ sub-Arctic tundra region in northeast European Russia for the period of 2006-2015 using process-based biogeochemical models. Modeled net annual CO$_2$ fluxes ranged from -300 g C m$^{-2}$ y$^{-1}$ [net uptake] in a willow fen to 3 g C m$^{-2}$ y$^{-1}$ [net source] in dry lichen tundra. Modeled annual CH$_4$ emissions ranged from -0.2 to 22.3 g C m$^{-2}$ y$^{-1}$ at a peat plateau site and a willow fen site, respectively. Interannual variability over the decade was relatively small (20-25%) in comparison to variability among the land cover types (150%). Using high-resolution land cover classification, the region was a net sink of atmospheric CO$_2$ across most land cover types but a net source of CH$_4$ to the atmosphere due to high emissions from permafrost-free fens. Using a lower-resolution for land cover classification resulted in a 20-65% underestimation of regional CH$_4$ flux relative to high-resolution classification and smaller (10%) overestimation of regional CO$_2$ uptake due to the underestimation of wetland area by 60%. The relative fraction of uplands versus wetlands was key to determining the net regional C balance at this and other Arctic tundra sites because wetlands were hotspots for C cycling in Arctic tundra ecosystems.
**Introduction**

The Arctic is warming at a faster rate than the global average (Hartmann *et al.*, 2013). Currently, the Arctic tundra region is generally a net sink of atmospheric CO₂ but a net source of methane (CH₄) (McGuire *et al.*, 2012), another potent greenhouse gas (Myhre *et al.*, 2013). However, warmer temperatures in the future may result in the switch of tundra from a net carbon (C) sink to a net C source if soil C losses exceed increase in C uptake by vegetation (Koven *et al.*, 2011). However, the current net sign or magnitude of the combined ecosystem C balance (CO₂ + CH₄) in tundra is not well known, especially at regional scales (100-10,000 km²).

Regional C budgets that include both CO₂ and CH₄ have been estimated for Barrow, Alaska (Sturtevant & Oechel, 2013) and Lake Tornetrask in Northern Sweden (Christensen *et al.*, 2007). CO₂ budgets have been calculated for more regions, including Kuparuk River Basin in Alaska (Oechel *et al.*, 2000, Vourlitis *et al.*, 2003), the Barrow experimental observatory (Alaska) (Zulueta *et al.*, 2011), Imnavait Creek and Arctic Alaska (Euskirchen *et al.*, 2017), and Seida (northeast European Russia) (Marushchak *et al.*, 2013). Regional CH₄ budgets have been separately calculated for some of the same areas (Christensen *et al.*, 2004, Marushchak *et al.*, 2016, Reeburgh *et al.*, 1998), the Lena River Delta in Siberia (Schneider *et al.*, 2009, Zhang *et al.*, 2012), the Yukon-Kuskokwim Delta in Alaska (Bartlett *et al.*, 1992), and northeast Greenland (Jorgensen *et al.*, 2015). Combining simultaneous estimates of both CO₂ and CH₄ for the same region at the same time is critical for estimating the net C balance of the circum-Arctic because both CO₂ and CH₄ play a substantial role in net C emissions (McGuire *et al.*, 2012, Zhuang *et al.*, 2015) and C emissions may be highly variable across the landscape and over time.
Accurate measurements of present-day regional C balance, including CO$_2$ and CH$_4$ exchange, are necessary to detect future changes in C balance, but must properly address the major sources of variability in C cycling: interannual variability and landscape heterogeneity. Interannual climatic variability results in high variability in tundra ecosystem CO$_2$ exchange, and can result in the ecosystem switching from a net C sink to a net C source (Griffis et al., 2000, Heikkinen et al., 2004, Lafleur et al., 2001, Lafleur & Humphreys, 2007, Oberbauer et al., 2007). Thus, multiple years of measurements are needed to overcome any bias caused by short-term natural climatic variability. Climatic variability also affects CH$_4$ fluxes: elevated atmospheric concentrations of CH$_4$ were observed in northern high latitudes during the wet and warm year of 2007, presumably caused by favorable environmental conditions that promoted CH$_4$ emissions from wetlands and tundra ecosystems (Bruhwiler et al., 2014). Additionally, episodic fluxes can dominate annual ecosystem CH$_4$ emissions but can occur infrequently (Mastepanov et al., 2008, Mastepanov et al., 2013), increasing the apparent interannual variability. Without multiple years of measurements, annual CH$_4$ emissions may be over- or under-estimated relative to the long-term mean, depending on the time of sampling (Mastepanov et al., 2013).

Landscape heterogeneity is a driver of the regional C balance in tundra ecosystems (Zulueta et al., 2011), in part because the vegetation composition, productivity, soil type, soil C storage, and permafrost conditions differ greatly within small areas (Hugelius et al., 2012, Virtanen & Ek, 2014). Within Arctic tundra, lakes and wetlands are hot spots for C cycling. Lakes tend to be hotspots for net CO$_2$ and CH$_4$ emissions (Sturtevant & Oechel, 2013), which are derived from the decomposition of autochthonous C, the decomposition of terrestrially-derived organic matter, and the lateral flow of dissolved gases including CO$_2$ and CH$_4$ (Cole et al.,
Tundra wetlands, such as fens and willow stands, are usually strong C sinks (Marushchak et al., 2013) but also release large quantities of CH$_4$ as a result of anaerobic decomposition in the water-logged sediments (Bartlett et al., 1992, Marushchak et al., 2016). Near Barrow, Alaska, the CO$_2$ and CH$_4$ released from lakes and wetlands, although limited in extent, nearly offset the net C uptake measured in the upland tundra and resulted in a near neutral regional C balance (Sturtevant & Oechel, 2013). On the other hand, despite hot spots of wetland CH$_4$ emissions from another tundra site in northeast Greenland, small rates of CH$_4$ uptake in the large areas of adjacent, well-drained, upland sites resulted in a net regional CH$_4$ sink rather than net regional source (Jorgensen et al., 2015). These findings highlight the importance of considering hot spots for C cycling together with the ecosystem types that cover larger areas even given low fluxes per unit area.

Accurately capturing the landscape heterogeneity that controls regional C balance requires relatively fine spatial resolution and an appropriate thematic resolution, meaning representation of land cover types with distinct C dynamics. The spatial resolution must be high enough to detect hot spots for C cycling, such as lakes and wetlands, within the landscape (Bartsch et al., 2016, Davidson et al., 2017, Virtanen & Ek, 2014), which can change greatly depending on the spatial resolution of classification (Muster et al., 2013). Capturing functional differences among ecosystem types requires a sufficient thematic resolution in landscape classification but must be distinctly and reliably identified using classification techniques. Increasing spatial and thematic resolution can significantly change the regional estimates of C balance (Jorgensen et al., 2015, Schneider et al., 2009, Vourlitis et al., 2003), largely due to the better quantification of emissions hot spots.
The goal of this study was to provide a decadal mean regional CO$_2$ and CH$_4$ balance and to characterize the uncertainty due to interannual variability and landscape heterogeneity on the regional CO$_2$ and CH$_4$ exchange for a well-characterized site, Seida, in Western Russia. Landscape heterogeneity at Seida is high, with several potential hotspots for C cycling, including upland tundra heath, permafrost peat plateaus, permafrost-free fens, and lakes located within 200 m$^2$. We used process-based biogeochemical models that were calibrated and validated with independent CO$_2$ and CH$_4$ flux measurements (Marushchak et al., 2016, Marushchak et al., 2013, Voigt et al., 2017) to estimate CO$_2$ and CH$_4$ fluxes between the dominant regional land cover types and the atmosphere. These estimates provide an important addition to high-latitude regional C budgets by addressing an existing spatial data gap at the tundra-taiga interface in the discontinuous permafrost zone in northwestern Russia.

Materials and Methods

Site description and classification

The study site, Seida, is located in the northern forest-tundra subzone with discontinuous permafrost, near the Seida settlement in northeast European Russia (67° 03’ N, 62° 56’ E; Figure 1). At Vorkuta climate station (67° 48’ N, 64° 10’; Figure 1), 70 km to the northeast of Seida, the mean average annual air temperature for 1977-2006 was -5.6° C and the mean annual precipitation was 501 mm (Komi Republican Centre for Hydrometeorological and Environmental Monitoring).

The regional landscape at Seida was divided into three major land cover types using land cover classification methods: upland tundra (58%), permafrost peat plateaus (24%), and low-lying, permafrost-free fens (14%; Table 1). Within these
major land cover types, several land cover sub-types were identified based on the
dominant vegetation (Figure S1). In this region, vegetation composition corresponds
to factors such as water table position, organic soil thickness, and pH, which are
related to local topography and drainage (Hugelius et al., 2011), as is common in
many northern landscapes (Bubier et al., 2006). The land cover classification was
derived from a QuickBird satellite image (2.4 m pixel size) covering 98.6 km² around
the flux measurement site, acquired on 6 July 2007 (QuickBird© 2007, DigitalGlobe).
Classifications were produced using an object-based classification with
multiresolution segmentation. Classification accuracy was tested with field collected
verification data. This approach also differs from broader land cover classifications
made at the circum-Arctic scale (e.g. Walker et al., 2005), which do not capture
much of the fine-scale landscape heterogeneity associated with local conditions. To
assess the effect of reduced spatial resolution, the land cover classification was
resampled to 20 m, 160 m, 320 m, and 1280 m resolution by calculating majority
land cover class in each pixel (Figure 2). Further detail on the soil, vegetation, and
classification schemes can be found in Marushchak et al. (2011, 2013) and Hugelius
et al. (2011).

The upland tundra, common throughout the study region, is developed on silty
to sandy well-drained soils overlain by variable, but relatively thin surface organic
horizons (<20 cm). The upland soil is covered with shrub tundra vegetation
dominated by *Betula nana*, numerous *Salix* sp. (including *Salix phylicifolia* and *Salix
glaucha* in wetter areas and dwarf willows such as *Salix reticulata*, *Salix arctica* and
*Salix polaris* in dry areas), and dwarf shrubs, such as *Vaccinium uliginosum* and
*Vaccinium vitis-idaea*. Four dominant vegetation types were identified: dry shrub
tundra heath, moist shrub tundra heath, dwarf birch tundra heath, and dry lichen tundra heath that was found primarily on ridge-tops.

The permafrost peat plateaus consist of variable, but often deep (up to 4 m), organic deposits whose surfaces are elevated above other peatlands due to frost-heave from the accumulation of massive ground ice. We used two land cover sub-types to represent the dry and moist bog vegetation types found on the peat plateaus. The dry peat plateau sub-type is well-drained and has *Ledum decumbens* and *Rubus chamaemorus* as dominant vascular plants, mosses (e.g. *Dicranum* spp.) and lichens (e.g. *Cladina* spp.) in the ground layer. The moist peat plateau sub-type, occurs in wet *Sphagnum* depressions with *R. chamaemorus* and *V. uliginosum*.

Permafrost-free fens and willow stands are located in low-lying parts of the landscape, often adjacent to the peat plateaus, and are dominated by graminoids (*Carex* spp., *Eriophorum* spp.), or willows (*Salix* spp.). In the fens, there is a floating *Sphagnum* mat and the water table is near the surface throughout the growing season. The dominant vascular plant types in fens were sedges (*Carex aquatilis*) and cotton grasses (*Eriophorum russeolum*). Willow, including *Salix phylicifolia* and *S. lapponum*, was the other type of dominant vegetation in fens, occurring in 50 to 120 cm high stands in low-lying areas with peaty soils.

In addition to upland tundra and peatlands, thermokarst lakes are interspersed throughout the peat plateaus and cover 1.1% of the study area. Deciduous and spruce forests are scattered across the broader Seida region, covering 2.3% of the study area, but do not occur within the calibration and validation study areas.
Ecosystem Modeling

We used the process-based model, NEST-DNDC (Zhang et al., 2012) to simulate C fluxes from the dominant regional land cover types: upland tundra, peat plateaus, and permafrost-free fens. Two additional, independent models simulated C fluxes from the forest and lake components of the Seida landscape. Modelling of the forested land cover type used LPJ-GUESS (Lund-Potsdam-Jena General Ecosystem Simulator, Smith et al., 2001), and modelling of the lakes was done using the Arctic Lake Biogeochemistry model (ALBM) (Tan et al., 2017, Tan et al., 2015).

Modeling of upland tundra, permafrost peat plateaus, and permafrost-free fens

We used the NEST-DNDC to model water table level, active layer thickness, and C fluxes for upland tundra heath, peat plateaus, and permafrost-free fens. NEST-DNDC is a process-based model that integrates an existing biogeochemical model DeNitrification-DeComposition (DNDC) (Li et al., 2000) with a permafrost model Northern Ecosystem Soil Temperature (NEST) (Zhang et al., 2003) and is capable of simulating an ecosystem domain consisting of a number of plant communities (Zhang et al., 2012). NEST-DNDC models rates of ecosystem respiration \( ER = R_h + R_a \), gross primary productivity (GPP), net ecosystem CO\(_2\) exchange \( NEE = GPP - ER \), and CH\(_4\) fluxes, including vegetation transport and ebullition emission pathways. Previously, NEST-DNDC has been tested against observations of CH\(_4\) fluxes measured by closed chambers and eddy covariance (EC) method in a polygonal permafrost area in the Lena River Delta, Russia (Zhang et al., 2012). We used a synthetic climate driver dataset for the period of 2006-2015 (Figure 3). The climate drivers were derived from a combination of site measurements (2006-2011) and bias-corrected observations for 2012-2015 from nearby Vorkuta (~70 km NE,
67° 30′ N, 64° 2′ E) and Salekhard (66.5294° N, 66.5294° E) meteorological stations (NOAA National Centers for Environmental Information, https://www.ncdc.noaa.gov/, 2012-2015). Additional, detailed information about model parameterizations and evaluation can be found in Appendix A.

Forest ecosystem modeling

We used the Arctic-enabled LPJ-GUESS to simulate forest ecosystem C dynamics for the Seida region. This model has been specifically developed to simulate treeline and shrub expansion in tundra ecosystems and has been validated for high-latitude regions in this region (Miller & Smith, 2012, Zhang et al., 2013), while the NEST-DNDC model used for non-forested land cover types could not be parameterized for forest stands in this region due to lack of field measurements in this ecosystem type. For this study, LPJ-GUESS (Smith et al., 2001) was modified to model upland, high-latitude ecosystems by incorporating recent developments to LPJ-DGVM that include improved determination of soil temperatures and soil freezing processes using a four-layer soil column and a snowpack (Wania et al., 2009, Wania et al., 2010, Wolf et al., 2008). The Arctic-enabled LPJ-GUESS has an expanded set of plant function types (PFTs) for use in high latitude upland regions. Thirteen PFTs were simulated in this study including five tree types, evergreen and deciduous short shrubs (up to 0.5 m in height), evergreen and deciduous tall shrubs (up to 2 m in height) and four open ground, herbaceous types (Wolf et al., 2008). The C balance simulated by the Arctic-enabled LPJ-GUESS used here is in broad agreement with other, similar bottom-up process-based models, inverse models and upscaled site-based observations (McGuire et al., 2012). Additional information on model parameterization can be found in Appendix A.
Lake ecosystem modeling

The Arctic Lake Biogeochemistry Model (ALBM) is a one-dimensional process-based climate-sensitive lake biogeochemistry model that simulates CO$_2$ and CH$_4$ emissions from Arctic lakes (Tan et al., 2017, Tan et al., 2015). Carbon dioxide and CH$_4$ emissions from Arctic lakes are determined by their surface concentrations and transfer velocities. To estimate surface CO$_2$ concentrations, the ALBM model simulates the processes of photosynthesis, the mineralization and deposition of organic matter, and the loading of organic and inorganic C through water flow and permafrost thawing within a one-dimensional sediment and water column (Tan et al., 2017). In the model, photosynthesis rates are controlled by the levels of photosynthetically active radiation, temperature, phosphorus and chlorophyll a. Mineralization of organic matter is represented in two pathways: microbial and photochemical degradation. To estimate surface CH$_4$ concentrations, the ALBM model simulates CH$_4$ production, oxidation and transport (both diffusion and ebullition) within a one-dimensional sediment and water column (Tan et al., 2015). Methane production occurs in both surface and deep sediments. The transfer velocities of CO$_2$ and CH$_4$ at the water-air interface are modeled as a function of wind speed, water mixing depth and gas Schmidt number (Tan et al., 2017). The climate drivers for ALBM were the same as for NEST-DNDC (3.1.1).

Measurements for model calibration and verification

DNDC and ALBM were calibrated and validated against independent field measurements from the Seida region (Appendix A). Soil temperature, water table, and seasonal thaw depth were measured during field campaigns in 2007-08. Snow
depths were measured during the winter of 2007-08. For C fluxes in DNDC, CO$_2$ and
CH$_4$ exchange rates were measured in all the vegetation sub-types on peat plateaus, fens, and uplands using a static chamber technique throughout the growing seasons in 2007, 2008, 2012, and 2013 and during the winter of 2007-08 (Marushchak et al., 2016, Marushchak et al., 2013, Voigt et al., 2017). Gross primary productivity was calculated as the difference between NEE using transparent chambers and ER, measured using opaque chambers. Observed daily CO$_2$ flux measurements were interpolated from the instantaneous chamber measurements using empirical relationships with PAR, LAI, soil temperature, soil moisture, and water table for each measurement location (Marushchak et al., 2013, Voigt et al., 2017 [Table S5, S6]). Interpolating the observations to daily values from instantaneous observations reduced bias in CO$_2$ flux measurements due to diurnal variation in PAR and soil temperatures; diurnal variability in CH$_4$ fluxes was assumed to be small at this site. The annual measurements from 2007-2008 were used for model calibration, whereas growing season measurements from 2012-2013 at a sub-site roughly 2 km northwest were used for verification purposes (Figure 1). We tested for model bias using linear regressions between interpolated measurements and model output using R (R Development Core Team, 2008) and report the results in Appendix A. The ALBM model was calibrated and validated at the Seida site using the measured CO$_2$ and CH$_4$ fluxes from three Seida lakes during the open water period of 2007 and 2008 (Repo et al., 2007). Details on specific calibration and validation methods are described in Tan et al. (2015, 2017).
Regional C balance and C feedback

We estimated the regional C balance from Seida using a simple upscaling approach using the areas of each land cover type within the study region (e.g. Marushchak et al., 2013, Oechel et al., 2000, Reeburgh et al., 1998) and the modeled decadal fluxes for each land cover type. We determined the gaseous net C exchange (CO₂-C + CH₄-C) and mean areal emissions for each land cover type. Using the mean areal emission allows a comparison of the contribution of each land cover type to the regional C balance. To determine the mean areal emissions (mean spatially-weighted emission) for each land cover type (LCT), we used the equation:

\[ F_{\text{regional-LCT}} = A_{\text{LCT}} * F_{\text{plot-LCT}} / A_{\text{total}} \]  

where \( F_{\text{regional-LCT}} \) is the mean areal emission of each land cover type normalized over the study domain, \( A_{\text{LCT}} \) is the area of each land cover type, \( F_{\text{plot-LCT}} \) is the modelled CO₂ or CH₄ flux that is comparable to the plot-scale measurements, and \( A_{\text{total}} \) is the total area of the Seida study region (98.6 km²).

We compared the variability in CO₂ and CH₄ emissions among land cover classifications and years using the coefficient of variation, calculated as the standard deviation/mean, given as a percent. This normalized metric allows the comparison of variability among samples.

Results

C fluxes during calibration (2007-08) and validation (2012-13) periods

In upland tundra heath vegetation types, NEST-DNDC simulated the magnitude and daily variation of CO₂ fluxes well during the calibration period of 2007-2008 (Figure 4a-c) and the validation period at nearby Seida II in 2012-2013 (Figure 4e-g). In tundra heath, both modelled and measured CH₄ fluxes were generally quite small (<
5 mg C m\(^{-2}\) d\(^{-1}\); Figure 4d,h), with noticeable CH\(_4\) emission peaks during the spring and fall periods due to ebullition events likely associated with soil freeze and thaw. Model output at the peat plateau site matched well with the daily interpolated flux chamber measurements during the calibration period of 2007-2008 for NEE, ER, and GPP (Figure 5a-c) and during the validation period of 2012-2013 (Figure 5-g), although the model had some difficulty capturing high rates of ER during the spring and early summer. The peat plateaus were net sinks of CH\(_4\) in the model (-0.1 g C m\(^{-2}\) y\(^{-1}\); Figure 5d), whereas measurements showed fluxes of 0.2 ± 0.2 g C m\(^{-2}\) y\(^{-1}\) (Marushchak et al., 2016); a similar trend occurred in 2012-13 (Figure 5h). The model also simulated noticeable CH\(_4\) emission peaks in the peat plateaus during the spring and fall due to episodic emissions associated with soil freeze and thaw. Modeled growing season soil temperatures depth were cooler than the observations, resulting in a shallower seasonal thaw depth than observations, particularly for tundra heath and peat plateau vegetation types (Appendix A).

Agreement between model output and daily fluxes at the fen vegetation types during the calibration period of 2007-2008 and the validation period 2012-2013 was quite good for CO\(_2\) flux components (Figure 6a-c,e-g) and CH\(_4\) flux (Figure 6d,h). The model simulated permafrost in the fen vegetation types in deeper soils (>150 cm), while permafrost was not observed in the field, which is likely related to local hydrologic conditions that affect lateral and vertical heat fluxes (Kurylyk et al., 2016). Further discussion of the model evaluation can be found in Appendix A.

Decadal variability among land cover types and years

Modeled CO\(_2\) fluxes averaged over the study period 2006-2015 differed greatly among land cover types, but nearly all land cover types were net sinks of CO\(_2\)
Willow fens showed strong net CO$_2$ uptake that was approximately three times larger than NEE in other land cover types (Figure 7a). NEE in Carex fens, peat plateaus, moist shrub and dwarf birch tundra heath were all similar in magnitude and ranged from -60 to -100 g C m$^{-2}$ y$^{-1}$. Both lakes and lichen tundra heath were net sources of CO$_2$ to the atmosphere, emitting 10 ± 0.4 g C m$^{-2}$ y$^{-1}$ and 3 ± 4 g C m$^{-2}$ y$^{-1}$, respectively (Table 1, Figure 7). Both ER and GPP were greatest in the Willow and Carex fen vegetation types and lowest in the Eriophorum fen and the lichen heath tundra (Table 1).

Modeled CH$_4$ emissions ranged from a small net uptake of CH$_4$ in the dry and upland land cover types to a significant source of CH$_4$ in the wetlands and a small source in the lakes (Figure 7c, Table 1). Generally, the net CH$_4$ flux from all the dry vegetation types, including both the vegetation types on the mineral tundra and the permafrost peat plateau bogs, were essentially zero (-0.04 ± 0.02 g C m$^{-2}$ y$^{-1}$). The vegetation types with highest NEE, Willow and Carex fens, also had the largest mean annual CH$_4$ emissions, which ranged from 17.2 to 22.3 g C m$^{-2}$ y$^{-1}$ (Figure 7a,c, Table 1). Of the three lakes modeled in the Seida region, CH$_4$ fluxes were the largest from a small thermokarst lake (3.3 ± 0.2 g C m$^{-2}$ y$^{-1}$) while fluxes for the other two, larger lakes were smaller by an order of magnitude (0.2 – 0.3 g C m$^{-2}$ y$^{-1}$) due to differences in organic matter inputs for CH$_4$ production associated with higher productivity and vegetation colonization.

There was significant interannual variability in the modeled regional C fluxes during this decadal period, although all years were net CO$_2$ sinks. Between 2006-15, NEE ranged from a low of -34 g C m$^{-2}$ y$^{-1}$ in 2010 to a high of -94 g C m$^{-2}$ y$^{-1}$ in 2014 (Figure 7b). Between 2006-15, CH$_4$ flux ranged from 2.9 g C m$^{-2}$ y$^{-1}$ in 2014 and 2015 to 5.6 g C m$^{-2}$ y$^{-1}$ in 2008 (Figure 7d). For the study region as a whole, the
coefficient of variation (standard deviation/mean) in NEE due to interannual variability was 25%. In comparison, the coefficient of variation of NEE due to differences among land cover types was 150% (Figure 7a,b). The interannual variability of CH$_4$ (22%) was less than NEE (25%; Figure 7d,b). In comparison, the coefficient of variation of CH$_4$ flux due to differences among land cover types was 155%.

Additionally, there were differences in the relative range of interannual variability within each land cover type for both modeled NEE and CH$_4$ flux between 2006 and 2015 (Table 1). The interannual variability of NEE was smallest in lakes (7%), followed by peat plateaus (37%), fens (53%), forest (70%), and tundra heath (76%). The high variability in tundra heath vegetation types was mainly due to high interannual variability in dry lichen tundra heath (490%) and dry shrub tundra heath (260%); these vegetation types were net C sinks in some years (2012-15) but net C sources in other years (2006-11). Similarly, Carex and Eriophorum fens also had relatively high interannual variability (~105%), with net C uptake occurring in most years except 2014 and 2015. The interannual variability in CH$_4$ flux was smallest in lakes (13%), followed by fens (28%). The interannual variability in CH$_4$ flux was larger in peat plateau (85%) and tundra vegetation types (105%), which were dry and had little or no CH$_4$ flux except for small pulse emissions during the spring and fall (Figures 3,4). The magnitude of the interannual variability among land cover types did not seem to follow any trends in vegetation or soil moisture (Table 1, S1).

Regional-scale C balance

During the study period 2006-2015, the Seida region was modeled to be a mean net CO$_2$ sink of -74 ± 12 g C m$^{-2}$ y$^{-1}$ when using high-resolution (2.4 m) land
cover data (Table 1, Figure 8a). A large part of the net CO$_2$ uptake, 35%, occurred in
the willow fens ($F_{\text{regional}}$; Table 1). Moist shrub tundra heath, dwarf birch tundra heath,
and moist permafrost bogs were also net sinks of CO$_2$ on the regional scale but
sequestered less than half of the willow fen uptake (Table 1). The region was
modeled to be a net CH$_4$ source to the atmosphere of 3.1± 0.3 g C m$^{-2}$ y$^{-1}$ due to the
substantial emissions from the willow and Carex fens, which together contributed
nearly 100% of the regional CH$_4$ emission. Modeled methane emissions from
wetlands were not offset by the small rates of modeled net CH$_4$ uptake from the dry
tundra vegetation types, but this uptake did slightly reduce (<5%) the regional CH$_4$
emission (Table 1, Figure 8b).

Role of spatial landscape heterogeneity

The regional C budget changed considerably when, instead of the highest
available 2.4 m pixel resolution, a lower-resolution land cover classification was used
(Figure 8). At 20 m resolution, the fraction of each major land cover type was still
similar to that from 2.4 m classification (Figure 8d), and subsequently, total regional
NEE and CH$_4$ were similar (within 5%) to the higher-resolution (2.4 m) classification
(Figure 8a-c). However, at lower resolutions ($\geq$160 m), the fraction of peat plateaus
increased at the expense of fen and tundra coverage (Figure 8d, Figure 2), causing
a significant decrease in the regional NEE and CH$_4$ of fens (5-120%) and a 40-120%
increase in NEE and CH$_4$ in peat plateaus (Figure 8a-c). Overall, the shift from fens
and tundra to peat plateaus using the lower-resolution classification increased the
total regional CO$_2$ uptake by <10% (Figure 8a) and decreased total regional CH$_4$
emissions by 20-60% (Figure 8b).
Discussion

Land cover type versus interannual variability

There have been a limited number of estimates of long-term regional C fluxes from Arctic tundra, and even fewer that combine CO$_2$ and CH$_4$ fluxes. This study allowed us to compare the relative effects of variability among years and land cover types on CO$_2$ and CH$_4$ emissions in a well-characterized region. The modeled interannual variability of CO$_2$ and CH$_4$ fluxes was 20\% - 25\% of the mean fluxes (Figure 7b,d), reflecting a range of climatic conditions from cool and wet in 2010 to warmer with intermediate precipitation in 2014 and 2015 (Figure 3). The interannual variability in fluxes was small, however, compared to the variability associated with land cover types (150\%). For example, permafrost-free willow fens had large net CO$_2$ uptake and high CH$_4$ emissions, dry lichen tundra heath had near neutral net CO$_2$ exchange and CH$_4$ flux, and lakes were a net source of both CO$_2$ and CH$_4$ (Figure 7a,c).

In remote sites like Seida, as well as for much of the Arctic, modeling can be an important tool for estimating net C exchange as extended monitoring of C fluxes is impractical. Accordingly, there are few long-term studies in northern high latitudes that capture interannual variability over a decade for comparison. Generally, these also show that interannual variability may not be as significant as variability among land cover types. In a 6-year eddy covariance study in upland tundra in interior Alaska, interannual variability in NEE was ~50\% (Celis et al., 2017), larger than the interannual variability in this study but still smaller than variability among land cover types. However, further north in Alaskan tundra, interannual variability in growing season NEE over 8 years measured with eddy covariance was 13\% (Euskirchen et al., 2017), slightly smaller than in this study or in the other interior Alaska site. In the
North Slope tundra, interannual variability was correlated with the day of soil thaw (Euskirchen et al., 2017). Similarly, much of the interannual variability in modeled NEE in this study was due to differences in the timing of the onset of CO$_2$ uptake, as well as other growing season processes (Figure 7b).

Other studies have shown that non-growing season emissions can be key to determining whether upland tundra is a net CO$_2$ sink or source (Natali et al., 2011). Capturing non-growing season CO$_2$ emissions in another site on the North Slope of Alaska resulted in significant variability among land cover types measured annually (105%), while a comparison of growing season NEE showed only small variability among land cover types (14%)(Euskirchen et al., 2017). In this study, the cold season fluxes resulted in differences in modeled NEE among land cover types (Figure 7a) but contributed little to the interannual variability of modeled NEE (Figure 7b). Modeled non-growing season CH$_4$ flux measurements were also important for variability among land cover types in this study (Figure 7c), but not as important for interannual variability (Figure 7d).

In this study, the modeled decadal emissions overlapped with the few annual measurements of C exchange at this site. Our results showed a modeled regional net CO$_2$ uptake of $-75 \pm 12$ g C m$^{-2}$ y$^{-1}$ (annual CO$_2$ flux: -39 to -100 g C m$^{-2}$ y$^{-1}$), in general agreement with previous site measurements of -41 to -71 g C m$^{-2}$ y$^{-1}$ from 2007-08 (Marushchak et al., 2013). The modeled regionally-weighted CH$_4$ fluxes in this study ranged from 2.1 to 4.8 g C m$^{-2}$ y$^{-1}$, in general agreement with the previously reported 5.0 g C m$^{-2}$ y$^{-1}$ at this site (Marushchak et al., 2016).

Capturing the differences in land cover variability, particularly between uplands and wetlands, was key for accurate regional estimates of NEE within Seida. Despite a larger area of uplands (60%, including both forest and tundra) compared to...
wetlands in the Seida study region, uplands were responsible for only 33% of the areally-weighted net C uptake (Table 2; Figure 8). The majority of the C uptake as NEE occurred in the permafrost peat plateaus (25%) and the permafrost-free fens (43%). In Northern Fennoscandia, peat plateaus are significant sinks of atmospheric CO₂, sequestering 46 g C m⁻² y⁻¹ (Olefeldt et al., 2012). In low polygon tundra in Barrow, more productive vegetation was found in wetter tundra areas that developed in drained thaw lakes, resulting in a disproportionately large sink in a regional estimate of CO₂ exchange (Zulueta et al., 2011). However, CO₂ efflux from lakes at Barrow (16% of area) nearly offset the strong C uptake in the wet tundra vegetation types (VTLB, 51% of area), demonstrating that wetland and aquatic components of the landscape necessitate consideration in regional NEE (Sturtevant & Oechel, 2013).

The relative fraction of uplands and lowlands is also key for the regional CH₄ balance, both within Seida and across other tundra sites. The total modeled CH₄ emissions from the fens at Seida in this study (17 – 22 g C m⁻² y⁻¹) were large enough that fluxes were not offset by the small modeled net CH₄ uptake in the relatively well-drained soils that covered nearly 85% of the region (Figure 8b; Table 2). However, in lower resolution classification, the fraction of wetlands decreased as their patch size was frequently smaller than pixel size (Figure 8d, S1). The reduced areal coverage of wetlands resulted in a significant (20-60%) decrease in the regionally-weighed CH₄ flux at Seida (Figure 8b, 7d), demonstrating the importance of accurately representing the spatial extent of wetlands when calculating regional CH₄ fluxes. Similar results were shown in a previous study where wetland area increased due to permafrost thaw, rather than decreased like in this study; a small
increase in wetland area (~7%) resulted in a ~40% increase in the regional CH$_4$ flux (Christensen et al., 2004).

In a broader context, the regional landscape composition of uplands versus lakes and wetlands also has significant effects on regional CH$_4$ emissions. Across tundra sites, higher regional CH$_4$ emissions were found from regions with more lakes and wetlands than Seida, while lower regional CH$_4$ fluxes were found in regions with a smaller areal extent of wetlands and lakes, as well as in colder regions. A region with a greater abundance of lakes and wetlands (30% area vs. 15.5% in this study), the Yukon-Kuskokwim Delta in Alaska, had 75% higher regional fluxes than the modeled CH$_4$ fluxes in this study (Bartlett et al., 1992). On the other hand, the areally-weighted CH$_4$ flux in tundra of the Kuparuk River Basin, North Slope, Alaska were 80% lower, due to a 5x lower mean wetland CH$_4$ flux and smaller wetland extent (6% of the area) (Reeburgh et al., 1998). Colder temperatures may have resulted in the 32% smaller areally-weighted CH$_4$ flux from Barrow tundra despite significant wetland and lake area (~67%) (Sturtevant & Oechel, 2013). Both the comparison among sites with regional CO$_2$ and CH$_4$ fluxes and the spatial analysis using lower resolution imaging (Fig. 7) show similar results. This shows that differences in the relative fraction of wetland area versus upland area results in significant differences in regional C fluxes, including both CO$_2$ and CH$_4$, at this site and among Arctic tundra ecosystems.

Using landscape heterogeneity to improve regional carbon flux estimates

In this study, regional estimates of C exchange were based on scaling measurements of individual land cover types based on vegetation composition using classifications at high spatial-resolutions. A previous study in this region showed that
a lower spatial resolution had little effect on total C pools, but had large effects on individual classes, most notably fen peatlands (Hugelius, 2012). Unlike total C pools, we showed here that the full C balance is highly sensitive to the representation of fen peatlands among spatial resolution in scaling (Figure 8). Lowering the spatial resolution of the regional C balance scaling introduced coefficients of variation exceeding 100% and 200% for CO₂ and CH₄, respectively. While the individual land cover types at this site reflect vegetation differences related to topography, including drainage, mean water table position, and pH, this scaling approach may underestimate the effects of smaller variations due to microsite conditions or short-term climatic variability. For example, small-scale phenological differences as well as broader spatial differences can affect regional estimates of NEE (Vourlitis et al., 2003). In this study, similar C fluxes were modeled and measured at the independent calibration and validation sites, which indicates much of the small-scale variability was captured in our approach (Table A3, Figures A6-A8). Ideally, future modeling efforts could incorporate more microsite variability, include factors such as lateral energy, water, and carbon transfer across the landscape.

Our findings support previous recommendations of land cover classifications using 30 m or finer resolutions (Bartsch et al., 2016, Davidson et al., 2017, Virtanen & Ek, 2014). Modeled net ecosystem exchange and CH₄ flux changed only slightly (≤5%) at 20 m pixel size compared to the 2.4 m resolution used as a default. This 20 m pixel size is approximately similar to spatial resolution of Landsat (30 m) and Sentinel-2 satellite imagery (10m, 4 spectral bands; 20m, extra 6 spectral bands). However, CH₄ emissions decreased substantially by 20-40% even at an intermediate lower resolution such as 160 m (Figure 8), which is still finer than the resolution provided by Modis and AVHRR satellite imagery (pixel size ≥ 250 m). CO₂ emissions
were not affected as strongly (Figure 8). Using lower resolution imagery may severely underestimate Arctic CH₄ emissions as many wetland areas may not be identified.

Our results have significant implications for the treatment of landscape scale heterogeneity in process-based models that run at regional to global spatial domains: using simple land cover classifications based on single (one) category and/or coarse resolution imagery could lead to significant biases in regional C emissions (Figure 8). Remedies include the implementation of different land cover types, especially wetlands and lakes, to represent the hotspots of C cycling in the landscape, which can be done using sub-grid cell tiling methods. Alternatively, scaling based on maps of continuous variables, like leaf area index (Oechel et al., 2000, Vourlitis et al., 2003), or sub-pixel classification methods could be used, in which one pixel would include some proportions of several land cover types (e.g. Muster et al., 2013).

Our results clearly showed that net ecosystem CO₂ exchange and CH₄ fluxes differed significantly between wetlands and uplands and both were important components of the regional C balance. As such, we found that the relative fraction of uplands and wetlands within a region was key to determining the net ecosystem C exchange of both within this site, Seida, and across other regions of Arctic tundra. The variability in modeled C exchange among land cover types was much greater than the interannual variability (Figure 7). This study highlights that capturing the variability due to the full variety of land cover types is perhaps more important than conducting extended measurement campaigns over longer periods. Accurately characterizing the landscape composition, particularly between uplands and
wetlands and lakes, is key to determining the net ecosystem C exchange in the changing Arctic.

Acknowledgments

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References


Table 1. Major land cover types, spatial coverage, and mean modelled CO$_2$ and CH$_4$ fluxes for 2006-2015. Values in parentheses indicate the standard error (SE) of the land cover type over the 10 years (n=10). CO$_2$ fluxes: gross primary productivity (GPP), ecosystem respiration (ER = R$_h$ + R$_a$), net ecosystem CO$_2$ exchange (NEE), and CH$_4$ flux. Plot scale flux measurements (F$_{Plot}$) represent the measured flux within each land cover type, while spatially-weighted fluxes (F$_{Regional}$) represent the contribution of each LCT to the regional flux (F$_{Regional, LCT}$ = F$_{Plot, LCT}$ * Area$_{LCT}$ / Area$_{tot}$). Positive fluxes indicate release to the atmosphere. Total area of the study region was 98.6 km$^2$.

| Major land cover type | Land cover sub-types (LCT) | Area | GPP (g C m$^{-2}$ y$^{-1}$) | ER (g C m$^{-2}$ y$^{-1}$) | NEE (g C m$^{-2}$ y$^{-1}$) | CH$_4$ (g C m$^{-2}$ y$^{-1}$) | F$_{Plot}$ | SE | F$_{Plot}$ | SE | F$_{Plot}$ | SE | F$_{Plot}$ | SE | F$_{Plot}$ | SE | F$_{Plot}$ | SE | F$_{Plot}$ | SE | F$_{Plot}$ | SE | F$_{Plot}$ | SE |
|-----------------------|---------------------------|------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------|-----|-----------|-----|-----------|-----|-----------|-----|-----------|-----|-----------|-----|-----------|-----|-----------|-----|-----------|-----|-----------|-----|-----------|-----|-----------|-----|-----------|-----|-----------|-----|-----------|-----|-----------|-----|-----------|-----|-----------|-----|--
| Tundra heath          | Moist shrub               | 20.2 | 270 (17)                    | 220 (5)                     | -60 (13)                    | -12 (2.6)                   | -0.1      | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) |
|                       | Dry shrub                 | 15.4 | 170 (11)                    | 160 (6)                     | -6.4 (5.2)                  | -1.0 (0.8)                  | 0.1       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) |
|                       | Dwarf birch               | 15.2 | 280 (16)                    | 200 (5)                     | -74 (11)                    | -11 (1.7)                   | -0.1      | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) |
|                       | Dry lichen                | 7.1  | 130 (7)                     | 130 (4)                     | 2.7 (4.1)                   | 0.2 (0.3)                   | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) |
| Peat plateau          | Dry tundra bog            | 8.3  | 260 (11)                    | 180 (4)                     | -78 (7.9)                   | -6.6 (0.7)                  | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) |
|                       | Moist tundra bog          | 15.0 | 340 (15)                    | 250 (5)                     | -83 (11)                    | -13 (1.7)                   | -0.2      | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) |
| Fen                   | Willow fen                | 8.7  | 840 (41)                    | 540 (66)                    | -300 (30)                   | -26 (2.6)                   | 22.3      | (2.1) | 2.0       | (0.2) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) |
|                       | Carex fen                 | 5.1  | 480 (19)                    | 380 (49)                    | -99 (33)                    | -5.1 (1.7)                  | 21.0      | (1.9) | 1.1       | (0.1) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) |
|                       | Eriophorum fen            | 0.6  | 110 (4)                     | 82 (12)                     | -29 (9.6)                   | -0.2 (0.1)                  | 17.2      | (1.5) | 0.1       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) |
| Other                 | Forest                    | 2.3  | 250 (12)                    | 220 (9)                     | -25 (5.5)                   | -0.6 (0.1)                  | 0.3       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) |
|                       | Lakes                     | 1.1  | 10 (0.4)                    | 0.1 (0.0)                   | 0.3 (0.0)                   | 0.0 (0.0)                   | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) | 0.0       | (0.0) |
**Table 2.** Major land cover types, spatial coverage, and mean (SE) modelled regional fluxes ($F_{\text{regional}}$), including NEE, and CH$_4$ flux, for 2006-2015. Positive fluxes indicate release to the atmosphere. Residual landscape area includes bare peat circles, human impacted tundra, sand and represents 1.1% of the regional area; fluxes from this region were assumed to be negligible.

<table>
<thead>
<tr>
<th>Major land cover type</th>
<th>Area (%)</th>
<th>NEE (g C m$^{-2}$ y$^{-1}$)</th>
<th>CH$_4$ (g C m$^{-2}$ y$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tundra heath</td>
<td>57.9</td>
<td>-24.2 (3.2)</td>
<td>0.0 (0.0)</td>
</tr>
<tr>
<td>Peat plateau</td>
<td>23.3</td>
<td>-19.1 (1.8)</td>
<td>0.0 (0.0)</td>
</tr>
<tr>
<td>Fen</td>
<td>14.4</td>
<td>-31.6 (3.1)</td>
<td>3.2 (1.4)</td>
</tr>
<tr>
<td>Forest</td>
<td>2.3</td>
<td>-0.6 (0.1)</td>
<td>0.0 (0.0)</td>
</tr>
<tr>
<td>Lake</td>
<td>1.1</td>
<td>0.1 (0.0)</td>
<td>0.0 (0.0)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100</strong></td>
<td><strong>-75 (8)</strong></td>
<td><strong>3.1 (0.2)</strong></td>
</tr>
</tbody>
</table>

* Using median upland forest daily flux of -0.07 g CH$_4$ m$^{-2}$ d$^{-1}$ from Olefeldt *et al.* (2013) and assuming 120-day emission season at Seida.
**Figure 1.** Map of the Seida study region. Top left: Location of Seida study region (red circle). Right: land cover classification and the locations of the flux measurement sites within the Seida study region. Squares indicate sites used in the NEST-DNDC model calibration (red; 2007-2008), NEST-DNDC model validation (purple; 2012-2013), and ALBM model validation (aqua).
Figure 2. Land cover classification for Seida derived from the same original image using different resolutions: a) original Quickbird 2.4 m resolution image; b) 20 m resolution; c) 160 m resolution; d) 1280 m resolution.
Figure 3. Climate driver data for Seida for 1 Jan. 2006 to 31 Dec. 2015. a) mean daily air temperature (circles) and mean monthly air temperature (line); b) total monthly precipitation (circles) and cumulative annual precipitation (line); c) daily incoming solar radiation (circles) and mean monthly incoming solar radiation (line).
Figure 4. Modeled and measured CO₂ and CH₄ flux data for calibration period of 2007-08 (left panels) and validation period of 2012-13 (right panels) for the tundra heath land cover types at Seida. Model results are shown by blue solid line, mean daily interpolated fluxes (Interp.) are shown by gray solid line, and instantaneous chamber measurements (Inst.) are shown by black crosses.
Figure 5. Modeled and measured CO$_2$ and CH$_4$ flux data for calibration period of 2007-08 (left panels) and validation period of 2012-13 (right panels) in the Seida peat plateaus. Model results are shown by blue solid line, mean daily interpolated fluxes (Interp.) are shown by gray solid line, and instantaneous chamber measurements (Inst.) are shown by black crosses.
Figure 6. Modeled and measured CO$_2$ and CH$_4$ flux data for calibration period of 2007-08 (left panels) and validation period of 2012-13 (right panels) for the permafrost-free fen land cover types at Seida. Fen II was not measured in 2012. Model results are shown by blue solid line, mean daily interpolated fluxes (Interp.) are shown by gray solid line, and instantaneous chamber measurements (Inst.) are shown by black crosses.
Figure 7. Modeled variability among land cover classes (left) and years (right) of cumulative NEE and CH$_4$ flux for 2006-2015. (a) Variability in the cumulative NEE among the land cover types using the decadal mean daily flux ($F_{\text{plot}}$); (b) Interannual variability in the cumulative NEE over the year for the region using 2.4 m resolution land cover classification ($F_{\text{regional}}$); (c) Variability in the cumulative CH$_4$ flux among the land cover types using the decadal mean daily CH$_4$ flux ($F_{\text{plot}}$); (d) Interannual variability in the cumulative CH$_4$ flux over the year for the region using 2.4 m resolution land cover classification ($F_{\text{regional}}$).
Figure 8. Modeled mean areal CO$_2$ and CH$_4$ fluxes ($F_{\text{regional}}$) during 2006-2015 for major land cover types using different resolutions for land cover classification, ranging from 2.4 m to 1280 m. Decadal mean modeled a) NEE, b) CH$_4$ emissions, c) net C exchange (CO$_2$ + CH$_4$), and d) areal coverage (%) for the major land cover types in the Seida region for present day at different resolutions (Figure 2).
Tundra landscape heterogeneity, not inter-annual variability, controls the decadal regional carbon balance in the Western Russian Arctic

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Supplemental Materials

Supplemental Figures (1)

Appendix A: Modeling supplement. Extended modeling materials & methods, results and evaluation.
Figure S1. Pictures showing the land cover types (LCTs) in the Seida study region. a) forest stand, b) moist shrub tundra heath, c) dry shrub tundra heath, d) dwarf birch tundra heath, e) dry lichen tundra heath, f) moist permafrost peat plateau bog, g) dry permafrost peat plateau bog, h) willow fen, i) Carex fen, j) Eriophorum fen, k) thermokarst lake and l) bare peat circles (not considered in this study).
Appendix A. Ecosystem Modeling
Extended Materials & Methods

Modeling of upland tundra, permafrost peat plateaus, and permafrost-free fens

We used the NEST-DNDC to model water table level, active layer thickness, and C fluxes for upland tundra heath, peat plateaus, and permafrost-free fens. NEST-DNDC is a process-based model that integrates an existing biogeochemical model DeNitrification-DeComposition (DNDC) (Li et al., 2000) with a permafrost model Northern Ecosystem Soil Temperature (NEST) (Zhang et al., 2003) and is capable of simulating an ecosystem domain consisting of a number of plant communities (Zhang et al., 2012b). In this study, we used a 1.8 m soil column to capture soil biogeochemical processes plus additional layers for the simulation of ground thermal dynamics to a depth of 37.8 m, including top soils, deep deposits and bedrock. To initialize the soil climatic conditions, we ran the soil thermal and hydrological sub-models of NEST–DNDC iteratively using a historic climate dataset until simulated annual mean soil temperature stabilized. We proceeded with the simulation from the historic period (1900-2005) and the study period (2006-2015) using the whole span of the model’s capacity including soil climate, hydrology and biogeochemistry.

We used field observations to parameterize the NEST-DNDC model whenever possible. The vegetation parameters (plant functional type, biomass, and leaf area index, LAI) were prescribed based on field observations for each land cover type using observations from 2007-08 (Table A1). Initial SOC stocks were derived from previously published observations and differed among land cover types (Hugelius et al., 2012, Hugelius et al., 2011). Snow drifting factor (fraction of snowfall blown away from the site, Table A2) was calibrated with observed near-surface (2 cm depth) soil temperature in winters of 2007-08 (Figure A1). The hydrological parameters for
lateral flows for each land cover type (Table A2) were calibrated by comparing with
the observed water table dynamics in 2007-08 (Repo et al., 2009) (Figure A2).

The model climate drivers included mean daily air temperature, daily air
temperature amplitude, precipitation, solar radiation, cloudiness, wind speed, vapor
pressure, and atmospheric pressure. The climate drivers were used for the energy
balance sub-model, which determined soil temperatures that controlled the
biogeochemical process rates in the biogeochemistry sub-model. A more detailed
description of the energy balance-biogeochemical model coupling can be found in
Zhang et al. (2012b). We used a synthetic climate driver dataset for the period of
2006-2015 (Figure 3). The synthetic dataset was derived from a combination of site
measurements (2006-2011) and observations from nearby climate station at Vorkuta
(67° 30′ N, 64° 2′ E) and Salekhard (66.5294° N, 66.5294° E; NOAA National
Centers for Environmental Information, https://www.ncdc.noaa.gov/, 2006, 2009-
2015). Vorkuta observations were bias-corrected using linear regressions developed
between concurrent observations at Seida, Vorkuta, and Salekhard in 2006-2011.

To initialize the permafrost conditions in NEST-DNDC model, we extended the
climate data back to 1900. We first calculated monthly climate anomalies based on
observations at climate stations relatively close to the study site (Ust-Tzilma
(65.4331° N, 52.2667° E), Salekhard (66.5294° N, 66.5294° E), and Vorkuta
(67.483° N, 64.016° E). Then we calculated the monthly values using these
anomalies and the averages during the reference period (1980-1999). Since climate
warming occurred mainly after the 1950s in this region, we calculated monthly
averages from 1900 to 1949 to spin-up the permafrost module in the NEST-DNDC.
After spinning-up, we ran the model from 1900 to 2015. The monthly averaged
climate data were down-scaled to daily for the spinup period using the daily observations during 2006-2011 as a template (Zhang et al., 2012a).

Forest ecosystem modeling

For this study, LPJ-GUESS (Smith et al., 2001) was modified to model upland, high-latitude forest ecosystems by incorporating recent developments to LPJ-DGVM that include improved determination of soil temperatures and soil freezing processes using a four-layer soil column and a snowpack (Wania et al., 2009, Wania et al., 2010, Wolf et al., 2008). The soil thermal model included twenty 10-cm soil layers that were underlain by 10 thicker layers representing the underlying thermally active soil column (48 m thickness), for a total depth of 50 m. For the upland soils considered here, soil C decomposition is treated as in the standard LPJ-GUESS model set-up (Smith et al., 2001) using parameters from Sitch et al. (2003).

The Arctic-enabled LPJ-GUESS has an expanded set of plant function types (PFTs) for use in high latitude upland regions. The full set of PFT parameters and demonstrations of model skill in matching high-latitude vegetation distributions, treeline, and productivity trends were published previously (Miller & Smith, 2012, Zhang et al., 2013). The only differences in PFTs in this study were slight adjustments to the summer warmth requirements - determined by fixed, minimum growing degree-day requirements (GDD5, growing-degree day above 5º C, see Smith et al. (2001)) to better match the treeline in the area west of the Ural Mountains.

The Arctic-enabled LPJ-GUESS was run for the region west of the Urals from 1901-2100 using the approach that was previously used by Hugelius et al. (2011) for the same region. The driving climatic data for LPJ-GUESS was from the HIRHAM5 regional climate model (RCM) with a 4-km horizontal resolution (Christensen et al.,
1996, Christensen et al., 2001, Stendel et al., 2010). The RCM, in turn, was driven by the ECHAM5/MPI-OM general circulation model following the IPCC SRES scenario A1B. The resulting NEE, ER, and GPP presented here are calculated from LPJ-GUESS output from the 25 km grid cell containing the Seida study region. Modern vegetation simulated by LPJ-GUESS consists of a mixture of tall and low shrub PFTs, and herbaceous PFTs, with an area-averaged biomass of less than 0.4 kg C m$^{-2}$, which is approximately same as present mean landscape level value in the region. A further description of the model development, validation, and calibration can be found in Miller and Smith (2012) and Zhang et al. (2013).

**Extended Results**

*Interannual climatic variability*

There were some variabilities in climate drivers among the study years (Figure 3). The warmest years were 2006 and 2014, when MAATs were -2.8 °C and -2.9 °C, respectively. The coldest year was 2010, when MAAT was -6.6 °C. Summer temperatures (JJA) were warmest in 2015 (12.8 °C) and coldest in 2010 (8.4 °C). The coldest winter (DJF) was in 2008-09 (-23.0 °C) and warmest was in 2007-08 (-13.2 °C). Total annual precipitation ranged from 420 mm in 2011 to 570 mm in 2006. The driest summer was in 2009 (90 mm) and wettest occurred in 2012 (310 mm).

*Model evaluation: Soil temperatures, snow depth, soil moisture, and water table levels*

Observed surface soil temperatures (2 cm depth) were simulated well for vegetation types in 2007-08 (Figure A1) in NEST-DNDC, in part because these data were used
for the development of the generalized snow cover parameterization (Table A2). Generally, growing season soil temperatures at 25 cm and 40 cm depths were cooler than the observations (Figure A1). This is also reflected in the seasonal thaw depth. The modeled seasonal thaw was shallower than in observations, particularly for tundra heath and peat plateau vegetation types (Figure A3). NEST-DNDC simulated permafrost in the fen vegetation types in deeper soils (>150 cm), while permafrost was not observed in fens in the field, which is likely related to local hydrologic conditions that affect lateral and vertical heat fluxes (Kurylyk et al., 2016).

Model snow depths were generally within the range of observations (Figure A4). Across the vegetation types, observations of snow depth were quite variable depending on the topographic position, ranging from 0 cm to 95 cm in the elevated tundra heath and peat plateaus, and from 46 cm to 145 cm in low-lying fens. In tundra heath vegetation types, the modeled snow depth was deeper than some observations, but fell within the observed range for land cover sub-types with greater snow cover (Figure A4). In peat plateau and fen vegetation types, modeled snow depths matched observations (Figure A4).

Modeled and observed soil moisture were in good agreement across the land cover types (Figure A5), as were the modeled and observed water table positions (Figure A2). In 2008, the modeled water table position in fen vegetation types was consistently 10-15 cm higher than the observed values (Figure A2).

Model evaluation: Carbon fluxes

The instantaneous observations of CO$_2$ tended to be greater in magnitude than the interpolated daily fluxes due to warmer conditions and higher PAR from sampling during the daytime, which are accounted for in calculating the interpolated values.
NEST-DNDC simulated daily values, which should be more directly comparable to the interpolated values. We did not interpolate CH$_4$ fluxes because we assumed that diurnal variability was low, and therefore, instantaneous measurements and modelled daily fluxes were comparable.

In upland tundra heath vegetation types, NEST-DNDC simulated the magnitude and daily variation of CO$_2$ fluxes well during the calibration period of 2007-2008 (Figure 3a-c) and verification period (Figure 3e-g). The agreement between observations and models for tundra during the calibration period was good, with $r^2$ ranging from 0.47 to 0.92 (Table A3, Figure A6). The model predictions during the validation period (2012/13) showed relatively good agreement with the independent verification data, with $r^2$ ranging from 0.29 to 0.62 (Table A3, Figure A6). Overall, the model significantly overestimated cumulative net C uptake by 23 g C m$^{-2}$ compared with observations during the period of overlapping measurements ($t=3.56$, d.f.=3, $P=0.04$; Table A4). In tundra heath, both modelled and measured CH$_4$ fluxes were generally quite small ($< 5$ mg C m$^{-2}$ d$^{-1}$; Figure 3d,h). However, there was no relationship between measured and modelled CH$_4$ fluxes ($P>0.05$, $r^2=0.0$), indicating that the model was unable to capture the variability or timing of the measured fluxes although it did capture the general magnitude of CH$_4$ fluxes during the period of overlap (Figure 3d,h; Table A4). This might be explained by the relatively high CH$_4$ fluxes simulated by the model during fall freeze-up and spring thaw that were associated with the release of CH$_4$ that had built up in the soil profile as the model simulates the process of ebullition CH$_4$ fluxes (Figure 3d,h).

Model output at the peat plateau vegetation types matched well with the daily interpolated flux chamber measurements during the calibration period of 2007-2008 for NEE, ER, and GPP (Figure 4a-c) and during the validation period of 2012-13.
The agreement between observations and models for tundra during the calibration period was good, with \( r^2 \) ranging from 0.69 to 0.91 (Table A3, Figure A7). The model predictions during the validation period (2012/13) showed relatively good agreement with the independent verification data for NEE and GPP, with \( r^2 \) values of 0.43 and 0.63, respectively (Table A3, Figure A7). During the validation period of 2012-2013, the model did not capture the high rates of ER during the spring and early summer (Figure 4e, f), resulting relatively poor agreement between modelled and observed ER (\( r^2 = 0.18 \); Figure A7). Overall, the model significantly overestimated cumulative net C uptake in peat plateaus by 27 g C m\(^{-2}\) compared with observations during the period of overlapping measurements (\( t = 3.87, \text{d.f.} = 3, P = 0.03; \text{Table A4} \)). The peat plateaus were net sinks of CH\(_4\) in the model annually (-0.1 g C m\(^{-2}\) y\(^{-1}\); Figure 4d), whereas interpolated measurements showed fluxes of 0.2 ± 0.2 g C m\(^{-2}\) y\(^{-1}\) (Marushchak et al., 2016). In 2012-13, the model simulated both CH\(_4\) oxidation and emission, whereas the measurements showed a flux of 0 g C m\(^{-2}\) y\(^{-1}\) (Figure 4h). Consequently, there was no relationship between measured and modelled fluxes in the peat plateau sites (\( P > 0.05, r^2 = 0.0 \)), indicating that the model was unable to capture the variability or timing of the measured fluxes. This is evident in the model simulation of relatively high CH\(_4\) fluxes at the beginning and end of the growing season corresponding to ebullition events, which were not observed in the data (Figure 4d,h). Again, the model captured the general magnitude of fluxes during the overlapping observation periods; cumulative fluxes were 0 g C m\(^{-2}\) y\(^{-1}\) (Table A4).

Model output at the fen vegetation types site matched well with the daily interpolated flux chamber measurements during the calibration period of 2007-2008 for NEE, ER, and GPP (Figure 5a-c) and during the validation period of 2012-13 (Figure 5e-g). The agreement between observations and models for fens during the
calibration period was good, with $r^2$ ranging from 0.6 to 0.91 (Table A3, Figure A8). The model predictions during the validation period (2012/13) showed relatively good agreement with the independent verification data for ER and GPP, with $r^2$ values of 0.45 and 0.66, respectively (Table A3, Figure A8). However, the daily NEE was not so well captured during the validation period (Table A3; Figure A8). Measurements of NEE during the validation period values were sparse (Figure 5g) and cumulative values agreed fairly well (Table A4). Overall, there were no significant differences between modelled and observed cumulative NEE during the overlapping period of measurement ($t=1.31$, d.f.=2, $P=0.32$). Differences in cumulative CH$_4$ flux between model and observations during the period of overlapping observations ranged from 0.3 to 1.8 g C m$^{-2}$ and were not significantly different than 0 ($t=1.6$, d.f.=2, $P=0.25$).

We conducted a sensitivity analysis to determine the effects of overestimating NEE in tundra and peat plateau land cover types (Table A4). We re-calculated $F_{\text{regional}}$ using bias-corrected NEE values to assess whether this bias significantly changed the trends that we report. To bias-corrected NEE for tundra and peat plateaus, we subtracted the areally-weighted mean difference between model and measurements for each LCT (Table A4) from NEE-regional (Table 2). The results show $F_{\text{regional}}$ decreased for bias-corrected tundra and peat plateau sites but net regional NEE still remained a sink, as does net regional C flux (Figure A9). Regional NEE decreases from -75 g C m$^{-2}$ y$^{-1}$ to -55 g C m$^{-2}$ y$^{-1}$ [net uptake], and from -75 g C m$^{-2}$ y$^{-1}$ to -52 g C m$^{-2}$ y$^{-1}$. This approach assumes that all model bias occurred during the period of overlapping measurements as it is difficult to evaluate model performance outside of this period.
Table A1. Vegetation characteristics, water table depth (WT, where positive values are below the surface), and active layer thickness (ALT) for each individual land cover types including shrub, sedge, and moss above-ground biomass and LAI (leaf area index). LAI was measured in the field during 2007-08.

<table>
<thead>
<tr>
<th>Major land cover type</th>
<th>Land cover subtypes (LCT)</th>
<th>Above-ground biomass (g C m⁻²)</th>
<th>LAI</th>
<th>WTD (cm)</th>
<th>ALT (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shrub</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>Moor shrub</td>
<td>201</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dry shrub</td>
<td>59</td>
<td>0.3</td>
<td>30</td>
<td>&gt;120</td>
</tr>
<tr>
<td></td>
<td>Dwarf birch</td>
<td>490</td>
<td>0.5</td>
<td>30</td>
<td>&gt;120</td>
</tr>
<tr>
<td></td>
<td>Dry lichen</td>
<td>11</td>
<td>0.1</td>
<td>30</td>
<td>&gt;120</td>
</tr>
<tr>
<td><strong>Sedge</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sedge</td>
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<tr>
<td></td>
<td>Sedge</td>
<td>111</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>Sedge</td>
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<td></td>
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<tr>
<td></td>
<td>Sedge</td>
<td>47</td>
<td></td>
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<td></td>
</tr>
<tr>
<td><strong>Moss</strong></td>
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<td></td>
<td></td>
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<td></td>
</tr>
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<td></td>
<td>Moss</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>Moss</td>
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<td></td>
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<tr>
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<td>Moss</td>
<td>47</td>
<td></td>
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<table>
<thead>
<tr>
<th>Major land cover type</th>
<th>Land cover subtypes (LCT)</th>
<th>Above-ground biomass (g C m⁻²)</th>
<th>LAI</th>
<th>WTD (cm)</th>
<th>ALT (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peat plateau</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dry tundra bog</td>
<td>66</td>
<td>0.5</td>
<td>37</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>Moist tundra bog</td>
<td>66</td>
<td>0.9</td>
<td>32</td>
<td>50</td>
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<table>
<thead>
<tr>
<th>Major land cover type</th>
<th>Land cover subtypes (LCT)</th>
<th>Above-ground biomass (g C m⁻²)</th>
<th>LAI</th>
<th>WTD (cm)</th>
<th>ALT (cm)</th>
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<td></td>
<td>Willow fen</td>
<td>123</td>
<td>3.1</td>
<td>16</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td>Carex fen</td>
<td>0</td>
<td>2.3</td>
<td>0</td>
<td>&gt;120</td>
</tr>
<tr>
<td></td>
<td>Eriophorum fen</td>
<td>0</td>
<td>0.4</td>
<td>8</td>
<td>&gt;120</td>
</tr>
</tbody>
</table>
Table A2. Lateral water flow parameters calibrated for each land cover type.

<table>
<thead>
<tr>
<th>Major land cover type</th>
<th>Land cover sub-types (LCT)</th>
<th>( R_{in} )</th>
<th>( D_{out1} ) (m)</th>
<th>( R_{out1} ) (d(^{-1}))</th>
<th>( D_{out2} ) (m)</th>
<th>( R_{out2} ) (d(^{-1}))</th>
<th>( F_{snow} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tundra heath</td>
<td>Moist shrub</td>
<td>0</td>
<td>-0.2</td>
<td>0.5</td>
<td>-0.3</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Dry shrub</td>
<td>0</td>
<td>-0.2</td>
<td>0.5</td>
<td>-0.31</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Dwarf birch</td>
<td>0</td>
<td>-0.2</td>
<td>0.5</td>
<td>-0.31</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Dry lichen</td>
<td>0</td>
<td>-0.15</td>
<td>0.5</td>
<td>-0.4</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Peat plateau</td>
<td>Dry tundra bog</td>
<td>0</td>
<td>-0.15</td>
<td>0.5</td>
<td>-0.2</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Moist tundra bog</td>
<td>0</td>
<td>-0.15</td>
<td>0.5</td>
<td>-0.35</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Fen</td>
<td>Willow</td>
<td>0</td>
<td>0.1</td>
<td>0.2</td>
<td>0</td>
<td>0.01</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Carex</td>
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<td>0.1</td>
<td>0</td>
<td>0.01</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Eriophorum</td>
<td>0.3</td>
<td>0.1</td>
<td>0.2</td>
<td>0</td>
<td>0.01</td>
<td>0</td>
</tr>
</tbody>
</table>

\( R_{in} \) is the rate of surface inflow defined as the fraction of rainfall (or water from snow melting) added to the site from its surroundings. \( D_{out1} \) is the lowest water table (positive for above the land surface, and negative for below the land surface) above which surface outflow occurring. \( D_{out2} \) is the lowest water table above which ground outflow occurring. \( R_{out1} \) is surface outflow rate, defined as the fraction of water table above \( D_{out1} \) will be reduced in a day. \( R_{out2} \) is ground outflow rate, defined as the fraction of water table above \( D_{out2} \) will be reduced in a day (Zhang et al., 2002).

There is no ground inflow for all the sites. They were calibrated by comparing the modeled and measured water table. \( F_{snow} \) is a snow drifting factor, defined as the fraction of daily snowfall blown away from the site. It was calibrated by comparing the modeled and measured near-surface soil temperature in winter.
Table A3. Regression parameters for measured vs. modeled flux data using linear regressions. The calibration period was 2007/8 at Seida I. The validation period was in 2012/13 at nearby Seida II. Parameterization from the calibration period was used for the region; thus results from the validation period in a nearby site Seida II offer an independent validation of the model performance. The relationship between modeled and measured values was significant for all variables ($P < 0.0001$, linear regression) except for CH$_4$ emissions in tundra and peat plateau, which indicates that CH$_4$ fluxes would be better predicted by the mean of the observed data than by the model. Cumulative observed CH$_4$ flux and modeled CH$_4$ flux for tundra and peat plateau land cover types were 0 g C m$^-2$ y$^-1$ (Table A4).

<table>
<thead>
<tr>
<th></th>
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<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tundra</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>slope</td>
<td>0.75</td>
<td>0.40</td>
<td>0.84</td>
<td>0.20</td>
<td>1</td>
<td>0.53</td>
<td>0.07</td>
<td>0.04</td>
</tr>
<tr>
<td>intercept</td>
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<td>-0.52</td>
<td>0.04</td>
<td>0.78</td>
<td>-0.04</td>
<td>-0.49</td>
<td>-0.71</td>
<td>-0.96</td>
</tr>
<tr>
<td>$r^2$</td>
<td>0.47</td>
<td>0.33</td>
<td>0.89</td>
<td>0.29</td>
<td>0.92</td>
<td>0.62</td>
<td>0 &amp; 0</td>
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</tr>
<tr>
<td><strong>Peat plateau</strong></td>
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<td></td>
<td></td>
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<tr>
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<td>0.99</td>
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<td>0.02</td>
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<td>1.02</td>
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<td>-1.32</td>
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<td>$r^2$</td>
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<td>0.43</td>
<td>0.8</td>
<td>0.18</td>
<td>0.91</td>
<td>0.63</td>
<td>0 &amp; 0</td>
<td></td>
</tr>
<tr>
<td><strong>Fen</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
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<tr>
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<td>-0.72</td>
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<td>-0.45</td>
<td>85.1</td>
<td>116</td>
</tr>
<tr>
<td>$r^2$</td>
<td>0.6</td>
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<td>0.77</td>
<td>0.45</td>
<td>0.91</td>
<td>0.66</td>
<td>0.45</td>
<td>0.20</td>
</tr>
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</table>
Table A4. Cumulative measured (interpolated) and modeled NEE and CH$_4$ across major land cover types during periods with both measurements and models shown in Figures 3-5.

<table>
<thead>
<tr>
<th>Year</th>
<th>NEE (g C m$^{-2}$)</th>
<th>CH$_4$ (g C m$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tundra</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured</td>
<td>15.5</td>
<td>-22.1</td>
</tr>
<tr>
<td>Modeled</td>
<td>-23.1</td>
<td>-37.4</td>
</tr>
<tr>
<td>Difference</td>
<td>38.6</td>
<td>15.3</td>
</tr>
<tr>
<td><strong>Peat plateau</strong></td>
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<td></td>
</tr>
<tr>
<td>Measured</td>
<td>-49</td>
<td>-57.9</td>
</tr>
<tr>
<td>Modeled</td>
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<td>-84.4</td>
</tr>
<tr>
<td>Difference</td>
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</tr>
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<td><strong>Fen</strong></td>
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<td></td>
</tr>
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<td>-230</td>
</tr>
<tr>
<td>Difference</td>
<td>35</td>
<td>96</td>
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Figure A1. Modeled and observed daily mean soil temperatures for all land cover types during 2007-08. Modeled (line) and measured (points) soil temperatures in a) tundra heath; b) peat plateaus; c) fens. Measurements were made at 2 cm (black), 25 cm depth (blue), and 40 cm depth (grey) for the summer of 2007 through summer 2008.
Figure A2. Modeled and observed water table for all land cover types during 2007-08. Mean daily modeled (black line) and measured (blue points) water table position in a) tundra heath; b) peat plateaus; c) fens. Note differing y-axis for fens (panel c). Measurements were made during the growing seasons of 2007 and 2008. A positive water table position indicates a water table above the soil surface (flooding).
Figure A3. Modeled and observed seasonal thaw depths for all land cover types during 2007-08. Modeled (black line) and measured (blue points) seasonal thaw depths in a) tundra heath; b) peat plateaus; c) fens. Measurements were made during the growing seasons of 2007 and 2008; multiple circles per date indicate replicate measurements for each land cover type.
Figure A4. Modeled and observed snow depths for all land cover types during 2007-08. Modeled (black line) and measured (blue points) snow depths in a) tundra heath; b) peat plateaus; c) fens. Measurements were made during the winter of 2008; multiple circles per date indicate replicate measurements for each land cover type.
**Figure A5.** Modeled and observed volumetric water content in tundra heath and peat plateau sites during 2007-08. Daily mean modeled (black line) and measured (blue points) volumetric water content in surface soils (3 cm) in a) tundra heath sites; b) peat plateau sites. Observations for tundra heath and peat plateau sites were made during the growing seasons of 2007 and 2008 for depths of 0-6 cm.
Figure A6. Measured vs. modeled C fluxes for tundra sites at Seida I (open circles, 2007-2008) and Seida II (filled circles, 2012-2013). Solid black line shows 1:1 line, regressions for Seida I and Seida II are shown with dashed black line and gray line, respectively. Regression coefficients are given in Table A3.
Figure A7. Measured vs. modeled C fluxes for Seida I (open circles, 2007-2008) and Seida II peat plateau sites (filled circles, 2012-2013). Solid black line shows 1:1 line, regressions for Seida I and Seida II are shown with dashed black line and gray line, respectively. Regression coefficients are given in Table A3.
Figure A8. Measured vs. modeled C fluxes for Seida I (open circles, 2007-2008) and Seida II fen sites (filled circles, 2013). Solid black line shows 1:1 line, regressions for Seida I and Seida II are shown with dashed black line and gray line, respectively. Regression coefficients are given in Table A3.
Figure A9. Sensitivity analysis of effects of model bias in NEE in tundra and peat plateau (PP) sites, as described in model C flux evaluation section.
References


