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The ABCflux database: Arctic-Boreal CO_2 flux observations and ancillary information aggregated to monthly time steps across terrestrial ecosystems

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Abstract

Past efforts to synthesize and quantify the magnitude and change in carbon dioxide (CO_2) fluxes in terrestrial ecosystems across the rapidly warming Arctic-Boreal Zone (ABZ) have provided valuable information, but were limited in their geographical and temporal coverage. Furthermore, these efforts have been based on data aggregated over varying time periods, often with only minimal site ancillary data, thus limiting their potential to be used in large-scale carbon budget assessments. To bridge these gaps, we developed a standardized monthly database of Arctic-Boreal CO_2 fluxes (ABCflux) that aggregates *in-situ* measurements of terrestrial net ecosystem CO_2 exchange and its derived partitioned component fluxes: gross primary productivity and ecosystem respiration. The data span from 1989 to 2020 with over 70 supporting variables that describe key site conditions (e.g., vegetation and disturbance type), micrometeorological and environmental measurements (e.g., air and soil temperatures) and flux measurement techniques. Here, we describe these variables, the spatial and temporal distribution of observations, the main strengths and limitations of the database, and the potential research opportunities it enables. In total, ABCflux includes 244 sites and 6309 monthly observations; 136 sites and 2217 monthly observations represent tundra, and 108 sites and 4092 observations represent the boreal biome. The database includes fluxes estimated with chamber (19 % of the monthly observations), snow diffusion (3 %) and eddy covariance (78 %) techniques. The largest number of observations were collected during the climatological summer (June-August; 32 %), and fewer observations were available for autumn (September-October; 25 %), winter (December-February; 18 %), and spring (March-May; 25 %). ABCflux can be used in a wide array of empirical, remote sensing and modeling studies to improve understanding of the regional and temporal variability in CO_2 fluxes, and to better estimate the terrestrial ABZ CO_2 budget. ABCflux is openly and freely available online (https://doi.org/10.3334/ORNLDAAC/1934, Virkkala et al., 2021a).

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1. Introduction

The Arctic-Boreal Zone (ABZ), comprising the northern tundra and boreal biomes, stores approximately half the global soil organic carbon pool (Hugelius et al., 2014; Tarnocai et al., 2009; Mishra et al., 2021). As indicated by this large carbon reservoir, the ABZ has acted as a carbon sink over the past millenia due to the cold climate and slow decomposition rates (Siewert et al., 2015; Hugelius et al., 2020; Gorham, 1991). However, these carbon stocks are increasingly vulnerable to climate change, which is occurring rapidly across the ABZ (Box et al., 2019). As a result, carbon is being lost from this reservoir to the atmosphere as carbon dioxide (CO_2) through increased ecosystem respiration (Reco) (Schuur et al., 2015; Parker et al., 2015; Voigt et al., 2017). The impact of increased CO_2 emissions on global warming depends on the extent to which respiratory losses are offset by gross primary productivity (GPP), the vegetation uptake of atmospheric CO_2 via photosynthesis (McGuire et al., 2016; Cahoon et al., 2016).

Carbon dioxide flux measurements provide a means to monitor the net CO_2 balance (i.e., net ecosystem exchange; NEE, a balance between GPP and Reco) across time and space (Baldocchi, 2008; Pavelka et al., 2018). There are three main techniques used to measure fluxes at the ecosystem level that represent fluxes from plants and soils: eddy covariance, automated and manual chambers, and snow diffusion methods (hereafter diffusion; for a comparison of the techniques, see Table 1 in McGuire et al. 2012). The eddy covariance technique estimates NEE at the ecosystem scale (ca. 0.01 to 1 km^2 footprint) at high temporal resolution (i.e., ½ hr) using nondestructive and automated measurements (Pastorello et al., 2020). Automated and manual chamber techniques measure NEE at fine spatial scales (< 1 m^2) and in small-statured ecosystems, common in the tundra, where the chambers can fit over the whole plant community (Järveoja et al., 2018; López-Blanco et al., 2017). The diffusion technique can be used to measure the transport of CO_2 within a snowpack (Björkman et al., 2010b). The eddy covariance technique has been used globally for over three decades, and chamber and diffusion techniques for even longer.

Historically, the number and distribution of ABZ flux sites has been rather limited compared to observations in temperate regions (Baldocchi et al., 2018). Due to these data gaps, quantifying

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the net annual CO_2 balance across the ABZ has posed a significant challenge (Natali et al., 2019; McGuire et al., 2016; Virkkala et al., 2021b). However, over the past decade, the availability of ABZ flux data has increased substantially. Many, but not all, of the ABZ eddy covariance sites are a part of broader networks, such as the global FLUXNET and regional AmeriFlux, Integrated Carbon Observation System (ICOS) and the European Fluxes Database Cluster (EuroFlux), where data are standardized and openly available (Paris et al., 2012; Novick et al., 2018; Pastorello et al., 2020). These networks primarily include flux and meteorological data, but do not often include other environmental descriptions such as soil carbon stocks, dominant plant species, or the disturbance history of a given site (but see, for example, BADM data in Ameriflux), which are important for understanding the controls on CO_2 fluxes. Moreover, even though some ABZ annual chamber measurements are included in the global soil respiration database (SRDB) (Jian et al., 2020), and in the continuous soil respiration database (COSORE) (Bond-Lamberty et al., 2020), standardized datasets providing ABZ CO_2 flux measurements from eddy covariance, chambers, and diffusion, along with comprehensive metadata, have been nonexistent. Such an effort would create potential for a more thorough understanding of ABZ CO_2 fluxes. Therefore, compiling these flux measurements and their supporting ancillary data into one database is clearly needed to support future modeling, remote sensing, and empirical data mining efforts.

Arctic-Boreal CO_2 fluxes have been previously synthesized in a handful of regional studies (Belshe et al., 2013; McGuire et al., 2012; Luyssaert et al., 2007; Baldocchi et al., 2018; Virkkala et al., 2018; Natali et al., 2019; Virkkala et al., 2021b) (Fig. 1 and Table 1). One of the main challenges in these previous efforts, in addition to the limited geographical coverage of ABZ sites and lack of environmental descriptions, has been the variability of the synthesized seasonal measurement periods. Most of these efforts have allowed the seasonal definitions and measurement periods to vary across the sites, creating uncertainty in the inter-site comparison of flux measurements. An alternative approach to define seasonality is to focus on standard time periods such as months (Natali et al., 2019). Although focusing on monthly fluxes may result in a small decrease in synthesizable data, because publications, particularly older ones, often provide seasonal rather than monthly flux estimates (see e.g., (Euskirchen et al., 2012; Nykänen et al., 2003; Björkman et al., 2010a; Oechel et al., 2000; Merbold et al., 2009)), compiling

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253 monthly fluxes has several advantages over the seasonal fluxes. These advantages include: (i)
254 better comparability of measurements, (ii) ability to bypass problems related to defining seasons
255 across large regions, and (iii) ease of linking these fluxes to remote sensing and models.
256
257 Our goal is to build upon past synthesis efforts and compile a new database of Arctic-Boreal CO_2
258 fluxes (ABCflux version 1) that combines eddy covariance, chamber, and diffusion data at
259 monthly timescales with supporting environmental information to help facilitate large-scale
260 assessments of the ABZ carbon cycle. This paper provides a general description of the ABCflux
261 database by characterizing the data sources and database structure (Section 2), as well as
262 describing the characteristics of the database (Section 3). Additionally, we describe the main
263 strengths, limitations, and opportunities of this database (Section 4), and its potential utility for
264 future studies aiming to understand terrestrial ABZ CO_2 fluxes.
265

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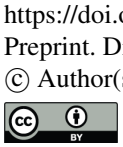

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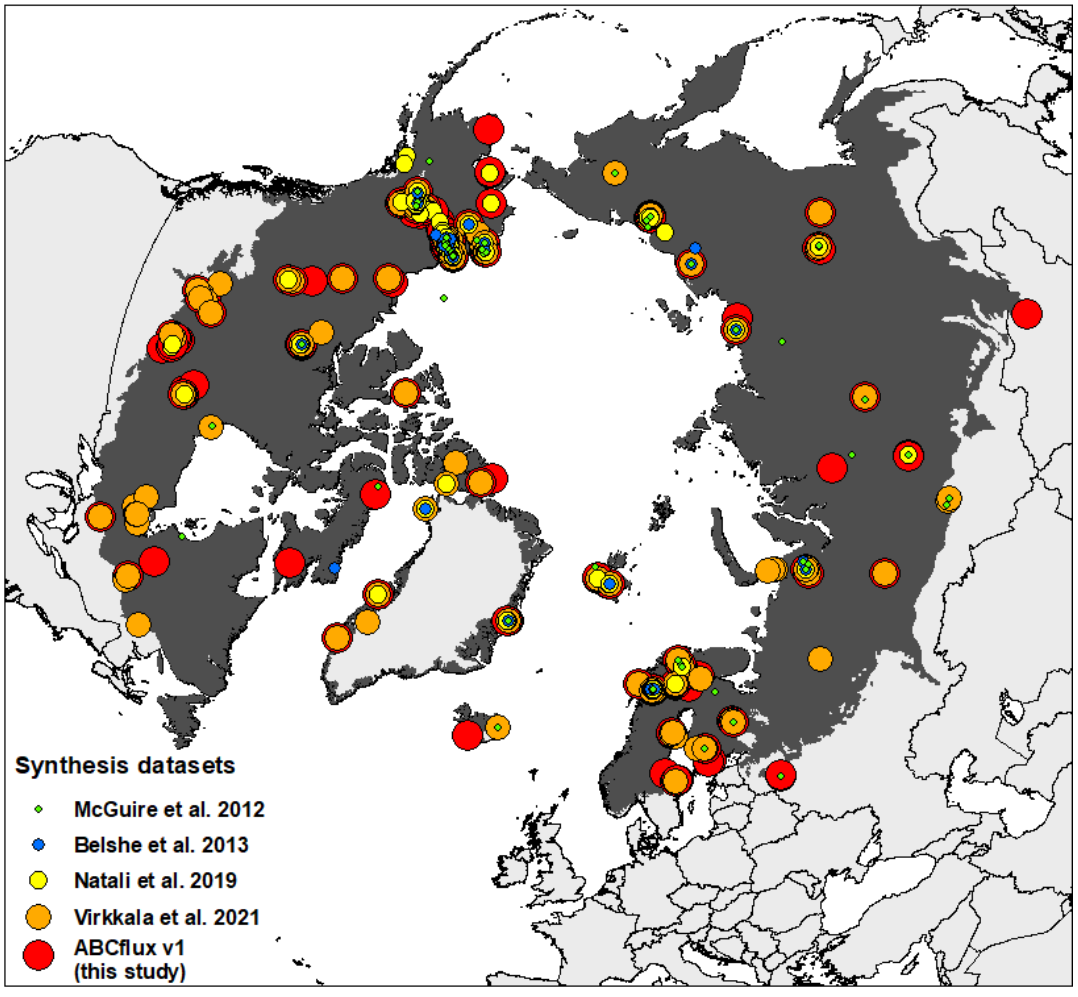

Fig 1. The flux site distribution in previous syntheses that focused on compiling fluxes from high latitudes (McGuire et al. 2012, Belshe et al. 2013, Natali et al. 2019, Virkkala et al. 2021b and this study (ABCflux)). The Arctic-Boreal Zone is highlighted in dark grey; countries are shown in the background. Based on the unique latitude-longitude coordinate combinations in the tundra, there were 136 tundra sites in ABCflux, 104 tundra sites in Virkkala et al. 2021b, 68 tundra sites in Natali et al., 2019, 34 tundra sites in Belshe et al. 2013, and 66 tundra sites in McGuire et al., 2012. Observations that were included in previous studies but not in ABCflux represent fluxes aggregated over seasonal, not monthly periods.

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276 **Table 1**. A summary of past CO_2 flux synthesis efforts. If site numbers were not provided in the
277 paper, this was calculated as the number of unique sets of coordinates.

Study	Number of sites	Synthesized fluxes and measurement techniques	Study domain	Study period	Flux aggregation
Luyssaert et al. (2007)	NA	GPP, Reco, and NEE measured with eddy covariance	Global forests (including boreal)	NA	Annual
McGuire et al. (2012)	60	GPP, Reco, and NEE measured with chambers, eddy covariance, diffusion technique and soda lime	Arctic tundra	Measurements from 1966-2009; focus on 1990-2009	Annual, growing and winter season
Belshe et al. (2013)	34	GPP, Reco, and NEE measured with chambers, eddy covariance, diffusion technique and soda lime	Arctic tundra	Measurements from 1966-2010	Annual, growing and winter season
Baldocchi et al. (2018)	9	GPP, Reco, and NEE measured with eddy covariance	Global (including boreal and tundra biomes)	NA (sites with 5-18 years of measurements)	Annual
Virkkala et al. (2018)	117	GPP, Reco, and NEE measured with chambers	Arctic tundra	Studies published during 2000-2016	Growing season
Natali et al. (2019)	104	Soil respiration (or NEE) measured with chambers, eddy covariance, diffusion	Northern permafrost region	Measurements from 1989-2017, focus on 2000-2017	Monthly or seasonal during winter

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		technique, and soda lime			
Virkkala et al. (2021b)	148	GPP, Reco, and NEE measured with chambers and eddy covariance	Arctic tundra and boreal biomes	1990-2015	Annual and growing season
ABCflux version 1 (this study)	244	GPP, Reco, and NEE (with some soil respiration and forest floor fluxes) measured with chambers, eddy covariance, and diffusion technique	Arctic tundra and boreal biomes	1989-2020	Monthly (whole year)

2. Data and methods

ABCflux focuses on the area covered by the northern tundra and boreal biomes (>45 °N), as characterized in (Dinerstein et al., 2017), Fig. 2)), and compiles *in-situ* measured terrestrial ecosystem-level CO_2 fluxes aggregated to monthly time periods (unit: g C m^{-2} $month^{-1}$). Although the three flux measurement techniques included in ABCflux primarily measure NEE, chamber and eddy covariance techniques can also be used to estimate GPP (the photosynthetic flux) and Reco (comprising emissions from autotrophic and heterotrophic respiration) (Keenan and Williams, 2018), which are also included in the database. At eddy covariance sites, GPP and Reco are indirectly derived from NEE using partitioning methods that primarily use light and temperature data (Lasslop et al., 2010; Reichstein et al., 2005). At chamber sites, Reco can be measured directly with dark chambers, from which GPP can be calculated by subtracting Reco from NEE (Shaver et al., 2007). In general, these partitioned GPP and Reco fluxes have higher uncertainties than the NEE measurements since they are modeled based on additional data and various assumptions (Aubinet et al., 2012). However, GPP and Reco fluxes were included in

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ABCflux because these component fluxes may help to better understand and quantify the underlying processes of land–atmosphere CO_2 exchange.

In addition to CO_2 fluxes, we gathered information describing the general site conditions (e.g., site name, coordinates, vegetation type, disturbance history, a categorical soil moisture variable, and soil organic carbon stocks), micrometeorological and environmental measurements (e.g., air and soil temperatures, precipitation, soil moisture, snow depth), and flux measurement technique (e.g., measurement frequency, instrumentation, gap filling and partitioning method, number of spatial replicates for chamber measurements, flux data quality), wherever possible.

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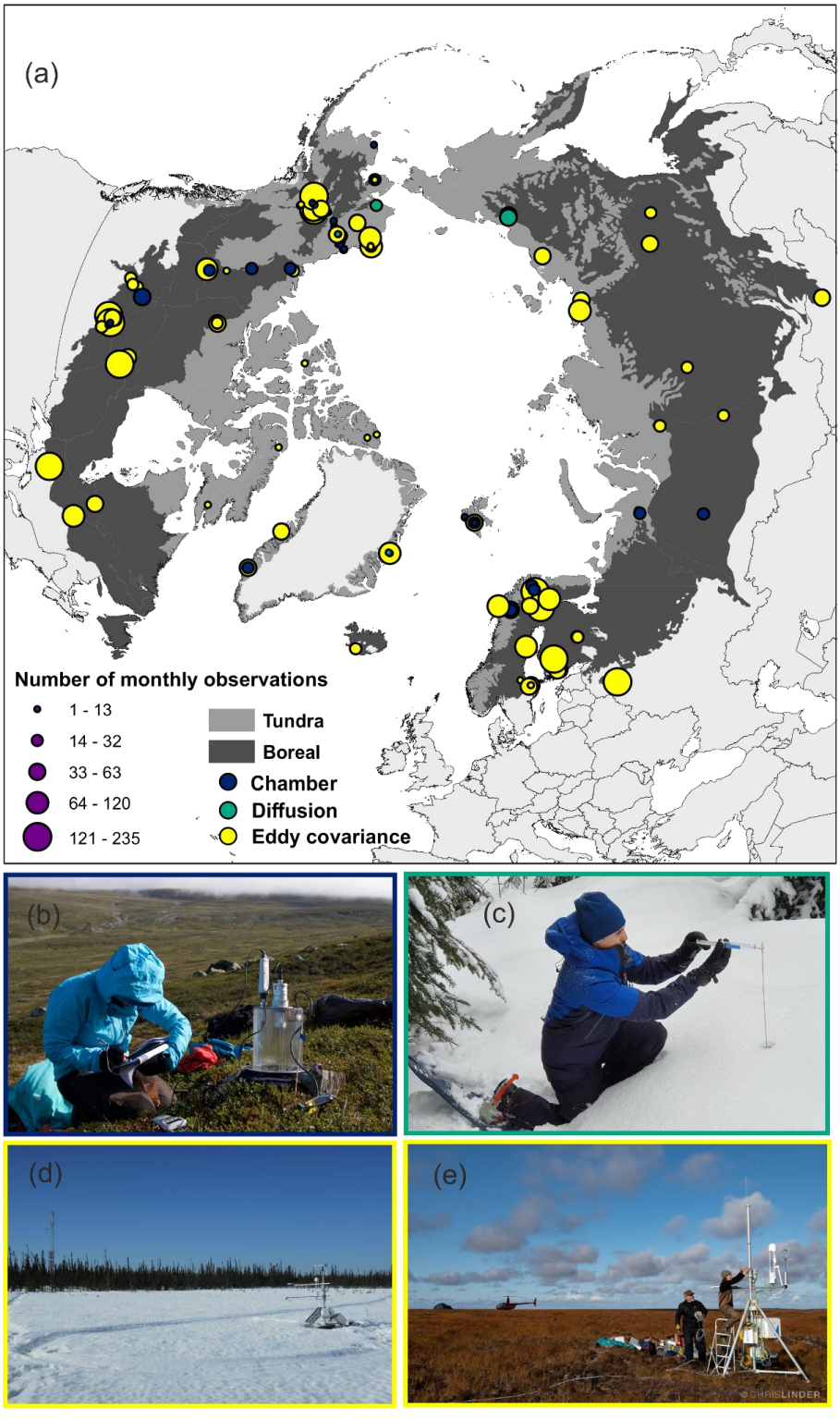

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304 **Fig 2**. Map showing the distribution and measurement technique at each site (a), and examples of
305 an eddy covariance tower (b), manual chamber (c), diffusion measurements (d), and two eddy
306 covariance towers in wetland and forest (e). Photographs were taken in Yukon-Kuskokwim
307 Delta, Alaska (September 2019), Kilpisjärvi, Finland (July 2016), Montmorency forest, Canada
308 (April 2021), and Scotty Creek, Canada (April, 2014). Image credits to: Markus Jylhä, Alex
309 Mavrovic, Gabriel Hould Gosselin, Chris Linder, Manuel Helbig.

310

311 ## 2.1. Data sources

312 ### 2.1.1 Literature search

313 We identified potential CO_2 flux studies and sites from prior synthesis efforts (Belshe et al.,
314 2013; McGuire et al., 2012; Virkkala et al., 2018; Natali et al., 2019; Virkkala et al., 2021b),
315 including a search of citations within and of the studies included in these prior syntheses. We
316 also conducted a literature search with the search words ("carbon flux" or "carbon dioxide flux"
317 or "NEE" or "net ecosystem exchange"), and ("arctic" or "tundra" or "boreal") in Web of
318 Science to ensure that our database included the most recent publications. We included studies
319 that reported at least NEE, presented at monthly or finer temporal resolution, and had supporting
320 environmental ancillary data describing the sites. We extracted our variables of interest (Section
321 2.3.) from these selected papers during 2018-2020. Data from line and bar plots were extracted
322 using Plot Digitizer (http://plotdigitizer.sourceforge.net/) and converted to our flux units (g C m^{-2}
323 $month^{-1}$) if needed. Papers including a low number of temporal replicates within a month (<3
324 individual measurements in summer months) and only one measurement month were
325 disregarded. For the spring (March-May), autumn (September-November), and winter
326 (December-February) months, one temporal replicate was accepted due to scarcity of
327 measurements outside the summer season (June-August); measurement frequency is included in
328 the database. Data from experimental treatments were excluded; however, we included flux data
329 from unmanipulated control plots. Winter chamber or diffusion measurements in forests from
330 Natali et al., (2019) were included in the "Ground_NEE" field, which represents forest
331 understory (not whole-ecosystem) NEE.

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333 2.1.2. Flux repositories

334 We downloaded eddy covariance and supporting environmental data products from AmeriFlux
335 (Novick et al., 2018), Fluxnet2015 (Pastorello et al., 2020), EuroFlux database cluster (ICOS,
336 Carbon Extreme, Carbo Africa, GHG Europe, Carbo Italy, INGOS) (Paris et al., 2012; Valentini,
337 2003), and Station for Measuring Ecosystem-Atmosphere Relations (Hari et al., 2013). Data
338 were downloaded in 2018-2020. When only daily gap-filled data were supplied, we summed the
339 data to monthly time steps and recorded the percentage of gap-filled data. We did not aggregate
340 any repository GPP, Reco, or NEE datasets that were not gap filled. We filtered out
341 measurements with low turbulence conditions based on friction velocity (USTAR) thresholds
342 (Aubinet et al., 2012). USTAR varied among sites due to differing site-level assumptions. We
343 downloaded only gap filled data that met the USTAR criteria for either the tower PI or given
344 through the database processing pipeline. However, Fluxnet2015 provides several different
345 methods for determining data quality based on different USTAR criteria. In this case, we used
346 the Fluxnet2015 common USTAR threshold (CUT, i.e. all years at the site filtered with the same
347 USTAR threshold (Pastorello et al., 2020)). For observations extracted from EuroFlux, USTAR
348 thresholds for each site were derived as described in (Papale et al., 2006; Reichstein et al., 2005)
349 using night-time data. If fluxes were available for the same period both in Natali et al., (2019)
350 and flux repository extractions, the flux repository observations were kept in the database. Some
351 repositories supplied eddy covariance data version numbers, which were added to the flux
352 database.
353

354 2.1.3. Permafrost Carbon Network data solicitation

355 A community call was solicited in 2018 through a CO_2 flux synthesis workshop (Parmentier et
356 al., 2019, Reconciling historical and contemporary trends in terrestrial carbon exchange of the
357 northern permafrost-zone, 2021), whereby the network of ABZ flux researchers were contacted
358 and invited to contribute their most current unpublished data. This resulted in an additional 39
359 sites and 1372 monthly observations (see column Extraction_source).
360

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2.2. Data quality screening

We screened for poor-quality data, potential unit and sign convention issues, and inaccurate coordinates. Repository data were processed and quality checked using quality flags associated with monthly data supplied by the repository processing pipeline. Fluxnet2015 and EuroFlux database include an aggregated data quality flag (fraction between 0-1, indicating percentage of measured and good-quality gap-filled data; average from daily data; 0=extensive gap-filling, 1=low gap-filling; for more details see (Pastorello et al., 2020)) which is reported for fluxes aggregated from finer temporal resolutions. We removed monthly data with a quality flag of 0. Eddy covariance data with quality flags >0 were left within the database for the user to decide on additional screening criteria. The database also includes a column describing the percentage of gap-filled data (0=no gap-filled data, 100=completely gap-filled data), however it was not used in data quality screening. These fields describe the amount and quality of the gap-filled data that need to be filled due to, for example, instrument malfunction, power shortage, extreme weather events, and periods with insufficient turbulence conditions.

We further screened for spatial coordinate accuracy by visualizing the sites on a map. If a given site was located in water or had imprecise coordinates, the site researchers were contacted for more precise coordinates. We screened for potential duplicate sites and observations that were extracted from different data sources. Duplicate NEE extracted from papers that were also extracted from flux repositories were compared to estimate uncertainties associated with using Plot Digitizer as a means for extracting monthly fluxes. A linear regression between paper (Plot Digitizer) and repository extraction showed that data extracted using Plot Digitizer were highly correlated with data from online databases, providing confidence in estimates extracted using Plot Digitizer (R^2=0.91, slope = 1.002, n=192). Out of these duplicate observations, we only kept the data extracted from the repository in the database. Finally, we asked site principal investigators (PIs) to verify that the resulting information was correct.

2.3. Database structure and columns

The resulting ABCflux database includes 94 variables: 16 are flux measurements and associated metadata (e.g., NEE, measurement date and duration), 21 describe flux measurement methods

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(e.g., measurement frequency, gap-filling method), 49 describe site conditions (e.g., soil moisture, air temperature, vegetation type), and 8 describe the extraction source (e.g., primary author or site PI, citation, data maturity). 61 variables are considered static and thus do not vary with repeated measurements at a site (e.g., site name, coordinates, vegetation type), while 33 variables are considered dynamic and vary monthly (e.g., soil temperature). Table 2 includes a description of each of the 94 variables, as well as the proportion of monthly observations present in each column. ABCflux is shared as a comma separated values (csv) file with 6309 rows; however, not all the rows have data in each column (indicated by NA).

We refer to all fields included in ABCflux as observations although we acknowledge that, for example, GPP and Reco are indirectly derived variables at eddy covariance sites, and that some flux and ancillary data can also be partly gap-filled. Further, our database does not include the actual raw observations, rather it provides monthly aggregates. Positive values for NEE indicate net CO_2 loss to the atmosphere (i.e., CO_2 source) and negative numbers indicate net CO_2 uptake by the ecosystem (i.e., CO_2 sink). For consistency, GPP is presented as negative (uptake) values and Reco as positive.

Table 2. Database variables and the proportion of monthly observations in each variable. There are in total 6309 monthly observations in the database.

Variable	Variable description and units	Details	Proportion of monthly observations having data
id	ID given to each individual monthly entry at each site		100%
Study_ID	ID given to study/site entry (see Details)	(PI/first author of publication)_(site name)_(tower/chamber)_(#); Eg., Schuur_EML_Tower_1. Note that there might be several chamber (or tower) Study_IDs for one site.	100%

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Study_ID_Short	ID given to study/site entry (see Details), individual chamber plots within a site not differentiated	(PI/first author of publication)_(site name)_(tower/chamber)_(#); Eg., Schuur_EML_Tower_1.	100%
Site_Name	Site name as specified in data source	Usually the location name	100%
Site_Reference	A more specific name used in data source	For towers, this is often the acronym for the site, and for chambers, this is the name of the particular chamber plot	95%
Data_contributor_or_Author	Data contributor(s) or primary author(s) associated with data set or publication	If you use unpublished data or data from flux repositories (see Extraction_source), please contact this person	100%
Latitude	Decimal degrees, as precise as possible		100%
Longitude	Decimal degrees, as precise as possible	Negative longitudes are west from Greenwich	100%
Email	Primary author email		93%
ORCID	personal digital identifier: https://orcid.org/		29%
Citation	Journal article, data citation, and/or other source (online repository, PI submitted, etc.).		70%
Data_adder	The person(s) who added the data to the database	Primarily researchers working at Woodwell	100%
Data_availability	Current availability of data: data available in a published paper, in an open online data repository, in an already published synthesis, or user contributed	Published_Paper, Published_Online, Published_Synthesis, User_Contributed	100%
Data_maturity	Current maturity of data	Preliminary, Processed, Published, Reprocessed	100%

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Extraction_source	Data source	paper, Virkkala or Natali syntheses, Euroflux, Fluxnet 2015, PI, Ameriflux, SMEAR, ORNL DAAC, Pangaea	100%
Biome	Biome of the site	Boreal, Tundra	100%
Veg_type	A detailed vegetation type for the site	B1=cryptogram, herb barren; B2=cryptogram barren complex; B3=noncarbonate mountain compled; B4=carbonatemountain complex; G1=rush/grass, forb, cryptogram tundra; G2=graminoid, prostrate dwarf-shrub, forb tundra; G3=nontussock sedge, dwarf-shrub, moss tundra; G4=tussock-sedge, dwarf-shrub, herb tundra; P1=prostrate dwarf-shrub, herb tundra; P2=prostrate/hemiprostrate dwarf-shrub tundra; S1=erect dwarf-shrub tundra; S2=low-shrub tundra; W1=sedge/grass, moss wetland; W2=sedge, moss, dwarf-shrub wetland; W3=sedge, moss, low-shrub wetland; DB=deciduous broadleaf forest; EN=evergreen needleleaf forest; DN=deciduous needleleaf forest; MF=mixed forest; SB=sparse boreal vegetation; BW=boreal wetland or peatland, following Watts et al. (2019). For more details about the tundra vegetation types, see Walker et al. (2005). These classes were classified based on information in Site_Reference and Veg_detail columns, or were contributed by the site PI.	100%
Veg_type_Short	A more general vegetation type for the site	B=barren tundra; G=graminoid tundra; P=prostrate dwarf-shrub tundra; S=shrub tundra; W=tundra wetland; DB=deciduous broadleaf forest; EN=evergreen needleleaf forest; DN=deciduous needleleaf forest; MF=mixed forest; SB=sparse boreal vegetation; BW=boreal wetland or peatland. For more details about the tundra vegetation types, see Walker et al. (2005). These classes were classified based on information in Site_Reference and Veg_detail columns, or were contributed by the site PI.	100%
Veg_detail	Detailed vegetation description from data source/contributor		96%
Country	Country of the site		100%
Permafrost	Reported presence or absence of permafrost	Yes, No	72%

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Disturbance	Last disturbance	Fire, Harvest, Thermokarst, Drainage, Grazing, Larval Outbreak, Drought	30%
Disturb_year	Year of last disturbance	Numeric variable, 0 = annual (e.g., annual grazing)	23%
Disturb_severity	Relative severity of disturbance	High, Low	11%
Soil_moisture_class	General descriptor of site moisture	Wet = At least sometimes inundated or water table close to surface. Dry = well-drained.	56%
Site_activity	Describes whether the site is currently active (i.e., measurements conducted each year)	Yes, No. Eddy covariance information was extracted from https://cosima.nceas.ucsb.edu/carbon-flux-sites/ by assuming that sites that were active in 2017 are still continuing to be active. We used our expertise to define active chamber sites that have measurements at least during each growing season.	60%
Meas_year	Year in which data were recorded		100%
Season	Season in which data were recorded	summer, autumn, winter, spring (based on climatological seasons)	100%
Interval	Measurement month		100%
Start_day	Start day of the measurement		100%
End_day	End day of the measurement		100%
Duration	Number of days during the measurement month	Should be the same as End_Day because this database compiles monthly fluxes	100%
Start_date	Date on which measurement starts	dd/mm/yyyy	100%
End_date	Date on which measurement ends	dd/mm/yyyy	100%
NEE_gC_m2	Net Ecosystem Exchange (g C-CO_2 m^{-2} for the entire measurement interval)	Convention: -ve is uptake, +ve is loss.	91%

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GPP_gC_m2	Gross Primary Productivity (g $C\text{-}CO_2$ m^{-2} for the entire measurement interval)	Report as -ve flux	68%
Reco_gC_m2	Ecosystem Respiration (g $C\text{-}CO_2$ m^{-2} for the entire measurement interval)	Report as +ve flux	73%
Ground_NEE_gC_m2	Forest floor Net Ecosystem Exchange, measured with chambers (g C-CO2 m-2 for the entire measurement interval)	Convention: -ve is uptake, +ve is loss. Chamber measurements from (primarily rather treeless) wetlands are included in the NEE_gC_m2 column.	4%
Ground_GPP_gC_m2	Forest floor Ecosystem Respiration, measured with chambers (g C-CO2 m-2 for the entire measurement interval)	Report as -ve flux. Chamber measurements from (primarily rather treeless) wetlands are included in the GPP_gC_m2 column.	1%
Ground_Reco_gC_m2	Forest floor Gross Primary Productivity, measured with chambers (g $C\text{-}CO_2$ m^{-2} for the entire measurement interval)	Report as +ve flux. Chamber measurements from (primarily rather treeless) wetlands are included in the Reco_gC_m2 column.	2%
Rsoil_gC_m2	Soil respiration, measured with chambers (g $C\text{-}CO_2$ m^{-2} for the entire measurement interval)	Report as +ve flux	4%
Flux_method	How flux values were measured	EC=eddy covariance, Ch=chamber, Diff=diffusion methods. No observations from experimental manipulation plots	100%
Flux_method_detail	Details related to how flux values were measured: closed- and open-path eddy covariance, mostly manual chamber measurements, mostly automated chamber measurements, a combination of chamber and cuvette measurements, diffusion measurements through the snowpack, chamber measurements on top of snow	EC_closed, EC_open, EC_enclosed, EC_open & closed, EC_enclosed, Chambers_mostly_manual, Chambers_mostly_automatic, Chambers_CUV, Snow_diffusion, Chambers_snow, NA	93%

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Measurement_frequency	Frequency of flux measurements	>100 characterizes high-frequency measurements. Manual chamber and diffusion techniques often have values between 1 and 30; 1=measurements done during one day of the month, 30=measurements done daily throughout the month.	100%
Diurnal_coverage	Times of day covered by flux measurements	Day, Day and Night	90%
Partition_method	Method used to partition NEE into GPP and Reco	Reichstein (night time=Reco partitioning), Lasslop (bulk/day-time partitioning), Reco_measured, ANN, or GPP=Reco-NEE (for chamber sites)	16%
Spatial_reps_chamber	Number of spatial replicates for the chamber plot	Usually, but not always, several chamber plots are measured to assure the representativeness of measurements	71%
Gap_fill	Gap filling method	e.g., Average, Linear interpolation, Lookup table, MDS (marginal distribution sampling), Light/temperature response, Neural network, a combination of these, or a longer description related to chamber measurements	70%
Gap_perc	% of NEE data that was gap-filled in the measurement interval (relative to standard measurement time step)		17%
Tower_QA.QC.NEE.flag	Overall monthly quality flag for eddy covariance aggregated observations; fraction between 0-1, indicating percentage of measured and good-quality gap-filled data	0=extensive gap-filling, 1=low gap-filling	44%
QA.QC.source	The source for the overall quality information for the eddy covariance observations	0=Fluxnet2015, 1=Euroflux	37%
Precip_int_mm	Total precipitation during measurement interval (mm)		37%
Tair_int_C	Mean air temperature during measurement interval (°C)		72%

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Tsoil_C	Mean soil Temperature during measurement interval (°C)		74%
Soil_moisture_perc	Mean soil moisture during the measurement interval (% by volume)		35%
Thaw_depth_cm	Mean thaw depth during the measurement interval (cm)	Report with positive values	6%
Tsoil_depth_cm	Depth of soil temperature measurement below surface (cm)		46%
Moisture_depth_cm	Depth of soil moisture measurement below surface (cm)		31%
ALT_cm	Active layer thickness (cm; maximum thaw depth), will change annually	Report with positive values	15%
WTD_cm	Mean water table depth during the measurement interval (cm); Positive is below the surface, negative is above (inundated)		7%
Snow_depth_cm	Mean snow depth during the measurement interval (cm)		14%
VPD_Pa	Mean vapour pressure deficit during the measurement interval (Pa)		30%
ET_mm	Total evapotranspiration during the measurement interval (mm)		4%
PAR_W_m2	Mean photosynthetically active radiation during measurement interval (W m^{-2})		5%

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PAR_PPFD_umol_m2_s	Mean photosynthetically active radiation during measurement interval (measured in Photosynthetic Photon Flux Density, PPFD; micromol m-2 s-1)		11%
Precip_ann_mm	Mean annual precipitation (mm), from site or nearby weather station as a general site descriptor. This should describe the longer-term climate for the site rather than a few years of study.		80%
Tair_ann_C	Mean annual air temperature (°C), from site or nearby weather station as a general site descriptor. This should describe the longer-term climate for the site rather than a few years of study.		79%
Met_source	Data source and years used to calculate mean annual temperature/precipitation		50%
Elevation_m	Elevation above sea level (m)		65%
LAI	Leaf Area Index		23%
SOL_depth_cm	Soil organic layer depth (cm)		23%
perc_C	Soil carbon percentage (%)		7%
perc_C_depth_cm	Depth at which soil carbon % was measured (cm)		7%
C_dens_kgC_m2	Soil carbon per unit area (kg C m^{-2})		16%
C_dens_depth_cm	Depth to which Soil organic carbon per unit area was		8%

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	estimated (cm)		
AGB_kgC_m2	Above ground biomass (kg C m^{-2})		11%
AGB_type	Types of above ground vegetation included in the AGB measurement	Trees, shrubs, graminoids, mosses, lichens	13%
Soil_type	General soil type, including source (e.g., USDA, CSSC, NCSCD)		42%
Soil_type_detail	Detailed soil type description, if available		9%
Citation_Data_Overlap	Another citation for the site		13%
High_freq_availability	Availability of high-frequency data		17%
Light_response_method_chamber	Details related to how the varying light response conditions were considered in chamber measurements		5%
PAR_cutoff_umol_m2_second	PAR level used to define night-time data and apply partitioning method (umol PAR m^{-2} $second^{-1}$)		17%
Aggregation_method	Method used to aggregate data to measurement interval		58%
Instrumentation	Description of instrumentation used		68%
Tower_Version	Version number of the eddy covariance dataset from the extraction source		21%
Spatial_variation_technique	Technique used to quantify spatial variation for flux measurements	e.g., standard error of replicate measurements for chambers, spatial error based on footprint partitioning for towers	10%

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Method_error_NEE_gC_m2	RMSE or other bootstrapped error of model fit for NEE (g C-CO_2 m^{-2} for the entire measurement interval)		23%
Method_error_technique	Technique used to quantify method errors for flux measurements	e.g., gap-filling and partitioning errors or uncertainty in data-model fit: bootstrap, MCMC, RMSE fit, etc.	1%
Tower_Data_restriction			12%
Tower_Corrections	Details related to processing corrections employed, including time, duration, and thresholds for u* and heat corrections		32%
Other_data	Other types of data from the data source that may be relevant		7%
Notes_SiteInfo	Any other relevant information		20%
Notes_TimeVariant	Any other relevant information		59%

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414 2.4. Database visualization

415 The visualizations in this paper were made with the full ABCflux database using each site-month
416 as a unique data point (from now on, these are referred to as monthly observations) and the sites
417 listed in the "Study_ID_Short" field. We visualized these across the vegetation types
418 ("Veg_type_Short"), countries ("Country"), biomes ("Biome"), and measurement method
419 ("Flux_method").
420
421 To understand the distribution and representativeness of monthly observations and sites across
422 the ABCflux as well as the entire ABZ, we used geospatial data to calculate the aerial coverages
423 of each vegetation type and country. Vegetation type was derived from the European Space
424 Agency Climate Change Initiative's (ESA CCI) land cover product aggregated and resampled to

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0.0083° for the boreal biome (Lamarche et al., 2013) and the raster version of the Circumpolar Arctic Vegetation Map (CAVM) for the tundra biome resampled to the same resolution as the ESA CCI product (Raynolds et al., 2019). ESA CCI layers were reclassified by grouping land cover types to the same vegetation type classes represented by ABCflux: boreal wetland and peatland (from now on, boreal wetland; classes 160, 170, 180 in ESA CCI product), deciduous broadleaf forest (60-62), evergreen needleleaf forest (70-72), deciduous needleleaf forest (80-82), mixed forest (90), and sparse and mosaic boreal vegetation (40, 100, 100, 120, 121, 122, 130, 140, 150, 151, 152, 153, 200, 201, 202). Croplands (10, 11, 12, 20, 30) and urban areas (190) were removed. We used the five main physiognomic classes from CAVM in the tundra. Glaciers and permanent water bodies included in either of these products were removed. Note that in ABCflux and for the site-level visualizations in this paper, vegetation type for each of the flux sites was derived from site-level information, not these geospatial layers. These same glacier, water, and cropland masks were applied to the country boundaries (Natural Earth - Free vector and raster map data at 1:10m, 1:50m, and 1:110m scales, 2021) to calculate the terrestrial area of each country.

3. Database summary

3.1. General characteristics of the database

ABCflux includes 244 sites and 6309 monthly observations, out of which 136 sites and 2217 monthly observations are located in the tundra (54 % of sites and 52 % of observations from North America, 46 % and 48 % from Eurasia), while 108 sites and 4092 monthly observations are located in the boreal biome (59 % of sites and 58 % of observations from North America, 41 % and 42 % from Eurasia) (Table 3). The largest source of flux data are the flux repositories (48 % of the monthly observations), while flux data extracted from papers or contributed by site PIs amount to 30 % and 22 % of the monthly observations, respectively. The database primarily includes sites in unmanaged ecosystems, but it does contain a small number (6) of sites in managed forests.

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Table 3. General statistics of the database. Number of monthly CO_2 flux measurements and sites derived from eddy covariance, chamber, and diffusion techniques, and the proportion of data coming from different data sources. Note that some of the data extracted from flux repositories and papers were further edited by the PIs; this information can be found in the database. For this table, observations that were fully contributed by the PI were considered as PI-contributed.

Flux measurement technique	Number of sites	Number of observations	Number of observations derived using different eddy covariance and chamber techniques	Number of observations extracted from different data sources
Eddy covariance	Total: 119 Tundra: 47 Boreal: 72	Total: 4957 Tundra: 1406 Boreal: 3551	Open-path: 1988 Closed path: 2085 Both: 245 Enclosed: 240 No information available: 399	Flux repository: 2775 Published: 810 PI-contributed: 1350
Chamber	Total: 104 Tundra: 73 Boreal: 31	Total: 1166 Tundra: 708 Boreal: 458	Manual: 435 Automated: 696 No information available: 35	Flux repository: 243 Published: 901 PI-contributed: 22
Diffusion	Total: 21 Tundra: 16 Boreal: 5	Total: 186 Tundra: 103 Boreal: 83		Flux repository: 0 Published: 186 PI-contributed: 0

The majority of observations in ABCflux have been measured with the eddy covariance technique (119 sites and 4957 monthly observations), whereas chambers and diffusion methods were used at 125 sites and 1352 observations (Table 3). About 46 % of the eddy covariance measurements are based on gas analyzers using closed-path technology (including enclosed analyzers), 40 % are based on open-path technology, 5 % include both and 8 % are unknown. 52 % of chamber measurements were automated chambers (monitoring the fluxes continuously throughout the growing season). Only 3 % of the measurements were completed using diffusion methods during the winter. Chamber and diffusion studies were primarily from the tundra and the sparsely treed boreal wetlands, but a few studies with ground surface CO_2 fluxes from forests

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(i.e., capturing the ground cover vegetation and not the whole ecosystem) are also included in their own fields so that they can not be mixed up with ecosystem-scale measurements ("Ground_NEE_gC_m2", "Ground_GPP_gC_m2", "Ground_Reco_gC_m2"). Further, a few soil CO_2 flux sites measuring fluxes primarily on unvegetated surfaces during the non-growing season are included in the database ("Rsoil_gC_m2"). These were included in the database because ground surface or soil fluxes during the non-growing season can be of similar magnitude to the ecosystem-level fluxes when trees remain dormant (Ryan et al., 1997; Hermle et al., 2010). Therefore, these ground or soil fluxes could potentially be used to represent ecosystem-level fluxes during some of the non-growing season months. However, we did not make an extensive literature search for these observations, rather we compiled observations if they came up in our NEE search. Therefore, the data in these ground surface and soil flux columns represents only a portion of such available data across the ABZ.

The geographical coverage of the flux data is highly variable across the ABZ, with most of the sites and monthly observations coming from Alaska (37 % of the sites and 28 % of the monthly observations), Canada (19 % and 29 %), Finland (7 % and 15 %), and Russia (14 % and 13 %) (Fig. 3). The sites cover a broad range of vegetation types, but were most frequently measured in evergreen needleleaf forests (23 % of the sites and 37 % of the monthly observations) and wetlands in the tundra or boreal zone (30 % and 27 %) (Fig. 4). The northernmost and southernmost ecosystems had fewer sites and observations than more central ecosystems (barren tundra: 45% of the sites and 3 % of the monthly observations, prostrate shrub: 2 % and <1 %, deciduous broadleaf forest: 1 % and 3 %, deciduous needleleaf forest: 5 % and 4 %, mixed forest <1 % and <1 %). ABCflux includes sites experiencing various types of disturbances, with the majority of disturbed sites encountering fires (24 sites and 901 monthly observations), thermokarst (4 sites and 113 monthly observations), or harvesting (6 sites and 258 monthly observations). However, ABCflux is dominated by sites in relatively undisturbed environments or sites lacking disturbance information (only 20 % of the sites and 30 % of the monthly observations include disturbance information).

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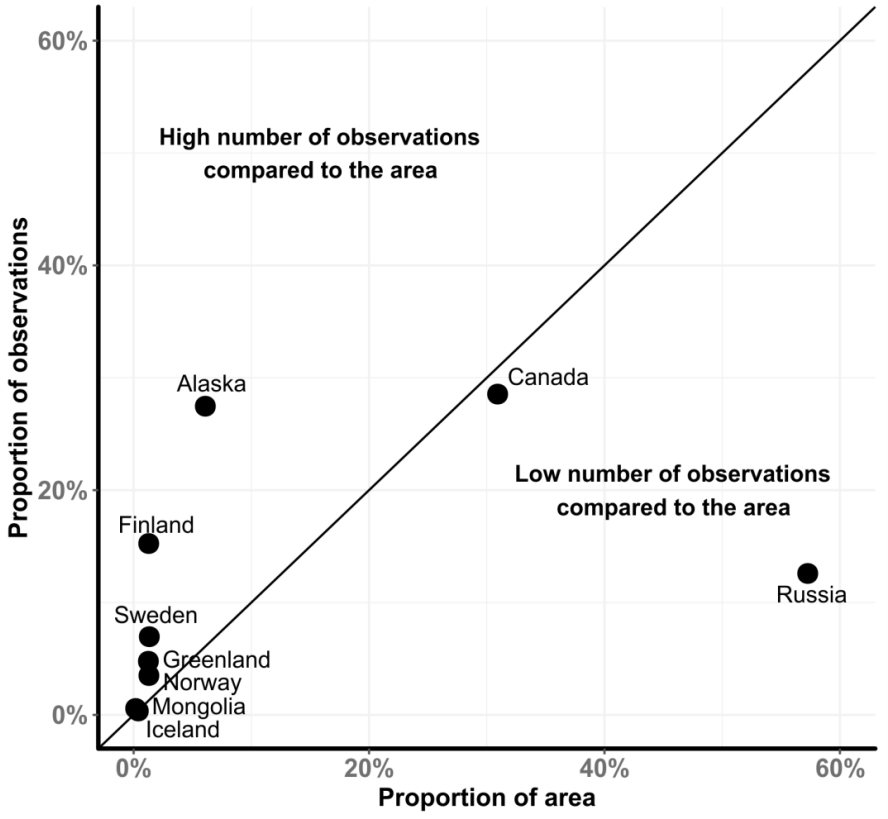

Fig 3. The proportion of monthly observations in each country/region compared to the proportion of the areal extent of the country/region across the entire Arctic-Boreal Zone. Ideally, points would be close to the 1:1 line (i.e., large countries/regions have more observations than small countries/regions). Permanent water bodies, croplands, and urban areas were masked from the areal extent calculation.

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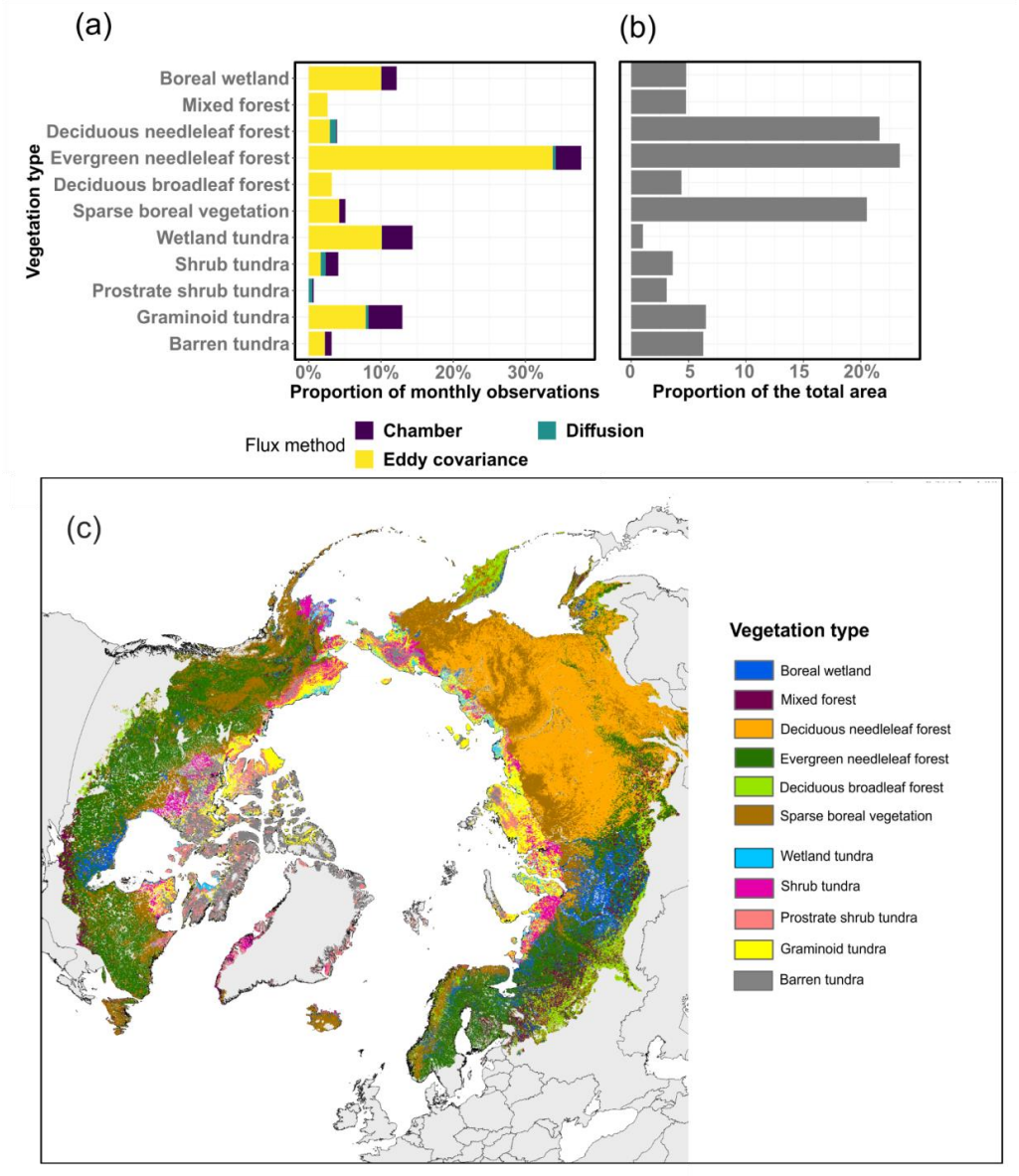

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Fig 4. The proportion of monthly observations in each vegetation type colored by the flux measurement technique (a) and the proportion of the areal extent of each vegetation type across the entire Arctic-Boreal Zone (b). Permanent water bodies, croplands, and urban areas were masked from the areal extent calculation. Sparse boreal vegetation class in the vegetation map includes vegetation mixtures and mosaics.

ABCflux spans a total of 31 years (1989-2020), but the largest number of monthly observations originate from 2000-2015 (80 % of the data) (Fig. 5). The largest number of measurements were conducted during the summer (June-August; 32 %) and the least during the winter (November-February; 18 %) (Fig. 5). The overall eddy covariance data quality and gap-filled data percentage were lowest during the winter compared to other seasons (0.76 compared to 0.8-0.85 for overall data quality, 0=extensive gap-filling, 1=low gap-filling; 69 % compared to 47 to 59 % for gap-filled data percentage).

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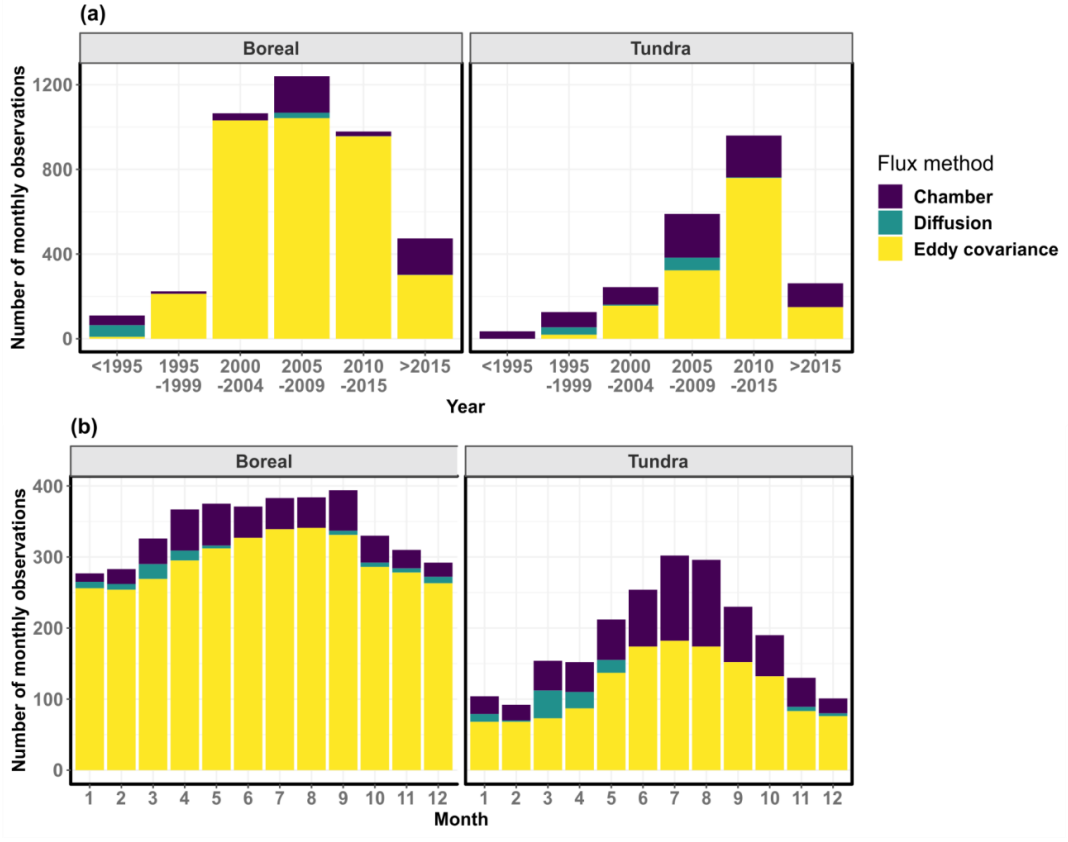

Fig 5. Histograms showing the number of monthly measurements across five-year periods (a) and across the tundra and boreal biomes (b). The bar plots are colored by the flux measurement technique. Chambers in the boreal biome measured fluxes in treeless or sparsely treed areas (primarily wetlands).

3.2. Coverage of ancillary data

All of the observations in ABCflux include information describing the site name, location, vegetation type, NEE, measurement technique (eddy covariance/chamber/diffusion), and how the data were compiled (Table 2). Details about the measurement technique (e.g., open or closed-path eddy covariance, manual or automated chambers) are included in 93 % of sites and 93 % of monthly observations. Most of the monthly observations further include information about

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permafrost extent (67 % of the sites and 72 % of the monthly observations), or soil moisture state (47 % of the sites and 56 % of the monthly observations). Data describing air temperature, soil temperature, precipitation, and soil moisture are included in 71, 73, 37, and 35 % of monthly observations, respectively. Some ancillary variables have low data coverage, such as soil organic carbon stocks (16 % of the monthly observations) or active layer thickness (15 % of the monthly observations).

3.3. Coverage and distribution of flux data

There are 110 sites and 4290 monthly observations for GPP, 121 sites and 4603 monthly observations for Reco, and 212 sites and 5759 monthly observations for NEE in ABCflux. Monthly values range from -2 to -516 g C m^{-2} $month^{-1}$ for GPP, from 0 to 550 g C m^{-2} $month^{-1}$ for Reco, and from -376 to 95 g C m^{-2} $month^{-1}$ for NEE (Table 4). NEE is typically negative during the summer (i.e., net CO_2 sink) and mostly positive during other seasons (i.e., net CO_2 source) (Fig. 6). Out of all site and year combinations, annual cumulative NEE (the sum of monthly NEE values for each year and site) can be calculated for 267 site-years. An average annual NEE calculated based on the site-level averages from 1995 to 2020 is -27.9 g C m^{-2} $year^{-1}$ (SD 85.4) for the entire region, -35.5 g C m^{-2} $year^{-1}$ (SD 93.7) for the boreal biome, and -3.3 g C m^{-2} $year^{-1}$ (SD 44.2) for the tundra. However, these averages do not account for the spatial or temporal distribution of the observations, and therefore represent coarse summaries of the database.

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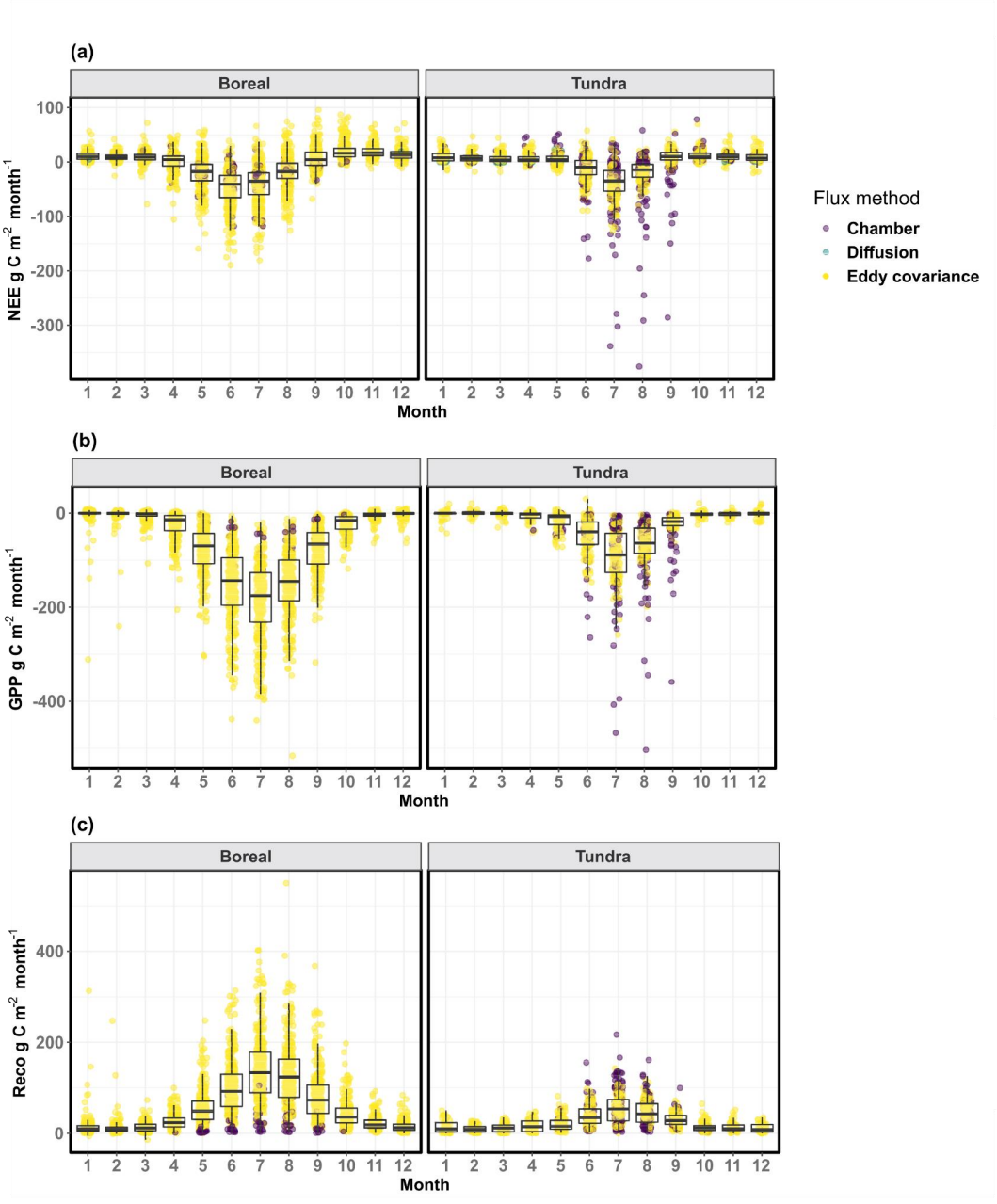

Fig 6. The distribution of net ecosystem exchange (NEE; a), gross primary productivity (GPP; b), and ecosystem respiration (Reco; c) across the months, colored by the flux measurement technique. Positive numbers for NEE indicate net CO_2 loss to the atmosphere (i.e., CO_2 source) and negative numbers indicate net CO2 uptake by the ecosystem (i.e., CO_2 sink). For

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564 consistency, GPP is presented as negative values and Reco as positive. The boxes correspond to
565 the 25th and 75th percentiles. The lines denote the 1.5 IQR of the lower and higher quartile,
566 where IQR is the inter-quartile range, or distance between the first and third quartiles. There is
567 not much chamber data from the boreal regions as they capture NEE only at treeless wetlands.

568

569 **Table 4**. Mean and standard deviation of monthly observations of net ecosystem exchange
570 (NEE), gross primary productivity (GPP), and ecosystem respiration (Reco) in g C m^{-2} $month^{-1}$.
571 Seasons were defined based on the climatological definition (autumn: September-November;
572 winter: December-February; spring: March-May; summer: June-August). Positive numbers for
573 NEE indicate net CO_2 loss to the atmosphere (i.e., CO_2 source) and negative numbers indicate
574 net CO_2 uptake by the ecosystem (i.e., CO_2 sink). For consistency, GPP is presented as negative
575 values and Reco as positive.

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Biome	**Climatological season**	**Mean monthly NEE**	**Mean monthly GPP**	**Mean monthly Reco**	**Standard deviation of monthly NEE**	**Standard deviation of monthly GPP**	**Standard deviation of monthly Reco**
Boreal	spring	-5	-40	34	25	49	32
Boreal	summer	-35	-163	124	36	79	71
Boreal	autumn	14	-38	52	18	45	46
Boreal	winter	11	-3	14	8	19	20
Tundra	spring	6	-11	18	9	16	14
Tundra	summer	-26	-72	48	38	60	30

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Tundra	autumn	10	-14	21	21	30	15
Tundra	winter	9	-2	12	10	9	11

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580

581 4. Strengths, limitations, and opportunities

582 ABCflux provides several opportunities for an improved understanding of the ABZ carbon cycle.
583 It can be used to calculate both short- and longer-term monthly, seasonal, or annual flux
584 summaries for different regions, or it can be combined with remote sensing and other gridded
585 data sets to build monthly statistical and process-based models for CO_2 flux upscaling. ABCflux
586 can further be utilized to study the inter- and intra-annual CO_2 flux variability resulting from
587 climate and environmental change. The site distribution in ABCflux can also be used to evaluate
588 the extent of the current flux network and identify under-sampled regions. From a
589 methodological perspective, data users can compare fluxes estimated with the different
590 measurement techniques which can help understand the uncertainties associated with individual
591 techniques. However, there are also some uncertainties that the data user should be aware of
592 when using ABCflux, which we describe below.
593

594 4.1. Comparing fluxes estimated with different techniques

595 The ABCflux database comprises aggregated observations using eddy covariance, chamber, and
596 diffusion methods. These methods measure CO_2 fluxes at different spatiotemporal resolutions
597 and are based on different assumptions. The eddy covariance technique is currently the primary
598 method to monitor long-term trends in ecosystem CO_2 fluxes (Baldocchi et al., 2018; Baldocchi,
599 2008), and the majority of observations in ABCflux (79 %) have been made using the technique.
600 Transforming high-frequency eddy covariance measurements to budgets includes several
601 processing steps that can, without harmonization and standardization of these steps (Baldocchi et
602 al., 2001; Pastorello et al., 2020), lead to highly different budget estimates (Soloway et al.,
603 2017). It is also important to acknowledge that the extent and size of the tower footprint differs
604 across the sites due to differences in the height of the tower and the direction and magnitude of

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605 the wind (Chu et al., 2021). When fluxes are aggregated over longer time periods to cumulative
606 budgets, one generally assumes the tower footprint remains relatively constant, capturing fluxes
607 from a similar part of the ecosystem (i.e., the assumption that monthly observations within one
608 site in ABCflux can be reliably compared with each other); but note that at shorter time periods
609 this might not be the case (Pirk et al., 2017; Chu et al., 2021).
610
611 The different gas analyzer technologies also play an important role for the fluxes estimated with
612 the eddy covariance technique. Sites located in the most northern and remote parts of the ABZ
613 experience a drop in irradiation during autumn and winter which limits solar power availability
614 for eddy covariance measurements. Closed-path systems require more power to run than open-
615 path sensors, but open-path sensors are known to have larger uncertainties. For example, open-
616 path eddy covariance sensors have been shown to incorrectly estimate NEE due to the self-
617 heating effect of the analyzer, which can result in systematically higher net CO_2 uptake
618 compared to closed-path sensors (Kittler et al., 2017a); however, this pattern was not clearly
619 observed in ABCflux when across-site comparisons were made. Furthermore, wintertime fluxes
620 indicating CO_2 uptake can be erroneous due to the limited ability of the gas analyzer to resolve
621 very high frequency turbulent eddies (Jentzsch et al., 2021). Recently, some types of open-path
622 infrared gas analysers have been found to be prone to biases in NEE that scale with sensible heat
623 fluxes in all seasons rather than with self-heating (Wang et al., 2017; Helbig et al., 2016).
624
625 While using eddy covariance to estimate small-scale spatial variability in NEE is challenging
626 (McGuire et al., 2012), this can be accomplished with chamber and diffusion techniques.
627 Chamber measurements can be done in highly heterogeneous environments as long as chamber
628 closure can be guaranteed; however, most of the chamber measurements in ABCflux have been
629 conducted in relatively flat and homogeneous graminoid- and wetland-dominated vegetation
630 types. Most chamber sites in ABCflux include ca.10-20 individual plots in total from ca. 3-5 land
631 cover types where fluxes are being measured (Virkkala et al., 2018). Chambers can also provide
632 more direct estimates of Reco and GPP relative to eddy covariance-derived fluxes, and are
633 therefore useful for estimating the magnitude and range of those component fluxes. However,
634 manual chamber and diffusion measurements are laborious and have limited temporal
635 representation, particularly during the non-growing season when they often have only one

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636 monthly temporal replicate in ABCflux (McGuire et al., 2012; Fox et al., 2008). Automated
637 chamber measurements during the non-growing season are also rare in ABCflux.
638
639 Because of these methodological differences across the eddy covariance, chamber and diffusion
640 techniques, comparing fluxes between the methods may result in inconsistencies (Fig. 6). It has
641 been shown that chamber measurements can be both larger or smaller than the fluxes estimated
642 with eddy covariance (Phillips et al., 2017). This difference can be related to the uncertainties
643 with the eddy covariance technique as described above, or to the uncertainties with the chamber
644 technique (e.g., accurate determination of chamber volume, pressure perturbations, temperature
645 increase during the measurement, collars disturbing the ground and causing plant root excision).
646 The differences can also be due to the mismatch between the chamber and tower footprints (<1
647 m vs. 250–3000 m radii over the measurement equipment, respectively) and the difficulty of
648 extrapolating local chamber measurements to landscape scales (Marushchak et al., 2013; Fox et
649 al., 2008). However, several studies have also shown good agreement across the eddy covariance
650 and chamber measurements (Laine et al., 2006; Wang et al., 2013; Eckhardt et al., 2019; Riutta
651 et al., 2007). Potential mismatches may also be due to a bias towards daytime measurements in
652 manual chamber measurements (see field "Diurnal_coverage"). During daytime, plants are
653 actively photosynthesizing whereas respiration is the dominant flux at night (López-Blanco et al.,
654 2017). Presumably because of these day vs. night-time differences, we observed stronger sink
655 strength in manual chamber measurements compared to other flux measurements in ABCflux,
656 even though eddy covariance measurements have also been observed to underestimate night-time
657 CO_2 loss. This underestimation in night-time eddy covariance measurements is due to suppressed
658 turbulent exchange linked to stable atmospheric stratification, and systematic biases due to
659 horizontal advection (Aubinet et al., 2012). Despite these uncertainties, including fluxes
660 estimated with all of these techniques into one database improves the understanding of
661 underlying variability of landscape-scale flux estimates. Indeed, there are roughly 10 sites in
662 ABCflux that include both eddy covariance and chamber/diffusion measurements conducted at
663 the same time. These observations might not have identical site coordinates but they are often
664 very close to each other (<500 m away from each other). Including multiple methods from the
665 same site provides an opportunity to compare estimates from different methods over a larger
666 number of sites.

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668 4.2. Uncertainties in eddy covariance flux partitioning

669 Monthly Reco and GPP fluxes derived from eddy covariance were primarily estimated using flux
670 partitioning based on night-time Reco based on the assumption that during night, NEE measured
671 at low PAR is equivalent to Reco (Reichstein et al., 2005). Focusing on night-time partitioning
672 ensured that data from older sites using this partitioning method could be included, and that most
673 of the fluxes were standardized using one common partitioning method. However, particularly at
674 sites at higher latitudes of the ABZ, low-light night-time conditions are restricted to rather short
675 periods during summer, limiting the database for assessing Reco rates and therefore increasing
676 uncertainties associated with the night-time partitioning (López-Blanco et al., 2020). Recent
677 research suggests that other methods such as daytime partitioning (Lasslop et al. 2010), and even
678 more recently artificial neural networks (ANN) (Tramontana et al., 2020), might be more
679 accurate methods for flux partitioning by addressing the assumptions from night-time
680 partitioning methods (Pastorello et al., 2020; Papale et al., 2006; Reichstein et al., 2005; Keenan
681 et al., 2019). Specifically, the assumption of a constant diel temperature sensitivity during night-
682 and daytime might introduce error in eddy covariance-based Reco estimates extrapolated from
683 night-time measurements (Järveoja et al., 2020; Keenan et al., 2019). It should be noted that
684 ABCflux database used night-time partitioning of fluxes extracted from repositories for
685 consistency; however, fluxes contributed by some databases, PIs or extracted from papers may
686 be based on other partitioning methods, as noted in the database. In a few cases, observations
687 from the same site were based on different partitioning methods, which limits the usage of data
688 at those sites for time-series exploration. These different gap-filling and partitioning approaches
689 can impact the magnitude of monthly CO_2 budgets. For example, a study comparing four gap-
690 filling methods in a boreal forest showed that the 14-year average annual NEE budget varied
691 from 4 to 48 g C m^{-2} $year^{-1}$ depending on the gap-filling approach (Soloway et al., 2017).
692 However, a comparison of multiple gap-filling and partitioning methods across sites showed that
693 variation in annual GPP and Reco between partitioning methods was small (Desai et al., 2008),
694 which provides confidence in estimates from partitioned GPP and Reco components from the
695 differing methods used in this database.
696

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We suggest data users remain cautious when using ABCflux data to understand mechanistic relationships between meteorological variables and fluxes, as the gap-filled and partitioned monthly fluxes already include some information about, for example, air or soil temperatures and light conditions. To completely avoid circularity in these exploratory analyses, we recommend data users download the original and non-gap filled NEE records, or download fluxes partitioned in a way that is consistent and biologically relevant for the particular research question from flux repositories.

4.3. Representativeness and completeness of the data

The ABCflux database site distribution covers all vegetation types and countries within the ABZ. However, there are regional and temporal biases in the database due to the differences in accessibility for sampling certain regions (also documented in (Virkkala et al., 2019)). As a result, the number of monthly observations does not always correlate with the size of the country/region or vegetation type. For example, Russia and Canada cover in total ca. 80 % of the ABZ but include only ca. 40 % of the monthly observations. While the distribution of these measurements seems to be rather balanced between the Russian tundra and boreal biomes, Canadian observations are primarily located in the boreal biome, largely due to the high amount of measurements conducted as part of the Boreal Ecosystem-Atmosphere Study (Sellers et al., 1997). Deciduous needleleaf (i.e., larch) forests, the primary vegetation type in central and eastern Siberia, has the smallest amount of data compared to its area (<5 % of monthly observations vs. >20 % coverage of the ABZ). Additional data gaps are located in barren and prostrate-shrub tundra and sparse boreal vegetation. Eddy covariance towers in mountainous regions are also rare as eddy covariance towers are most often set up over homogeneous and flat terrains to avoid advection (Baldocchi, 2003; Etzold et al., 2010). Alaska and Finland cover <10 % of the ABZ but include >40 % of the monthly observations. Sites with NEE observations have the largest geographical coverage, with less availability for partitioned GPP and Reco fluxes. Therefore, regional summaries of Reco and GPP do not sum up to NEE. Moreover, although the oldest records in ABCflux originate from 1989, observations from the 1990s are primarily located in a few boreal or Alaskan tundra sites. The measurement records from tundra sites are

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shorter than boreal sites over the full time span of the database, and it is therefore more uncertain to investigate long-term temporal changes in tundra fluxes. Finally, the lowest amount of flux data in ABCflux is from winter, which is the most challenging period for data collection in high latitudes (Kittler et al., 2017b; Jentzsch et al., 2021). Fluxes are generally small during this period (Natali et al., 2019), leading to higher relative uncertainties in flux estimation compared to other seasons. These regional and temporal biases need to be considered in future analyses to assure the robustness of our understanding of C fluxes across the ABZ.

Although ABCflux includes a comprehensive compilation of flux and supporting environmental and methodological information, the information is not exhaustive. We acknowledge that this database is missing some eddy covariance sites that were recently summarized in a tower survey (see preliminary results in https://cosima.nceas.ucsb.edu/carbon-flux-sites/), because these data were unavailable at the time of database compilation. Moreover, the overall quality or the gap-filled percentage of the eddy covariance observations is not reported for each eddy covariance site, limiting the potential to explore the effects of data quality on fluxes across all the eddy covariance sites. Comparing soil temperature or moisture across sites has uncertainties due to differences in sensor depths, which are not always reported in the database. We hope to improve and increase the flux and supporting data in the future as new data are being collected, for example, by leveraging the ONEflux pipeline and its different outputs (Pastorello et al., 2020), as well as aggregating new measurements that are not part of any networks.

5. Data use guidelines

Data are publicly available using a Creative Commons Attribution 4.0 International copyright (CC BY 4.0). Data are fully public, but should be appropriately referenced by citing this paper and the database (see Section 6). We suggest that researchers planning to use this database as a core dataset for their analysis contact and collaborate with the database developers and relevant individual site contributors.

6. Data availability and access

The database associated with this publication can be found at Virkkala et al. 2021a (https://doi.org/10.3334/ORNLDAAC/1934).

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7. Conclusions

ABCflux provides the most comprehensive database of ABZ terrestrial ecosystem CO_2 fluxes to date. It is particularly useful for future modeling, remote sensing, and empirical studies aiming to understand CO_2 budgets and regional variability in flux magnitudes, as well as changes in fluxes through time. It can also be used to understand how different environmental conditions influence fluxes, and to better understand the current extent of the flux measurement network and its representativeness across the Arctic-Boreal region.

8. Author contributions

The ABCflux database was conceptualized and developed by a team led by SMN, BMR, JDW, MM, AMV, and EAGS, with additional comments from OS. KS and SJC compiled the data, with contributions from AMV, MM, DP, CM, and JN, and data screening by AMV and SMN. AMV drafted and coordinated the manuscript in close collaboration with SMN, BMR, JDW, KS, and MM. All authors contributed to the realization of the ABCflux database and participated in the editing of the manuscript. PIs whose data were extracted from publications are not coauthors in this paper, unless new data were provided, but their contact details can be found in the database.

9. Competing interests

The authors declare that they have no conflict of interest.

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