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Evaluation of terrestrial pan-Arctic carbon cycling using a data-assimilation system

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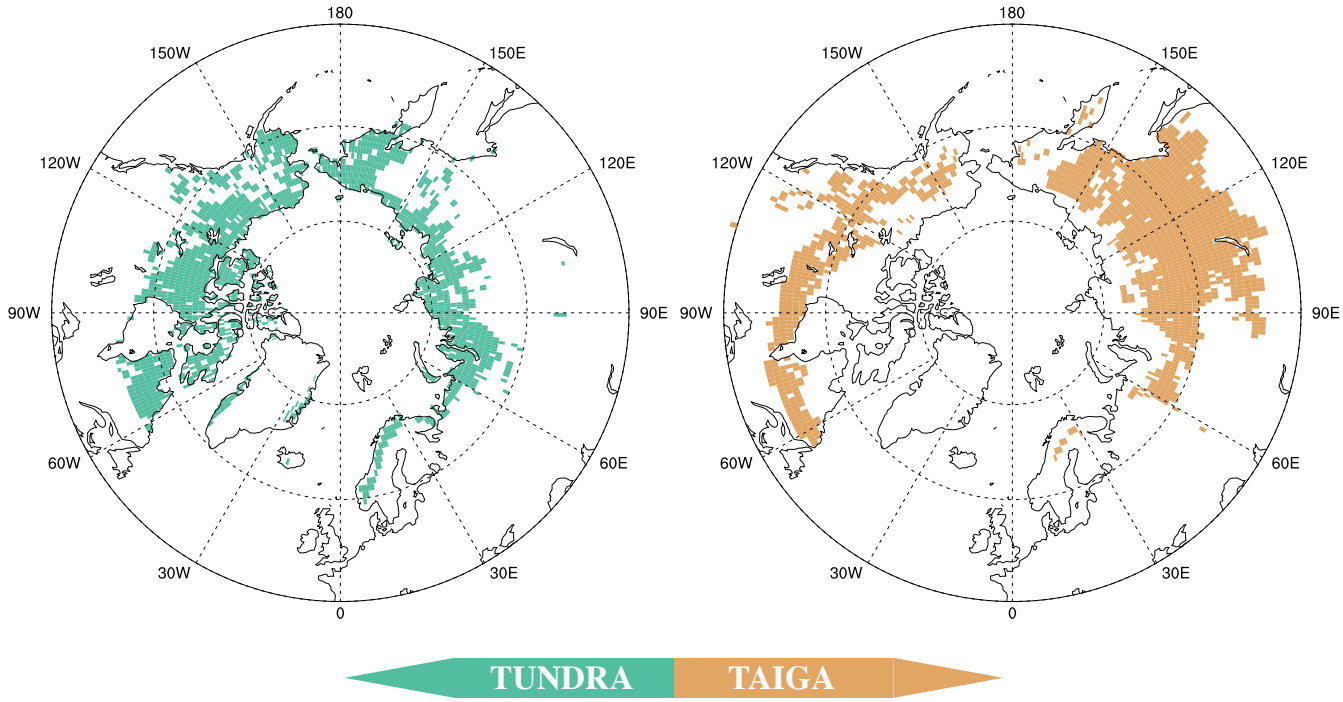

Figure S1. Spatial domain defined by the Northern Circumpolar Soil Carbon Database version 2 (NCSCDv2) region. The tundra-taiga regions were separated based on the presence-absence of forested areas using the GlobCover map (http://due.esrin.esa.int/page_globcover.php). Forested areas (taiga) included: closed to open broadleaved evergreen or semi-deciduous forest (>5m), closed (>40%) broadleaved deciduous forest (>5m), open (15-40%) broadleaved deciduous forest/woodland (>5m), closed (>40%) needleleaved evergreen forest (>5m), open (15-40%) needleleaved deciduous or evergreen forest (>5m) and closed to open (>15%) mixed broadleaved and needleleaved forest (>5m). Non-forested areas (tundra) included the rest of classes: mosaic forest or shrubland (50-70%) / grassland (20-50%),mosaic grassland (50-70%) / forest or shrubland (20-50%), closed to open (>15%) (broadleaved or needleleaved, evergreen or deciduous) shrubland, closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses), sparse (<15%) vegetation, closed to open (>15%) broadleaved forest regularly flooded (semi-permanently or temporary), closed (>40%) broadleaved forest or shrubland permanently flooded, and closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged, post-flooding or irrigated croplands (or aquatic), rainfed croplands, mosaic cropland (50-70%) / vegetation (grassland/shrubland/forest) (20-50%), mosaic vegetation (grassland/shrubland/forest) (50-70%) / cropland (20-50%), bare areas and permanent snow and ice. On top of that, latitudes lower than 52°N within the tundra domain were neglected to focus on higher latitudes.

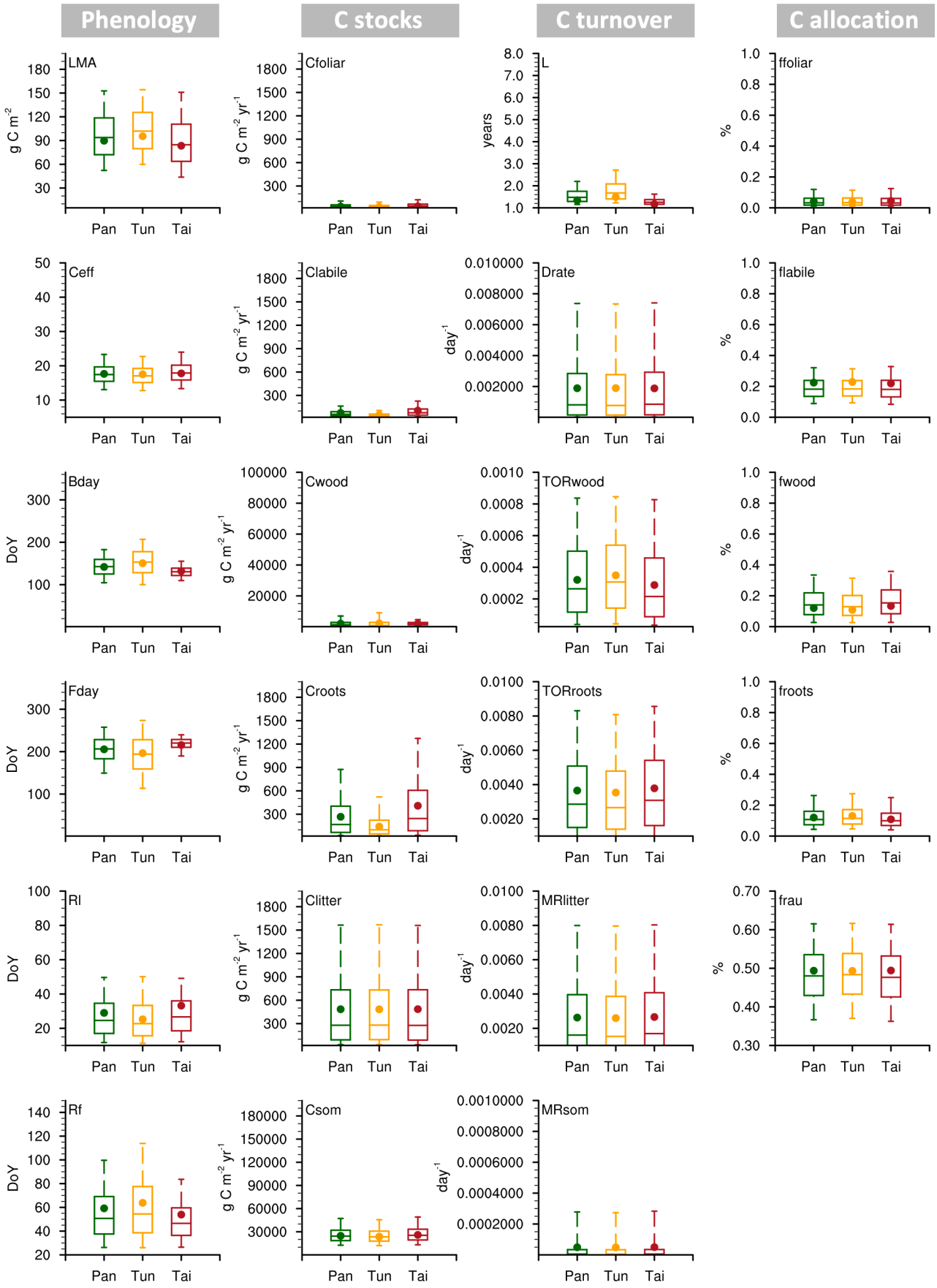

Figure S2. Posterior distributions of parameters estimated for the CARDAMOM assimilation framework in the Pan-Arctic pan-Arctic, tundra and taiga. All y-axes have been scaled to indicate prior ranges (Table S2). Whiskers indicate 90% confidence interval (P05-P95), box indicates interquartile range (P25-P75) and center line represents the median (P50). The whisker plots represents the average (spatial variability in pan-Arctic, tundra and taiga domains) for each percentile (P05, P25, P50, P75, P95).

Table S1. List of supplementary information detailing acronyms related to model structure, environmental forcing, data constraints, C flux, stocks, and transit times variables, model intercomparison projects, Global Vegetation Models, and statistical analyses.

Model structure used in this paper	
CARDAMOM	CARbon Data MOdel fraMework
DALEC2	Data Assimilation Linked Ecosystem Carbon version 2
ACM	Aggregated Canopy Model
MHMCMC	Metropolis-Hastings Markov Chain Monte Carlo
EDC	Ecological and Dynamic constraints
Environmental forcing	
ERA-Interim	European Centre for Medium-Range Weather Forecast Reanalysis interim dataset
Data constraints	
MODIS - LAI	MODerate resolution Imaging Spectroradiometer - Leaf Area Index
NCSCD - SOC	Northern Circumpolar Soil Carbon Database - Soil Organic Carbon
C flux variables	
NEE	Net Ecosystem Exchange
GPP	Gross Primary Production
NPP	Net Primary Production
R_{eco}	Ecosystem Respiration [Autotrophic Respiration + Autotrophic Respiration]
R_a	Autotrophic Respiration
R_h	Heterotrophic Respiration
C stock variables	
C_{photo}	Photosynthetic C stock [leaf + labile]
C_{veg}	Vegetation C stock [leaf + labile + stem + root]
C_{dom}	Soil C stock [litter + soil organic carbon]
C_{tot}	Total C stock [leaf + labile + stem + root + litter + soil organic carbon]
Transit times variables	
TT_{photo}	Photosynthetic transit time [leaf + labile]
TT_{veg}	Vegetation transit time [leaf + labile + stem + root]
TT_{dom}	Soil transit time [litter + soil organic carbon]
TT_{tot}	Total transit time [leaf + labile + stem + root + litter + soil organic carbon]
Model Intercomparison projects	
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
Global Vegetation Models (GVM)	
DLEM	Dynamic Land Ecosystem Model
LPJmL	Lund-Postdam-Jena managed Land
LPJ-GUESS	Lund-Postdam-Jena General Ecosystem Simulator
ORCHDEE	ORganizing Carbon and Hydrology In Dynamic Ecosystems Environment
VEGAS	Vegetation Global Atmosphere Soils
VISIT	Vegetation Integrative SImulator for Trace Gases
LPJ-WHyMe	Lund-Postdam-Jena - Wetland Hydrology and Methane model
TEM	Terrestrial Ecosystem Model
TCF	Terrestrial Carbon Flux model
CLM4C	Community Land Model for Carbon
CLM4CN	Community Land Model for Carbon and Nitrogen
O-CN	ORCHIDEE - Carbon Nitrogen
TRIFFID	Top-down Representation of Interactive Foliage and Flora Including Dynamics
BETHY/DLR	Biosphere Energy-Transfer Hydrology Model
Statistical analyses	
R^2	Coefficient of determination
RMSE	Root Mean Square Error
BIAS	Bias error
P05	5^{th} percetile
P25	25^{th} percetile
P50	50^{th} percetile
P75	75^{th} percetile
P95	95^{th} percetile

Table S2. DALEC2 model parameter description, and prior ranges based on ecologically viable limits allowed in the MHMCMC.

Process	Parameter	Name	Prior range	Units
Plant phenology	B_{day}	Leaf onset day	1-365	day
	F_{day}	Leaf fall day	1-365	day
	L_f	Leaf fall duration	20-150	day
	R_l	Labile C release duration	10-100	day
	C_{eff} *	Canopy efficency *	5.0-50	
	L	Lifespan	1.001-8	day
	LMA	Leaf mass per area	5-200	g C m^{-2}
Allocation of NPP	f_{rau} *	Fraction of GPP respired (Autotropic respiration) *	0.3-0.7	%
	f_{foliar}	Fraction of NPP to foliage C pool	0.01-1	%
	f_{labile}	Fraction of NPP to labile C pool	0.01-1	%
	f_{roots}	Fraction of NPP to roots C pool	0.01-1	%
	f_{wood}	Fraction of NPP to wood C pool	0.01-1	%
C pools	C_{foliar}	Foliar C stock	20-2000	g C m^{-2}
	C_{labile}	Labile C stock	20-2000	g C m^{-2}
	C_{wood}	Woody C stock	100-100000	g C m^{-2}
	C_{roots}	Fine root C stock	20-2000	g C m^{-2}
	C_{litter}	Litter C stock	20-2000	g C m^{-2}
	C_{SOM}	Soil organic matter C stock	100-200000	g C m^{-2}
Turnover rates	TOR_{wood}	Wood turnover	0.000025-0.001	day^{-1}
	TOR_{roots}	Root turnover	0.0001-0.01	day^{-1}
	MR_{litter}	Litter mineralization	0.0001-0.01	day^{-1}
	MR_{som}	Soil organic matter mineralization	0.0000001-0.001	day^{-1}
	D_{rate}	Decomposition rate	0.00001-0.01	day^{-1}
	T_{dep}	Temperature dependence exponent factor	0.018-0.08	

* Parameter log-normal prior distributions are described in Bloom et al., 2016 SI text, secion S1.

Table S3. Forcing dataset, observational constraints and independent validation datasets used in this study's experimental design.

Dataset	Source	Forcing	Constraint	Validation
ERA-Interim	Dee et al. (2011)	X		
MODIS - LAI	Myneni et al. (2002)		X	
NCSCD - SOC	Hugelius et al. (2003)		X	
Biomass	Carvalhais et al. (2014)		X	
NEE, GPP, R_{eco}	FLUXNET2015			X
GPP	Jung et al. (2017)			X
R_h	Hashimoto et al. (2015)			X

Table S4. Data set description of the 8 selected sites derived from the FLUXNET2015 database. MAT stands for Mean Annual Temperature while MAP for Mean Annual Precipitation.

Site ID	DK-NuF	DK-ZaH	RU-Ha1	US-Prr	CA-Man	CA-NS7	RU-Sam	RU-Tks
Site Name	Nuuk Fen	Zackenberg Heath	Hakasia	Poker Flat	Manitoba	UCI-1998 burn site	Samoylov	Tiksi
Latitude	64.1	74.5	54.7	65.1	55.9	56.6	72.4	71.6
Longitude	-51.4	-20.6	90.0	-147.5	-98.5	-99.9	126.5	128.9
MAT (°C)	-1.4	-9.0	-	-2.0	-3.2	-3.5	-	-12.7
MAP (mm)	750.0	211.0	-	275.0	520.0	483.0	-	323.0
Eco-type	Wetland	Heathland	Grasslands	Evergreen Needleleaf	Evergreen Needleleaf	Open shrubland	Grassland	Grasslands
Tundra-Taiga	Tundra	Tundra	Tundra	Taiga	Taiga	Taiga	Tundra	Tundra
Data availability	2008-2015	2000-2014	2002-2004	2010-2014	1994-2008	2002-2005	2002-2014	2010-2014

Table S5. General properties and degree of complexity of each ISI-MIP2a model [DLEM, LPJmL, LPJ-GUESS, ORCHIDEE, VEGAS and VISIT] included in this study. (m) stands for the cause of mortality in each vegetation model. The model details included in this study have been retrieved from https://www.**isimip.org/impactmodels/.**

GVM	Model version	Vegetation	PFT	Spin-up	Nitrogen	Permafrost	Age (m)	Fire (m)	Drought (m)	Reference
DLEM	**v2**	Fixed PFT	14	Yes	Yes	Yes	Yes	No	No	Tian et al. (2015)
LPJmL	**-**	DGVM	17	Yes	No	Yes	No	Yes	No	Sitch et al. (2003); Schaphoff et al. (2013)
LPJ-GUESS	**v3.1**	DGVM	11	Yes	Yes	No	Yes	Yes	No	Smith et al. (2014)
ORCHIDEE	**rev3013**	Fixed PFT	16	Yes	No	No	No	Yes	No	Guimbertau et al. (2018)
VEGAS	**v2.3**	DGVM	7	Yes	Yes	Yes	Yes	Yes	Yes	Zeng et al. (2005)
VISIT	**VISITa**	Fixed PFT	33	Yes	No	No	No	Yes	No	Ito and Inatomi (2012)

Table S6. Statistics of linear fit between the CARDAMOM framework (independent) and the FLUXNET2015 field observations (dependent) per individual site and per C flux [NEE, Net Ecosystem Exchange; GPP, Gross Primary Production; R_{eco}, ecosystem Respiration]. The units for RMSE and bias are g C m^{-2} $month^{-1}$.

Flux	Site	Country	Intercept	Slope	R^2	RMSE	Bias
NEE	**Hakasia**	**[RU]**	0.89	1.40	0.85	0.67	0.49
	Kobbefjord	**[GL]**	-0.11	0.35	0.58	0.21	0.08
	Manitoba	**[CA]**	0.10	0.66	0.70	0.55	0.41
	Poker Flat	**[US]**	0.15	0.83	0.81	0.37	0.25
	Samoylov	**[RU]**	0.06	0.45	0.87	0.05	0.14
	Tiksi	**[RU]**	0.00	0.38	0.41	0.26	0.02
	UCI-1998	**[CA]**	-0.26	0.59	0.65	0.50	-0.15
	Zackenberg	**[GL]**	0.03	0.37	0.54	0.07	0.04
GPP	**Hakasia**	**[RU]**	-0.24	1.80	0.98	0.57	1.21
	Kobbefjord	**[GL]**	0.31	0.62	0.80	0.35	-0.07
	Manitoba	**[CA]**	0.63	1.30	0.93	0.73	1.15
	Poker Flat	**[US]**	0.06	1.20	0.93	0.51	0.30
	Samoylov	**[RU]**	0.01	0.70	0.98	0.06	-0.14
	Tiksi	**[RU]**	0.14	0.78	0.87	0.36	-0.05
	UCI-1998	**[CA]**	1.00	1.30	0.82	0.95	1.32
	Zackenberg	**[GL]**	0.22	0.57	0.84	0.14	-0.01
R_{eco}	**Hakasia**	**[RU]**	0.59	1.20	0.98	0.30	0.87
	Kobbefjord	**[GL]**	0.12	0.65	0.86	0.17	-0.22
	Manitoba	**[CA]**	0.96	0.91	0.80	0.81	0.81
	Poker Flat	**[US]**	0.21	1.20	0.89	0.35	0.34
	Samoylov	**[RU]**	0.06	0.87	0.89	0.11	0.01
	Tiksi	**[RU]**	0.20	0.64	0.76	0.35	-0.15
	UCI-1998	**[CA]**	0.57	1.20	0.83	0.59	0.81
	Zackenberg	**[GL]**	0.24	0.66	0.86	0.09	0.10