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Key Points:

- Terrestrial carbon export from the Laptev Sea shelf to the slope and rise is studied using δ¹³C/Δ¹⁴C, biomarkers and ²¹⁰Pb mass accumulation
- The accumulation of terrestrial carbon declines by 52% at the shelf edge and by 68% from slope to rise due to transport and degradation dynamics
- A terrestrial carbon budget for the Laptev Sea suggests 80%–90% of the input is retained on the shelf via accumulation and re-mineralization

Supporting Information:

Supporting Information may be found in the online version of this article.

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Off-Shelf Transport and Biogeochemical Cycling of Terrestrial Organic Carbon Along the East Siberian Continental Margin

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Abstract Continental margins receive, process and sequester most of the terrestrial organic carbon (terrOC) released into the ocean. In the Arctic, increasing fluvial discharge and collapsing permafrost are expected to enhance terrOC release and degradation, leading to ocean acidification and translocated CO₂ release to the atmosphere. However, the processes controlling terrOC transport beyond the continental shelf, and the amount of terrOC that reaches the slope and the rise are poorly described. Here we study terrOC transport to the Laptev Sea continental slope and rise by probing surface sediments with dual-isotope ($\delta^{13}C/\Delta^{14}C$) source apportionment, degradation-diagnostic terrestrial biomarkers (n-alkanes, n-alkanoic acids, lignin phenols) and 210 Pb_{xs}-based mass accumulation rates (MAR). The MAR-terrOC (g m⁻² yr⁻¹) decrease from 14.7 ± 12.2 on the shelf, to 7.0 ± 5.8 over the slope, to 2.3 ± 0.3 for the rise. Scaling this to the respective regimes yields that 80% of the terrOC accumulates on the shelf, while 11% and 9% of the accumulation occurs in slope and rise sediments, respectively. TerrOC remineralization is evidenced by biomarker degradation proxies (CPI of nalkanes and 3,5Bd/V) indicating 40% and 60% more terrOC degradation from slope to rise, consistent with a decline in terrOC concentrations by 57%. TerrOC degradation only partially explains this decline. An updated Laptev Sea terrOC budget suggests that sediment transport dynamics such as turbidity currents may drive terrOC shelf-basin export, contributing to the observed accumulation pattern. This study quantitatively demonstrates that Arctic shelf seas are key receptor systems for remobilized terrOC, emphasizing their importance in the carbon cycle of the rapidly changing Arctic.

1. Introduction

Land-ocean export of terrestrial organic carbon (terrOC) is an important component of the global biogeochemical cycle and the climate-carbon system (Battin et al., 2009; Berner, 1989; Hedges & Keil, 1995; Hilton et al., 2015). In the Arctic region, climate warming at rates three times the global average (AMAP, 2021; Meredith et al., 2019; Rantanen et al., 2022) raises concerns about permafrost thawing and an associated increase in terrOC export to the Arctic Ocean. Over the past half-century, Arctic warming has already led to an 8% increase in river discharge (Durocher et al., 2019; Peterson et al., 2002; Shiklomanov et al., 2021). Continued warming is expected to accelerate permafrost thawing, causing significant degradation of Arctic peatlands (Hugelius et al., 2020; Romanovsky et al., 2017), and accelerating erosion of Ice-rich Permafrost coastlines (i.e., ICD) around the Arctic Ocean (Fritz et al., 2017; Jones et al., 2018; Vonk et al., 2012). These processes may amplify terrOC translocation to the extensive Arctic shelf seas (Hugelius et al., 2020; Nielsen et al., 2022; Schuur et al., 2015; Vonk & Gustafsson, 2013), where most of the terrOC undergoes either re-mineralization or accumulates in shelf sediments (Bröder et al., 2018; Martens et al., 2022; Sánchez-García et al., 2011; Stein & Macdonald, 2004). However, a fraction of the terrOC escapes degradation during the shelf passage and is transported offshore to the continental slope, continental rise and deep ocean basin. Depending on the re-mineralization and burial efficacy of the continental margin, shelf-basin export of terrOC can contribute to severe ocean acidification and atmospheric emissions of greenhouse gases (Anderson et al., 2009; Semiletov et al., 2016). Alternatively, it may sequester carbon in sediments, thereby removing it from active biogeosphere-atmosphere cycling. The land-ocean export of terrOC particularly impacts the East Siberian Arctic Shelf (ESAS) consisting of the Laptev Sea (LS), the





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East Siberian Sea (ESS) and the Russian Chukchi Sea. This region alone, constituting the World's largest shelf sea system, receives 50% (or 22 Tg) of the total annual release of circum-Arctic terrOC (Martens et al., 2022).

The expected increase in terrOC mobilization has led to a growing body of research focusing on the degradation and fate of terrOC in the recipient ESAS seas. Previous studies have utilized a variety of molecular and isotopic tools in surface sediments to study terrOC degradation with its increasing distribution across the shelf (e.g., Bröder et al., 2016; Matsubara et al., 2022; Vonk et al., 2010) and offshore transport time (Bröder et al., 2018). However, there is a lack of comprehensive studies beyond the shelf boundaries. Across the ESAS, different terrOC sources exhibit varying vulnerability to degradation (Bröder et al., 2016; Matsubara et al., 2022; Vonk et al., 2010), which may partly reflect the intrinsic degradability of the source material. The degradability of the terrOC transported to the ESAS is influenced by the different OC phases, that is, dissolved OC (DOC) and particulate OC (POC) (Alling et al., 2010; Karlsson et al., 2016; Sánchez-García et al., 2011). Furthermore, hydrodynamic sorting of sediments during transport across the shelf further complicates degradation patterns (Bröder et al., 2018; Tesi et al., 2016). Outside the ESAS, the importance of degradation in the slope and rise are largely unknown, and slope-basin terrOC transport may be dictated by poorly understood resuspension processes and turbidity currents (Fahl & Nöthig, 2007), leaving the amount of terrOC reaching these systems uncertain. Estimates of shelf-basin export of terrOC in the ESAS region vary widely, ranging from 0.032 to 0.068 (Sánchez-García et al., 2011) to 1.03 Tg yr⁻¹ (Stein et al., 2004), diverging by a factor of 20. Consequently, off-shelf terrOC export remains poorly defined, resulting in large uncertainties in quantifying the fate of terrOC along the Siberian continental margin.

This study quantifies terrOC accumulation across the entire Laptev Sea continental margin with the particular novelty being to examine the role of the continental slope and rise systems as terrOC receptor systems. To quantify terrOC export, we utilize quantitative OC source apportionment based on OC isotopes (13 C-OC and 14 C-OC), an assessment of terrOC degradation using a suite of diagnostic terrestrial biomarkers (high-molecular weight HMW *n*-alkanes and *n*-alkanoic acids, as well as lignin phenols) in surface sediments recovered across a depth range from the shelf (<100 m below sea level—bsl) to the continental slope (210–2,200 m bsl) and rise (2,200–3,100 m bsl). We also use mass accumulation rates (MAR) of terrOC, determined by 210 Pb_{xs} (based on the excess of 210 Pb radioactivity over 226 Ra) analysis of sediment cores, to investigate terrOC fluxes along the shelf-basin continuum. We take advantage of observations from the well-studied Laptev Sea shelf (e.g., Bröder et al., 2016; Karlsson et al., 2011; Tesi et al., 2016; Vonk et al., 2021a, 2021b) and add to these observations new analysis of sites on the Laptev Sea slope and rise. In addition, central to this work is a slope- and rise-focused expansion of 210 Pb_{xs} determination for 12 new sediment cores. This permits an updated terrOC budget for the Laptev Sea, aiming to refine the poorly quantified shelf-basin terrOC vector for the ESAS region and as a model for comprehending terrOC dynamics in other Arctic continental margins.

2. Materials and Methods

2.1. Sample Material

This study includes surface sediments and sediment cores collected primarily along three study transects from two expeditions to the ESAS and the central Arctic Ocean (Figure 1; Table 1). We define the three study systems (continental shelf, slope and rise) based on the physiographic province classification of the Arctic Ocean by Jakobsson et al. (2003), which is based on steepness (shelf $0-0.5^\circ$, slope >1.5°, rise $0.5-1.5^\circ$, basin <0.5°). Transect A spans along 125° East, ranging from the outer Laptev Sea shelf at 64 m to the continental rise at 3,120 m water depth, which was previously included in research centered around terrOC degradation along a 130° East cross-shelf transect (Bröder et al., 2016) that in turn builds on various prior studies in this area (e.g., Karlsson et al., 2011; Tesi et al., 2016; Vonk et al., 2012). To expand the data on transect A, this study includes new data for a yet largely unstudied transect B around 137° East (Figure 1). This transect stretches from the outer shelf at 70 m bsl in the eastern Laptev Sea to the slope and rises at 3,100 m bsl. Both transects were sampled during the Swedish-Russian-US Arctic Ocean Investigation of Climate-Cryosphere-Carbon Interactions (SWERUS-C3) in 2014 onboard the icebreaker *Oden*. To provide additional observations of slope sediments in the western Laptev Sea, a new third transect along the upper slope at depths between 150 and 360 m bsl was added (Figure 1). This additional transect is based on samples collected on the International Siberian Shelf Study 2020 (ISSS-2020) expedition onboard the research vessel *Akademik M. Keldysh*.





Figure 1. Overview maps of the Laptev Sea continental margin and the study area. Map a shows the different sampling locations as colored symbols and the locations for mass accumulation rates (MAR) indicated as hexagonal symbols. Map b shows the three depositional regimes investigated in this study, that is, the Laptev Sea shelf, slope and rise. The dashed line indicates the cross-section of the Laptev Sea continental margin illustrated in Figure 4.

2.2. Bulk Carbon and Isotope Analysis

To assess the quantity and sources of organic carbon (OC) across all surface samples in this study, we conducted a gap-filling analysis of bulk OC and its isotopes (¹³C-OC, ¹⁴C-OC; Table 1). Data for transect A (Figure 1) were previously published by Bröder et al. (2016). For transect B, most data were made available through CASCADE (Martens et al., 2021a, 2021b), while we analyzed ¹⁴C-OC for three samples to complete the data set. For the new outer Laptev Sea slope transect, all bulk OC and isotope data were generated for the purpose of this study. These analyses followed established laboratory routines at Stockholm University, as detailed by for example, Martens et al. (2021a, 2021b). Briefly, freeze-dried and homogenized surface sediments (0–1 cm) were weighed into silver cups and repeatedly acidified with 1M hydrochloric acid (HCl) to remove marine carbonates. For OC and ¹³C-OC analysis, samples were measured using a Finnigan Delta Plus XP mass spectrometer coupled to a Thermo Fisher Scientific Flash 2000 Isotope Ratio Mass Spectrometer Element Analyzer via a Conflo II interface. Measurements of ¹⁴C-OC were conducted at the Tandem Laboratory of Uppsala University.

2.3. Sediment Surface Area

The mineral-specific surface area (SA; $m^2 g^{-1}$ sediment) is used as a conservative parameter to normalize OC sub-fraction and biomarker concentrations in marine environments to reveal degradation patterns. For sediment SA analysis, we followed a laboratory protocol as described in detail by Bröder et al. (2016), which has been applied in various other studies (e.g., Martens et al., 2021a, 2021b; Tesi et al., 2016). This protocol includes a procedure where freeze-dried sediments are combusted at 400°C for 12 hr to remove organic matter, followed by repeated rinses with MQ water and freeze-drying. Samples were degassed with N₂ for 2 hr at 200°C in a Micromeritics FlowPrep 060 Sample Degas System and analyzed on a Micromeritics Gemini VII Surface Area and Porosity analyzer.

2.4. Dual-Isotope Source Apportionment

To quantify the fraction of terrOC to the total OC in marine surface sediments, a dual-isotope $(\delta^{13}C/\Delta^{14}C)$ mass balance was used, integrated in a Markov Chain Monte Carlo method. Our approach builds on a series of studies primarily conducted on the Siberian Shelf, aiming to quantify OC source fractions originating from permafrost soils, particularly the seasonally thawed active layer, and OC mobilized from the erosion of coastal



Table 1

Overview of the Sampling Locations and Data Used in This Study

						MAR	SA				HMW	HMW n-alkanoic	Lionin	TerrOC
Q	T .		D 1	P	D 11.1	$(g m^{-2})$	(m^2)	OC	$\delta^{13}C$	$\Delta^{14}C$	<i>n</i> -alkanes	acids	phenols	flux
Station	Lat	Lon	Depth	Dep. env.	Expedition	yr ')	g ')	(%)	(%0)	(%0)	(ng m ⁻)	(ng m ²)	(µg m ²)	(g yr ⁻)
LS Transect 130°	E 71.620	120.050	7	61 16	1000 2000	22228	11 db	1.010	26.06	504.49	10(1)	11.517b	25 1 ch	50.0 + 0.2
YS-14	71.050	130.050	10	Shelf	1555 2008	3333-	11.4 [°]	1.91	-26.2	-504.4	1061°	11,51/*	35.18°	50.8 ± 8.3
YS-13	/1.968	131./01	19	Shelf	1555 2008		23.5	1.89	-25.9	-542.6	639 1600	2,271	0.51 45.15	
1B-46	72.701	130.175	0	Shelf	1555 2008		12.0	2.58	-26.5	-436.0	1688 45 4b	7,129	45.15	
YS-9	73.366	129.997	23	Shelf	1555 2008	2027f	16.9 [°]	1.31-	-26.1	-422.7	454°	1,049°	5.58°	20 7 . 7 2
15-0 SW 24	75.500	130.010	32	Shell	1555 2008	2857 1054	31.0°	1.80	-25.7	-405.2	170b	907	2.05 0.75b	38.7 ± 7.3
5w-24	75.599	129.558	40	Snell	2014	1954	37.0	1.07	-24.5	-284.5	179	1,392	0.75	10.2 ± 3.0
YS-4	75.987	129.984	50	Shelf	SWERUS 2014		31.4 ^b	1.34 ^a	-24.3 ^a	-436.6 ^a	136 ^b	918 ⁶	0.85 ^b	
SW-23	76.171	129.333	56	Shelf	SWERUS 2014	986 ^f	21.7 ^b	1.58 ^b	-25.0 ^b	−333.3 ^b	160 ^b	1,188 ^b	0.95 ^b	8.9 ± 2.4
Additional MAR l	ocations on	the LS shelf												
YS-19 2B	73.035	133.456	27	Shelf	ISSS 2008	2517 ^f	30.9	1.82 ^a	-25.8 ^a	-556.8^{a}				9.0 ± 1.6
SW-28	77.342	135.007	49	Shelf	SWERUS 2014	1125 ^f	36.4	1.40 ^g	-23.8 ^g	-416.5 ^g				36.4 ± 5.3
Transect A (125°)	E)													
SW-14	76.894	127.798	64	Shelf	SWERUS 2014	919 ^f	19.4 ^b	0.89 ^b	-24.3 ^b	-314.0 ^b	148 ^b	462 ^b	1.01 ^b	4.1 ± 1.1
SW-6	77.150	127.352	92	Shelf	SWERUS 2014	1,315	14.9 ^b	0.76 ^b	-23.2 ^b	-363.9 ^b	181 ^b	662 ^b	0.66 ^b	4.9 ± 1.0
SW-4	77.938	126.518	2,186	Rise	SWERUS 2014	360	41.5 ^b	1.32 ^b	-22.5 ^b	-428.0 ^b	93 ^b	104 ^b	0.41 ^b	2.5 ± 0.4
SW-3	78.238	126.150	2,601	Rise	SWERUS 2014		31.8 ^b	1.06 ^b	-22.6 ^b	-426.3 ^b	126 ^b	750 ^b	0.33 ^b	
SW-2	78.581	125.607	2,900	Rise	SWERUS	324	38.3 ^b	1.38 ^b	-22.7 ^b	-391.8 ^b	128 ^b	569 ^b	0.40 ^b	2.2 ± 0.4
SW-1	78.950	125.232	3,120	Rise	SWERUS		34.0 ^b	1.04 ^b	-22.3 ^b	-418.1 ^b	141 ^b	266 ^b	0.55 ^b	
Transect B (137°)	E)													
SW-30	78.182	138.355	69	Shelf	SWERUS 2014	1,377	27.7 ^h	1.08 ^h	-23.3 ^h	-465.1 ⁱ	138	59	0.33	8.5 ± 1.2
SW-38	78.481	137.274	118	Shelf	SWERUS 2014	804	25.9 ^h	0.89 ^h	-22.7 ^h	-403.2 ⁱ	120	40	0.19	3.6 ± 0.6
SW-37	78.521	137.170	205	Slope	SWERUS	958	22.6	0.80 ⁱ	-23.1 ⁱ	-387.5	157	96	0.29	3.8 ± 0.7
SW-36	78.581	137.338	360	Slope	SWERUS	835	30.6	0.99 ⁱ	-22.7 ⁱ	-409.6	140	101	0.17	4.2 ± 0.6
SW-35	78.600	137.061	541	Slope	SWERUS	858	37.9	1.18 ⁱ	-23.3 ⁱ	-430.2 ⁱ	148	120	0.18	5.5 ± 0.8
SW-34	78.758	136.501	1,880	Slope	SWERUS	546	41.3	1.38 ⁱ	-22.8^{i}	-418.5 ⁱ	117	63	0.60	3.9 ± 0.6
SW-33	78.927	136.178	2,264	Slope	SWERUS		38.6	1.37 ⁱ	-22.8 ⁱ	-425.6 ⁱ	152	83	0.15	
SW-32	79.093	135.760	2,540	Rise	2017	378	36.6	1.27 ⁱ	-22.8 ⁱ	-455.3 ⁱ	146	102	0.18	2.6 ± 0.3



Table 1

(LO	ni	in	u	20

Station	Lat	Lon	Depth	Dep. env.	Expedition	MAR (g m-2 yr-1)	SA (m2) g-1	OC (%)	δ ¹³ C (‰)	Δ^{14} C (‰)	HMW <i>n</i> -alkanes (ng m ⁻²)	HMW <i>n</i> -alkanoic acids (ng m ⁻²)	Lignin phenols (µg m ⁻²)	TerrOC flux (g yr ⁻¹)
					SWERUS 2014									
SW-31	79.396	135.497	3,056	Rise	SWERUS 2014		33.5	1.23 ⁱ	-23.1 ⁱ	-489.4 ^g	176	111	0.19	
LS slope sedimen	nts													
AMK-6939	77.285	122.097	290	Slope	ISSS 2020		27.4	0.98	-25.3	-383.3	131	101	0.38	
AMK-6941	77.101	125.096	360	Slope	ISSS 2020	2,286	8.3	0.35	-23.5	-485.2	193	148	0.78	4.8 ± 0.6
AMK-6943	77.067	125.783	210	Slope	ISSS 2020		6.9	0.27	-22.5	-502.4	206	270	1.01	
AMK-6945	77.100	126.480	150	Shelf	ISSS 2020		9.5	0.45	-25.1	-739.7	413	363	3.33	
AMK-6946	77.142	126.795	305	Slope	ISSS 2020	2,434	17.7	0.59	-23.2	-693.4	311	206	1.45	10.3 ± 0.6
AMK-6994	77.272	120.608	275	Slope	ISSS 2020		19.6	0.65	-23.6	-374.9	126	160	0.34	

Note. All published data were retrieved from CASCADE (Martens et al., 2021a, 2021b), originating from previous work as follows. ^aData from Vonk et al. (2012). ^bData from Bröder et al. (2016). ^cData from Karlsson et al. (2011). ^dData from Tesi et al. (2016). ^cData from Sparkes et al. (2016). ^fData from Martens et al. (2022). ^gData from Salvadó et al. (2016). ^hData from Bröder et al. (2019). ⁱData from Martens et al. (2019).

ice-rich and old ICD. This approach follows a method initially introduced in this region by Vonk et al. (2010), and was further refined by Andersson et al. (2015) and applied in a series of studies across various regions (e.g., Bröder et al., 2018; Karlsson et al., 2016; Vonk et al., 2012; Wild et al., 2019) and time scales (Martens et al., 2019, 2020). More recently, the method was further advanced by correcting for terrOC aging during cross-shelf transport (Martens et al., 2022), which was quantitatively described by Bröder et al. (2018). The source apportionment builds on large collections of $\Delta^{14}C/\delta^{13}C$ fingerprints of different OC sources as end members. We consider as terrOC sources $\Delta^{14}C/\delta^{13}C$ observations of samples from the permafrost active layer down to a depth of 1 m as well as from coastal ICD exposures, while $\Delta^{14}C/\delta^{13}C$ observations of marine phytoplankton samples serve as the marine end member. For the two terrestrial end member data sets, only observations from within the Laptev Sea watershed were considered. The $\delta^{13}C$ value of the surface soil end member was $-26.9 \pm 1.0\%$ (n = 46) and the Δ^{14} C was $-227.8 \pm 212.1\%$ (n = 23), while for ICD, the isotope ratios were $-963.0 \pm 64.1\%$ (*n* = 286) for Δ^{14} C and $-26.2 \pm 0.7\%$ (*n* = 568) for δ^{13} C. For marine OC, a wide δ^{13} C endmember was chosen to account for the potential influence of terrOC on the isotopic composition of marine phytoplankton in the Laptev Sea ($-23.2 \pm 3.5\%$; n = 52), while for Δ^{14} C, the end member is more sharply defined $(-16 \pm 53\%)$; n = 12). The complete end member database used in this study is provided in Data Set S1. To correct for terrOC aging during cross-shelf transport, the distance between sampling stations and the closest river mouth (i.e., the Lena River in the Buor Kaya Bay) was used for the surface soil OC end member. For ICD-OC, the offshore distance to sites of coastal erosion was used. The source apportionment was run in Matlab 2022b using the script published by Martens et al. (2022), with 1,000,000 runs and a burn-in period of 100,000 runs per sample. Detailed results of the source apportionment are reported in Table S2 of the Supporting Information S1.

2.5. Terrestrial Biomarker Analyses

To support dual-isotope source apportionment of OC, this study utilized terrestrial biomarkers to further resolve terrOC sources and investigate its degradation during shelf-basin transport. Terrestrial biomarkers included high molecular weight (HMW) compounds of leaf waxes, that is, *n*-alkanes with homolog chain lengths >23 and *n*-alkanoic acids with chain lengths >24, as well as lignin phenols. For transect A, we re-evaluated wax lipid and lignin phenols data previously published by Bröder et al. (2016). For all samples from transect B and the additional slope samples, we analyzed wax lipids and lignin phenols.

The HMW n-alkanes and n-alkanoic acids were extracted from freeze-dried sediments using an accelerated solvent extraction method (ASE, Dionex 300) and underwent a chemical clean-up procedure as described by Matsubara et al. (2022). Briefly, 3 g of freeze-dried sediment was extracted using dichloromethane:methanol (DCM:MeOH, 9:1 v/v) alongside five internal recovery standards (tetracosane-d50, triacontane-d62, eicosanoic acid-d39, 2-hexadecanol and stigmasterol-d5). Extracts were separated into their acid fraction (containing nalkanoic acids) and neutral fraction using a BondElut cartridges (Agilent Technologies USA) with diethyl ether +4% acetic acid and dichloromethane: isopropanol (2:1), respectively. The neutral fraction was further separated on a 100% activated Al_2O_3 column with eluents hexane:dichloromethane (9:1), resulting in a nonpolar fraction (including *n*-alkanes), and methanol:dichloromethane (1:1) to elute polar compounds. The acid and non-polar fractions were analyzed using a gas chromatograph with mass spectrometer detector (GC-MS 7820A, Agilent Technologies USA) in splitless mode with a DB-5 column (30 m, 0.25 µm film, 0.32 mm diameter). Integrated peak signals were quantified using external quantification standards of long-chain *n*-alkanes and *n*-alkanoic acids. We report concentrations of HMW *n*-alkanes ($\sum C_{23}$ - C_{33}) and *n*-alkanoic acids ($\sum C_{24}$ - C_{32}) as normalized to SA (ng m^{-2}). The carbon preference index (CPI) was used as a degradation proxy of terrOC for both compound classes (CPI_{alk} for HMW *n*-alkanes; CPI_{acid} for HMW *n*-alkanoic acids). The CPI_{alk} is based on the degree of the odd-over-even predominance of HMW n-alkane homologs, while the CPIacid is based on the even-over-odd predominance of HMW n-alkanoic acids (Marzi et al., 1993). Both CPI's are expected to decrease toward 1 with increasing degradation.

For lignin phenols analysis, a CuO oxidation method was employed using an UltraWAVE Milestone 215 microwave digestion system, as described previously (Martens et al., 2019; Tesi et al., 2014). About 0.5 g of freezedried sediment was loaded into Teflon tubes together with 300 mg of cupric oxide (CuO), 50 mg of ammonium iron (II) sulfate hexahydrate, 10 ml of 2 M NaOH solution, and extracted for 90-min duration at 130°C in the microwave system. Internal recovery standards (ethyl-vanillin, cinnamic acid) were added and the samples were acidified to pH 1 using concentrated HCl, and extracted from the water phase using ethyl acetate. The ethyl acetate was evaporated in a CentriVap (Christ RVC 2–25) at 60°C for 1 hr and extracts were redissolved in pyridine, and derivatized using bis-trimethylsilyl trifluoroacetamide (BSTFA) with 1% trimethylchlorosilane (TMCS) prior to analyzes using a GC-MS (7820A, Agilent Technologies USA) using a DB5-MS column (30 m, 0.25 µm film, 0.32 mm diameter). We report total lignin concentrations as a sum of vanillin (Vl), acetovanillone (Vn), vanillic acid (Vd), syringaldehyde (Sl), acetosyringone (Sn), syringic acid (Sd), p-coumaric acid (pCd) and ferulic acid (Fd) normalized to SA (ng m⁻²). Additionally, we used the ratio of 3,5-dihydrobenzoic acid (3,5-Bd) to vanillyl lignin phenols (V) to assess terrOC degradation, as abundant research in the Arctic Ocean demonstrates that 3,5-Bd and V are in this system overwhelmingly originating from soil organic matter (e.g., Tesi et al., 2014).

2.6. Determination of Mass Accumulation Rates Using ²¹⁰Pb_{xs}

Mass accumulation rates (MAR) of Laptev Sea sediments were used to estimate terrOC accumulation rates in sediments from the shelf, slope and rise. Previous MAR determinations using ²¹⁰Pb_{xs} in the Laptev Sea were restricted to the shelf areas (Martens et al., 2022; Vonk et al., 2012). This study adds new MAR data for 12 locations from the slope and the rise of the Laptev Sea. The calculation of MAR is based on depth-integrated inventories of ²¹⁰Pb_{xs} in shallow sediment profiles, following the approach by Vonk et al. (2012). Excess ²¹⁰Pb was determined based on measurements of both ²¹⁰Pb and ²²⁶Ra carried out by Flett Research (Winnipeg, Canada) for 10 cores from transect A and B. Two cores from the Laptev Sea slope transect were analyzed at the GEOKhI Institute in Moscow, Russia (AMK82-6941 and AMK82-6946). The ²¹⁰Pb and ²²⁶Ra data are shown in Figure S1 of the Supporting Information S1 and are detailed in Table S4 of the Supporting Information S1. To calculate terrOC accumulation rates, we multiplied the MAR (g m⁻² yr⁻¹) by the OC contents (wt%) and terrOC fractions. The total terrOC fluxes for the Laptev Sea shelf, slope, and rise were estimated by multiplying the terrOC accumulation rates by the aerial extents of these depositional environments (Table 2). The uncertainties of our estimates are based on the standard deviation of the underlying data population.

3. Results and Discussion

3.1. Distribution and Sources of Terrestrial Carbon Across the Laptev Sea Margin

The dual-isotope source apportionment of OC in sediments reveals a predominant contribution of terrOC to the total OC. This dominance is consistent across the entire shelf ($64\% \pm 12\%$), the slope ($57\% \pm 7\%$), and the rise

Table 2	Та	ble	2
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Mass Accumulation Rates (MAR) of Sediments and Terrestrial Organic Carbon (terrOC) Across Three Depositional Regimes of the Laptev Sea Continental Margin

Regime	Area (km ²)	$^{210}\mathrm{Pb}_{\mathrm{xs}}^{\mathbf{a}}\left(n\right)$	MAR mean \pm s.d. (kg m ⁻² yr ⁻¹)	$TerrOC^{b}\left(n\right)$	terrOC MAR \pm s.d. (gOC m ⁻² yr ⁻¹)	Total terrOC MAR (Tg yr ⁻¹)
Laptev Sea shelf	515,106	11	1.6 ± 0.9	43	14.7 ± 12.2	$3.5 \pm 2.9^{\circ}$
Laptev Sea slope	69,269	5	1.4 ± 0.9	8	7.0 ± 5.8	0.5 ± 0.4
Laptev Sea rise	169,085	3	0.4 ± 0.03	6	2.3 ± 0.3	0.4 ± 0.1

^aStation-specific MAR is provided in Table S1 of the Supporting Information S1. ^bStation-specific terrOC fractions are provided in Table S2 of the Supporting Information S1. ^cThe total terrOC MAR estimate for the Laptev Sea shelf only considers the shelf area with water depths >30 m (i.e., 46% of the shelf area or 236,800 km²).

 $(53\% \pm 3\%)$, with only a minor decrease between the three systems, and despite the substantial distances from shore of 500–800 km for the outermost two systems. However, there is considerable spatial variability in the terrOC fraction among individual samples and locations. Along a Laptev Sea slope transect in the 150–360 m bsl depth range (Figure 1), the fraction terrOC ranged from 52% to 84% (Table S2 in Supporting Information S1). In contrast to the relative terrOC fraction, the terrOC concentrations per m² SA show >50% lower values in sediments of the continental slope and rise $(0.20 \pm 0.03 \text{ and } 0.18 \pm 0.02 \text{ mg C m}^{-2})$ compared to shelf sediments (0– 100 m with 0.48 ± 0.43 mg C m⁻²). This decrease in concentrations is likely indicative of terrOC losses due to degradation during transport across the Laptev Sea slope and rise systems (Bröder et al., 2016; Matsubara et al., 2022). However, this decline may also be influenced by hydrodynamic sorting during cross-shelf transport (Bröder et al., 2018; Tesi et al., 2016). In this process, coarse-grained sediments rich in plant debris are retained on the shelf, while fine-grained material bound to the mineral matrix is transported further offshore either during suspension or through protracted cross-shelf transport involving repeated burial and resuspension.

The patterns of specific terrestrial biomarkers largely followed the pattern of the bulk terrOC distributions within and beyond the boundaries of the Laptev Sea shelf. However, the molecular dimension offers a more differentiated picture between compound classes (HMW *n*-alkanoic acids, *n*-alkanes and lignin phenols). In shelf sediments, concentrations of HMW *n*-alkanes exhibited a wide range of 120–1,688 ng m⁻². The concentrations declined with increasing water depth—and increasing distance from its source—to generally lower and less variable levels in the slope (average 169 ± 61) and rise (135 ± 27 ng m⁻²; Figure 2; Table 1). Concentrations of lignin phenols exhibited a stronger contrast across the shelf, slope and rise. Shelf sediments showed high and variable concentrations between 0.2 and 45.2 μ g m⁻², while slope and rise samples revealed much lower levels and variability (0.56 ± 0.44 and 0.34 ± 0.14 μ g m⁻²). The concentrations of HMW *n*-alkanoic acids presented a less clear pattern with increasing water depth. Average concentrations of HMW *n*-alkanoic acids of 2.0 (0.04– 11.5) μ g m⁻² on the shelf and 611 ± 574 ng m⁻² combined for slope and rise sediments were statistically indistinguishable (two-sample *t*-test).

The removal of terrOC is also apparent in the shifting relative biomarker concentrations across the Laptev Sea shelf-slope-rise system. Among the biomarker concentrations in slope and rise samples (this study), the lignin/*n*-alkanes and the lignin/*n*-alkanoic acid ratios exhibit clear linear relationships with the concentration of terrOC per m^2 SA ($R^2 = 0.46$ with p < 0.01 for lignin/*n*-alkanes; and $R^2 = 0.36$ with p = 0.01 for lignin/*n*-alkanoic acids; Figure S2 in Supporting Information S1). Including samples from the shelf reveals that the lignin/*n*-alkane ratio closely follows the decline in terrOC per m^2 SA with $R^2 = 0.90$ (p < 0.01). Our slope and rise centered data set adds to a recent shelf-focused study on the ESAS that built on a comprehensive data set (Matsubara et al., 2022), which found that lignin phenols degrade about two times faster than lipid biomarkers across the shelf (Matsubara et al., 2022). This discrepancy in biomarker removal likely reflects fractionation in the removal of different terrOC components. For instance, the biopolymer lignin associates with macroscopic plant remains, preferentially binding to low-density sediment particles that are typically retained in near-coastal settings (Tesi et al., 2016). Similar to the shelf-focused studies by Bröder et al. (2016) and Matsubara et al. (2022), no clear depth or offshore trends were observed for the *n*-alkanoic acids/*n*-alkanes ratio across the shelf and slope. With lignin phenols and HMW *n*-alkanes standing out as more reliable tracers of terrOC decline along the shelf-basin continuum, we discuss their degradation patterns in greater detail in Section 3.2.





Figure 2. Mineral surface-area normalized concentrations of terrestrial organic carbon (terrOC/SA; panel a), terrestrial biomarkers (lignin phenols, high-molecular weight (HMW) *n*-alkanes and *n*-alkanoic acids with homolog chain lengths of >23 and >24, respectively; panel b). Furthermore, mass accumulation rates (MAR) of terrOC are shown (panel c), including two linear regression plots for the water depth intervals 7–92 and 118–2,900 m below sea level (bsl). The gray shade indicates the depth of the Laptev Sea shelf edge. Note that the axis scale of the water depth scale is logarithmic. Terrestrial biomarker concentrations normalized instead to gOC are shown in Figure S3 of the Supporting Information S1.

3.2. Patterns of Terrestrial Carbon Degradation

Based on the intrinsic recalcitrance of certain compounds, the carbon preference index of *n*-alkanes (CPI_{alk}) and the 3,5-Bd/V ratio of lignin phenols both signal variations in the degradation status of terrOC with increasing water depth (Figure 3; Table S1 in Supporting Information S1). Accordingly, the CPI_{alk} in shelf and slope sediments were 4.0 \pm 1.0 and 4.2 \pm 0.9, higher than for the continental rise (2.5 \pm 0.6). This disparity reflects terrOC degradation in the rise through the removal of the odd-over-even predominance of HMW *n*-alkanes (Marzi et al., 1993). This offshore trend aligns with the 3,5-Bd/V ratio, which mirrors the selective degradation of the more bioavailable vanillyl phenols compared to the more recalcitrant 3,5-Bd (Prahl et al., 1994). Like the CPI_{alk}, the 3,5-Bd/V ratio suggests a similar terrOC degradation status on the shelf (0.32 \pm 0.15) and the slope (0.34 \pm 0.16), and more advanced degradation in the rise system (0.52 \pm 0.08). The increase in terrOC degradation by 40% (CPI_{alk}) and 60% (3,5-Bd/V) from slope to rise is similar to the decline of terrOC/SA loadings by 57% between the shelf and the slope, suggesting that terrOC degradation is an important mechanism for its removal with increasing water depth and distance from the source. These findings broadly align with shelfcentered studies in this region (Bröder et al., 2016; Matsubara et al., 2022), while the present study shows generally stronger terrOC degradation in the Laptev Sea slope and rise.

Compared to the CPI of *n*-alkanes and the 3,5-Bd/V ratio, the CPI of HMW *n*-alkanoic acids (CPI_{acid}) and the lignin acid to aldehyde ratio degradation proxies (Ad/Al; Vd/Vl) revealed less conclusive results. Similar to the





Figure 3. Biomarker proxies indicating terrestrial organic carbon (terrOC) degradation versus water depth below sea level (bsl). The panels plot (a) the carbon preference indices (CPI) for high molecular weight (HMW; i.e., homolog chain lengths with >23) *n*-alkanes; (b) the ratio of 3,5-dihydroxybenzoic acid to vanillyl phenols (3,5-Bd/V); and (c) acid to aldehyde ratios of lignin phenols, including ratios of syringyl acid (Sd) over aldehyde (Al), as well as vanillyl acid (Vd) over aldehyde (Vl). The gray shade indicates the depth of the Laptev Sea shelf edge. The CPI of HMW *n*-alkanoic acids is shown in Figure S3 of the Supporting Information S1.

larger shelf-limited data set by Matsubara et al. (2022), the CPI_{acid} declined across the shelf (with an average of 4.1 ± 0.8) and through the slope (3.4 ± 0.2), highlighting degradation of terrestrial, odd-numbered, *n*-alkanoic acids. Toward the rise, CPI_{acid} values (4.0 ± 0.3) increased, contradicting the shelf-slope trend attributed to terrOC degradation (Figure S3 in Supporting Information S1). One plausible explanation may be that *n*-alkanoic acids interact differently with the sediment matrix (i.e., grain size, surface area, material, and interaction time) than bulk terrOC, lignin phenols and HMW *n*-alkanes. This idea would be supported by a weak yet statistically significant correlation between CPI_{acid} values and SA in slope and rise sediments ($R^2 = 0.33$; p = 0.02; Figure S2-d in Supporting Information S1), suggesting decreasing degradation of *n*-alkanoic acids with increasing SA. For reference, there is a negative correlation between CPI_{alk} and SA in the same data set ($R^2 = 0.29$; p = 0.05; Figure S2-d in Supporting Information S1), indicating increasing degradation with increasing SA. This would support the idea that physico-chemical interactions between permafrost organic matter and mineral particles (e.g., Martens et al., 2023) may influence the fate of terrOC during transport. Moreover, these findings add to the shelf-focused assessment by Matsubara et al. (2022), highlighting that HMW *n*-alkanoic acids may be less suitable to trace terrOC degradation beyond the shelf edge.

For the lignin acid to aldehyde ratios Sd/Sl and Vd/Vl, we noticed a similar pattern as CPI_{acid}. While both ratios showed significant terrOC degradation across the Laptev Sea shelf—consistent with the comprehensive assessment by Matsubara et al. (2022)—we found decreasing Sd/Sl and Vd/Vl ratios with water depth beyond the shelf edge along transects A and B (Figure 3c). Cross-shelf trends of the Sd/Sl and Vd/Vl proxies, contradictory to those of other degradation proxies (e.g., 3,5-Bd/V), could be related to the contrasting adsorption affinity of acids and aldehydes to mineral particles. It may be for the same reason that lignin material primarily delivered via rivers to the ESAS appears more degraded (Sd/Sl and Vd/Vl) than lignin released by coastal erosion of the more mineral-associated ICD (Matsubara et al., 2022). While we can only speculate about the processes causing these contradictory degradation trends (CPI_{acid}, Vd/Vl and Sd/Sl of lignin phenols), we recognize that the more promising degradation markers (CPI_{alk} and 3,5-Bd/V proxies) align conservatively with bulk terrOC/SA removal, indicating considerable terrOC degradation beyond the shelf edge.

3.3. Accumulation of Terrestrial Carbon Along the Continuum From the Laptev Sea Shelf to the Arctic Ocean Central Basin

The ${}^{210}Pb_{xs}$ -based MAR exhibited a decrease in terrOC accumulation with increasing depth and distance offshore (Figure 2). In comparison to shelf sediments (15 \pm 12 g m⁻² yr⁻¹), terrOC accumulation decreased to 7.0 ± 5.8 g m⁻² yr⁻¹ in the slope and further declined to 2.3 ± 0.3 g m⁻² yr⁻¹ in the rise sediments (Table 2). This represents a decline by 52% and 85%, respectively. These MAR estimates for the Laptev Sea slope and rise derived from the extensive ${}^{210}\text{Pb}_{xs}$ data set are, on average, 2–3 times higher than previous assessments based on ¹⁴C dating of carbonaceous fossils in longer sediment cores (Stein & Fahl, 2000). The latter may more accurately represent the late/mid-Holocene "average" of the terrOC-MAR, while the ²¹⁰Pb_{xs} data provide a more contemporary perspective on the system of the past ~ 100 years (Martens et al., 2022; Rusakov & Borisov, 2023; Vonk et al., 2012). It is also noteworthy that MARs are likely not steady over longer time scales but may change due to hydrology and sediment transport dynamics (Rusakov & Borisov, 2023). Spatially integrating terrOC-MAR across the three investigated bathymetric regimes (Figure 1, right panel; Table 2) where the sea floor is available for carbon burial and resuspension is negligible (depths >30 m, while depths <30 m are affected by wind and wave resuspension; Dudarev et al., 2022; Dudarev et al., 2006) reveals that 80% of the total terrOC accumulation in the Laptev Sea was sequestered by shelf sediments $(3.5 \pm 2.9 \text{ Tg yr}^{-1})$. In contrast, terrOC accumulation on the continental slope and rise was 11% and 9%, respectively (0.5 and 0.4 Tg yr⁻¹). For comparison, the MAR of total OC (terrOC + marine OC) was 5.2 ± 4.2 Tg yr⁻¹ on the shelf, 0.9 ± 0.7 Tg yr⁻¹ on the slope and 0.7 ± 0.1 Tg yr⁻¹ in the rise. This suggests that a combined 23% of the OC accumulates within the slope-rise system. Both of these estimates roughly align with the global-scale perspective established by Hedges and Keil (1995), who estimated that 90% of the global carbon accumulation budget in oceans is concentrated within coastal margin regions and deltaic sediments.

The largest decline in terrOC-MAR occurred near the shelf edge (100–200 m bsl), indicating a fourfold change between the shelf and slope-rise systems (Figure 2). This contrast in terrOC accumulation likely results from a combination of transport and degradation processes. Despite degradation proxies showing no significant change in the terrOC degradation status around the shelf edge, a noticeable shift was observed around the slope-rise interface (Figure 3). The inconsistency between terrOC-MAR and degradation proxies across the margin, coupled with a larger decline in terrOC-MAR compared to degradation proxies, suggests that degradation alone cannot fully explain the decrease in terrOC accumulation between these regimes. The abrupt decrease of terrOC around the shelf edge may be attributed to increased slope and transport energy beyond the shelf edge, facilitating slope-basin terrOC transport previously described as turbidity currents (Fahl & Nöthig, 2007). Near-bottom re-suspension and transport within the near-bottom nepheloid layer may also be critical for the across-shelf transport of terrOC, indicated by ¹³C depletion (pointing to more terrOC) and higher lignin concentrations in POC near the bottom surface (Salvadó et al., 2016). Hence, it appears that sediment transport dynamics and burial exert strong control on terrOC (re-)distribution between shelf, slope, rise, and presumably the deep basin.

3.4. The Terrestrial Carbon Budget of the Laptev Sea Continental Margin

We here propose an updated terrOC budget for the Laptev Sea continental margin (Figure 4; Table S3 in Supporting Information S1). This revised budget provides a refined picture of terrOC dispersal, degradation and sequestration within its shelf-slope-rise systems. TerrOC is introduced into the Laptev Sea through rivers and



Figure 4. Terrestrial organic carbon (terrOC) budget of the Laptev Sea continental margin based on the cross-sections shown in Figure 1b. The accumulation rates across the Laptev Sea shelf, slope and continental rise (this study) are highlighted in red. The other terrOC flux and stock estimates are shown as reported by their literature sources as detailed in Table S3 of the Supporting Information S1. All fluxes are reported as Teragram (Tg) per year (yr⁻¹), while numbers in parentheses show stock estimates in Petagram (Pg). Abbreviations: AO—Arctic Ocean, DIC—dissolved inorganic carbon, DOC—dissolved organic carbon, ICD—Ice Complex Deposits, PF—Permafrost, POC—particulate organic carbon.

coastal erosion. The Lena river is the primary conduit for the fluvial component, contributing 5.7 Tg C yr⁻¹ as DOC and 0.81 Tg C yr⁻¹ as POC based on recent estimates (Holmes et al., 2012; McClelland et al., 2016). An earlier assessment by Lara et al. (1998) estimated the annual modern Lena River DOC discharge to 3.6 Tg, while Semiletov et al. (2011) estimated the annual Lena River discharge of POC to 0.38 Tg. It should be noted that most estimates of Lena River OC export are based on measurements at the Kyusyur gauging station (located about 200 km upstream from the Lena Delta). Furthermore, it has been suggested that 85%-95% of the suspended particles (incl. POC) precipitate in the Lena River Delta "marginal filter," which would lower the Lena River POC exported to the Laptev Sea to 0.04 Tg yr⁻¹ (Semiletov et al., 2011, and references cited therein). When considering the entire Laptev Sea, including other substantial river basins (e.g., Yana, Khatanga and Olenek rivers), Wegner et al. (2015) estimated a total terrOC input of 8.88 Tg yr⁻¹ (Figure 4). Additionally, coastal erosion may contribute $0.66-3.7 \text{ Tg yr}^{-1}$ according to Wegner et al. (2015), based on data originally published by Vonk et al. (2012), which is similar to an older estimate by Rachold et al. (2004) of 1.8 Tg yr⁻¹. These terrOC export/input estimates yield a combined total input of 9.5 ± 4.8 Tg yr⁻¹ (Table S3 in Supporting Information S1), also accounting for aeolian input, which is estimated to be relatively smaller (Stein et al., 2004). The total POC inventory of the Laptev Sea shelf was estimated to 1.32 ± 0.09 Tg (Sánchez-García et al., 2011), while that of predominantly river-derived DOC was 33 Tg (Alling et al., 2010).

In our Laptev Sea budget, water column degradation and sediment sequestration are the largest processes responsible for terrOC removal (Figure 4; Table S3 in Supporting Information S1). First signs of effective oxidation of permafrost-derived POC were found in the 1990s with the degradation of POM causing anomalously high aqueous CO₂ concentrations in the near shore zone along coastal erosion sites rich in Pleistocene-age terrOC (Semiletov, 1999; Semiletov et al., 2007). Previous studies have suggested that 3.4 Tg yr⁻¹ of the large (river-dominated) DOC pool undergo re-mineralization to CO₂ (based on the 1/3 areal extent of the Laptev Sea to the ESAS, where the estimate is 10 Tg for the ESAS), leading to CO₂ oversaturation with respect to the atmosphere, alongside ocean acidification and atmospheric CO₂ (Alling et al., 2010; Anderson et al., 2009; Semiletov et al., 2007, 2016). Another estimate of terrOC degradation rates based on ¹³C depletion of dissolved inorganic carbon (DIC), that is, for DOC and POC combined, arrived at 6.2 Tg yr⁻¹ (Humborg et al., 2017). For the smaller yet more reactive POC pool, approximately 1.5 ± 0.9 Tg yr⁻¹ may be degraded each year (Sánchez-García et al., 2011). Recent estimates by Martens et al. (2022) suggested an accumulation of terrOC in surface sediments of the Laptev Sea shelf at a rate of 7.1 ± 2.4 Tg C yr⁻¹. In the present study, a more simple approach (based on simple average budget calculation vs. spatial interpolation in Martens et al. (2022)) that excludes the shallow shelf

(<30 m depth) due to possible resuspension by wind and wave action yields an estimate of 3.5 ± 2.9 Tg C yr⁻¹ (Table 2, Figure 4). More importantly, this study provides, for the first time, constraints on the sediment sequestration for a combined slope and rise system of 0.9 ± 0.5 Tg C yr⁻¹.

Quantifying the flux and removal of terrestrial DOC and POC to/from the water column within the slope and rise sectors poses significant challenges. Mass balance considerations in Sánchez-García et al. (2011) suggested that off-shelf export of terr-POC likely constitutes less than 2% of the total shelf-based POC removal (=0.03–0.07 Tg yr⁻¹). There are also estimates for off-shelf sea ice transport of terrOC, mostly as POC, of 0.18 Tg yr⁻¹ (Rachold et al., 2004) as well as shelf-basin terrOC transport via bottom and turbidity currents of 1.03 Tg yr⁻¹ (Stein et al., 2004). Despite large uncertainties, our crude terrOC budget for the shelf system, suggesting a total terrOC input of 9.5 ± 4.8 Tg yr⁻¹ and an output of 9.9 ± 4.9 Tg yr⁻¹ (Figure 4; Table S3 in Supporting Information S1), appears to be reasonably balanced and broadly consistent with prior estimates. While acknowledging the large error margins, our budget analysis suggests that approximately 12% of the annual terrOC input (0.9 Tg yr⁻¹ combined for slope + rise, out of 9.5 ± 4.8 Tg yr⁻¹) evades sequestration or degradation within the continental shelf and is exported to the slope-rise system.

In this context, it is important to recognize that terrOC accumulation in surface sediments is not equal to a permanent removal from the modern-day carbon cycle. Post-depositional re-mineralization of OC through microbial respiration emits carbon back into the water column, primarily as dissolved inorganic carbon (DIC) and to a smaller amount as CH₄. TerrOC degradation in surface sediments of the entire ESAS is estimated to respire 1.7 ± 0.97 Tg yr⁻¹ (Bröder et al., 2019), 0.57 ± 0.33 Tg yr⁻¹ of which would be proportional to the extent of the Laptev Sea (1/3 of the ESAS). Using depth-integrated O₂ consumption in shallow sediment profiles of outer shelf, slope and rise sediments, results by Brüchert et al. (2018) suggest that the respiration of terrOC in Laptev Sea sediments is ~ 2.4 Tg C yr⁻¹, with an additional 0.14 Tg C yr⁻¹ being removed via anaerobic respiration. Although in situ respiration is overall 3-5 times larger in the shelf sediments than for the slope and rise sediments, it appears that in situ re-mineralization in slope and rise sediments may still be large enough to remove more than half of the terrOC reaching these systems. This aligns with the established paradigm that lower sedimentation rates lead to longer O_2 exposure and consequently more efficient re-mineralization (Hedges & Keil, 1995). Based on these rough estimates, the terrOC remineralization at or below the sea floor across the entire continental margin (shelf, slope and rise) constitutes a potentially significant source of greenhouse gas release. This adds to the emissions from water column degradation of DOC and POC, which we have shown to be predominantly occurring within the Laptev Sea shelf. Regarding the slope-rise system, it appears that the $\sim 12\%$ of terrOC exported from the shelf not only undergoes further degradation during sediment transport processes and sorting but is also, to a large extent, transformed within slope-rise sediments (Figure 4; Table S3 in Supporting Information S1). These degradation processes combined release inorganic carbon, contributing to acidification of the Arctic Ocean and CO_2 release to the atmosphere. Further, the impact of terrOC degradation on the carbonate system of the Siberian Arctic Ocean weakens its capacity to absorb CO₂ from rising atmospheric concentrations, which is in contrast to for example, the Chukchi Sea—a sink for atmospheric CO_2 (Semiletov et al., 2007). Given the significant contribution of terrOC to the Arctic Ocean, these findings underscore the importance of the sloperise system in the Arctic carbon cycle.

4. Conclusions

Tracing the biogeochemical fate of terrestrial organic carbon (terrOC) across the extensive Siberian continental margin (and beyond) is essential for quantifying the climate-sensitive Arctic carbon cycle. This study focused on the dispersal of terrOC beyond the shelf break and its degradation and accumulation along the continental slope and rise of the outer Laptev Sea. This was accomplished by utilizing a substantial set of surface sediment samples for dual-isotope ($\delta^{13}C/\Delta^{14}C$) source apportionment of OC, employing terrestrial biomarkers to trace the degradation status of terrestrial organic carbon (terrOC; via high molecular weight, HMW, *n*-alkanes, *n*-alkanoic acids and lignin phenols), and utilizing ²¹⁰Pb_{xs}-based mass accumulation rates (MAR).

The results reveal terrOC-MAR on the continental slope and rise to be 52% and 68% lower relative to rates established for the shelf regime. Molecular degradation proxies indicate that the terrOC decline may be partly, but not entirely, related to degradation. The carbon preference index (CPI) of HMW *n*-alkanes and the 3,5-Bd/V ratio of lignin phenols suggest no apparent change in terrOC degradation status between the shelf and the slope, while significant terrOC transformation occurs as the material is transported from the slope to the rise. Hydrodynamic

sediment transport, including processes such as turbidity currents or ice-rafted terrOC, is inferred to play an important role in dispersal across the slope and rise systems.

Taken all together, about 80% of the coastally exported terrOC accumulates in sediments in the shelf regime, while about 11% are sequestered in the slope and 9% on the rise. The overwhelming containment of terrOC within the shelf boundaries lends credence to research utilizing shelf seas as receptor systems to unravel the dynamics of large-scale terrOC remobilization from the circum-Arctic drainage basins. Finally, an improved understanding of terrOC re-mineralization efficacy in the Arctic Ocean is crucial for understanding current and predicting future responses to the amplified release of terrOC due to collapsing permafrost, including translocated carbon-climate feedback.

Data Availability Statement

All data shown in figures and tables will be made available at the permanent data base of the Bolin Centre for Climate Research (https://bolin.su.se/data/martens-2024-offshelf-terroc-1) (Martens et al., 2024) and will be integrated in future versions of the Circum-Arctic Sediment Carbon DatabasE (CASCADE; https://bolin.su.se/data/cascade).

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