Shoreline exposure controls teal carbon accumulation in boreal lakes

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Tables and Equations

Material and Methods

Study Area

Table S1. Water quality of sampled lakes (Syke, 2025).

Lake	Vesijärvi	Kallavesi	Oulujärvi
Type	Large clearwater	Large humic	Large humic
Chlorophyll-a [µg L^{-1}]	5.1 (N basin) – 7.6 (S basin)	10.5 (S basin) – 12.1 (N basin)	5.7
Total Phosphorus [µg L^{-1}]	15 (N basin) – 33 (S basin)	20 (S basin) – 27 (N basin)	13
Total Nitrogen [µg L^{-1}]	351 (N basin) – 459 (S basin)	629 (S basin) – 719 (N basin)	351
Colour [mg Pt L^{-1}]	14 (N basin) – 25 (S basin)	65 (S basin) – 102 (N basin)	86

Sampling procedure

Table S2. Coordinates (WGS84) of sampled sediment cores and description of sampled areas. Vegetation density is presented as all stems, followed by only *Phragmites australis* inside parenthesis.

Lake	Site	Zone	Latitude	Longitude	Depth of standing water [m]	Main vegetation	Vegetation density [stems m^{-2}]	Slope [distance depth $^{-1}$]	Average fetch length [m]
Oulujärvi	A	landside	64.52355	26.81908	0.20	*Equisetum*, *Carex*	369 (0)	294	338
		transitional	64.52355	26.81866	0.44	*Equisetum*	680 (0)		
		waterside	64.52355	26.81804	0.37	*Equisetum*, *Carex*	409 (0)		
	B	landside	64.35013	28.02235	0.21	*Carex*, *Equisetum*	61 (0)	197	186
		transitional	64.35030	28.02277	0.34	*Equisetum*, *Carex*	62 (0)		
		waterside	64.35048	28.02319	0.50	*Equisetum*, *Carex*	254 (0)		
	C	landside	64.28800	27.56502	0.15	*Carex*	156 (0)	108	2834
		transitional	64.28818	27.56543	0.29	*Carex*, *Equisetum*, *Phragmites*	220 (10)		
		waterside	64.28826	27.56564	0.55	*Phragmites*, *Equisetum*	157 (141)		
Kallavesi	D	landside	62.99400	27.51157	0.22	*Phragmites*, *Carex*	71 (17)	119	1161
		transitional	62.99382	27.51117	0.90	*Phragmites*	66 (66)		
		waterside	62.99338	27.51018	1.05	*Phragmites*	33 (33)		
	E	landside	62.76276	27.68925	0.24	*Phragmites*	73 (73)	22	411
		transitional	62.76285	27.68944	0.46	*Phragmites*	230 (230)		
		waterside	62.76294	27.68964	1.10	*Phragmites*	125 (125)		
	F	landside	62.78582	27.93125	0.60	*Phragmites*, *Equisetum*	113 (83)	227	784
		transitional	62.78573	27.93124	1.13	*Phragmites*, *Carex*	63 (62)		
		waterside	62.78546	27.93123	1.23	*Phragmites*	68 (68)		

Table S2. Continuation.

Lake	Site	Zone	Latitude	Longitude	Depth of standing water [m]	Main vegetation	Vegetation density [stems m^{-2}]	Slope [distance depth $^{-1}$]	Average fetch length [m]
Vesijärvi	G	landside	61.17794	25.50480	0.10	*Phragmites*	119 (119)	169	1631
		transitional	61.17758	25.50481	0.15	*Phragmites*	197 (197)		
		waterside	61.17695	25.50484	0.75	*Phragmites*	165 (165)		
	H	landside	61.07740	25.45393	0.05	*Phragmites*	98 (97)	169	819
		transitional	61.07740	25.45319	0.05	*Phragmites*, *Equisetum*	375 (330)		
		waterside	61.07738	25.45189	0.70	*Phragmites*, *Equisetum*	79 (77)		
	I	landside	61.03494	25.59853	0.55	*Phragmites*	52 (52)	173	1314
		transitional	61.03495	25.59871	0.50	*Phragmites*	58 (58)		
		waterside	61.03495	25.59890	0.70	*Phragmites*	62 (62)		

Data analyses

Wet bulk density (WBD) and dry bulk density (DBD) were determined based on the sediment density corrected by organic matter content (Eq. 1 from the main text), the water content and the sample volume. Porosity Φ as a fraction of 1 and sediment content [%] were then used to calculate WBD and DBD (Eq. 2 and Eq. 3 in the main text). The step-by-step calculation follows bellow:

$$Water\ content\ [\%] = \frac{Wet\ sample\ weight\ [g] - Dry\ sample\ weight\ [g]}{Wet\ sample\ weight\ [g]} * 100 \quad \text{(S1)}$$

$$Sediment\ content\ [\%] = 100 - Water\ content\ [\%] \quad \text{(S2)}$$

$$Relative\ sediment\ volume = \frac{Sediment\ content\ [\%]}{Sediment\ density\ \left[{}^{g}/_{cm^3}\right]} \quad \text{(S3)}$$

$$Sediment\ volume\ [\%] = 100 * \frac{Relative\ sediment\ volume}{Relative\ sediment\ volume + Water\ content\ [\%]} \quad \text{(S4)}$$

$$Porosity\ \Phi\ [fraction\ of\ 1] = \frac{(100 - Sediment\ volume\ [\%])}{100} \quad \text{(S5)}$$

Results

Table S3. Results from the post hoc Tukey Pairwise Comparison test used to compare grain size distribution across lakes and zones.

Significance codes based on *p*-value: '*': < 0.001; '**' < 0.01; '*': < 0.05; '.': < 0.1.**

	Difference in means	***p*-adjusted**	**Significance**
Across lakes			
Vesijärvi – Kallavesi	-22.3	0.0000	***
Oulujärvi – Kallavesi	3.5	0.5849	
Oulujärvi – Vesijärvi	25.8	0.0000	***
Across zones			
transitional – landside	7.0	0.1526	
waterside – landside	-10.3	0.0184	*
waterside - transitional	-17.3	0.0000	***

Table S4. Results from the post hoc Tukey Pairwise Comparison test used to compare total organic carbon (TOC) content across lakes, zones and grain size classes.

Abbreviations: C sand = coarse sands; M sand = medium sands; F sand = fine sands; VF sand = very fine sands.

Significance codes based on *p*-value: '*': < 0.001; '**' < 0.01; '*': < 0.05; '.': < 0.1.**

	Difference in means	*p*-adjusted	Significance
Across lakes			
Vesijärvi - Kallavesi	-0.4	0.0054	**
Oulujärvi - Kallavesi	0.4	0.0072	**
Oulujärvi - Vesijärvi	0.8	0.0000	***
Across zones			
transitional - landside	0.1	0.9034	
waterside - landside	-0.4	0.0119	*
waterside - transitional	-0.4	0.0029	**
Across grain size classes			
M sand - C sand	-0.7	0.1464	
F sand - C sand	-0.4	0.5727	
VF sand - C sand	-0.3	0.8491	
silt - C sand	1.0	0.0040	**
F sand - M sand	0.3	0.4992	
VF sand - M sand	0.4	0.0678	.
silt - M sand	1.7	0.0000	***
VF sand - F sand	0.1	0.8085	
silt - F sand	1.4	0.0000	***
silt - VF sand	1.3	0.0000	***

Table S5. Results from the post hoc Tukey Pairwise Comparison test used to compare sedimentary organic carbon (SOC) stocks across lakes, zones, vegetation types and grain size classes.

Abbreviations: C+M sand = coarse and medium sands; F+VF sand = fine and very fine sands.

Significance codes based on *p*-value: '*': < 0.001; '**' < 0.01; '*': < 0.05; '.': < 0.1.**

	Difference in means	*p*-adjusted	Significance
Across lakes			
Vesijärvi - Kallavesi	-0.2	0.6670	
Oulujärvi - Kallavesi	0.3	0.4542	
Oulujärvi - Vesijärvi	0.5	0.1146	
Across zones			
transitional - landside	0.0	0.9812	
waterside - landside	-0.3	0.3462	
waterside - transitional	-0.4	0.2623	
Across vegetation types			
Mixed - Phragmites	-0.1	0.8906	
Others - Phragmites	0.6	0.0230	*
Others - Mixed	0.7	0.0272	*
Across grain size classes			
(F+VF) sand - (C+M) sand	-0.1	0.9425	
silt - (C+M) sand	0.7	0.0529	.
silt - (F+VF) sand	0.8	0.0001	***

Table S6. Significance of the four environmental numerical parameters used to explain variations in sedimentary organic carbon (SOC) stocks using a generalized linear model (GLM; pseudo-R^2: 0.69; n = 27).

Significance codes based on *p*-value: '*': < 0.001; '**' < 0.01; '*': < 0.05; '.': < 0.1.**

	***t*-value**	***p*-value**	**Significance**	**Regression Coefficient**
Vegetation density [stems m^{-2}]	-1.781	0.0893	.	-0.00013
Water depth [m]	1.704	0.1031		0.10431
Slope [distance $depth^{-1}$]	3.141	0.0049	**	0.00037
Average fetch length [m]	4.788	0.0001	***	0.00025

55

Figures

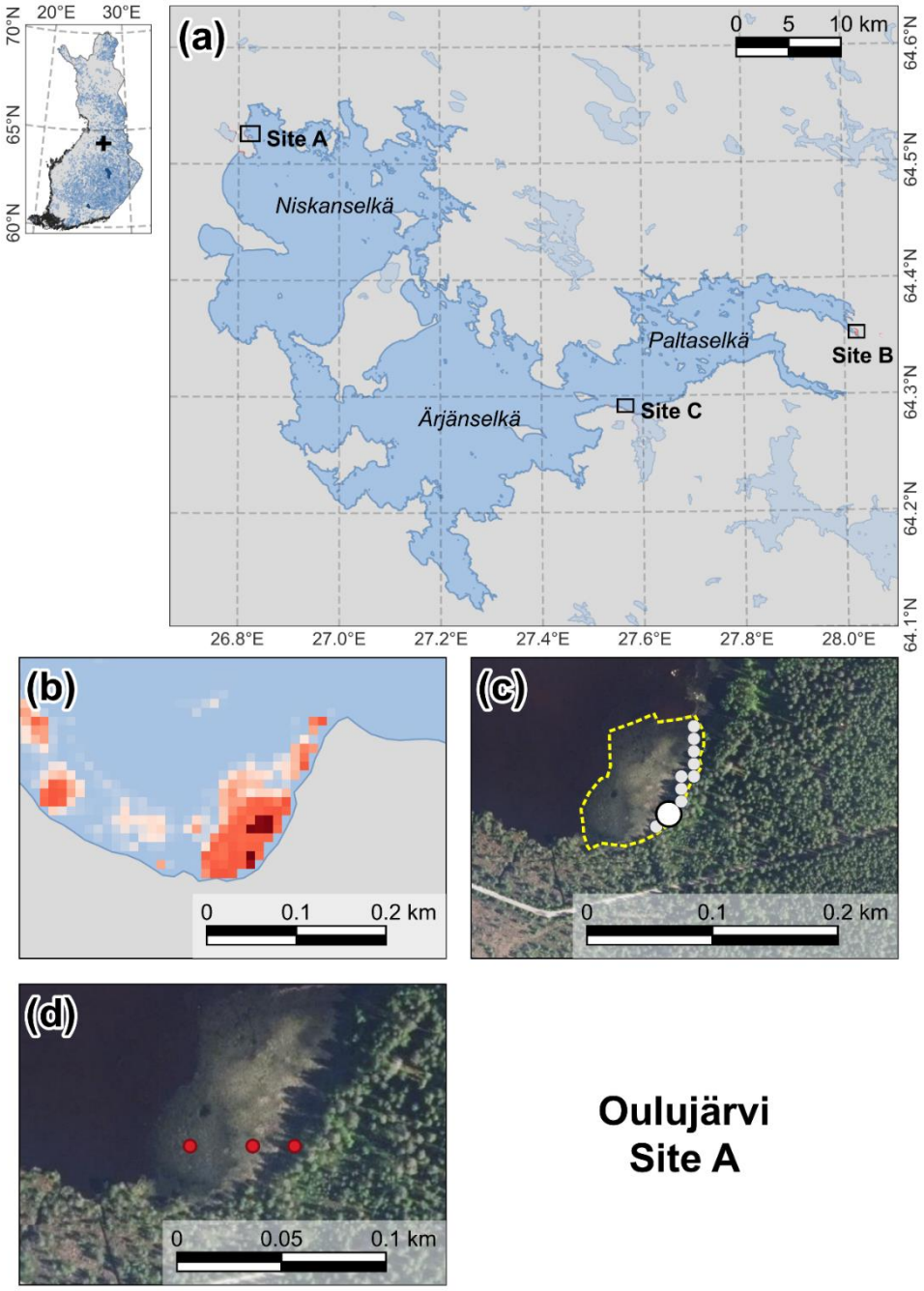

Figure S1. Location of sampling Site A in Oulujärvi (a), with details of: (b) the vegetation patch (Koponen et al., 2022); (c) the starting points of the transect following a grid of 10 x 10 m; (d) the location of the sediment cores following the transect of landside, transitional and waterside. Aerial images from Finnish National Geoportal (Orthophotos) (2023).

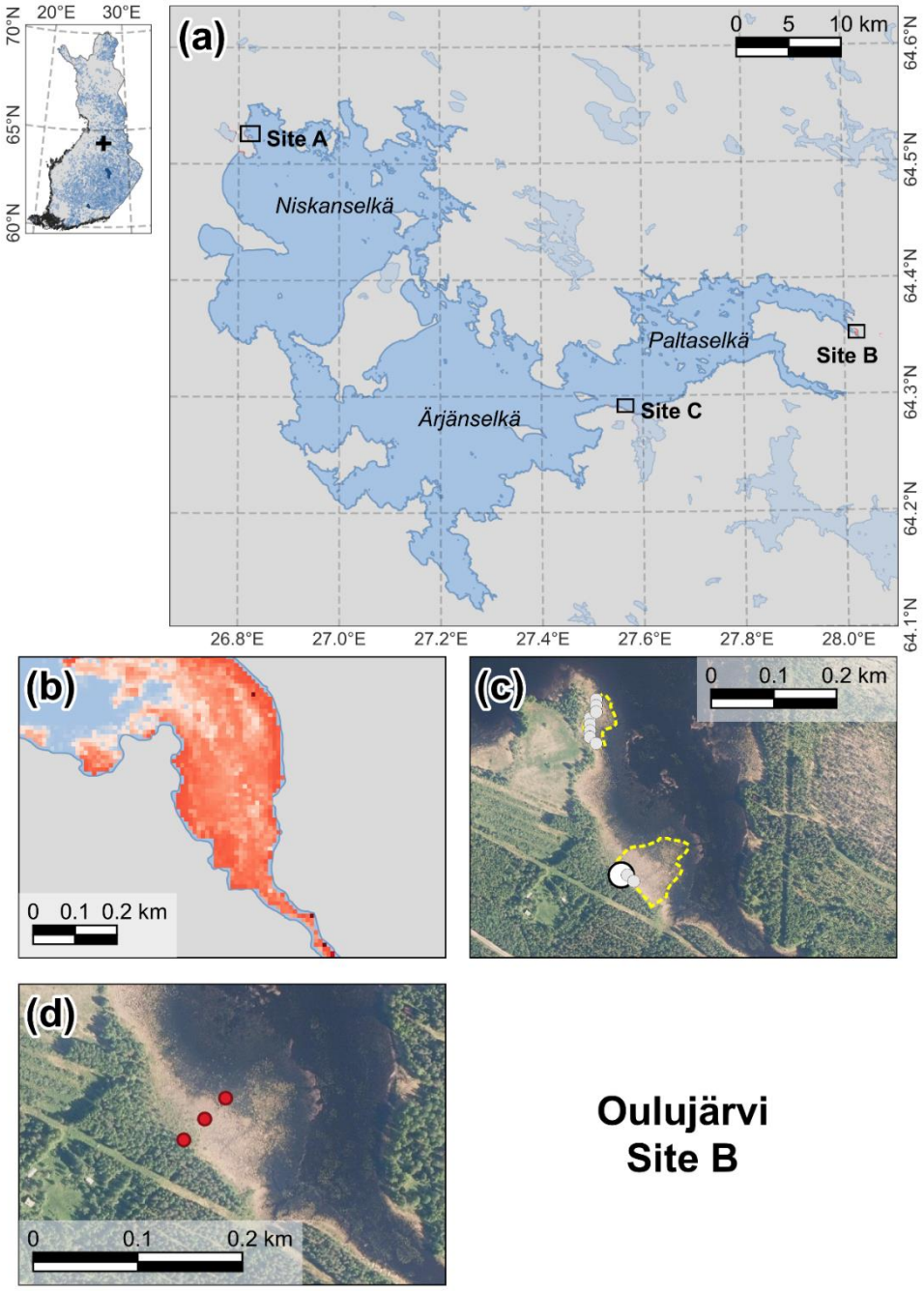

Figure S2. Location of sampling Site B in Oulujärvi (a), with details of: (b) the vegetation patch (Koponen et al., 2022); (c) the starting points of the transect following a grid of 10 x 10 m; (d) the location of the sediment cores following the transect of landside, transitional and waterside. Aerial images from Finnish National Geoportal (Orthophotos) (2023).

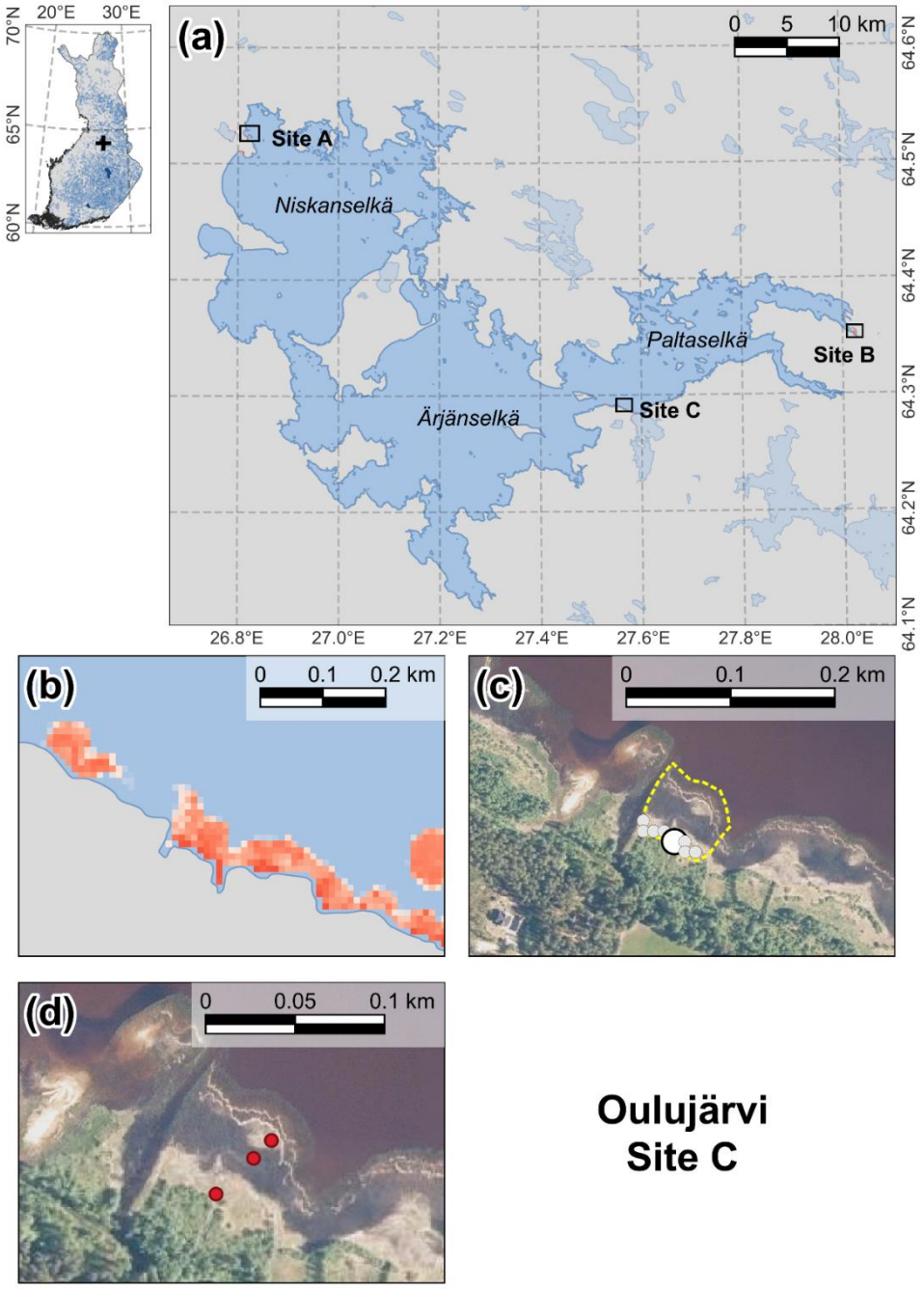

Figure S3. Location of sampling Site C in Oulujärvi (a), with details of: (b) the vegetation patch (Koponen et al., 2022); (c) the starting points of the transect following a grid of 10 x 10 m; (d) the location of the sediment cores following the transect of landside, transitional and waterside. Aerial images from Finnish National Geoportal (Orthophotos) (2023).

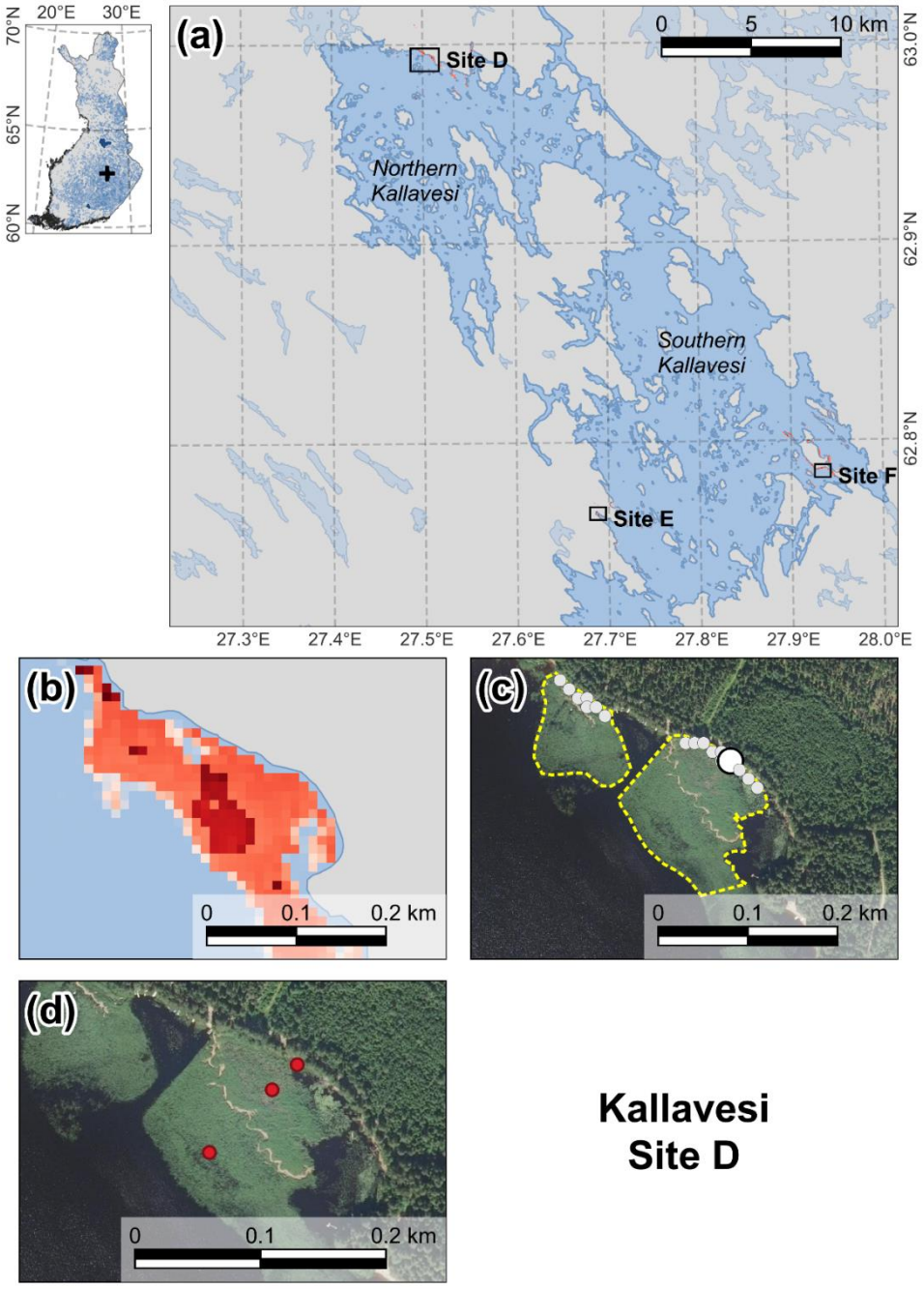

Figure S4. Location of sampling Site D in Kallavesi (a), with details of: (b) the vegetation patch (Koponen et al., 2022); (c) the starting points of the transect following a grid of 10 x 10 m; (d) the location of the sediment cores following the transect of landside, transitional and waterside. Aerial images from Finnish National Geoportal (Orthophotos) (2023).

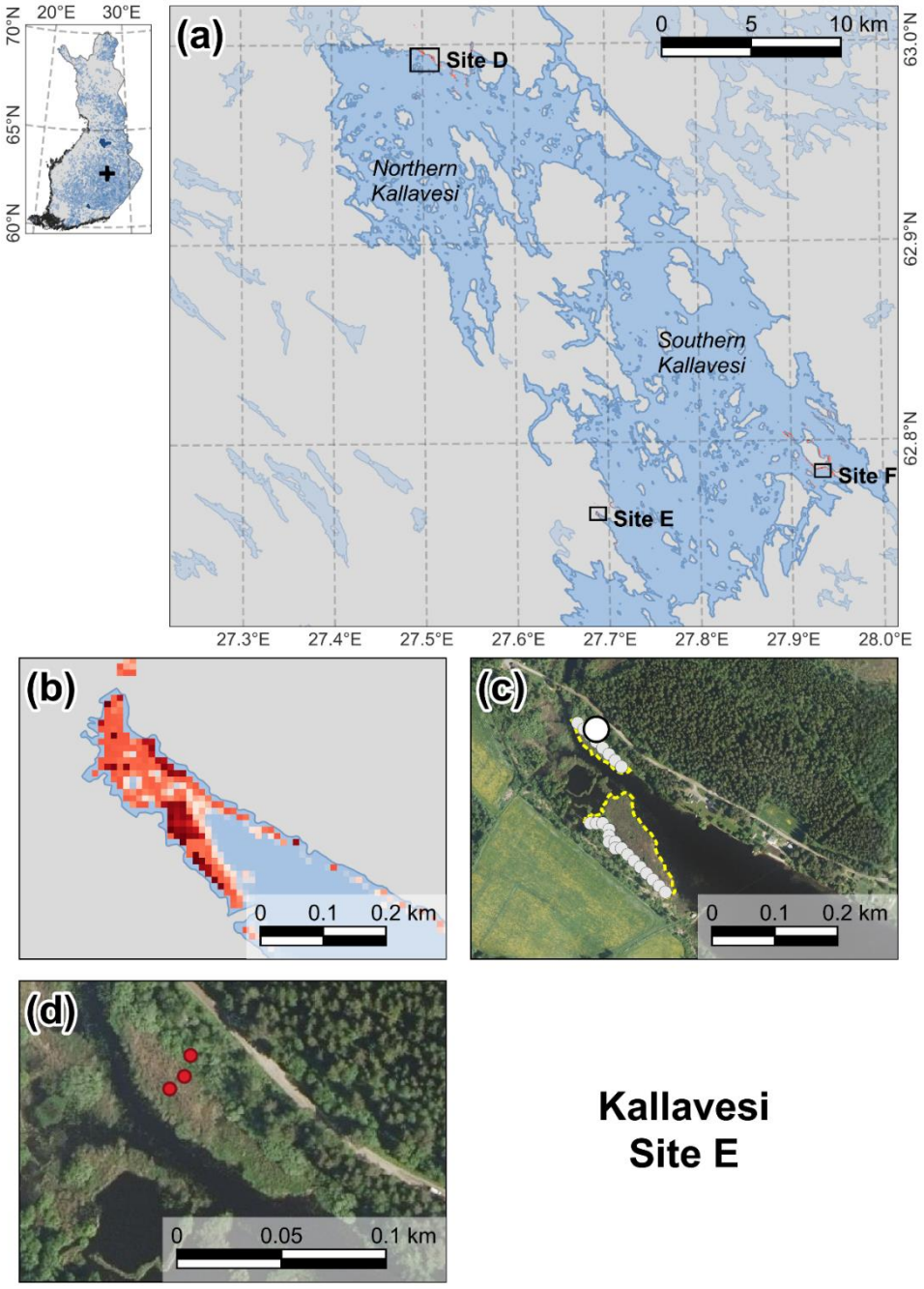

Figure S5. Location of sampling Site E in Kallavesi (a), with details of: (b) the vegetation patch (Koponen et al., 2022); (c) the starting points of the transect following a grid of 10 x 10 m; (d) the location of the sediment cores following the transect of landside, transitional and waterside. Aerial images from Finnish National Geoportal (Orthophotos) (2023).

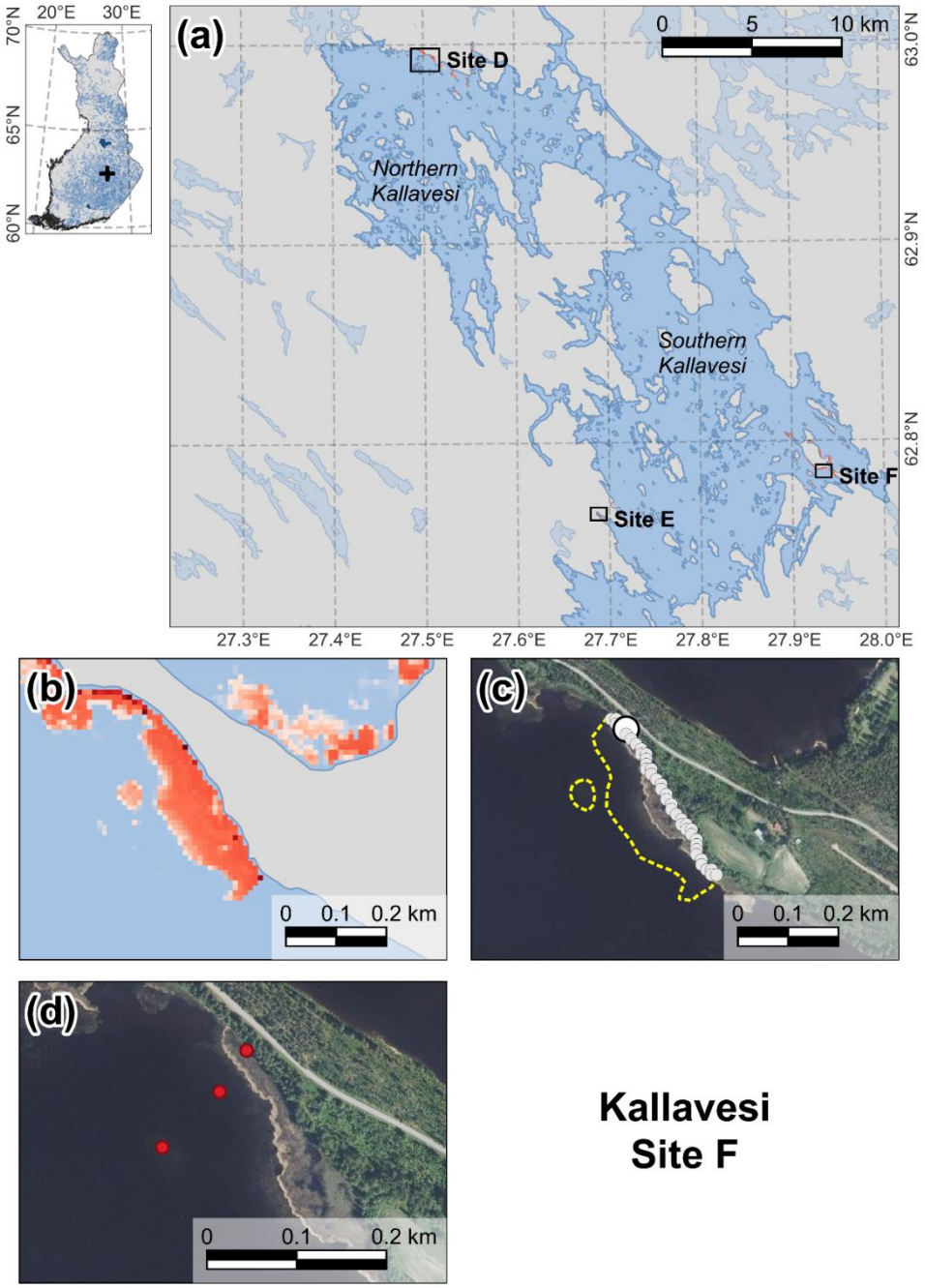

Figure S6. Location of sampling Site F in Kallavesi (a), with details of: (b) the vegetation patch (Koponen et al., 2022); (c) the starting points of the transect following a grid of 10 x 10 m; (d) the location of the sediment cores following the transect of landside, transitional and waterside. Aerial images from Finnish National Geoportal (Orthophotos) (2023).

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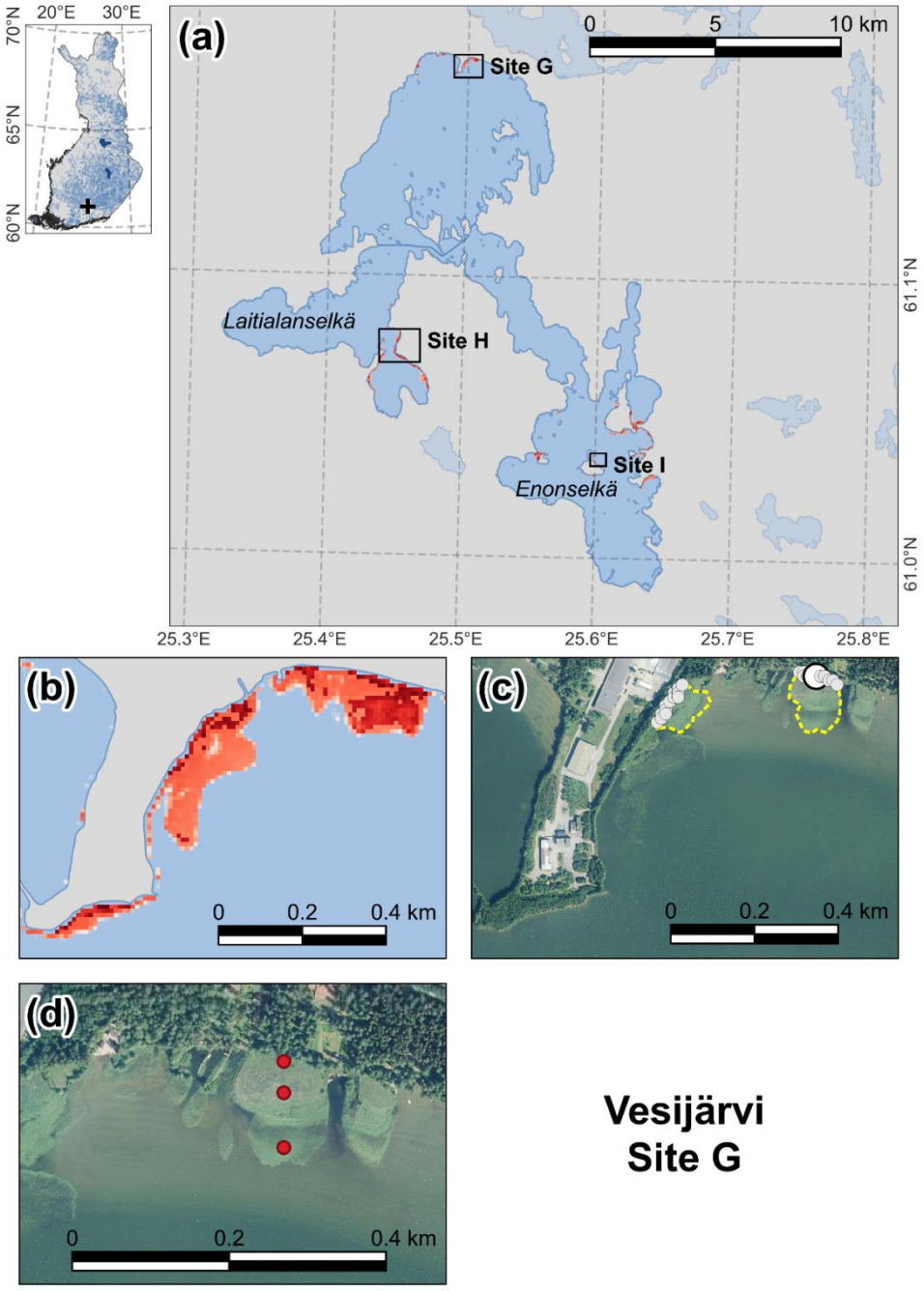

Figure S7. Location of sampling Site G in Vesijärvi (a), with details of: (b) the vegetation patch (Koponen et al., 2022); (c) the starting points of the transect following a grid of 10 x 10 m; (d) the location of the sediment cores following the transect of landside, transitional and waterside. Aerial images from Finnish National Geoportal (Orthophotos) (2023).

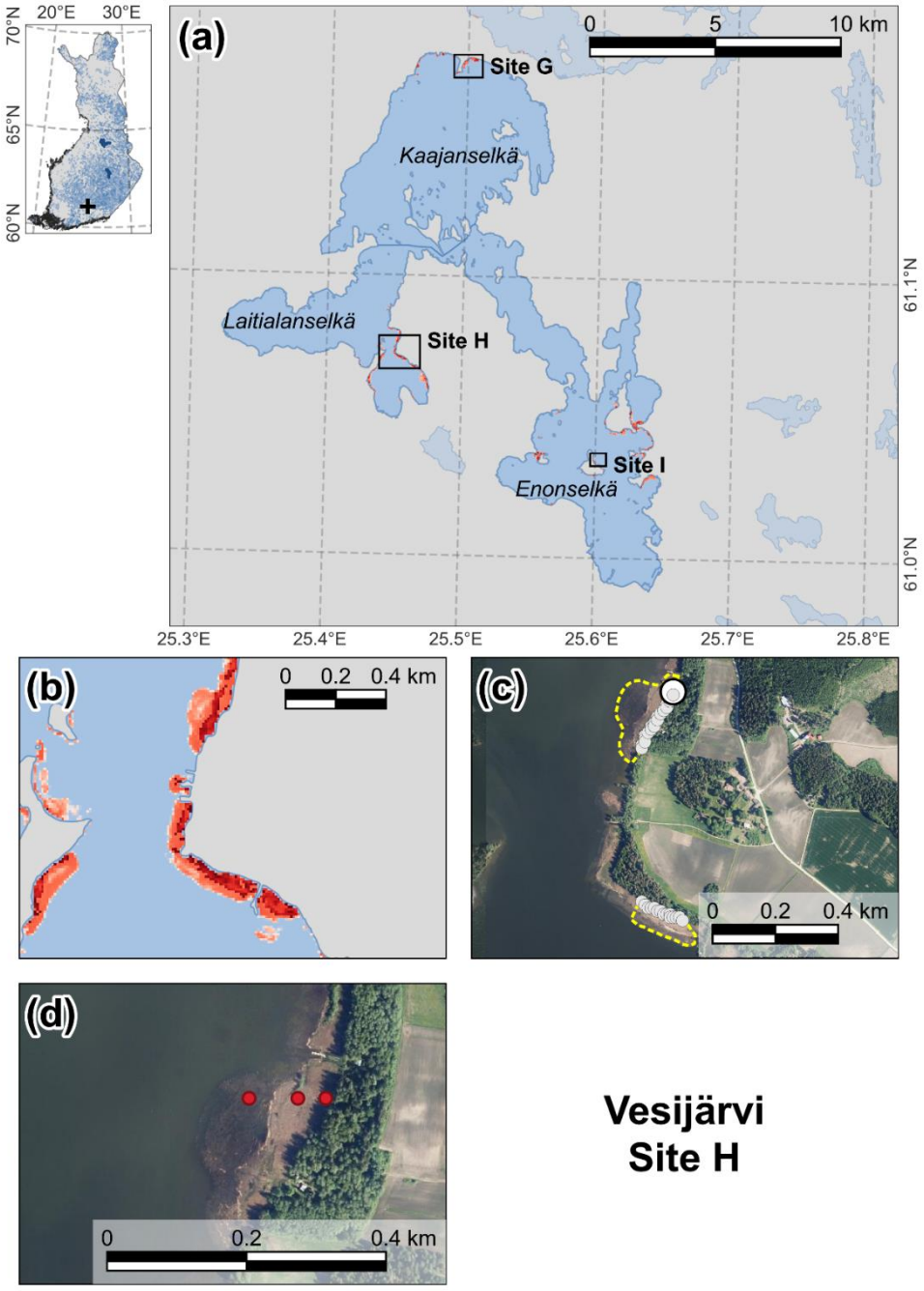

Figure S8. Location of sampling Site H in Vesijärvi (a), with details of: (b) the vegetation patch (Koponen et al., 2022); (c) the starting points of the transect following a grid of 10 x 10 m; (d) the location of the sediment cores following the transect of landside, transitional and waterside. Aerial images from Finnish National Geoportal (Orthophotos) (2023).

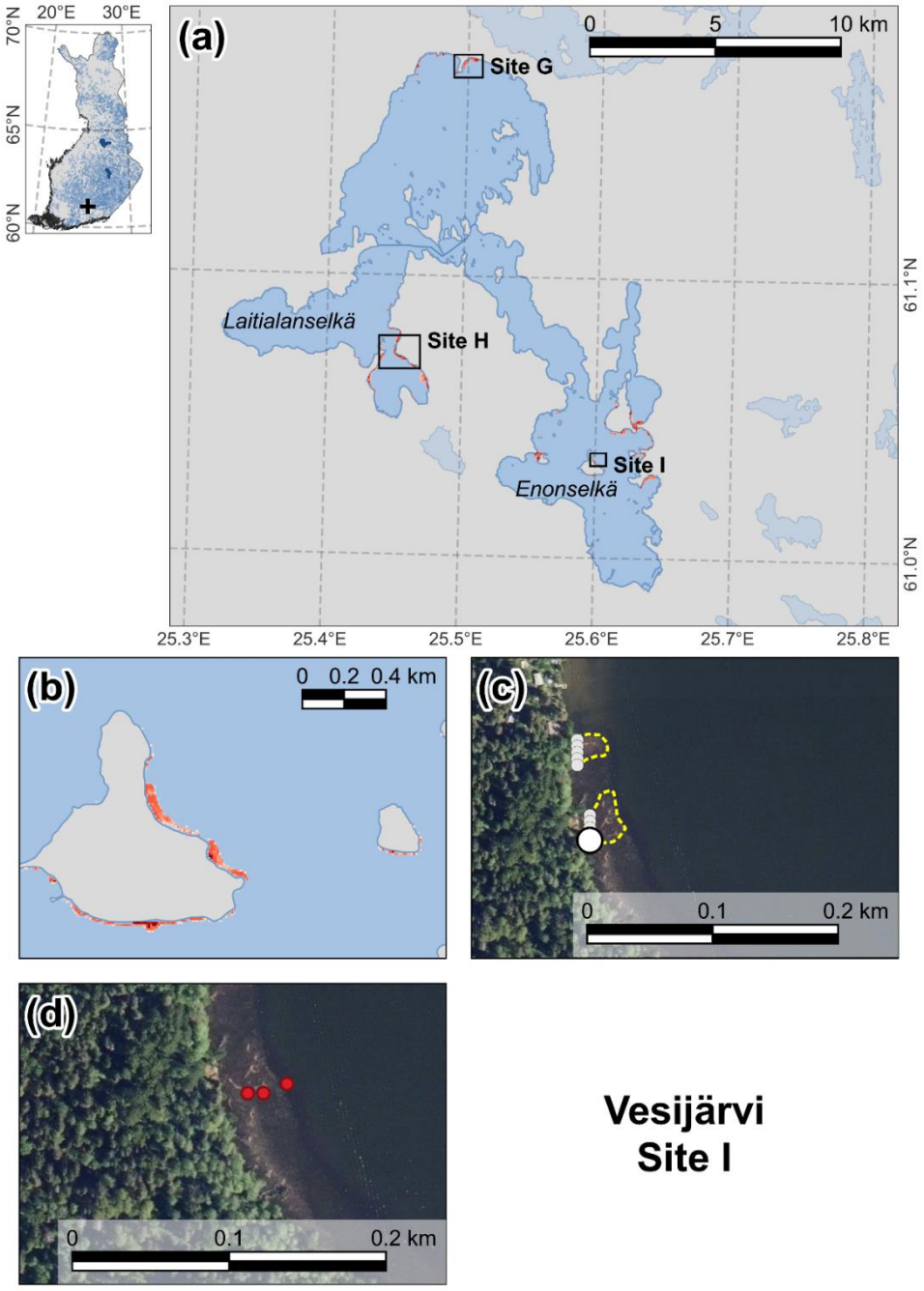

Figure S9. Location of sampling Site I in Vesijärvi (a), with details of: (b) the vegetation patch (Koponen et al., 2022); (c) the starting points of the transect following a grid of 5 x 5 m; (d) the location of the sediment cores following the transect of landside, transitional and waterside. Aerial images from Finnish National Geoportal (Orthophotos) (2023).

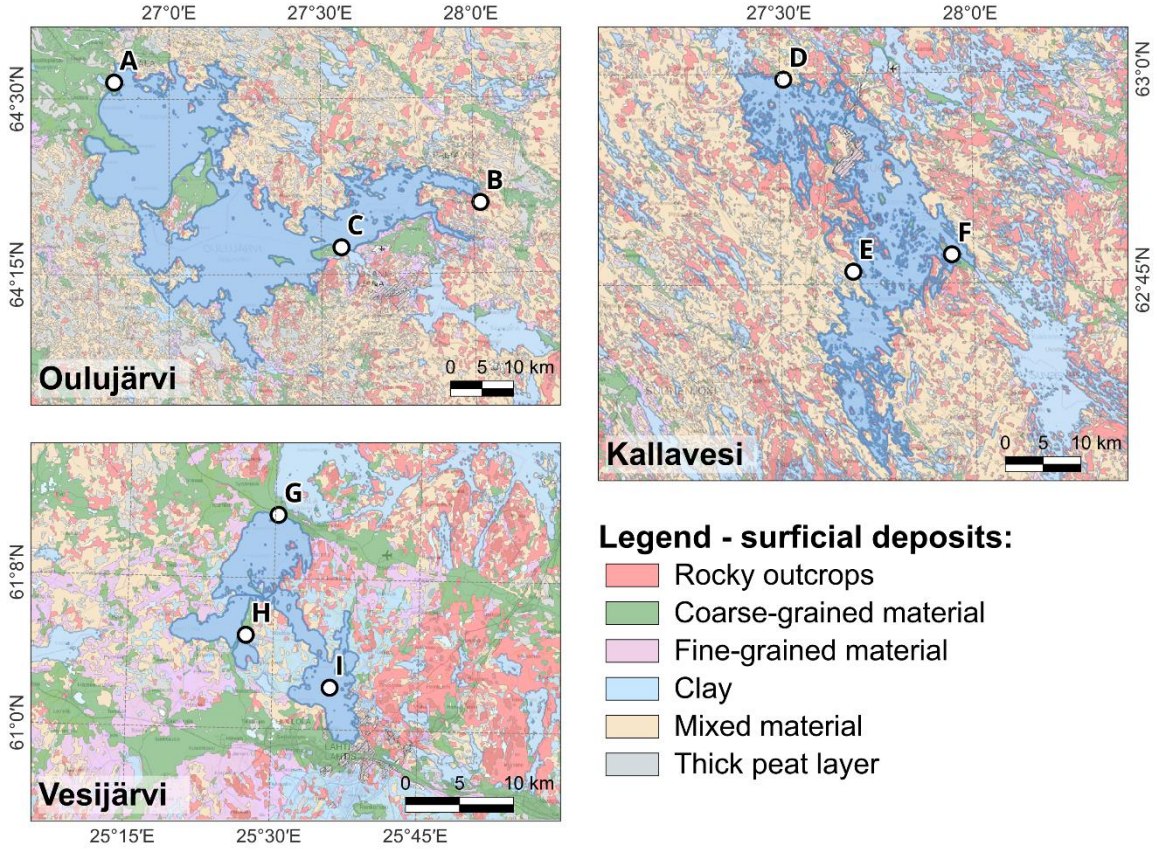

Figure S10. Main surficial deposits found in the surroundings of lakes Oulujärvi (top left panel), Kallavesi (top right panel) and Vesijärvi (bottom left panel) (GTK, 2024).

70

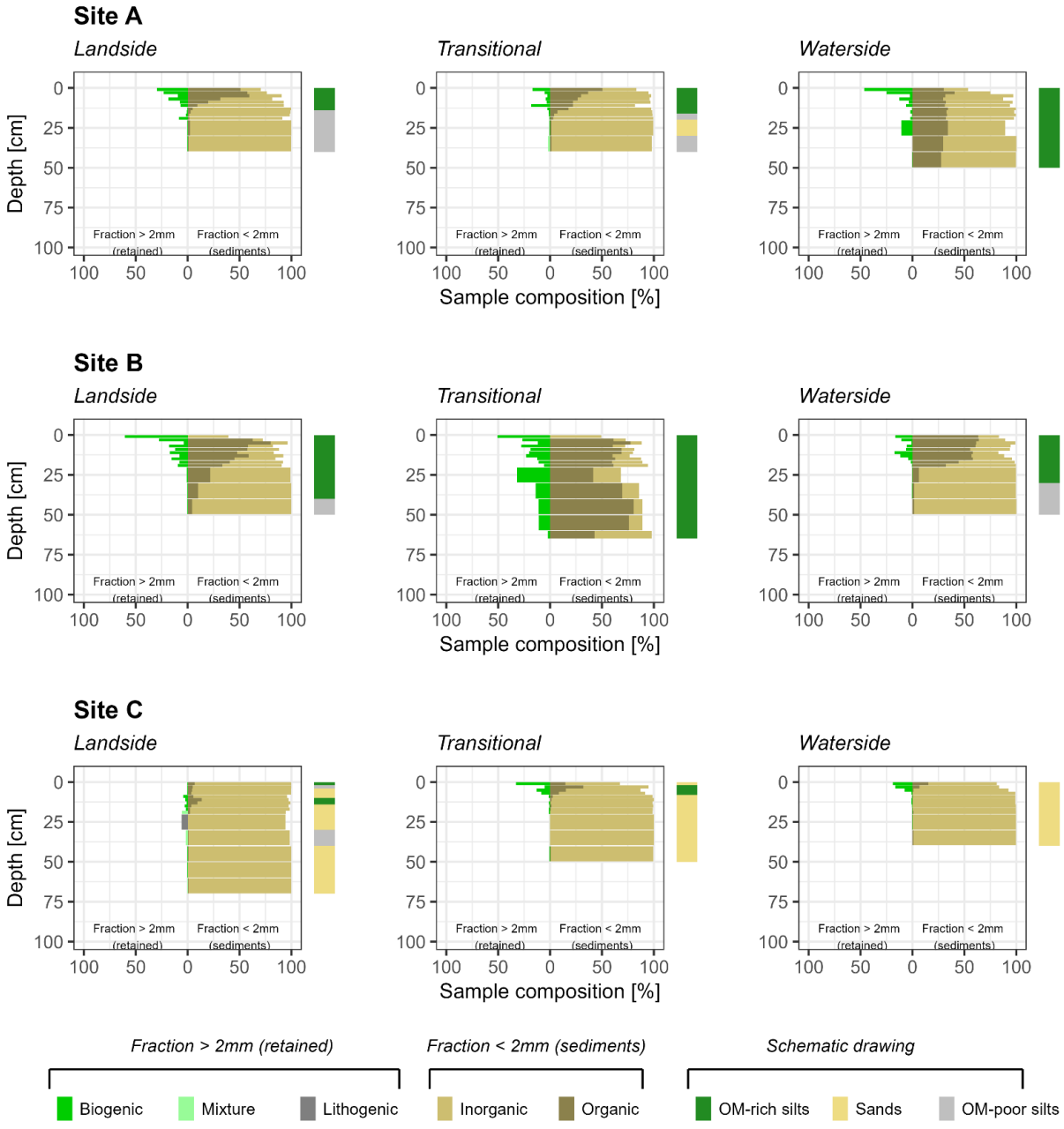

Figure S11. Sedimentary composition in sites A, B and C from lake Oulujärvi. Leftward bars represent the material retained in the 2 mm sieve, and rightward bars indicate the % of organic matter from the total sieved material. The schematic drawing on the right side of each bar plot shows a visual categorization based on grain-size and total organic carbon (TOC) content: "sands" (d50 ≥ 62.5 mm), "OM-poor silts" (d50 < 62.5 and TOC ≤ 5%) and "OM-rich silts" (d50 < 62.5 and TOC > 5%).

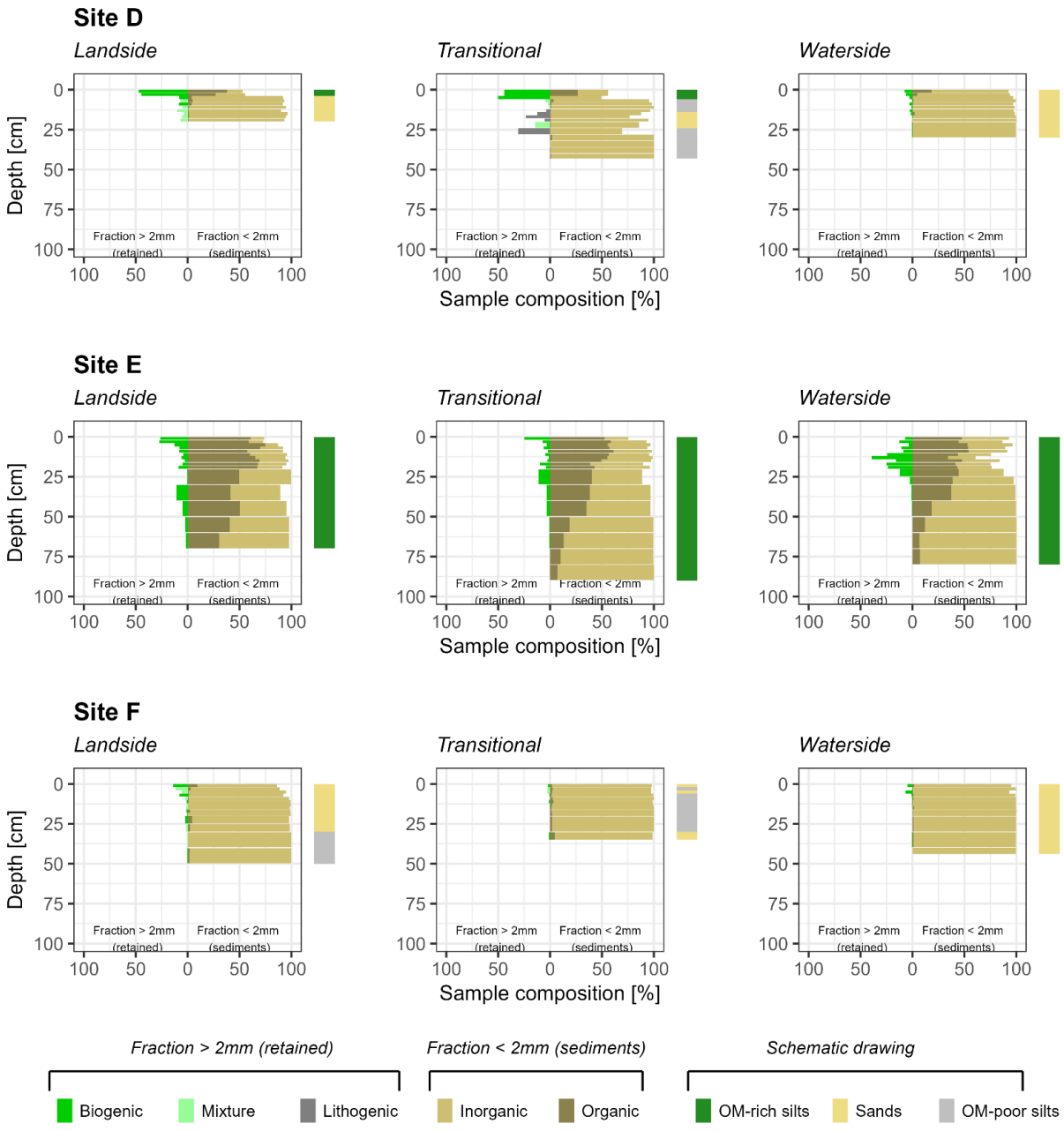

Figure S12. Sedimentary composition in sites D, E and F from lake Kallavesi. Leftward bars represent the material retained in the 2 mm sieve, and rightward bars indicate the % of organic matter from the total sieved material. The schematic drawing on the right side of each bar plot shows a visual categorization based on grain-size and total organic carbon (TOC) content: "sands" (d50 ≥ 62.5 mm), "OM-poor silts" (d50 < 62.5 and TOC ≤ 5%) and "OM-rich silts" (d50 < 62.5 and TOC > 5%).

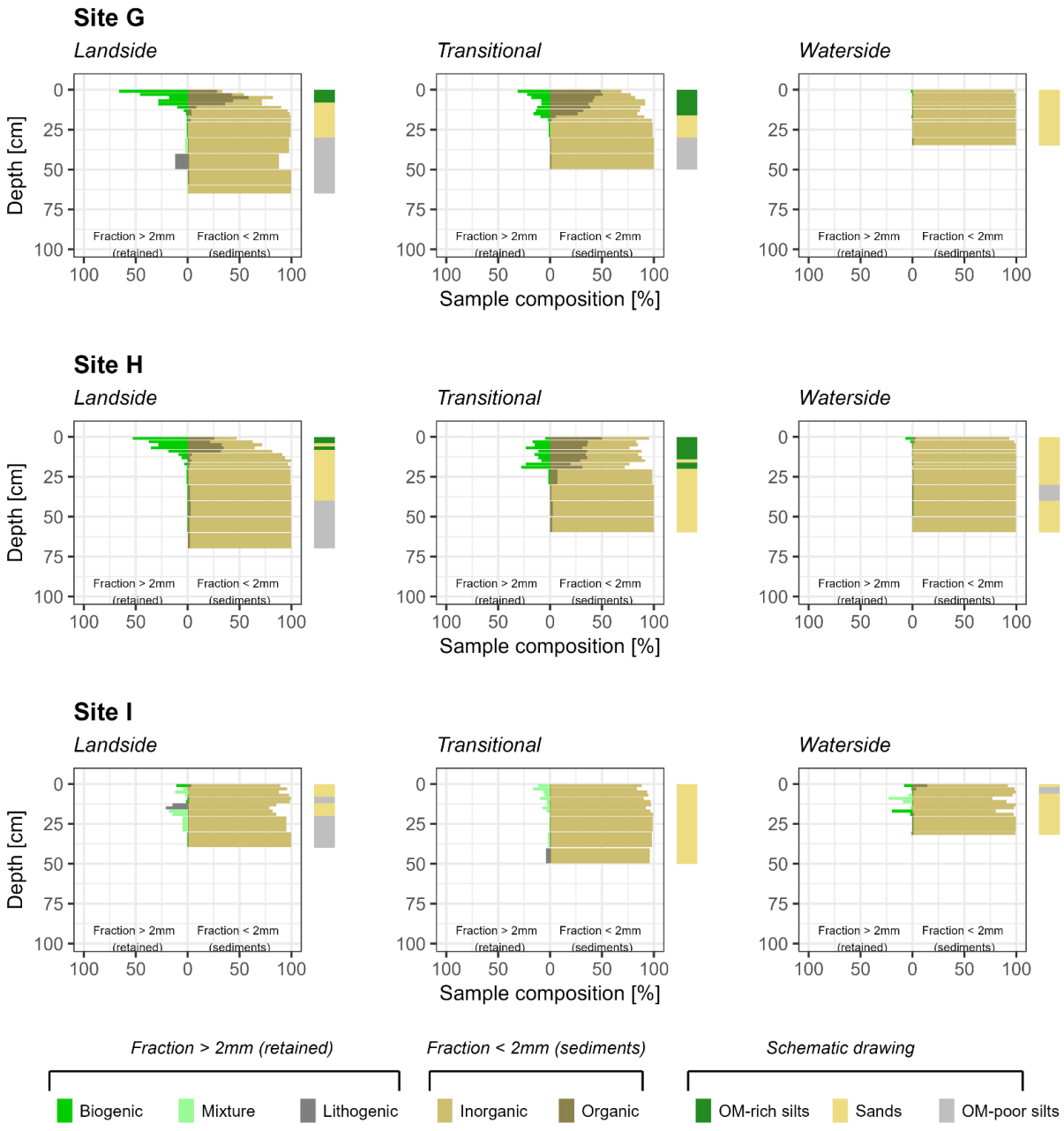

Figure S13. Sedimentary composition in sites G, H and I from lake Vesijärvi. Leftward bars represent the material retained in the 2 mm sieve, and rightward bars indicate the % of organic matter from the total sieved material. The schematic drawing on the right side of each bar plot shows a visual categorization based on grain-size and total organic carbon (TOC) content: "sands" (d50 ≥ 62.5 mm), "OM-poor silts" (d50 < 62.5 and TOC ≤ 5%) and "OM-rich silts" (d50 < 62.5 and TOC > 5%).

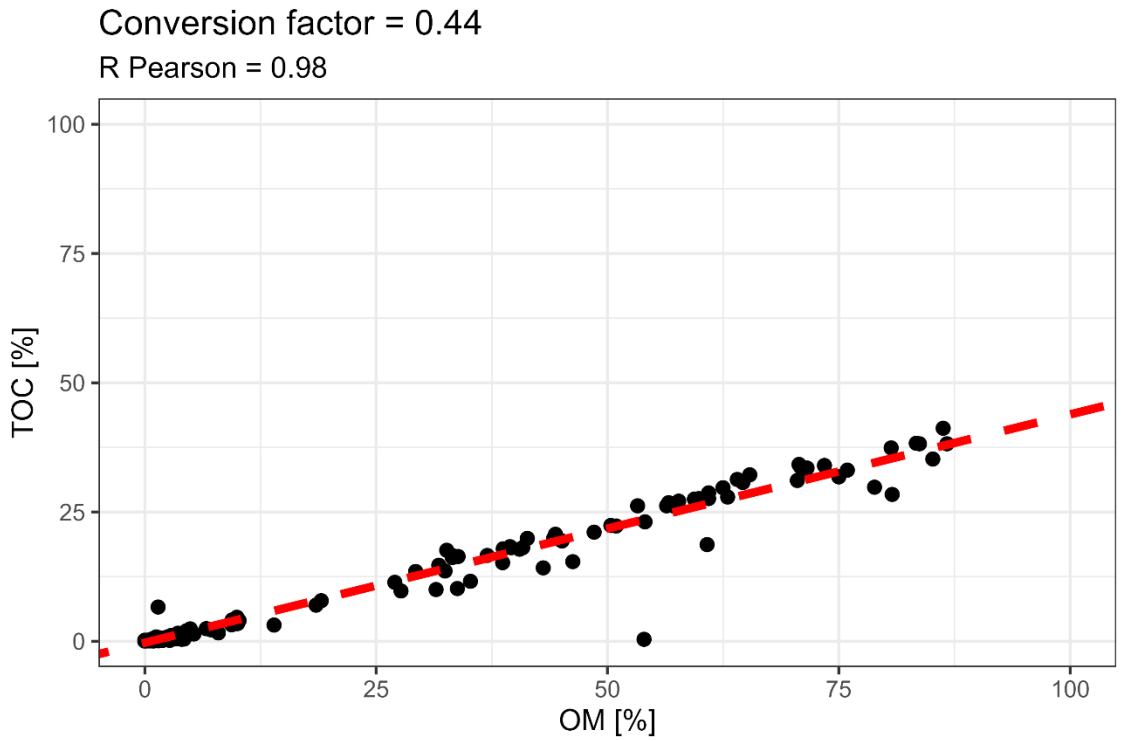

Figure S14. Scatterplot between organic matter (OM) and total organic carbon (TOC) content for 173 sediment samples.

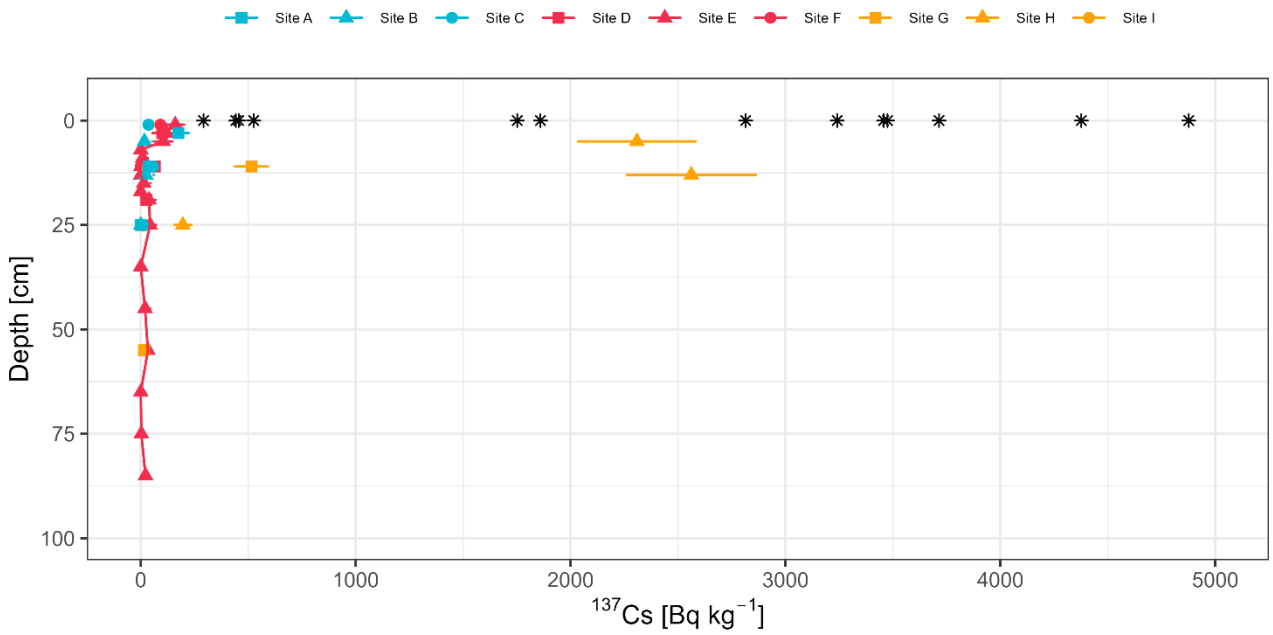

Figure S15. ^{137}Cs distribution in our cores [Bq kg^{-1}]. The * symbols indicate peak values of total ^{137}Cs deposition observed in deeper areas of the studied lakes (Junna et al., *in press*).

Site C – Transitional:	
Site G – Landside:	

Figure S16. Pictures of selected sediment cores evidencing the clear unconformities between a surface layer rich in organic material and basal organic-poor material.

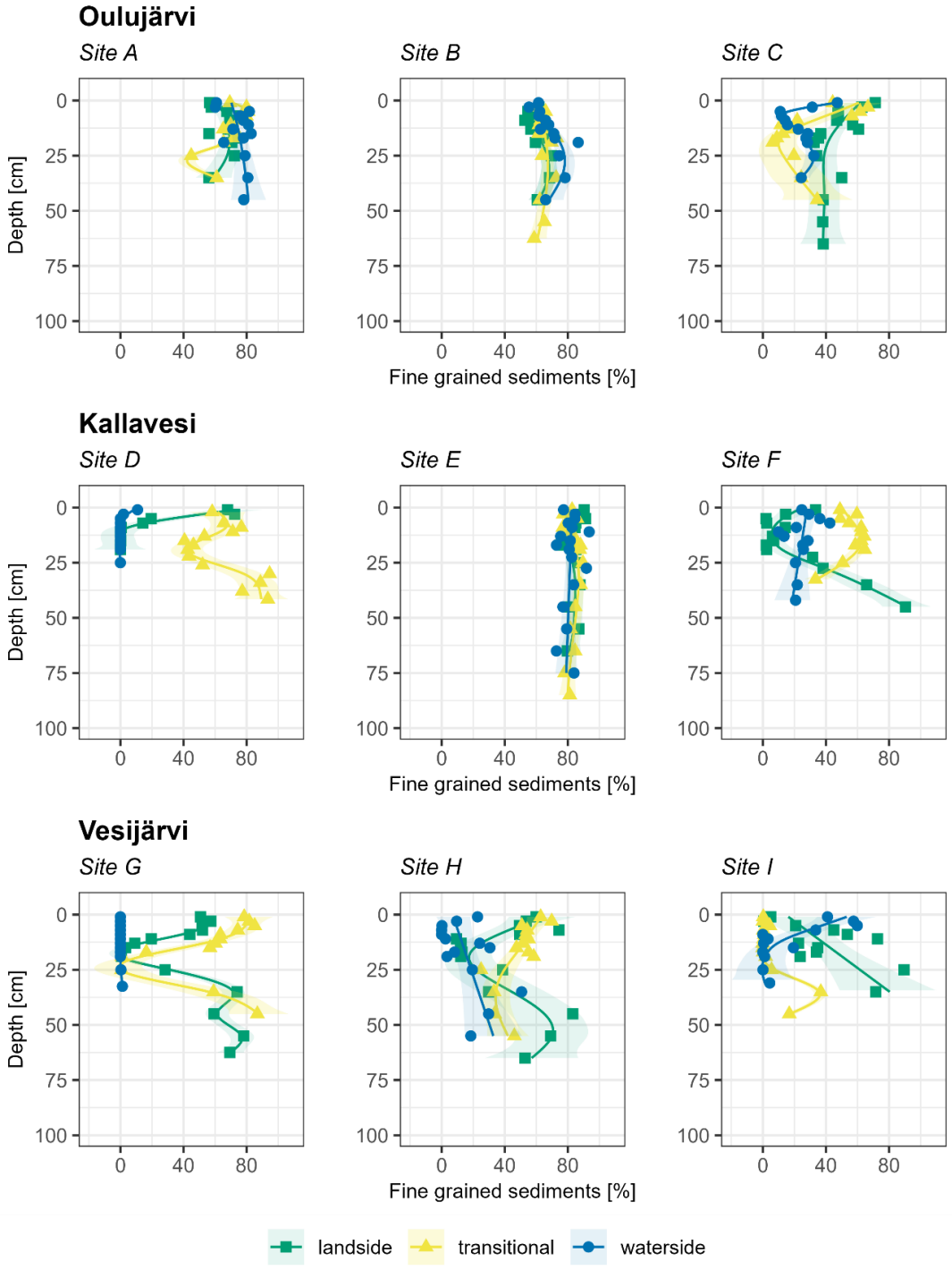

Figure S17. Vertical profiles of grain size distribution.

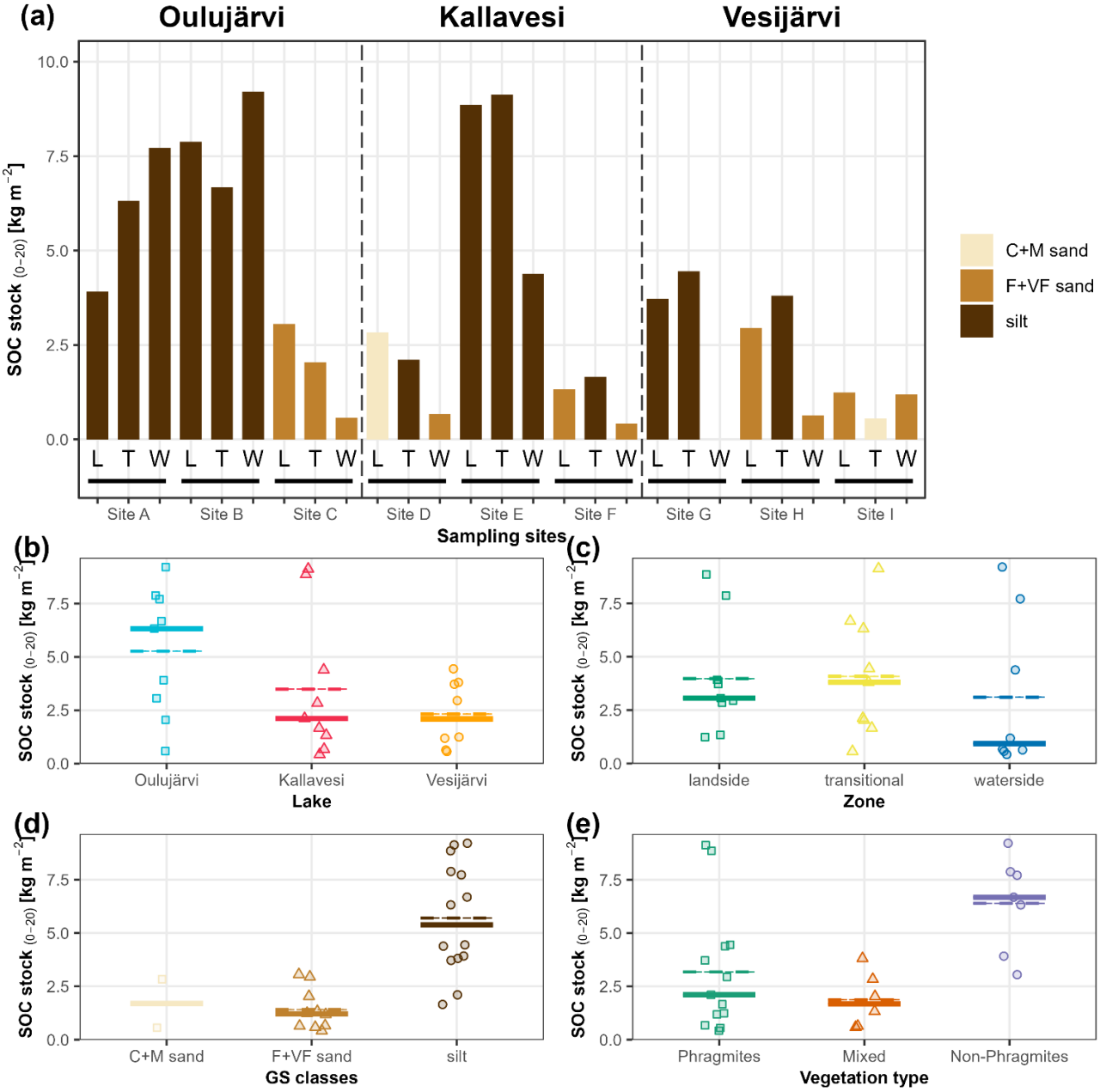

Figure S18. Sedimentary organic carbon (SOC) stocks [kg m^{-2}] of the top 20 cm of the sediment cores (a) and grouped by lakes (b), shoreline zones (c), grain size classes (d) and vegetation type (e). Stock estimates consider only samples with > 1 % of organic matter. In panels (b) to (e), the dashed horizontal lines indicate the mean, and the continuous bold horizontal lines indicate the median. Abbreviations: L = landside zone; T = transitional zone; W = waterside zone; C+M sand = coarse and medium sands; F+VF sand = fine and very fine sands. In (a), the bars are coloured according to the grain size averaged through the whole sediment core.

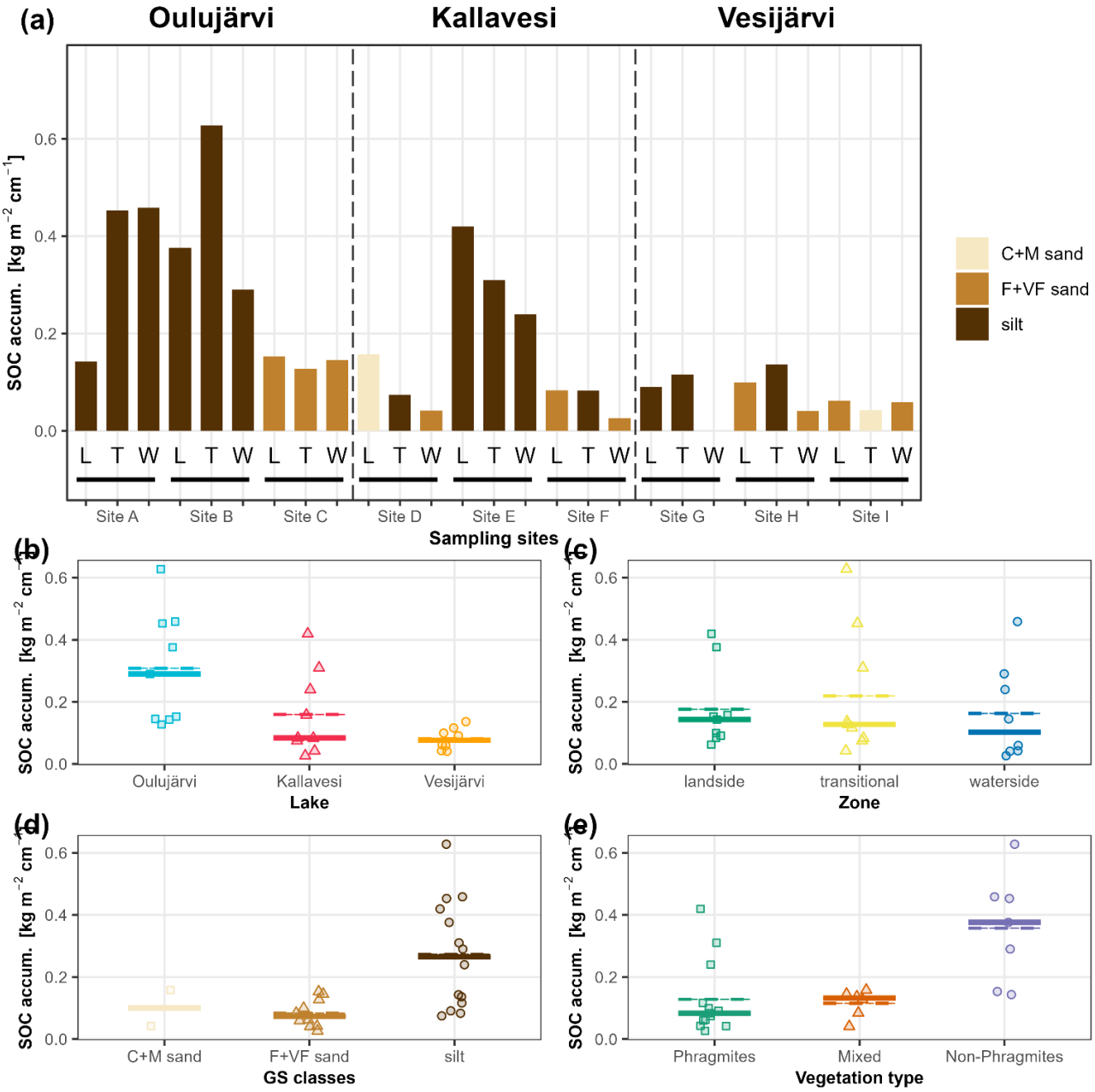

Figure S19. Sedimentary organic carbon (SOC) accumulation [kg m^{-2} cm^{-1}] of the sediment cores (a) and grouped by lakes (b), shoreline zones (c), grain size classes (d) and vegetation type (e). Accumulation estimates consider only samples with > 1 % of organic matter. In panels (b) to (e), the dashed horizontal lines indicate the mean, and the continuous bold horizontal lines indicate the median. Abbreviations: L = landside zone; T = transitional zone; W = waterside zone; C+M sand = coarse and medium sands; F+VF sand = fine and very fine sands. In (a), the bars are coloured according to the grain size averaged through the whole sediment core.

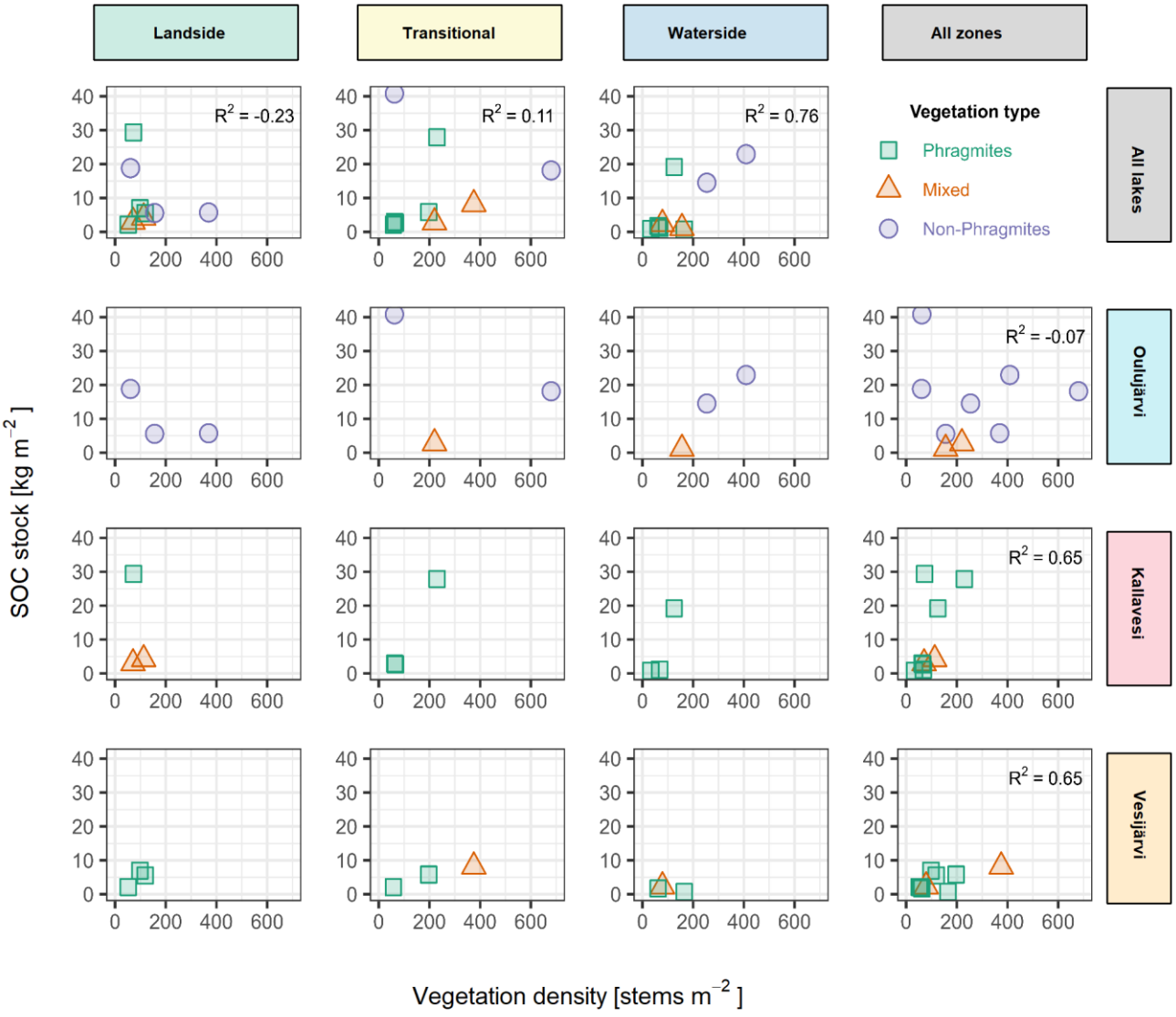

Figure S20. Comparison between sedimentary organic carbon (SOC) [kg m^{-2}] and vegetation density [stems m^{-2}], grouped by zones (columns), lakes (rows) and type of vegetation (symbol colours).

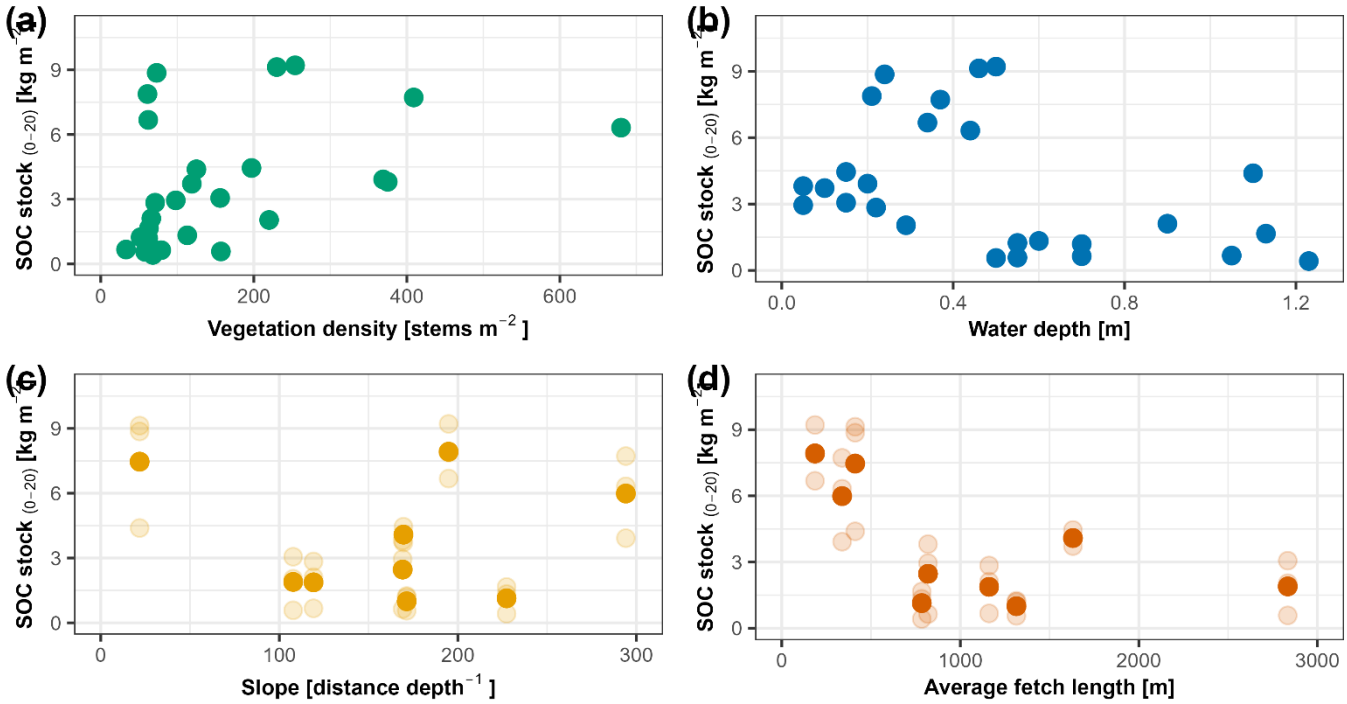

Figure S21. Relationship between sedimentary organic carbon (SOC) stocks [kg m^{-2}] based on the top 20 cm of the sediment cores and environmental parameters: (a) vegetation density [number of helophyte stems, in stems m^{-2}], (b) water depth [m], (c) slope (calculated as the distance between the landside and waterside sampling locations divided by the difference in their depth), (d) and the average fetch length [m]. In plots (c) and (d), the translucent points indicate the SOC stocks per zone (landside, transitional, waterside) in each site (A to I), while the opaque points indicate the average SOC stock estimates in each site.

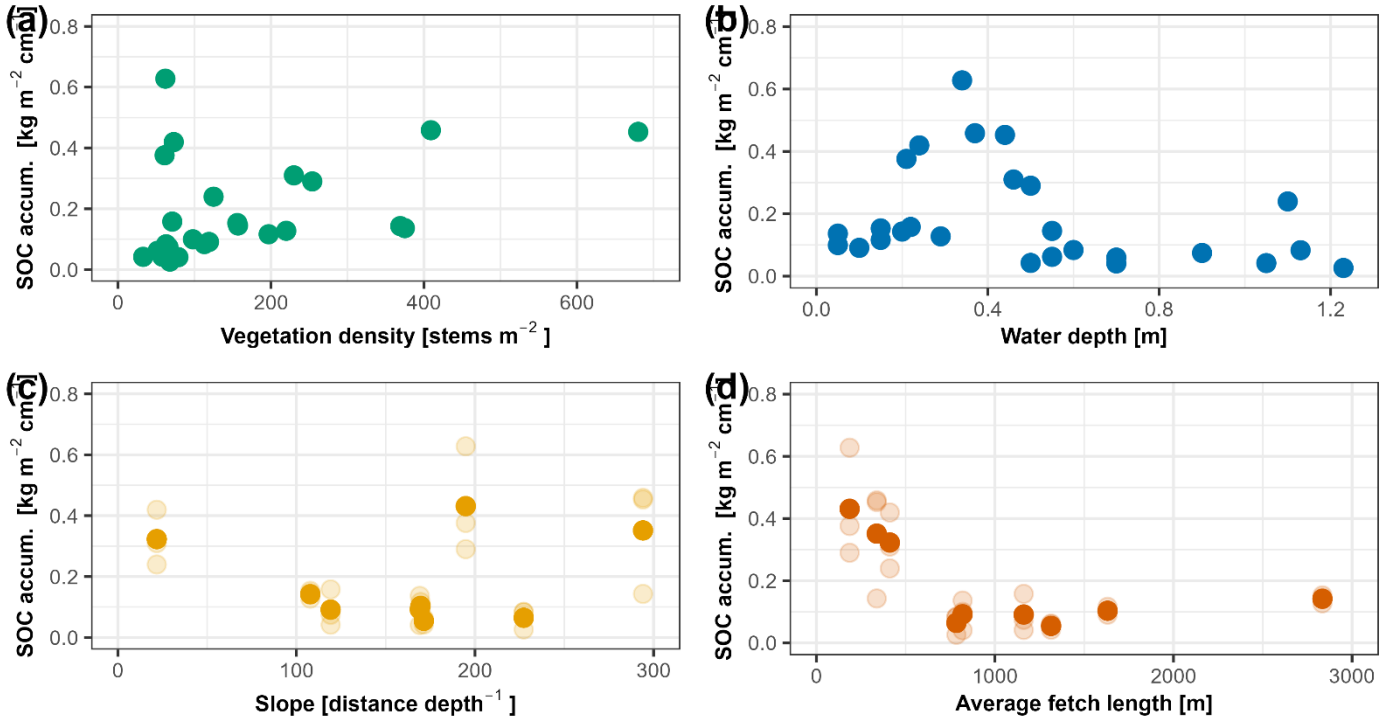

Figure S22. Relationship between sedimentary organic carbon (SOC) accumulation [kg m^{-2} cm^{-1}] and environmental parameters: (a) vegetation density [number of helophyte stems, in stems m^{-2}], (b) water depth [m], (c) slope (calculated as the distance between the landside and waterside sampling locations divided by the difference in their depth), (d) and the average fetch length [m]. In plots (c) and (d), the translucent points indicate the SOC stocks per zone (landside, transitional, waterside) in each site (A to I), while the opaque points indicate the average SOC stock estimates in each site.

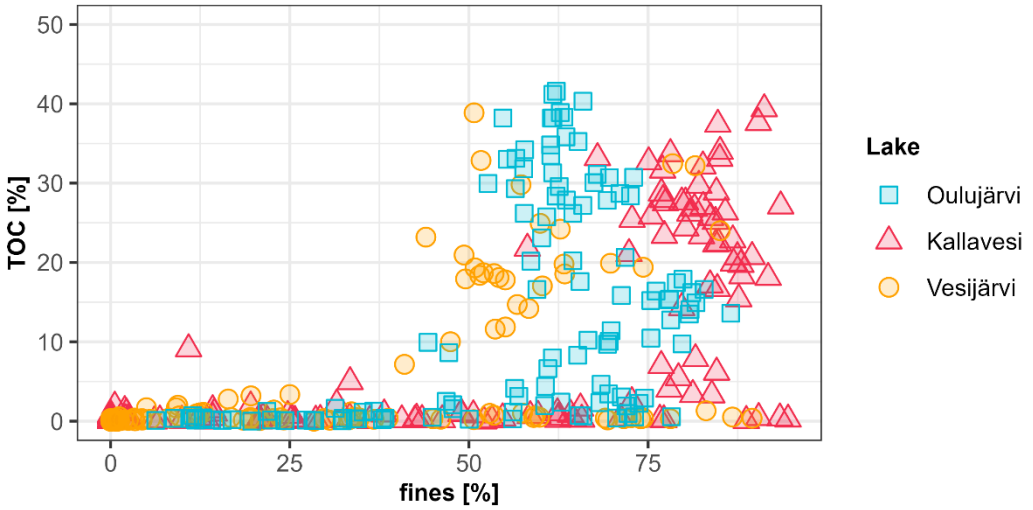

Figure S23. Relationship between total organic carbon (TOC, in % dw) with grain size distribution (% of fine-grained sediments (silt + clay)).

85

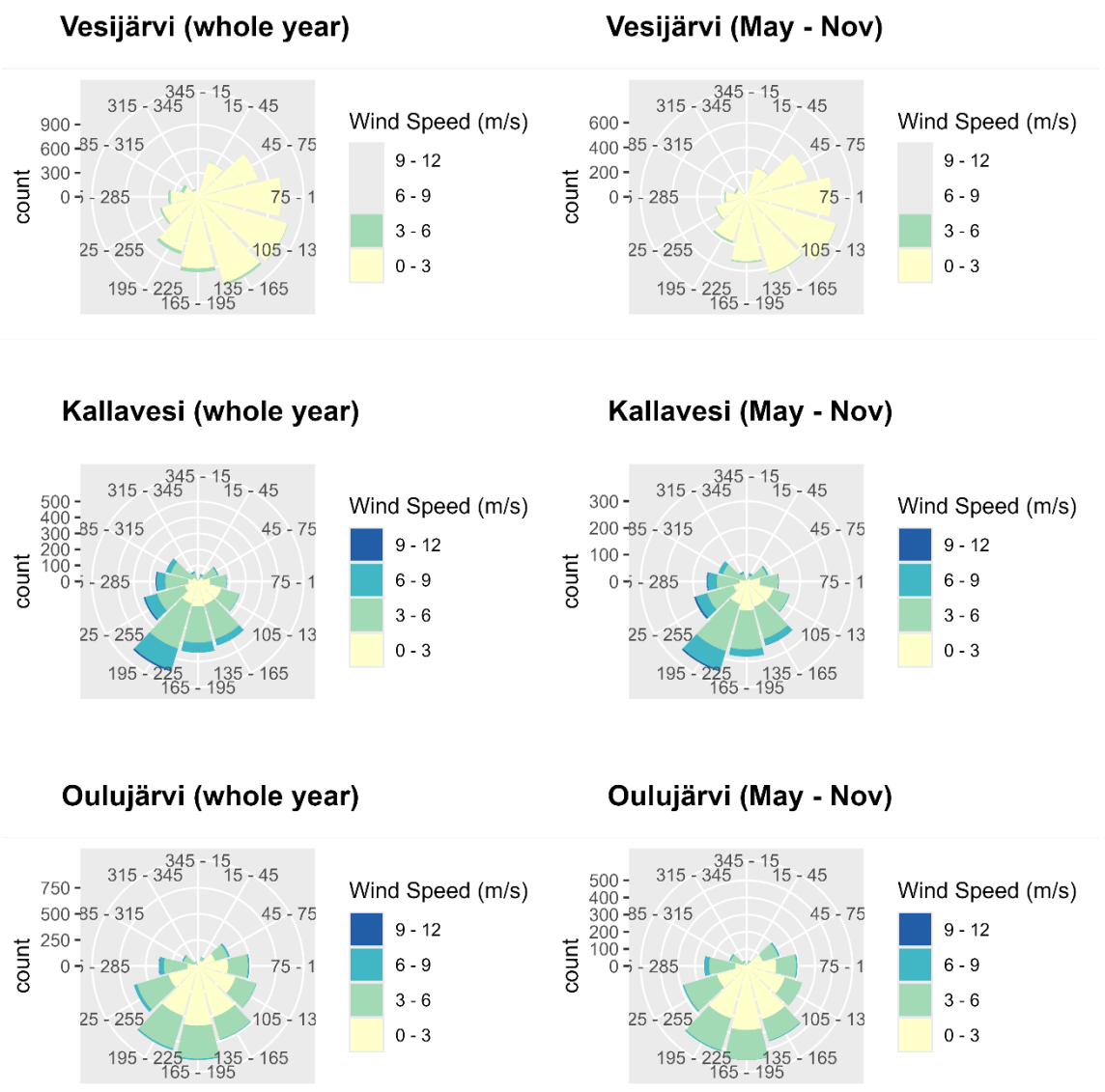

Figure S24. Wind roses of the three studied lakes, considering the whole year (left panels) and between May and November (no ice coverage, right panels) (FMI database, 2025).

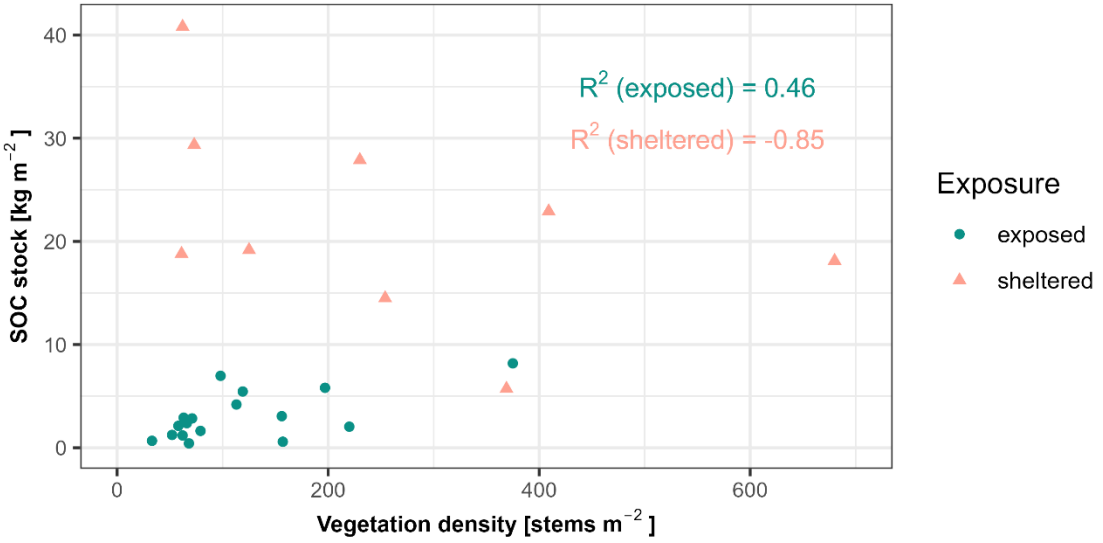

Figure S25. Comparison between sedimentary organic carbon (SOC) [kg m^{-2}] and vegetation density [stems m^{-2}], grouped by average fetch length ("exposed": fetch > 500 m; "sheltered": fetch <= 500 m).

90

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