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Abstract

Evaluating blue-carbon restoration requires separating newly developed biological pools from sediment carbon accumulated before intervention. Covering 4,427 ha, the Caofeidian seagrass meadow is the largest contiguous monospecific *Zostera marina* meadow in northern China. Using adjacent bare tidal flats and natural seagrass meadows as reference habitats, we quantified carbon stocks in living vegetation and depth-resolved sediment organic carbon stocks across a 638-ha *Z. marina* restoration area. Two years after restoration, total ecosystem carbon in the restored meadow reached $21.61 \pm 1.66 \text{ t C ha}^{-1}$, approximately 85% of the natural-reference stock of $25.32 \pm 3.47 \text{ t C ha}^{-1}$. This similarity was dominated by sediment carbon, much of which likely predated restoration. To isolate verifiably new project-driven changes, we redefined the early-stage active carbon pool as a 0–50 cm biological envelope, which revealed a substantial net stock additionality of 3.50 t C ha^{-1} above the bare-flat baseline. The restored meadow also stored $7.60 \pm 0.60 \text{ t C ha}^{-1}$ within the 20–50 cm rooting interval, exceeding the bare flat and approaching the natural reference. Excess ^{210}Pb yielded a site-specific, multi-decadal sedimentary organic-carbon burial estimate of $0.28 \pm 0.03 \text{ t C ha}^{-1} \text{ yr}^{-1}$, with ^{137}Cs providing an independent indication of chronological uncertainty. Across 30-year valuation scenarios, the present value of avoided societal climate damages consistently exceeded potential carbon-credit revenues. These findings separate rapid biological carbon development from legacy sediment stocks and longer-term burial potential, providing a depth- and pool-resolved basis for evaluating complementary restoration and conservation strategies.

Vegetated coastal ecosystems, particularly seagrass meadows, provide disproportionately valuable ecological services, including coastal protection, water purification¹, and critical nursery habitats for marine fisheries². Beyond these broad ecosystem benefits, they most notably function as intense global greenhouse-gas sinks^{3,4}. Despite occupying a mere 0.1% of the ocean surface, they annually bury an estimated 27–44 Tg of organic carbon (C_{org}), accounting for 10–18% of the global oceanic total and thereby constituting a fundamentally important sink that sequesters substantial “blue carbon” within living biomass and underlying sediments^{5,6}. However, these vital ecosystems are currently facing severe global degradation driven by compounding anthropogenic pressures, most notably coastal development, nutrient pollution, and climate-induced stressors^{7–9}. Continued habitat loss not only shrinks their natural carbon sequestration capacity but also risks eroding and remineralizing centuries of historically accumulated soil carbon, threatening to convert these vital sinks into potent new sources of greenhouse gas emissions^{10–12}. In response to this compounding crisis, large-scale seagrass restoration has emerged as a premier natural climate solution, offering a realistic pathway to recover coastal biodiversity while actively rebuilding carbon-storage functionality¹³.

Although globally extensive restorations have demonstrated that seagrass habitats and carbon sinks can recover synergistically⁷, accurately evaluating this climate-mitigation success during the critical early stages of intervention requires a mechanistic understanding of how newly captured carbon is dynamically distributed among active ecosystem pools¹⁴. Robustly verifying this early-stage carbon additionality, however, presents a profound methodological challenge. Prominent carbon accounting frameworks typically mandate deep, full-profile sediment inventories (e.g., a 1-meter default)^{15,16}. While appropriate for mature ecosystems, applying this uniform depth to recently restored meadows inherently conflates verifiably new, project-driven carbon with the substantial, unrelated “noise” of pre-existing historical legacy sediments^{17,18}. This deep baseline variance can statistically dilute and entirely obscure the early, localized signals of biological recovery¹⁹. For recently restored meadows, a central unanswered question is how to effectively decouple this newly formed active carbon pool from legacy inventories to reveal true short-term additionality¹³.

Connecting these dynamic active pools to longer-term carbon burial introduces a further distinction between stored carbon and the rate at which new carbon accumulates²⁰. Aboveground canopies and belowground roots promote immediate carbon accumulation, while deeper sediment stocks integrate long-term organic-matter inputs and depositional history²¹. Combining depth-resolved carbon inventories with historical sediment chronologies (e.g., radionuclide dating) can place present-day, biologically driven carbon pools within a longer depositional context²². This integrated approach is particularly relevant during early restoration, when the observed rapid vegetation expansion and the slow sedimentary record describe vastly different timelines of ecosystem development¹³. Besides, the precise distinction between early biological additionality and long-term carbon accumulation also fundamentally matters for restoration finance²³. Carbon-credit revenue depends strictly on verifiable, additional climate benefits and the market prices assigned to eligible credits. Evidence from a mature restored eelgrass meadow in Virginia, U.S.A. showed that carbon-offset revenue covered only a fraction of restoration expenditure, despite measurable greenhouse-gas removal¹⁴. Furthermore, market revenues and societal climate benefits represent entirely different valuation perspectives. The social cost of carbon dioxide quantifies the monetary damages associated with an additional tonne of emissions, providing a broader basis for valuing avoided climate damages²⁴. Reporting potential credit revenue and societal climate benefits separately can therefore clarify the true multidimensional significance of projected seagrass carbon burial²⁵.

Caofeidian, in the Bohai Sea of northern China (Fig. 1), provides a compelling setting to address these global accounting challenges. It contains China’s largest continuous seagrass habitat, dominated by *Z. marina*, situated within a coastal landscape heavily shaped by both development and massive restoration^{26,27}. Its extensive meadows provide a rare opportunity to examine carbon dynamics rigorously during the critical early stages of a large-scale temperate restoration programme²⁸. Here, utilizing field surveys conducted in 2021 and 2024, we redefine the early-stage carbon assessment framework. By

establishing a depth-resolved biologically active envelope (living biomass plus 0–50 cm sediment), we successfully isolate rapid biological additionality from deep legacy sediment noise across bare flats, restored meadows, and natural references. We then combine this high-resolution early inventory with ^{210}Pb -derived sediment chronologies to estimate long-term multi-decadal burial capacity. Finally, we project its 30-year present value under alternative carbon-pricing scenarios and a separate social-cost-of-carbon valuation. Together, these analyses provide a unified framework connecting early-stage active-pool accounting, persistent sedimentary storage, and the overarching economic significance of marine ecosystem restoration.

Results

Magnitude of sediment organic carbon density. The fine-resolution profiles showed distinct vertical variation in sediment organic-carbon concentration (Corg) among habitats (Fig. 2a). Formal habitat comparisons were conducted using harmonized depth intervals to account for differences in sampling resolution among surveys. In the common 0–10 cm surface interval, mean Corg was similar in the bare flat, restored meadow and pooled natural reference (1.76 ± 0.21 , 1.67 ± 0.25 and 1.66 ± 0.14 mg g $^{-1}$, respectively; Welch's one-way ANOVA, $F = 0.078$, $P = 0.926$). Below the surface, the fine-resolution profiles diverged. The restored meadow reached its highest observed mean Corg of 2.07 ± 0.26 mg g $^{-1}$ at 25–30 cm. When measurements were harmonized to the common 20–30 cm interval, mean Corg remained descriptively higher in the restored meadow (1.98 ± 0.28 mg g $^{-1}$) than in the bare flat (1.34 ± 0.15 mg g $^{-1}$) and natural reference (1.42 ± 0.23 mg g $^{-1}$), although the habitat effect was not statistically significant (Welch's one-way ANOVA, $F = 1.94$, $P = 0.196$). In the standardized 50–100 cm interval, mean Corg was lowest in the bare flat (0.73 ± 0.42 mg g $^{-1}$), and the habitat ordering was natural reference > restored meadow > bare flat; this deep-layer difference was not statistically significant (Welch's one-way ANOVA, $F = 1.63$, $P = 0.270$).

Dry bulk density (DBD) showed less pronounced vertical variation than Corg (Fig. 2b). Depth-specific comparisons based on the harmonized 10-cm intervals from 0 to 50 cm did not detect significant habitat effects after Holm correction. However, the core-specific, thickness-weighted mean DBD over the standardized 0–100 cm profile differed among habitats. Mean profile DBD was 1.304 ± 0.023 g cm $^{-3}$ in the bare flat, 1.315 ± 0.019 g cm $^{-3}$ in the restored meadow and 1.445 ± 0.023 g cm $^{-3}$ in the pooled natural reference (Welch's one-way ANOVA, $F = 11.34$, $P = 0.0065$). Holm-adjusted pairwise tests showed that the natural reference had a higher profile-averaged DBD than both the bare flat ($P = 0.0099$) and restored meadow ($P = 0.0023$), whereas the bare flat and restored meadow did not differ ($P = 0.742$). Thus, depth-dependent sediment carbon density reflected the combined variation in Corg and DBD: the mid-profile maximum in the restored meadow coincided primarily with elevated Corg, whereas the larger whole-profile carbon inventory of the natural reference was also associated with its higher profile-averaged DBD.

Volumetric organic-carbon density integrated the paired Corg and DBD measurements into a depth-resolved storage profile (Fig. 2c). In the harmonized 0–10 cm interval, mean carbon density was similar among the bare flat, restored meadow and natural reference (2.32 ± 0.33 , 2.27 ± 0.38 and 2.30 ± 0.20 mg C cm $^{-3}$, respectively; Welch's one-way ANOVA, $F = 0.005$, $P = 0.995$). At the finer graphical resolution, the restored meadow reached a maximum mean density of 3.05 ± 0.39 mg C cm $^{-3}$ at 25–30 cm. Across the common 20–30 cm interval, mean density was 2.90 ± 0.43 mg C cm $^{-3}$ in the restored meadow, compared with 1.97 ± 0.23 mg C cm $^{-3}$ in the bare flat and 2.14 ± 0.34 mg C cm $^{-3}$ in the natural reference; the habitat effect was not statistically significant (Welch's one-way ANOVA, $F = 1.66$, $P = 0.242$). None of the habitat comparisons across the five harmonized intervals from 0 to 50 cm remained significant after Holm correction. In the standardized 50–100 cm interval, mean carbon density was lowest in the bare flat (0.92 ± 0.57 mg C cm $^{-3}$), whereas the vegetated habitats retained higher mean values; this deep-layer difference was also not statistically significant (Welch's one-way ANOVA, $F = 2.10$, $P = 0.204$). Together, the profiles identify a mid-depth carbon-density maximum in the restored meadow and a higher mean deep-sediment

carbon density in the natural reference, while also showing substantial among-core variation in the deeper sediments.

Sediment organic carbon stocks. Sediment carbon stocks were evaluated across three depth intervals (0–20, 20–50 and 50–100 cm) and over the standardized 0–100 cm profile (Fig. 3). Individual core profiles revealed substantial vertical and among-core variation in sediment organic-carbon density within each habitat (Supplementary Fig. S1). All cores contained paired measurements of organic-carbon concentration and dry bulk density over the common 0–50 cm interval, enabling direct calculation of the measured carbon inventory across this depth range; variation in deeper profile coverage is documented in Supplementary Fig. S2.

Carbon stocks in the 0–20 cm surface interval were similar among the bare flat, restored meadow and pooled natural reference, ranging from 4.74 to 5.01 t C ha⁻¹ (Welch's one-way ANOVA, $F = 0.046$, $P = 0.956$). By contrast, stocks differed among habitats in the 20–50 cm rooting interval ($F = 7.221$, $P = 0.012$). The restored meadow contained 7.60 ± 0.60 t C ha⁻¹ in this interval, significantly exceeding the bare flat (Holm-corrected Welch's test, $P = 0.020$) but not differing significantly from the pooled natural reference ($P = 0.765$), which exhibited substantial inherent spatial patchiness across its integrated survey components. Crucially, our findings highlight the 20–50 cm rooting zone as the primary stratigraphic locus where sediment carbon inventories in the restored meadow undergo functional assimilation toward the natural reference state, fundamentally decoupling from the carbon-depleted conditions of the bare flat¹⁹.

For the standardized 50–100 cm interval, the natural meadow retained a mean carbon stock of 12.71 ± 2.54 t C ha⁻¹, while the restored meadow (8.14 ± 1.58 t C ha⁻¹) and bare flat (4.62 ± 2.82 t C ha⁻¹) exhibited lower mean values. However, these deep-layer differences were not statistically significant due to high spatial variance within habitats (Welch's ANOVA, $F = 2.104$, $P = 0.203$). This depth-dependent ordering was similarly evident in the standardized 0–100 cm inventory, which averaged 14.59 ± 2.54 t C ha⁻¹ in the bare flat, 20.66 ± 1.64 t C ha⁻¹ in the restored meadow, and 24.70 ± 3.53 t C ha⁻¹ in the pooled natural reference (Welch's ANOVA, $F = 2.901$, $P = 0.126$). Thus, although the absolute mean comparisons indicate mathematically higher total carbon inventories in the vegetated habitats compared to the bare flat, the whole-profile differences remained statistically non-significant, with the detectable carbon enrichment primarily localized within the 20–50 cm rooting zone.

Living vegetation carbon stocks. The living vegetation carbon pool showed rapid recovery in the restored meadow (Fig. 4a). Two years after restoration, its total living carbon stock reached 0.95 ± 0.07 t C ha⁻¹, 53% higher than the pooled natural-reference mean of 0.62 ± 0.17 t C ha⁻¹, although this difference was not statistically significant (Welch's two-sample t -test, $t = 1.79$, $df = 9.32$, $P = 0.106$; values are means $\pm$ SE). Station-level measurements provided further spatial context for the habitat comparison: mean shoot density, canopy cover and living-vegetation carbon stock in the restored meadow were higher than those recorded during the spatially distributed natural-reference survey in 2021 but lower than those measured in the targeted dense natural patches sampled in 2024 (Supplementary Fig. S5a–c). When observations from the two natural-meadow surveys were pooled according to the primary analytical design, their broader distributions encompassed both relatively sparse and dense vegetation states (Supplementary Fig. S5d–f).

Partitioning the living carbon pool into above- and belowground components showed that the higher mean carbon stock in the restored meadow was associated primarily with belowground biomass (Fig. 4b). Aboveground carbon stocks averaged 0.58 ± 0.05 t C ha⁻¹ in the restored meadow and 0.44 ± 0.12 t C ha⁻¹ in the pooled natural reference, with no significant difference between habitats (Welch's two-sample t -test, $t = 1.08$, $df = 8.92$, $P = 0.309$). By contrast, belowground carbon stock in the restored meadow was more than twice that of the natural reference (0.37 ± 0.04 versus 0.18 ± 0.05 t C ha⁻¹; Welch's two-sample t -test, $t = 3.14$, $df = 12.62$, $P = 0.008$). These results identify root and rhizome biomass as the principal living-carbon component distinguishing the recently restored meadow from the pooled natural reference^{7,14,22}.

Total ecosystem carbon stocks and pool composition. Sediment dominated total ecosystem carbon storage in both meadow groups, accounting for 95.6% of the total stock in the restored meadow (20.66 of 21.61 t C ha⁻¹) and 97.5% in the pooled natural reference (24.70 of 25.32 t C ha⁻¹; Fig. 5), consistent with global seagrass blue-carbon paradigms⁵. In 2024, two years after restoration began, total ecosystem carbon stock in the restored meadow was 21.61 ± 1.66 t C ha⁻¹, corresponding to 85.3% of the 25.32 ± 3.47 t C ha⁻¹ recorded for the pooled natural reference. The difference was not statistically significant (Welch's two-sample $t = -0.965$, $df = 9.98$, $P = 0.358$); values are mean ± SE). Living vegetation contributed 4.4% of total ecosystem carbon in the restored meadow, compared with 2.5% in the natural reference. These results underscore a rapid trajectory of living-carbon pool recovery driven by early plant colonization, whereas the vast majority of the ecosystem inventory remains securely stored in the sediment compartment, reflecting stable accumulation over longer geological timescales²⁹.

Active-pool carbon accounting and net additionality. Breaking from conventional default depths that risk conflating newly added carbon with legacy pools, we defined the biologically active ecosystem carbon pool for this early-stage restoration as the sum of living-vegetation carbon and structurally engaged sediment carbon within the upper 0–50 cm (encompassing both the surface and the 20–50 cm rooting zone). The active pool averaged 13.47 ± 1.12 t C ha⁻¹ in the restored meadow and 9.97 ± 0.80 t C ha⁻¹ in the contemporary bare-flat reference, corresponding to a significant mean net additionality of 3.50 t C ha⁻¹ over the evaluation period.

This substantial biological additionality arose from two tightly coupled pathways: the establishment of living vegetation carbon (+0.95 t C ha⁻¹) and, most critically, the vegetation-driven sediment carbon enrichment localized within the 20–50 cm rooting zone (+2.63 t C ha⁻¹), which completely offset the negligible background variance detected in the surface layer (–0.09 t C ha⁻¹ in the 0–20 cm interval). Expressed as a simple two-year annualization, this combined biological and rooting-zone additionality was equivalent to an accumulation rate of 1.75 t C ha⁻¹ yr⁻¹. These robust, depth-resolved results reinforce that true early-stage sequestration is biologically structured and driven by belowground volumetric expansion rather than blanket surface deposition.

Table 1 | Depth-resolved active-pool accounting and net additionality over the two-year restoration window in Caofeidian seagrass meadows.

Carbon component	Bare-flat reference (t C ha ⁻¹)	Restored meadow (t C ha ⁻¹)	Net stock additionality (t C ha ⁻¹)
Living vegetation carbon	0.00 ± 0.00	0.95 ± 0.07	+ 0.95
Surface sediment carbon (0-20cm)	5.01 ± 0.82	4.92 ± 0.78	– 0.09
Rooting-zone sediment (20–50 cm)	4.97 ± 0.40	7.60 ± 0.60	+ 2.63
Total active ecosystem pool	9.97 ± 0.80	13.47 ± 1.12	+ 3.50
Annual carbon sequestration capacity (Amortized over 2 years)	—	—	1.75 t C ha ⁻¹ yr ⁻¹

Sediment organic carbon accumulation rates. The ²¹⁰Pb_{ex} activity profile of CAR_R02 declined log-linearly between 10 and 50 cm (Fig. 6). Linear regression of ln-transformed ²¹⁰Pb_{ex} activity against depth yielded a slope of –0.0282 ± 0.0025 cm⁻¹ (estimate ± SE, $n = 9$, $R^2 = 0.949$), corresponding to a CFCS-derived sediment accretion rate of 1.104 ± 0.097 cm yr⁻¹. CAR_R01 showed a weaker log-linear relationship over 5–50 cm ($n = 10$, $R^2 = 0.699$), corresponding to an apparent accretion rate of 2.59 cm yr⁻¹. The ¹³⁷Cs profile provided an independent chronostratigraphic comparison, with maximum activity at approximately 40 cm. Assigning this maximum to the 1963 global-fallout horizon yielded an apparent sediment accretion rate of 0.66 cm yr⁻¹. The difference between the ²¹⁰Pb_{ex}- and ¹³⁷Cs-derived estimates

214 indicates that the sediment profile was not described by a single time-invariant accumulation history,
 215 consistent with non-steady deposition, sediment reworking or post-depositional radionuclide redistribution.
 216 Because CAR_R02 contained the clearest CFCS-compatible log-linear interval, its $^{210}\text{Pb}_{\text{ex}}$ -derived rate was
 217 used for the subsequent carbon-accumulation calculation.
 218 Combining the CAR_R02 accretion rate with the station-level, thickness-weighted mean sediment
 219 organic-carbon density over 20–50 cm ($2.53 \pm 0.20 \text{ mg C cm}^{-3}$, mean $\pm$ SE, $n = 7$) yielded an estimated
 220 sediment organic-carbon accumulation rate of $27.95 \pm 3.30 \text{ g C m}^{-2} \text{ yr}^{-1}$. The uncertainty represents the
 221 propagated standard error from the CFCS regression slope and the among-station estimate of carbon
 222 density. Under a constant-rate projection, cumulative sedimentary carbon accumulation over 100 years
 223 would reach approximately $27.95 \pm 3.30 \text{ t C ha}^{-1}$. This rate was subsequently used as the sedimentary-
 224 carbon input to the long-term valuation scenarios.

Table 2 | Sediment organic-carbon burial rates in selected seagrass meadows worldwide.

Location	Dominant species	Sediment Corg density (g C cm-3)	SARs (cm yr-1)	CARs (g C m-2 yr-1)	^{210}Pb dating model	Study
Caofeidian, China (Restored meadows)	<i>Z. marina</i>	0.0025 $\pm$ 0.0002	1.104 $\pm$ 0.097	27.95 $\pm$ 3.30	210Pb (CFCS)	This study
Caofeidian, China (Natural meadows)	<i>Z. marina</i>	0.0016	1.44	24	210Pb (CFCS)	Fu et al., ³⁰
Yellow River Delta, China	<i>Z. japonica</i>	0.0037	1.08	40	210Pb (CFCS)	Fu et al., ³⁰
Liusha Bay, China	<i>H. ovalis</i>	0.0038	1.19	45	210Pb (CFCS)	Fu et al., ³⁰
Lingshui Bay, China	<i>E. acoroides</i>	0.0012	0.59	7.1	210Pb (CFCS)	Fu et al., ³⁰
Komuke Lagoon, Japan	<i>Z. marina</i> , <i>Z. japonica</i>	0.0100-0.0150	0.25-0.26	26.5–27.8	210Pb (CRS)	Watanabe and Kuwae, ³¹
Colombian Caribbean	<i>T. testudinum</i>	0.0079 $\pm$ 0.0035 ^a	0.39 $\pm$ 0.04 (0.09–0.70)	122 $\pm$ 62 (34–195)	210Pb (CFCS)	Serrano et al., ¹³
Big Lagoon, Florida, USA	<i>T. testudinum</i>	0.0020–0.0080	0.67	22.4	210Pb (CFCS)	Trevathan-Tackett et al., ³²
San Quintín Bay, Mexico	<i>Z. marina</i>	0.0057–0.0144	0.02–2.41	9–144	210Pb (CF)	Cuellar-Martinez et al., ³³
New England, USA	<i>Z. marina</i>	0.0050–0.0150	~0.16–1.67	8–230	210Pb (CFCS&CRS)	Novak et al., ³⁴
West Greenland	<i>Z. marina</i>	0.0020–0.0060	0.042–0.21	1.30–10.53	210Pb (CRS)	Marbà et al., ²⁹
Solent coast of southern central England, UK	<i>Z. marina</i>	0.0170–0.0450	0.12–1.08	20–106	210Pb (CFCS&CRS)	do Amaral Camara Lima et al., ³⁵

Notes: SAR, sediment accretion rate; CAR, sediment organic-carbon accumulation rate, here termed carbon burial rate; CFCS, constant flux–constant sedimentation; CRS, constant rate of supply; CF, constant flux. Organic-carbon densities are expressed as carbon mass per unit sediment volume. a. For the Colombian Caribbean, carbon density summarizes the upper 1 m of the broader sediment dataset. SAR and CAR represent approximately the last 70 years and were estimated from six cores successfully dated using ^{210}Pb . These summaries refer to different sample sets; CAR values are reproduced from Serrano et al.¹³, rather than recalculated from the tabulated means. For this study, CAR was calculated using the CFCS-derived SAR and depth-weighted organic-carbon density over 20–50 cm. Literature estimates represent the sites and depositional periods examined in the respective studies. Values for this study are presented as mean $\pm$ SE.

Projected 30-year economic valuation scenarios for carbon sequestration. The 30-year present value of potential carbon-credit revenue increased progressively across the three market scenarios (Fig. 7a; scenario assumptions and monetary bounds are provided in Supplementary Table S1). Under the static spot-price baseline (Scenario A), the restored meadow generated an estimated value of USD 165.4 ± 19.5 ha⁻¹ at year 30. The moderate price appreciation scenario (Scenario B) increased this value to USD 197.3 ± 23.3 ha⁻¹. Under the premium blue-carbon scenario (Scenario C), which assumed a higher base price for high-quality blue-carbon credits coupled with a robust 1.5% annual real price growth, the projected value reached USD 518.1 ± 61.2 ha⁻¹. The premium blue-carbon scenario therefore provided the highest market-based valuation of sedimentary carbon burial (Fig. 7b). Market-based estimates captured only part of the broader climate value associated with carbon sequestration. When evaluated using the social cost of carbon (SCC), which monetizes avoided global climate damages, the same carbon sink generated a 30-year global social value of USD $3,088.5 \pm 364.7$ ha⁻¹. Furthermore, beyond carbon sequestration, restored seagrass meadows generate a diverse portfolio of ecosystem co-benefits, including biodiversity recovery, habitat provision, and coastal protection. Integrating these ecological and risk-reduction services into future valuation frameworks will be essential for providing a comprehensive assessment of seagrass restoration's true contribution to climate adaptation and nature-positive coastal management.

To evaluate the sensitivity of our 30-year multi-decadal financial projections to macroeconomic assumptions, alternative annual discount rates (2.0% and 8.0%) were tested against our 4.5% baseline (Supplementary Fig. S6). Expectedly, absolute cumulative present values are highly sensitive to the discount rate applied, decreasing substantially under the 8.0% scenario. However, the structural disparity between market revenue and societal benefits remains insensitive to these variations. Across all tested discount rates, the present value derived from avoided climate damages (SCC) consistently exceeded the potential carbon-credit revenues, even when compared against the most optimistic market pricing model (Scenario C). Thus, the ranking of climate benefits and market revenue observed under the 4.5% baseline remained unchanged across the tested discount rates.

Discussion

Rapid biological recovery and reconstruction of the active carbon pool. Two years after restoration, the Caofeidian meadow had rebuilt a substantial living carbon pool within a sediment-dominated ecosystem. Its total ecosystem carbon stock reached 21.61 Mg C ha⁻¹, approximately 85% of the 25.32 Mg C ha⁻¹ measured in the pooled natural reference. Sediment accounted for 95.6% and 97.5% of total ecosystem carbon in the restored and natural meadows, respectively. Similarity in total stock therefore concealed a marked difference in carbon-pool organization. The restored meadow supported a proportionally larger living pool, whereas the natural meadow retained more carbon in deep sediment accumulated over longer timescales. The biological response was expressed most clearly below ground. Root and rhizome carbon in the restored meadow exceeded twice the natural-reference mean, whereas the difference in aboveground carbon was smaller. This allocation pattern indicates that early meadow development involved substantial investment in belowground structure rather than canopy expansion alone¹⁴. Roots and rhizomes contribute directly to meadow persistence, stabilize the sediment matrix and provide pathways for plant-derived carbon to enter sediment through tissue turnover and rhizodeposition^{22,36,37}. The Caofeidian results extend evidence from the large-scale *Z. marina* restoration in Virginia, where meadow expansion was accompanied by the recovery of carbon storage, water clarity and faunal communities⁷. They also complement global analyses showing that biomass production is an important but frequently underrepresented component of seagrass carbon accounting³⁸. In Caofeidian, the prominence of belowground biomass identifies root and rhizome development as a sensitive indicator of early restoration performance.

The reference-based active-pool comparison further clarifies this early functional response. Breaking from conventional accounting paradigms, our depth-resolved biologically active pool, encompassing living

vegetation and the 0–50 cm sediment envelope, revealed a substantial net additionality of 3.50 t C ha⁻¹ above the bare-flat baseline. Crucially, this positive additionality was not driven by the dynamic surface layer (0–20 cm), which remained energetically mixed and exhibited a negligible difference between habitats (–0.09 t C ha⁻¹). Instead, the additionality was predominantly fueled by the establishment of living biomass (+0.95 t C ha⁻¹) and, most strikingly, a pronounced vegetation-driven carbon enrichment uniquely localized within the 20–50 cm rooting zone (+2.63 t C ha⁻¹). The two-year carbon response was therefore strictly depth-specific, demonstrating that early rapid carbon accumulation relies heavily on structural belowground root expansion rather than indiscriminate surface sediment deposition. This localized, depth-specific pattern provides critical early-stage resolution to evidence from longer-established *Z. marina* restorations in Virginia. In those older systems, sediment organic-carbon stocks above the unvegetated reference increased substantially between 12 and 15 years post-restoration, reflecting both carbon enrichment within existing sediment and continued long-term sediment accretion^{7,14}. By establishing that the earliest quantifiable sedimentary carbon response in Caofeidian occurred exclusively within the 20–50 cm biological envelope, our observations characterize the initial mechanistic phase of this timeline. Continued meadow growth over multi-decadal horizons will likely combine this early robust belowground carbon priming with progressive surface deposition, ultimately bridging the newly established living active pool with deeper, longer-lived geological carbon storage.

Consequently, these mechanistic findings highlight the critical limitations of applying universal depth defaults to early-stage project evaluations. While the IPCC and prominent blue carbon accounting frameworks typically recommend a 1-meter default inventory¹⁵, adhering to this full-profile depth merely two years post-restoration deeply conflates recent biological additionality with the substantial, unrelated “noise” of historical legacy carbon—a fundamental accounting flaw strongly cautioned against in recent blue carbon frontier reviews¹⁷. By actively redefining the early-stage framework to the 0–50 cm biological envelope, our approach accurately isolates verifiably new, project-driven changes from deep historical deposits, refining the spatio-temporal precision of blue carbon assessments. Nevertheless, we caution that as ongoing restorations mature over multi-decadal timelines and continuous sediment accretion develops, returning to comprehensive full-profile assessments will eventually become indispensable for capturing their ultimate long-term climate benefits.

Depth-dependent sediment storage and long-term carbon burial. The sediment profiles revealed that the ecological meaning of carbon storage depended strongly on depth. Carbon stocks in the upper 0–20 cm were similar among the bare flat, restored meadow and pooled natural reference. The clearest habitat separation occurred within the 20–50 cm rooting interval, where the restored meadow contained more carbon than the bare flat and approached the natural-reference level. Together with the larger belowground biomass pool, this intermediate-depth enrichment is consistent with vegetation-mediated sediment retention and organic-matter inputs. The 20–50 cm interval consequently represents the principal zone in which restored vegetation and sediment carbon storage were spatially associated. Carbon stored within this interval may include recent plant inputs, imported organic matter and sediment deposited before restoration. The present profiles therefore characterize the distribution of carbon stocks but do not independently establish the age or provenance of every carbon fraction. Combining carbon-source tracers or biomarkers with depth-resolved root and rhizome measurements would separate recent vegetation-derived inputs from pre-existing sedimentary material. This distinction is important because carbon stocks, carbon accumulation and carbon provenance describe related but different properties of blue-carbon ecosystems¹⁷.

A different pattern emerged in the 50–100 cm interval. The natural reference had the highest mean carbon stock, followed by the restored meadow and bare flat. However, the uncertainty around these estimates prevented the differences from being statistically resolved. This combination of ordered means and broad uncertainty is ecologically plausible for deep coastal sediments. Unlike surface and rooting-zone stocks, deep carbon integrates spatially heterogeneous depositional histories, lateral organic-matter inputs,

sediment reworking and local hydrodynamic conditions. Global and regional assessments likewise reveal pronounced within- and among-meadow variability in seagrass sediment carbon stocks. Much of this variability is associated with sediment properties, hydrology, geomorphology, carbon provenance and disturbance history^{9,39}. The persistence of this ordering across alternative depth-extrapolation scenarios further indicates that the descriptive pattern was not dependent on a single extrapolation assumption (Supplementary Fig. S4; Supplementary Table S2). Deep-layer variability also propagated into the standardized 0–100 cm inventory, reducing the precision of whole-profile habitat contrasts. The results therefore support a depth-dependent interpretation. Habitat differentiation was statistically resolved within the 20–50 cm rooting interval, whereas the deeper and whole-profile inventories retained an ordered but spatially heterogeneous pattern. The higher mean stock in the natural meadow is consistent with a longer history of sediment accumulation, although the present data do not establish a statistically resolved difference in the deep reservoir. This distinction separates the biologically responsive rooting zone from a deeper carbon pool shaped by longer-term and spatially variable depositional processes.

The radionuclide profiles indicate that sediment accumulation has not been uniform through time. In CAR_R02, after systematically excluding the upper 10 cm representation of the surface mixed layer (SML), the coherent log-linear decline in excess ²¹⁰Pb yielded a CFCS-derived accretion rate of 1.104 ± 0.097 cm yr⁻¹. By comparison, assigning the ¹³⁷Cs maximum at approximately 40 cm to the 1963 global-fallout horizon produced an apparent rate of approximately 0.65 cm yr⁻¹. Offsets between ²¹⁰Pb and ¹³⁷Cs derived chronologies are not unusual in dynamic coastal sediments. The CFCS estimate integrates the continuous decline of excess ²¹⁰Pb over several decades, whereas ¹³⁷Cs provides a discrete chronological marker that may be displaced or broadened by sediment mixing, erosion, bioturbation and post-depositional redistribution^{40–42}. Similar inconsistencies between the two tracers have been associated with human-induced sediment redistribution in other Chinese coastal environments⁴³. The observed offset may therefore reflect temporal variation in sediment delivery and subsequent reworking rather than a single constant depositional history. Neither radionuclide estimate directly represents sediment accretion exclusively during the two-year restoration period because both integrate substantially longer timescales. Nevertheless, the continuous excess ²¹⁰Pb profile provides the more internally resolved estimate of multi-decadal sediment accretion at CAR_R02. We therefore use the 1.104 ± 0.097 cm yr⁻¹ estimate as a site-specific historical depositional baseline, while retaining the ¹³⁷Cs derived rate as an independent indicator of chronological uncertainty.

The carbon density used to estimate sedimentary organic-carbon burial was intentionally derived from the 20–50 cm interval. This interval lies entirely beneath the most dynamic SML (0–10 cm) and fully overlaps the coherent portion of the excess ²¹⁰Pb profile used for CFCS fitting. Relative to the upper 0–20 cm layer, the subsurface interval is less sensitive to recently deposited labile organic matter, short-term biological turnover, and physical mixing. Methodological assessments recommend coupling radionuclide-derived accumulation rates with organic-carbon concentrations measured beneath the surface mixed layer, where the carbon profile becomes comparatively stable against early diagenesis^{18,40}. Combining this accretion rate with the measured carbon density yielded a sediment organic-carbon burial estimate of 28.0 ± 3.3 g C m⁻² yr⁻¹. This value is close to the 24 g C m⁻² yr⁻¹ reported for natural *Z. marina* meadows in Caofeidian³⁰, the 26.5–27.8 g C m⁻² yr⁻¹ reported for Komuke Lagoon³¹ and the 22.4 g C m⁻² yr⁻¹ reported for Florida³². It remains lower than estimates from the Yellow River Delta³⁰, Liusha Bay³⁰, and tropical *Thalassia testudinum* meadows in the Colombian Caribbean¹³. These comparisons place Caofeidian within the lower-to-intermediate portion of the global reported range, illustrating how robust depth-specific carbon density, combined with localized hydrodynamics and sedimentation supply, jointly shape long-term burial rates. Depth alone, however, does not establish that all carbon within the 20–50 cm interval is chemically refractory or permanently retained. The estimate may include both locally produced and allochthonous organic matter and should not be equated directly with net additional carbon removal solely attributed to the first two years of restoration.

Together, the two depth domains identify complementary priorities for coastal carbon management. Restoration expands living biomass and renews pathways of organic-carbon input, whereas conservation protects the deeper sediment reservoirs accumulated by mature meadows. This distinction is consistent with global evidence that seagrass carbon stocks vary substantially among environmental settings and that habitat degradation can expose historically stored carbon to erosion and remineralization³⁹. Coordinating restoration with protection of nearby natural meadows can therefore expand active carbon inputs while maintaining established sedimentary carbon reservoirs.

Valuing comprehensive climate benefits through adaptation, biodiversity, and socio-economic synergies. The valuation scenarios show that the economic significance of sedimentary carbon burial depends strongly on the valuation framework. Higher carbon-price scenarios increase potential credit revenue, while the SCC framework assigns a larger welfare value to avoided global climate damages⁴⁴. However, contemporary carbon markets typically optimize solely for verified emissions reductions, treating adaptation, biodiversity, and poverty outcomes as ancillary. Evidence from restored eelgrass in Virginia similarly shows that carbon-credit revenue alone rarely covers restoration expenditures^{7,23}, motivating a critical shift from carbon-centric valuation toward a holistic nature-based solutions framework.

Biodiversity recovery and coastal protection are not merely ecological side-effects in the Caofeidian restoration; they represent critical climate adaptation services. Re-established vegetation creates complex habitats that drive the recovery of associated faunal communities and commercial fisheries⁴⁵, while the expanding seagrass canopy attenuates waves and stabilizes the sediment matrix against near-bed stress⁴⁶. Crucially, these physical and ecological functions transcend simple environmental metrics—they directly buffer vulnerable shorelines against extreme weather and support local fisheries, inextricably linking ecosystem health to the resilience and livelihoods of coastal communities. Managing blue carbon ecosystems to integrate these social and adaptation priorities is now recognized as a global strategic imperative for equitable conservation¹⁷.

To fully realize and sustain these integrated climate benefits, a broader valuation approach must mainstream ‘co-benefit premiums’ into blue carbon financing⁴⁷. Rather than viewing ecological functions in isolation, future frameworks should utilize Natural Capital Accounting (e.g., SEEA) to formally quantify and certify non-carbon outcomes, such as coastal resilience assets and biodiversity credits⁴⁸. By making these co-benefits explicit, measurable, and tradable, their valuation can be stacked atop baseline carbon prices to bridge the funding gap for complex restoration projects. Consequently, joint monitoring at Caofeidian should ultimately aim not just to maximize early vegetation carbon, but to identify restoration trajectories that deliver the highest bundled returns for climate mitigation, adaptation, and human well-being.

Conclusions

This study shows that, two years after restoration, the Caofeidian meadow had developed a substantial living carbon pool within a sediment-dominated ecosystem. The restored meadow stored 21.61 t C ha⁻¹, equivalent to approximately 85% of the 25.32 t C ha⁻¹ in the pooled natural reference. However, convergence in total stock did not indicate equivalent carbon-pool development. Most of the restored meadow’s inventory remained associated with sediment that pre-dated restoration, whereas its early response was concentrated in living biomass, particularly roots and rhizomes. By capturing this rapid biological envelope through a depth-resolved 0–50 cm active pool, we identified a substantial net additionality of 3.50 t C ha⁻¹ above the bare-flat baseline. This positive stock additionality was almost exclusively driven by living biomass and distinct carbon enrichment within the newly colonized 20–50 cm rooting interval, rather than surface deposition. These findings identify a strictly depth-dependent pattern of early carbon-pool development, tightly linking rapid belowground biological establishment with a more gradual and spatially heterogeneous sedimentary response.

The ²¹⁰Pb-derived burial rate of 0.28 ± 0.03 t C ha⁻¹ yr⁻¹ provides a site-specific, multi-decadal depositional baseline rather than a direct measure of carbon accumulated during the two-year restoration

415 period. It nevertheless places Caofeidian within the lower-to-intermediate range reported for seagrass
416 sedimentary carbon burial worldwide. In the 30-year valuation scenarios, the projected present value of
417 avoided societal climate damages consistently exceeded potential carbon-credit revenue across the tested
418 discount rates. Absolute monetary values remained sensitive to discounting, carbon prices and continued
419 burial assumptions, but the relative importance of societal benefits was maintained. Restoration and
420 conservation therefore fulfil complementary carbon-management functions. Restoration renews living
421 biomass and pathways of organic-carbon input, whereas conservation protects the deeper sediment
422 reservoirs accumulated by mature natural meadows. Long-term sediment monitoring, repeated stock
423 inventories and carbon-source tracers will be essential for determining how early biological gains translate
424 into persistent sediment burial and for refining the climate value attributed to seagrass restoration.

425 **Methods**

426 **Study area description.** Caofeidian, located on the northern coast of Bohai Bay in Tangshan, Hebei
427 Province, supports the largest contiguous single-species seagrass bed in northern China, covering
428 approximately 4,427 ha. Dominated by eelgrass (*Z. marina*)⁴⁹, this seagrass bed is a nationally important
429 area for seagrass conservation and restoration in China. The study area lies northwest of Long Island,
430 between 39°02'18"–39°04'35" N and 118°40'21"–118°44'46" E (Fig. 1). Regional vegetation surveys
431 recorded a mean seagrass cover of 44%, a mean canopy height of 83.5 cm and a mean shoot density of
432 123 shoots m⁻² (based on our 2024 field surveys). The area forms part of a barrier–lagoon system
433 associated with the ancient Luan River delta, comprising shallow lagoons, tidal channels and extensive
434 intertidal flats. Lagoon depths generally range from 1 to 2 m, with substantial areas exposed at low tide⁵⁰.
435 Tides are mixed, predominantly semidiurnal, with a mean tidal range of 1.54 m⁵¹. Bottom sediments consist
436 mainly of very fine sand and silt, with coarser sediments in tidal channels. The region experiences a warm-
437 temperate continental monsoon climate, with mean annual air temperatures of 10.2–11.8 °C and annual
438 precipitation of approximately 413 mm⁵². Rainfall is concentrated in July and August, whereas seasonal
439 sea ice generally occurs from December to early March. These conditions provide a temperate coastal
440 setting for examining seagrass carbon storage under pronounced seasonal and tidal variability.

441 Large-scale restoration of the Caofeidian seagrass beds began in 2019, with the second-phase project
442 launched in 2022 and its main construction completed by the end of 2023. The second-phase project
443 covers approximately 638 ha, including about 533 ha of restoration through propagation and expansion,
444 and 105 ha of restoration through substrate modification in bare patch areas⁵³. Restoration combined seed
445 sowing, shoot and seedling transplantation, sediment rehabilitation and the removal of destructive fishing
446 gear with natural recovery. Across both phases, approximately 938 ha were restored, establishing
447 Caofeidian as a major demonstration site for seagrass ecosystem restoration in China⁵³.

448 **Field sampling design and collection.** Field sampling was conducted in August 2021 and June 2024 to
449 characterize vegetation and sediment carbon stocks in Caofeidian seagrass habitats. In August 2021, six
450 stations (CFD_FN01–CFD_FN06) were sampled in the northern natural meadow, with four 0.25 × 0.25 m
451 quadrats per station. In June 2024, sampling covered seven restored-meadow stations (CFD_R01–
452 CFD_R07), three adjacent bare-flat stations (CFD_B01–CFD_B03), and two natural-reference stations
453 (CFD_N01–CFD_N02). Three quadrats of the same dimensions were sampled at each station. Seagrass
454 biomass was collected within quadrats and separated into aboveground tissues (leaves and shoots) and
455 belowground tissues (roots and rhizomes). Tissue subsamples from each fraction were collected for
456 carbon-concentration measurements. Sediment cores for carbon-stock estimation were obtained by
457 manually inserting PVC tubes, 1 m long and 7 cm in internal diameter, into the sediment. Recovered core
458 lengths ranged from approximately 52 to 100 cm. Core recovery was defined as the ratio of recovered
459 sediment length to tube penetration depth, with the sampling protocol specifying a minimum ratio of 0.70.
460 Three additional 50-cm cores were collected for ²¹⁰Pb and ¹³⁷Cs analyses: one from a bare flat (CAR_B03)

and two from restored seagrass habitats (CAR_R01 and CAR_R02). All cores were capped, sealed and transported upright to the laboratory.

Reference conditions were informed by multiple sampling locations, consistent with restoration frameworks that emphasize ecological variation and complementary sources of reference information⁵⁴. Natural meadow surveys comprised six spatially distributed stations in August 2021 and two stations targeting dense, vigorous seagrass patches in June 2024. The surveys therefore contributed complementary observations: broader spatial coverage in 2021 and dense-patch conditions in 2024. Observations from both surveys were pooled to construct a sample-based composite natural reference for comparisons of carbon stocks and carbon-pool composition with the restored meadow. Comparative visualization of the sediment profiles and integrated carbon stocks confirmed broadly overlapping distributional ranges across both campaigns (Supplementary Fig. S3). This empirically justifies their integration into a single robust baseline, where the sampling year is incorporated as a representative component of inherent spatial and historical variance rather than a confounding inferential factor.

Laboratory sample processing and depth standardization. Vegetation samples were oven-dried at 60–80 °C to constant mass and weighed separately by aboveground and belowground fraction. Tissue subsamples were ground and passed through an 80-mesh sieve. Organic carbon concentrations were determined separately for each fraction using a Vario TOC analyser (Elementar, Germany). The three radionuclide cores were extruded and sectioned continuously at 5-cm intervals. Cores collected for carbon-stock estimation were sectioned according to their original sampling intervals, with each section processed separately. Visible plant remains, faunal remains, stones larger than 2 cm and shell fragments were removed before homogenization. Sample volumes and wet masses were recorded, and sediment samples were oven-dried at 60 °C to constant mass. Dry bulk density was calculated as dry sediment mass divided by the corresponding original sample volume and expressed in g cm⁻³, following standardized coastal blue carbon practices¹⁶. Dried sediment subsamples were ground using an agate mortar and pestle, passed through a 100-mesh sieve and stored under dry conditions for organic-carbon analysis.

Sediment carbon-stock calculations were standardized to nine depth intervals: 0–5, 5–10, 10–15, 15–20, 20–25, 25–30, 30–40, 40–50 and 50–100 cm. Measured properties were assumed uniform within each original sediment section and assigned to the corresponding standardized intervals. For example, measurements from a 0–10 cm section were applied to both the 0–5 and 5–10 cm intervals. Carbon stocks were calculated using section-specific volumetric carbon densities and the sediment thickness represented within each target interval. For cores shorter than 100 cm, the unsampled intervals were extrapolated down to the 1-m baseline^{5,15} using the thickness-weighted mean C_{org} derived from all available measurements below 50 cm. This extrapolated concentration was subsequently coupled with the 50–100 cm dry bulk density measured for that specific core to estimate the 0–100 cm inventory. Cores with fully recovered 1-m empirical profiles retained their observed values. The direct carry-forward of the terminal-layer concentration (i.e., extending only the deepest recovered section), alongside alternative lower- and upper-bound treatments, were strictly reserved for sensitivity analyses (Supplementary Fig. S4 and Supplementary Table S2).

Organic carbon measurements and stock calculations. Aboveground and belowground vegetation carbon stocks were calculated by multiplying dry biomass per unit area by the corresponding carbon mass fraction. These components were summed to obtain total living vegetation carbon.

Sediment carbon stocks were calculated by integrating organic-carbon concentration and dry bulk density over each depth interval:

$$C_{sed} = 0.1 \sum_{i=1}^n C_{org,i} \rho_{b,i} \Delta z_i \quad (1)$$

Here, $C_{org,i}$ is organic-carbon concentration (mg C g^{-1}), $\rho_{b,i}$ is dry bulk density (g cm^{-3}), and Δz_i is layer thickness (cm). The summation includes the n layers within the specified interval, and the factor 0.1 converts the resulting stock to t C ha^{-1} . Sediment stocks were estimated separately for the 0–20, 20–50 and 50–100 cm intervals and summed to obtain the 0–100 cm inventory. Ecosystem carbon stocks combined living vegetation carbon with the estimated 0–100 cm sediment inventory.

Active-pool carbon accounting and net additionality estimation. For the early-stage restoration assessment, the active-pool accounting boundary was expressly defined to capture biologically driven carbon additionality while excluding the high intrinsic variance of deep historical legacy deposits (e.g., 50–100 cm). This specific depth selection is empirically justified by our depth-resolved inventory (Fig. 3), which demonstrates that calculating a traditional 0–100 cm profile statistically dilutes and obscures the significant early carbon additionality achieved within the shallow rooting zone. The biologically active ecosystem carbon pool was therefore defined as the sum of total living vegetation carbon (C_{veg}) and sediment carbon integrated over the upper 0–50 cm ($C_{sed(0-50)}$), a boundary encompassing both the dynamic surface and the biologically influenced rooting zone.

To quantify the annualized biological carbon sequestration capacity (R_{seq} , expressed in $\text{t C ha}^{-1} \text{ yr}^{-1}$), we applied a robust space-for-time substitution chronosequence approach that is well-established in blue carbon assessments for quantifying project-driven sequestration against a comparative baseline^{14,22}. In strict accordance with the stock-change assessment frameworks recommended by the Verified Carbon Standard (VCS)⁵⁵, adjacent unvegetated bare flats outside the meadow were utilized effectively as the ‘without project’ pre-restoration (time = 0) control. Applying this standardized contemporary spatial baseline, the combined depth-resolved active-pool sequestration was calculated as follows:

$$R_{seq} = \frac{(C_{veg, \text{restored}} + C_{sed(0-50), \text{restored}}) - C_{sed(0-50), \text{bare}}}{\Delta t} \quad (2)$$

where Δt represents the two-year restoration duration in this study. This space-for-time baseline derivation, coupled with our 0–50 cm biological envelope constraint, yields a rigorous metric for early habitat reconstruction, explicitly isolating the immediate project-driven biological signal from the confounding noise of deep geological legacy carbon.

Sediment ^{210}Pb and ^{137}Cs chronostratigraphy. Sediment radionuclide activities were measured in cores CAR_R01, CAR_R02 and CAR_B03 to characterize recent sediment accumulation. Total ^{210}Pb activity was determined indirectly from ^{210}Po by alpha spectrometry, assuming secular equilibrium between the two radionuclides. Samples were spiked with a ^{209}Po yield tracer, digested using an HNO_3 –HF mixture and subjected to spontaneous polonium deposition onto silver discs⁵⁶. Supported ^{210}Pb activity was estimated from ^{226}Ra activity, quantified by gamma spectrometry through its short-lived daughter ^{214}Pb . Excess ^{210}Pb activity ($^{210}\text{Pb}_{ex}$) was calculated as the difference between total and supported ^{210}Pb activities. Assuming independent analytical errors, the uncertainty in $^{210}\text{Pb}_{ex}$ was propagated as the square root of the summed squared uncertainties in total ^{210}Pb and ^{226}Ra activities.

The constant flux–constant sedimentation (CFCS) model^{40,57} was fitted to the exponentially declining portion of each $^{210}\text{Pb}_{ex}$ profile. For CAR_R02, the primary regression was fitted over 10–50 cm ($n = 9$). The uppermost 5-cm observation was retained in the radionuclide profile but excluded from the regression because it did not belong to the log-linear declining interval. Ordinary least-squares regression was applied to ln-transformed $^{210}\text{Pb}_{ex}$ activity as a function of depth:

$$\ln[A_{ex}(z)] = \alpha + bz \quad (3)$$

where $A_{ex}(z)$ is the excess ^{210}Pb activity at depth z and b is the fitted slope. The sediment accretion rate, S , was calculated as:

$$S = -\lambda/b \quad (4)$$

where $\lambda = \ln(2)/22.3 \approx 0.0311 \text{ yr}^{-1}$ is the radioactive decay constant of ^{210}Pb . The CAR_R02 regression yielded a robust slope of $b = -0.0282 \pm 0.0025 \text{ cm}^{-1}$ ($R^2 = 0.949, P < 0.001$), deriving an accretion rate of $1.104 \pm 0.097 \text{ cm yr}^{-1}$ (95%CI: 0.91-1.39 cm yr^{-1}). Applying the same model to CAR_R01 over 5–50 cm produced a less linear profile ($R^2 = 0.70$) and a higher estimated rate of 2.59 cm yr^{-1} . CAR_B03 lacked a statistically supported log-linear decline and was therefore not used to derive a CFCS accretion rate.

^{137}Cs activity was measured by gamma spectrometry as an independent chronostratigraphic comparison. In CAR_R02, the activity maximum observed at 40 cm was compared with the 1963 atmospheric-fallout maximum. Assigning this maximum to 1963 implied an apparent sedimentation rate of approximately 0.65 cm yr^{-1} , lower than the CFCS-derived $^{210}\text{Pb}_{\text{ex}}$ estimate. The ^{137}Cs profile was therefore used to identify a chronostratigraphic offset potentially associated with non-steady deposition, sediment reworking or radionuclide redistribution. It was not used to calibrate the CFCS model or calculate the sedimentary carbon-burial rate in this study.

The CAR_R02 CFCS estimate was combined with the thickness-weighted mean volumetric organic-carbon density measured over the 20–50 cm interval to estimate the sedimentary organic-carbon burial rate. When sediment accretion was expressed in cm yr^{-1} and carbon density in g C cm^{-3} , their product was multiplied by 100 to obtain $\text{t C ha}^{-1} \text{ yr}^{-1}$. This calculation yielded an estimated burial rate of approximately $0.28 \pm 0.03 \text{ t C ha}^{-1} \text{ yr}^{-1}$. This radiometric estimate represents longer-term subsurface carbon retention and was evaluated separately from living-vegetation carbon and sediment carbon within the upper 0–20 cm over the two-year restoration period.

Blue carbon economic value of seagrass restoration. We evaluated sediment carbon burial in the restored meadow using market-price scenarios and the social cost of carbon (SCC). Unlike studies relying on shallow surface inventories or gross sedimentation rates that necessitate an empirical decay discount (e.g., to account for early diagenetic remineralization), our study specifically targets the deep, structurally stable stratigraphic intervals. By physically stripping away the surficial dynamic active pools (0–20 cm) subject to rapid biological turnover and contemporary perturbation¹⁸, our core estimates inherently represent ‘net long-term permanent burial’. Applying an additional decay rate to such deep-derived metrics would constitute a systematic double penalization of the carbon sink capacity¹³. Instead, annual carbon accumulation was rigorously calculated by coupling the CFCS-derived baseline sediment accretion rate (stable 10–50 cm interval) with spatial thickness-weighted organic-carbon densities from the legacy 20–50 cm interval:

$$\text{CAR} = 0.1R\bar{C}_{\text{vol}} \quad (5)$$

Here, CAR is the carbon accumulation rate ($\text{t C ha}^{-1} \text{ yr}^{-1}$), R is sediment accretion (cm yr^{-1}), and $\bar{C}_{\text{vol}}$ is organic-carbon density (mg C cm^{-3}). The factor 0.1 converts these units to $\text{t C ha}^{-1} \text{ yr}^{-1}$. Carbon accumulation was converted to CO_2 mass by multiplying by 44/12. The annual input used for valuation was $1.025 \pm 0.121 \text{ t CO}_2\text{e ha}^{-1} \text{ yr}^{-1}$, held constant over the 30-year projection period.

Market valuation utilized two 2023 price benchmarks reported by Ecosystem Marketplace: a baseline of USD 9.91 $\text{Mg}^{-1} \text{ CO}_2\text{e}$ representing the volume-weighted mean for forestry and land-use credits, and a premium of USD 26.03 $\text{Mg}^{-1} \text{ CO}_2\text{e}$ derived from mangrove credits to serve as a coastal blue-carbon proxy⁵⁸. A 30-year horizon was selected as it aligns with standard crediting periods for tidal wetland restoration under global voluntary carbon frameworks (e.g., Verified Carbon Standard), captures the functional maturation of restored seagrass sinks, and concords with mid-century net-zero trajectory timelines⁵⁹. We specified three market-price scenarios for the 30-year valuation period (Supplementary Table S1). Scenario A maintained a constant baseline carbon price of USD 9.91 $\text{t}^{-1} \text{ CO}_2\text{e}$. Scenario B applied the same initial price, followed by an annual real appreciation rate of 1.5% from year 2 onwards. Scenario C used an initial premium blue-carbon price of USD 26.03 $\text{t}^{-1} \text{ CO}_2\text{e}$, which also increased by 1.5% yr^{-1} from year 2 onwards. The 1.5% annual real price-appreciation rate applies the expert-informed default

of the Blue Carbon Cost Tool (BCCT)⁶⁰, reflecting a consensus among over 60 global blue-carbon financial experts and establishing a conservative economic baseline. The annual sedimentary carbon input was held constant at 1.025 t CO₂e ha⁻¹ yr⁻¹ over the projection period. Annual monetary values were calculated by multiplying this quantity by the corresponding scenario-specific carbon price. The cumulative present value for scenario *s* was calculated as⁶¹:

$$PV_s(T) = \sum_{t=1}^T \frac{qP_{s,t}}{(1+r)^t} \quad (6)$$

Here, *q* is the annual sedimentary carbon accumulation expressed as CO₂e, *P_{s,t}* is the carbon price under scenario *s* in year *t*, and *T* = 30 years. We applied a 4.5% annual discount rate, with monetary flows assigned to the end of each year. The resulting market values represent discounted gross carbon-credit revenue before restoration, monitoring, verification and transaction costs.

Uncertainty in the annual carbon input was propagated from the standard errors of the CAR_R02 CFCS regression slope and the station-level, thickness-weighted mean sediment organic-carbon density over 20–50 cm. Assuming independence between these two estimates, their relative standard errors were combined in quadrature:

$$u_q = \sqrt{\left(\frac{SE_b}{|b|}\right)^2 + \left(\frac{SE_{\bar{\rho}}}{\bar{\rho}}\right)^2} = 0.1181 \quad (7)$$

where *b* = -0.028167 ± 0.002473 cm⁻¹ and $\bar{\rho}$ = 2.533 ± 0.200 mg C cm⁻³. This calculation yielded an annual carbon input of 1.025 ± 0.121 t CO₂e ha⁻¹ yr⁻¹. Because cumulative present value is linear in *q*, the same relative standard error of 11.81% was applied to the projected monetary values. Carbon prices, appreciation rates and discount rates were treated as fixed scenario parameters rather than components of the propagated sampling uncertainty.

Global climate benefits were valued using an SCC of USD 185 Mg⁻¹ CO₂ in 2020 dollars, which is the mean estimate reported by Rennert et al.²⁴ under a 2% near-term risk-free discount rate. We held this benchmark constant and applied the same present-value calculation, using 4.5% to discount annual benefits over the projection period. Market revenue and SCC-based benefits were reported separately. While 4.5% was designated as the baseline social discount rate to remain economically conservative and regionally relevant, environmental valuations over multi-decadal horizons are intrinsically sensitive to this parameter.

Sensitivity analyses. Two complementary sensitivity analyses were conducted to evaluate the robustness of the standardized sediment-carbon inventories and economic valuations to their principal analytical assumptions. For cores that did not extend to 100 cm, the primary treatment extrapolated the thickness-weighted mean organic-carbon concentration measured below 50 cm to the base of the standardized profile. Four alternative treatments were tested: extension of the deepest measured concentration, extension of the thickness-weighted mean concentration below 40 cm, and use of the minimum and maximum concentrations observed at or below 40 cm as deterministic lower and upper bounds. Cores measured to 100 cm were retained unchanged across treatments. Sensitivity was evaluated from changes in habitat-level mean stocks, the restored-to-natural stock ratio, habitat ranking and statistical inference. Habitat differences within each treatment were assessed using Welch's one-way ANOVA, followed by pairwise Welch tests with Holm correction. The directly measured 0–50 cm inventory was analysed separately as an extrapolation-independent reference (Supplementary Fig. S4 and Supplementary Table S2).

For the economic valuation, sensitivity to the social discount rate was evaluated by recalculating all 30-year present values using rates of 2.0%, 4.5% and 8.0%, while holding the annual carbon input, carbon prices and price-growth assumptions constant. The 4.5% rate constituted the baseline analysis, whereas the 2.0% and 8.0% rates represented lower- and higher-discounting alternatives, respectively. The

632 projection period, sediment-carbon burial estimate, carbon-price trajectories and social cost of carbon
 633 assumptions were held constant across discount-rate scenarios. Biophysical uncertainty associated with
 634 the annual sediment-carbon burial estimate was propagated consistently through all projections.
 635 Robustness was assessed by comparing changes in absolute present values and determining whether the
 636 relative ordering of the carbon-market scenarios and the relationship between potential carbon-credit
 637 revenue and avoided climate damages remained consistent across discount rates (Supplementary Fig. S6).

638 Data availability

639 The data supporting the findings of this study are available in the Figshare repository at
 640 10.6084/m9.figshare.33989614. The deposited dataset contains the measurements and derived values
 641 underlying the main and Supplementary figures and tables.

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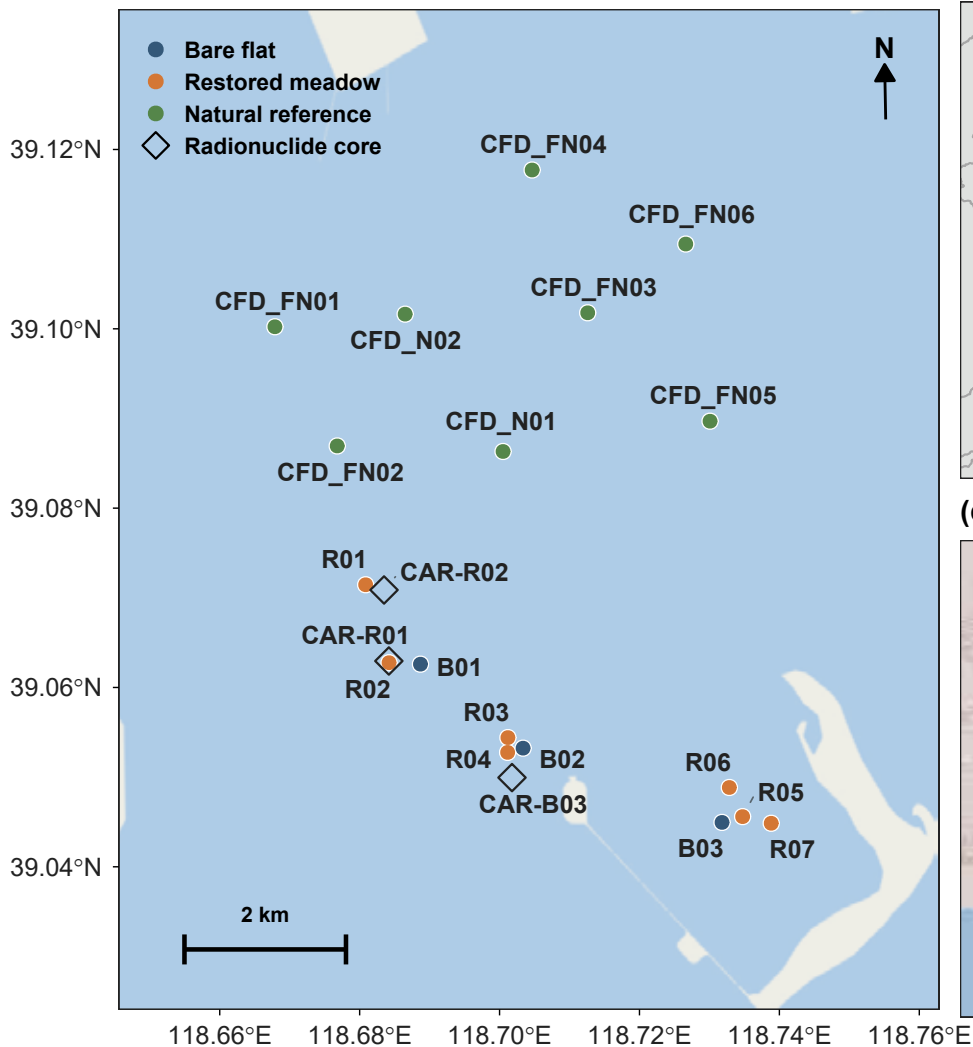
801 **Author contributions**

802 C.L., Z.Z., L.Z. and W.C. conceived and designed the study. C.L., S.N., S.X., H.W. and Y.L. conducted the
803 field surveys, processed the samples and generated the vegetation and sediment carbon data. C.L., S.N.,
804 S.X. and L.Z. performed the radionuclide measurements and sediment-chronology analyses. C.L. and S.X.
805 conducted the statistical analyses, calculated the carbon stocks and burial rates, and prepared the figures.
806 P.L., X.Z., W.C. and B.G. developed and interpreted the economic valuation. C.L. wrote the original
807 manuscript. Z.Z., L.Z., C.L., Y.L. and W.C. supervised the research, coordinated the project and acquired
808 funding. All authors contributed to the interpretation of the results, reviewed and edited the manuscript, and
809 approved the final version.

810 **Competing interests**

811 The authors declare no competing interests.

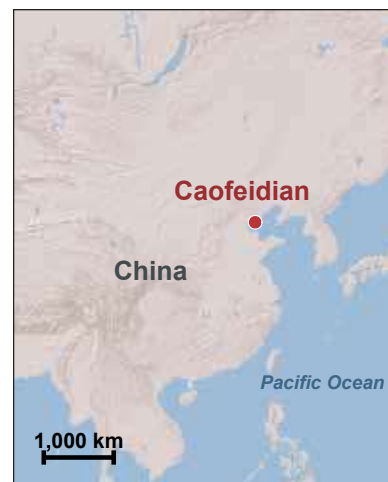
(a) Sampling stations

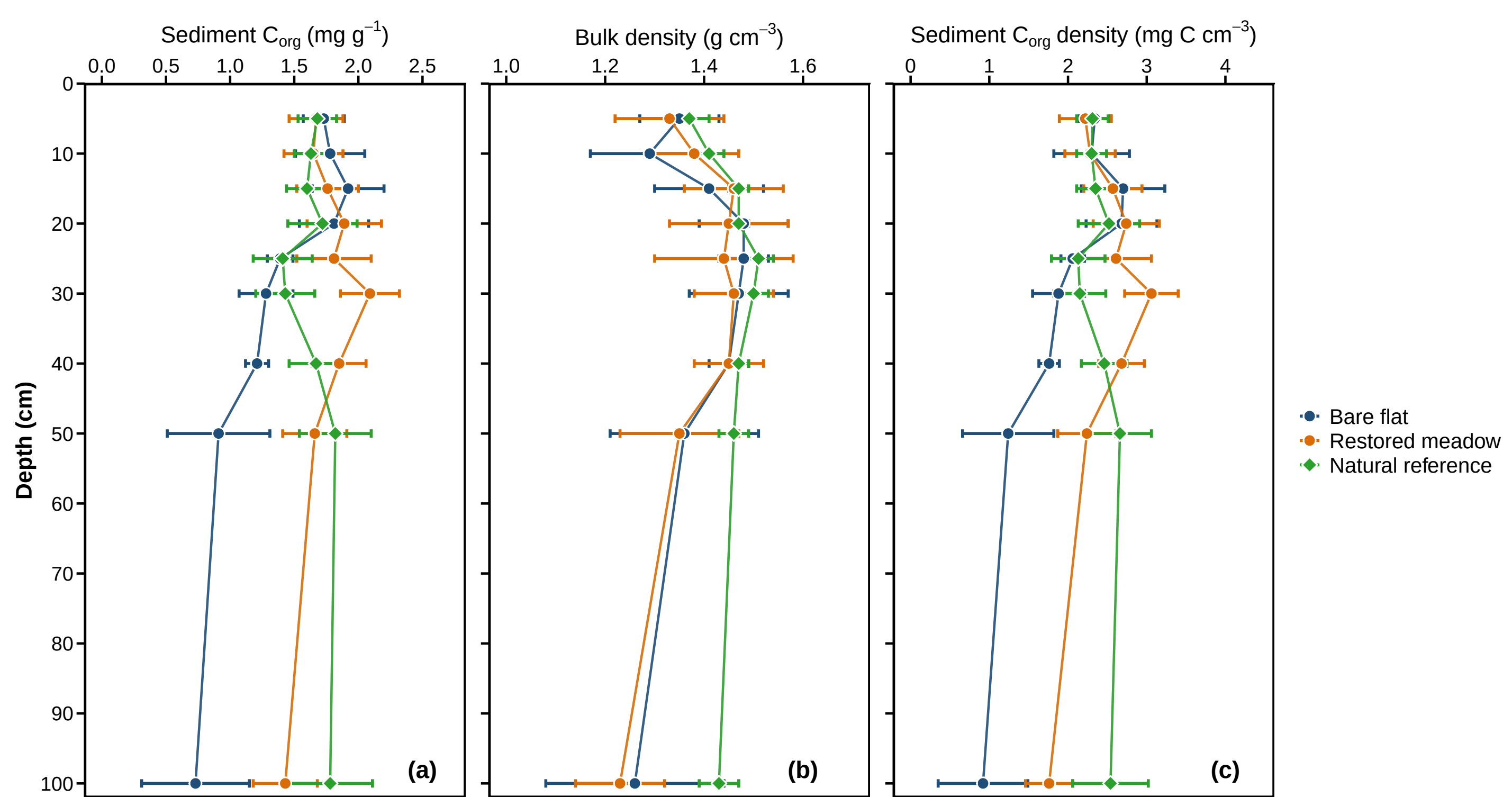


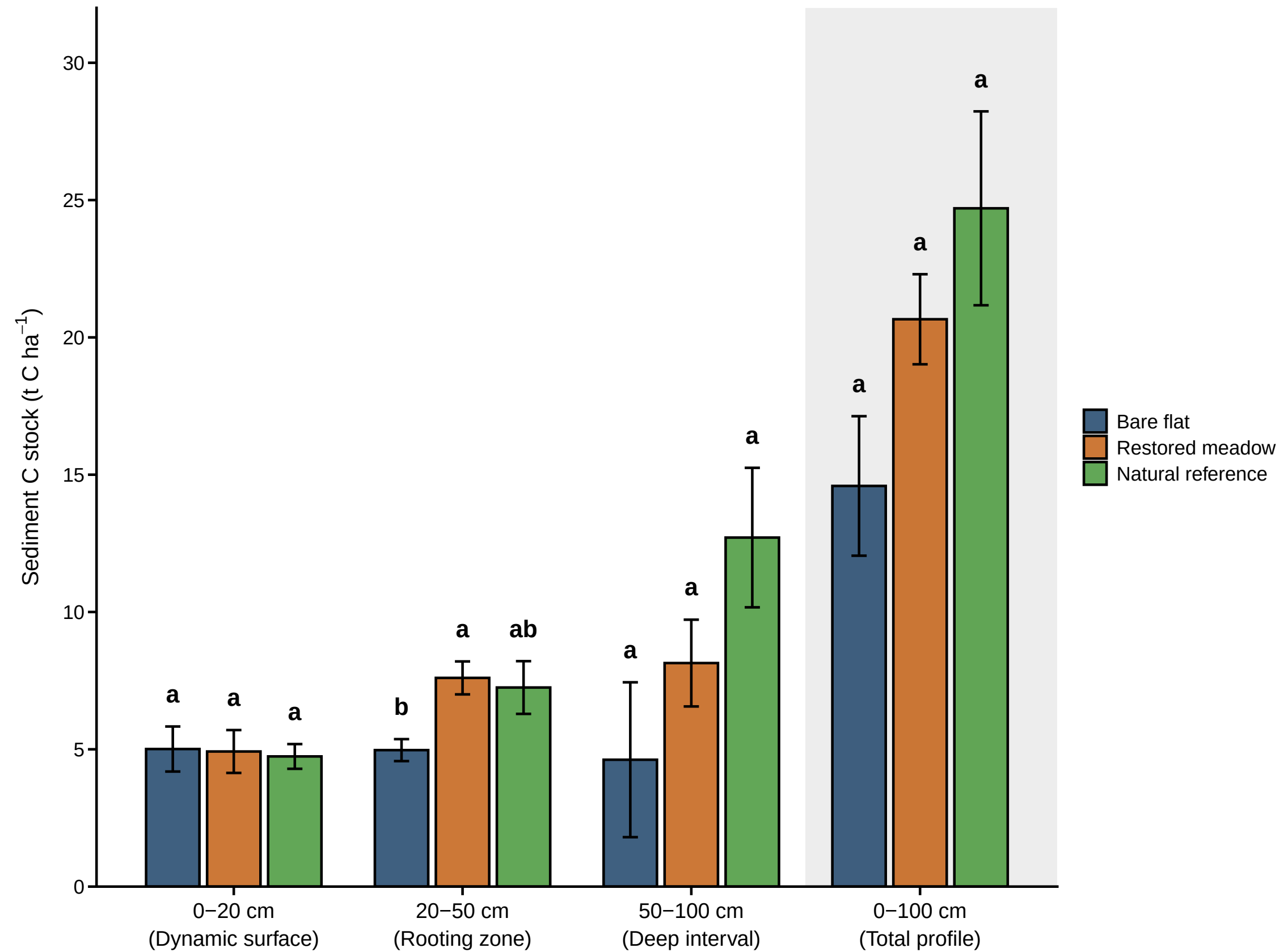
(b) Northern Bohai Bay



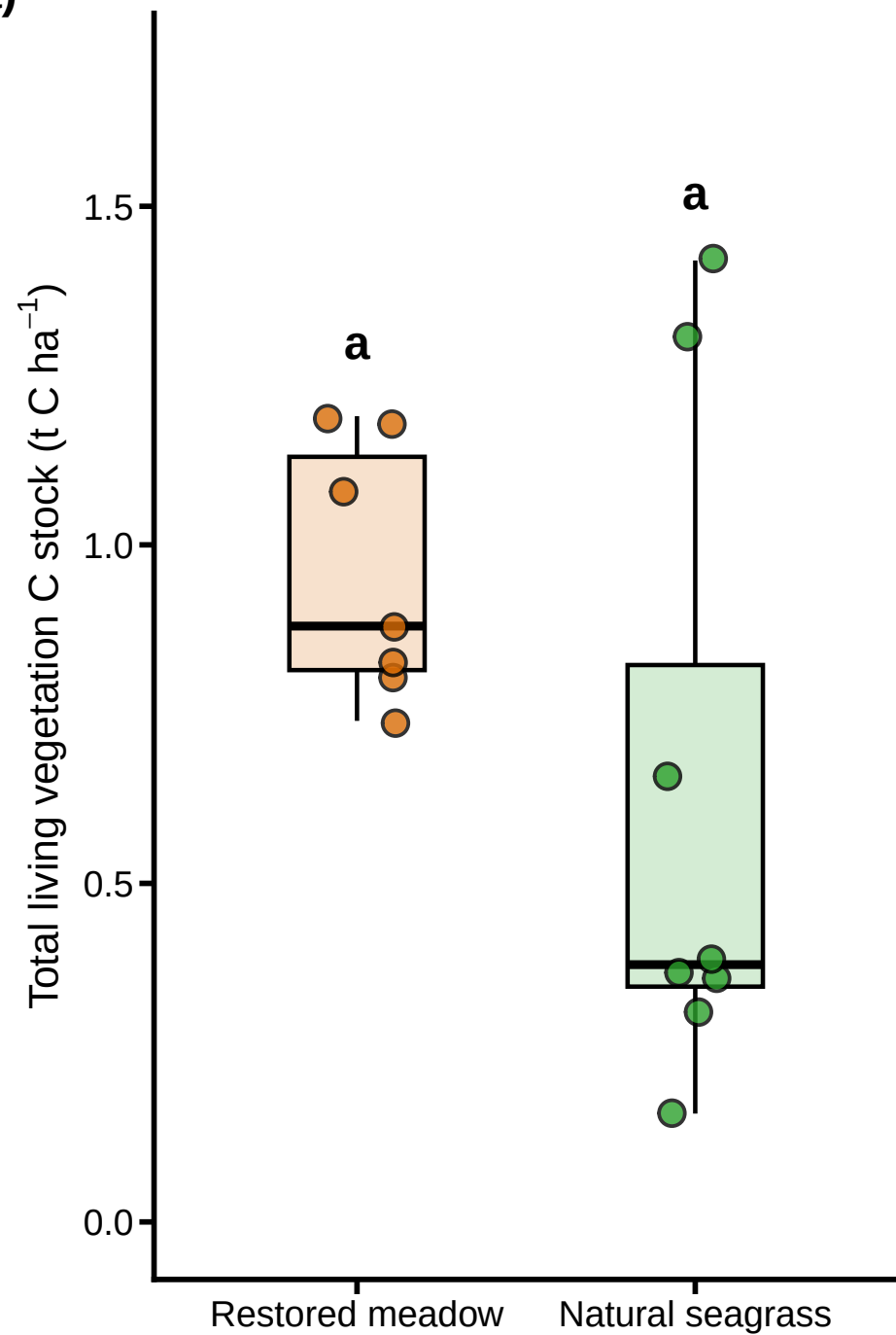
(c) Location in China



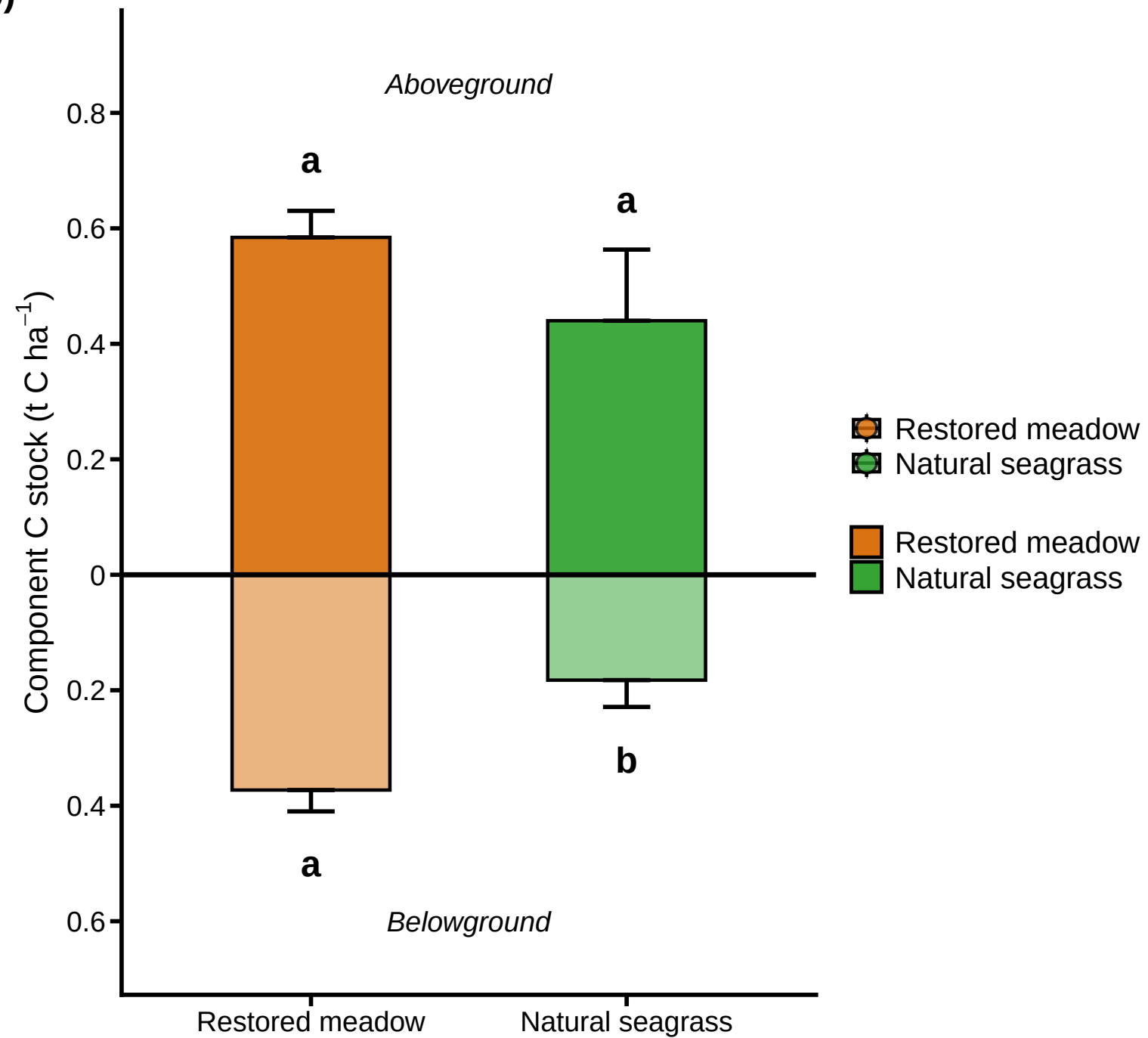




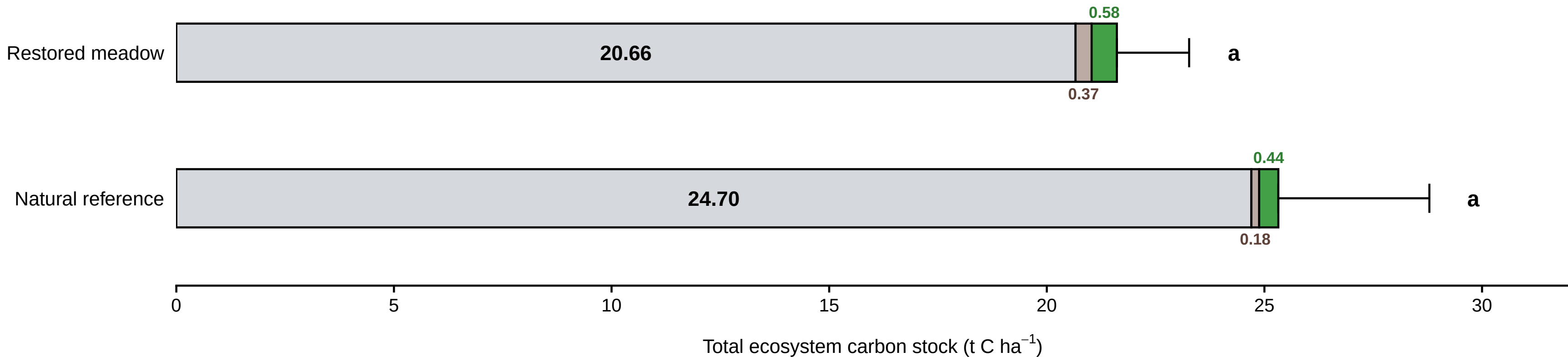
(a)

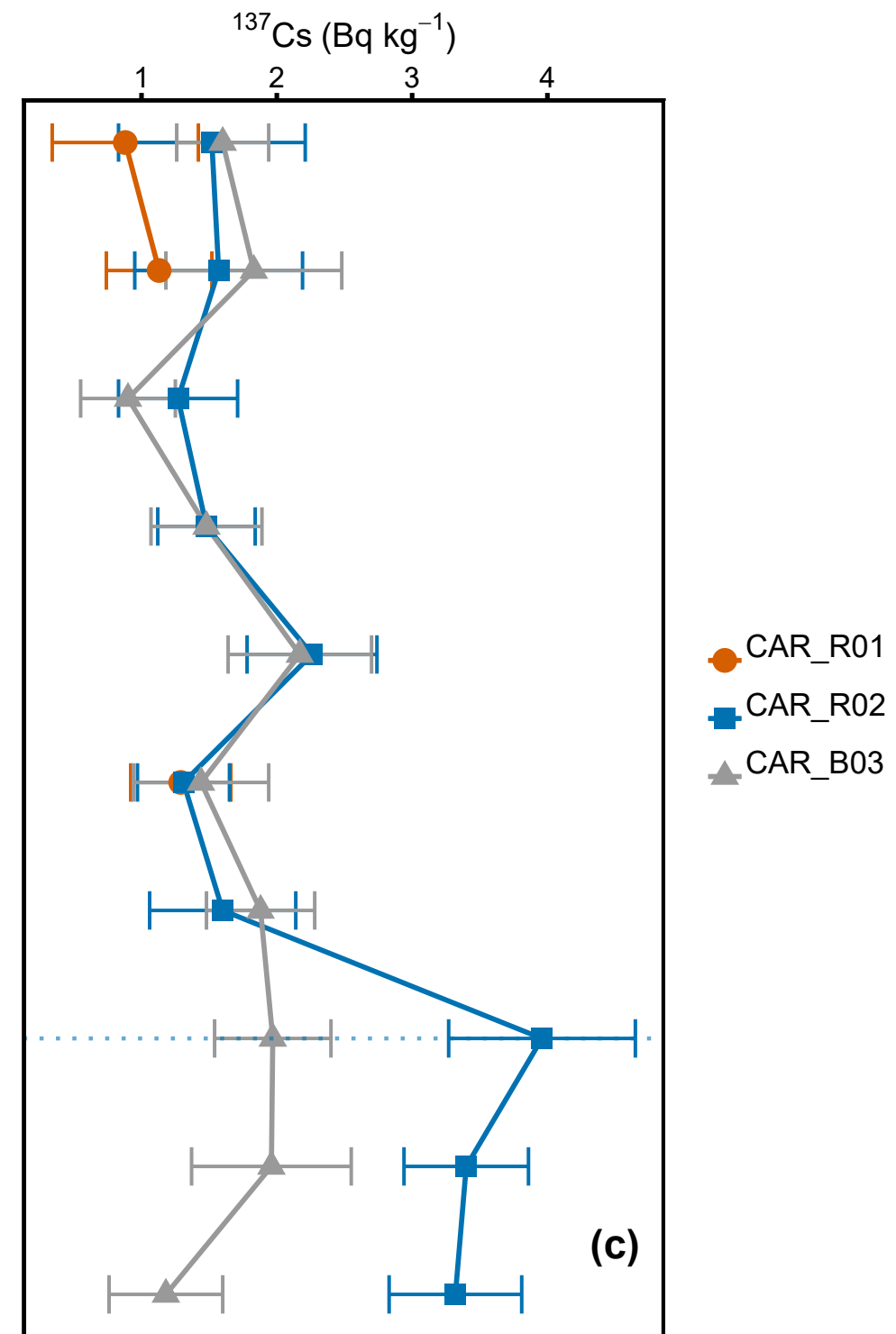
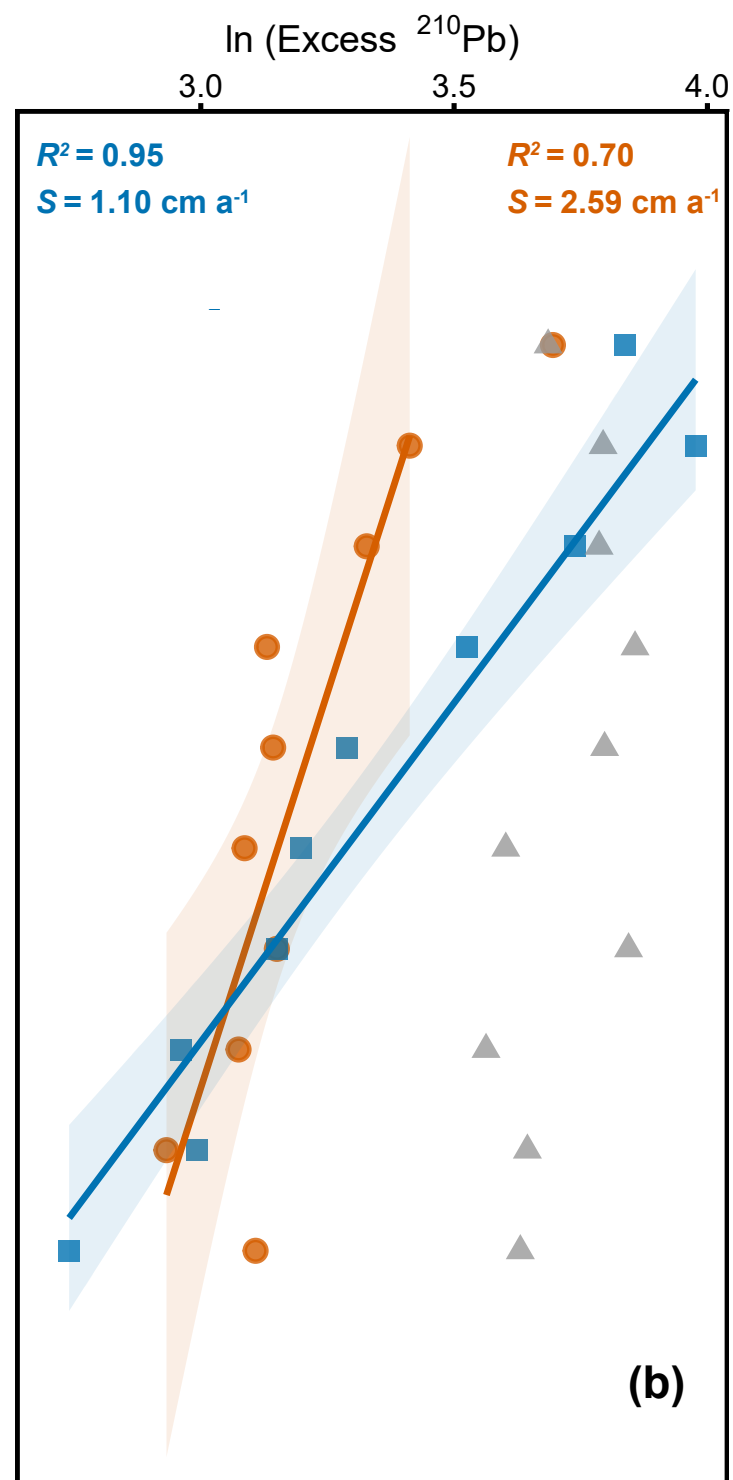
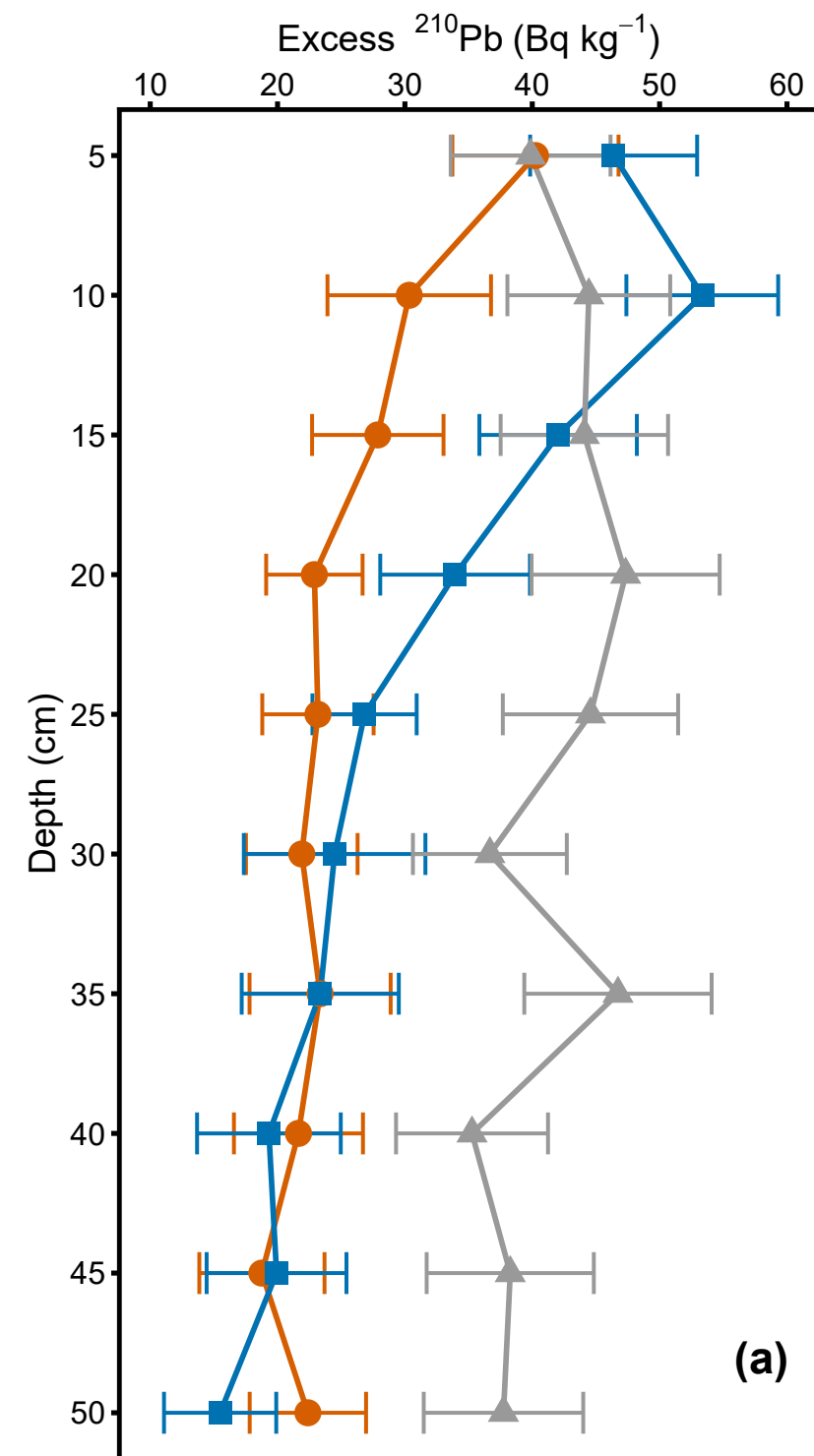


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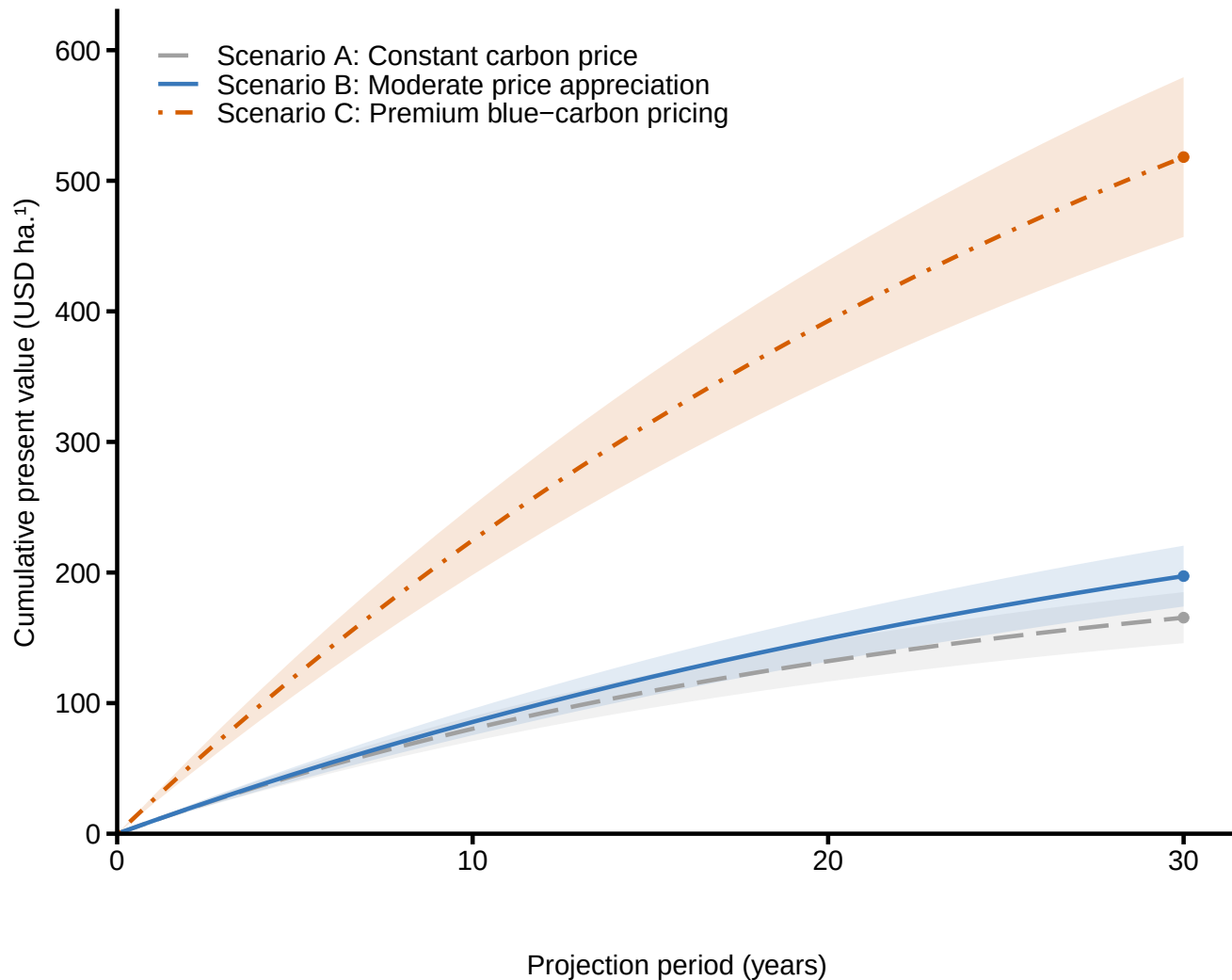


Sediment
 Belowground
 Aboveground

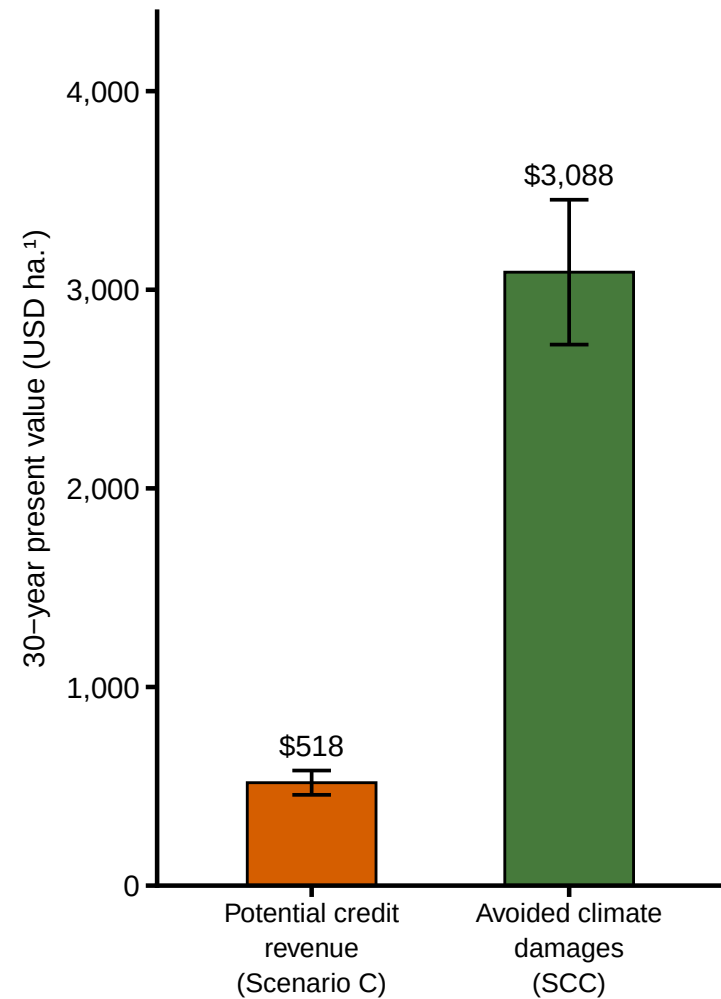




(a) Projected carbon-credit revenue



(b) Market revenue and climate benefits



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