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Accelerating tidal marsh loss in Canada reveals the limits of static area-based protection

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22 Abstract

23 Canada hosts the world's second largest extent of tidal marshes, serving as a critical bellwether for
24 high latitude carbon sinks. Yet, the long-term dynamics of these vital ecosystems is unknown. Existing
25 Canadian tidal marsh inventories have relied largely on global products or regional data compilations,
26 resulting in conflicting estimates of the country's marsh extent and trajectories and thus hindering
27 informed conservation decisions. To overcome this critical challenge, we adapted a novel, dense Landsat
28 time series (41,563 images) and tide-informed change-detection framework, producing the first spatially
29 consistent annual records of tidal marsh extent across Canada's Atlantic and Pacific coasts, each year
30 across the past four decades. Relatively stable total marsh extent over this period conceals two emerging
31 vulnerabilities. First, small but persistent net marsh habitat losses have been accelerating since 1988, with
32 loss rates tripling by 2023 ($\sim 150 \text{ ha yr}^{-1}$). Second, the apparent offsetting of marsh habitat losses by gains
33 elsewhere creates a false sense of ecological resilience, as newly formed marshes cannot immediately
34 replace the long-term soil organic carbon stocks and ecosystem functions of established systems.
35 Counterintuitively, net marsh losses were concentrated in minimally modified regions rather than along
36 the most heavily modified coastlines, highlighting that low surrounding human pressure alone does not
37 ensure marsh persistence. Finally, although over one-quarter of Canada's tidal marshes are covered by
38 spatial protections, placing them close to the 30 by 30 global protection target, marsh area within PCAs
39 continued to decline on average after designation. Our results underscore the importance of
40 complementing static spatial protections with dynamic, climate-adaptive coastal management tools to
41 sustain these critical blue carbon ecosystems through this century's climate change.

42 Main

43 Tidal marshes are dynamic intertidal ecosystems situated at the frontlines of coastal change, where
44 rising seas and expanding human development intersect ¹. A large and growing proportion of the global
45 population resides near coastlines, with approximately one in eight people living on land less than 10 m
46 above current high-tide lines ². As coastal modification, land reclamation, and climate-driven sea level
47 rise intensify, tidal marshes face increasing pressure worldwide ³. Loss of tidal marshes erodes not only
48 the habitat, but also the critical ecosystem services they provide, including carbon sequestration and long-
49 term storage, shoreline stabilization, attenuation of storm surges and flooding, and biodiversity support,
50 thus directly undermining the capacity for nature-based solutions.

51 Globally, tidal marshes are unevenly distributed, with the United States, Canada, and Russia together
52 holding over 60% of total extent ⁴ . Recent global syntheses report widespread 21st century declines, with
53 64% of losses concentrated in the United States and Russia ⁵ . Canada, by contrast, has not emerged as a
54 major hotspot of marsh loss during the Landsat observation era in the past half century, yet this apparent
55 stability must be interpreted cautiously. Substantial losses occurred earlier through land reclamation and
56 drainage associated with European colonization and industrialization ⁶⁻⁸, and the policy frameworks that
57 emerged since the 1990s under Canada's Federal Policy on Wetland Conservation (1991)⁹ were designed
58 precisely to halt further direct conversion and establish a "no net loss" objective. This period also coincides
59 with the availability of sufficiently dense Landsat archives for robust, long-term monitoring of coastal
60 ecosystem change ¹⁰ . More recently, rapid expansion of protected and conserved areas (PCAs) since the
61 mid-2010s has further increased coverage of coastal and marine habitats, aligning with the Kunming-
62 Montreal Global Biodiversity Framework's 30 by 30 target ¹¹. As a result, an increasing share of Canada's
63 tidal marshes now falls within designated protected areas, raising expectations that expanding
64 conservation coverage will translate into improved tidal marsh persistence.

65 Yet whether these protection expectations are being met remains unknown. It is unclear whether the
66 absence of large-scale losses in Canada reflects effective conservation and management, or whether it
67 conceals more complex ecosystem dynamics. Existing inventories rely on global products not calibrated
68 to Canadian conditions or on fragmented regional compilations, yielding conflicting extent estimates, high
69 error magnitudes, and unreliable change trajectories (refer to Supplementary Figure S1) ^{12,13}. This critical
70 monitoring gap undermines evaluation of conservation effectiveness, coastal adaptation planning, and
71 national blue carbon accounting, and leaves Canada, one of the world's most important tidal marsh nations,
72 without the observational foundation needed to manage these ecosystems through accelerating climate
73 change ¹⁴.

74 Here, we apply a dense time-series change-detection approach (**Extended Data Fig. 1 &**
75 **Supplementary Video S1**) ¹⁵ to the 30 m Landsat archive from Landsat 5 onward, leveraging more than
76 41,000 satellite images, to produce the first spatially and temporally consistent, annual record of tidal
77 marsh extent and change across Canada's Pacific and Atlantic coasts. Using this dataset, we address two
78 central questions. First, are Canada's tidal marshes truly persisting in the 21st century? Second, how do
79 indirect human pressures and expanding area-based protection relate to marsh trajectories across the
80 country? To answer these questions, we integrate our time series annual marsh extents with the spatially
81 explicit Global Human Modification v3 dataset of cumulative human pressures ¹⁶ and the Canadian

Protected and Conserved Areas Database¹⁷, allowing us to evaluate how tidal marsh gains and losses vary across gradients of human impact, and within versus outside protected areas. By linking consistent long-term monitoring with conservation policy context, we assess whether regulation and spatial protection have been sufficient to sustain tidal marsh stability in recent decades under accelerating climate change.

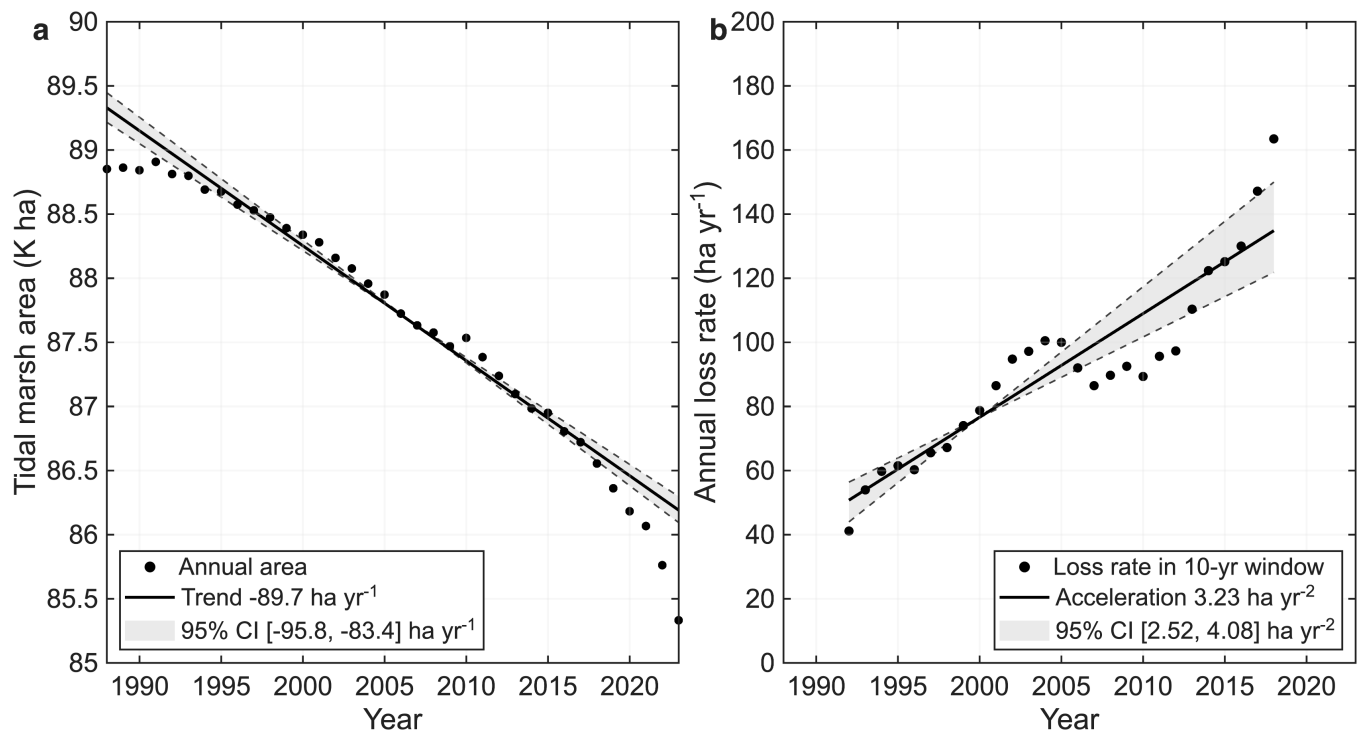
National extent and change since 1988

We generated annual extent and change of Canada's tidal marshes spanning 1988-2023 and evaluated its spatial consistency against existing nationwide maps derived from global products. For the 2020 tidal marsh extent, our product exhibited lower error magnitude within inter-product disagreement areas and more balanced commission-omission patterns across both coasts (refer to Supplementary Table S1 & Figure S1). In the Pacific, error magnitude was 6.5% (95% CI: 1.9–11.2%), comparable to Worthington et al.⁴ (6.5%) and markedly lower than Zhang et al.¹⁸ (91.6%). In the Atlantic, error magnitude was 15.7% (9.6–22.6%), substantially lower than Worthington et al.⁴ (62.6%) and Zhang et al.¹⁸ (37.4%). In contrast to global products, which exhibited strong coast-dependent variation, error levels in our dataset remained consistently low between Atlantic and Pacific regions, indicating robust performance across distinct geomorphic and tidal settings. For tidal marsh change (2000-2020), our product also showed more balanced errors and fewer unconfirmed change detections (refer to Supplementary Table S2 & Figure S1). These results demonstrate that a Canada-calibrated, dense time-series framework improves the consistency of tidal marsh extent change monitoring across both space and time. By accounting for macroalgal-covered tidal flats, extensive intertidal seagrass meadows along the Pacific coast, floating or beached logs near river mouths and estuaries, and high-latitude landscapes (> 50°N), and by minimizing the influence of tidal variability, our approach reduces the risk of misclassifying these features as tidal marshes and spurious marsh change.

In 2023, tidal marshes along Canada's Pacific and Atlantic coasts covered an estimated 85,332 ha (95% CI: 75,950–94,714 ha), including 14,582 ha (95% CI: 12,979–16,185 ha) on the Pacific and 70,750 ha (95% CI: 62,972–78,528 ha) on the Atlantic coast. Between 1988 and 2023, total tidal marsh extent declined by 3,519 ha (**Fig. 1a**). This net loss represents approximately 4% of Canada's tidal marsh area over nearly four decades, indicating a modest but persistent decline at the national scale. The net reduction includes losses of 1,492 ha along the Pacific coast and 2,027 ha (3%) along the Atlantic coast, representing 9% and 3% of their respective tidal marsh extents in 1988 (**Extended Data Fig. 2**). Approximately 79,938 ha (90%) of tidal marsh remained continuously stable throughout the study period, with cumulative gains

112 (5,395 ha) partially offsetting larger cumulative losses (8,912 ha). The observed reduction occurred
 113 gradually, corresponding to a net loss rate of 89.7 ha yr^{-1} (95% CI: $83.4\text{--}95.8 \text{ ha yr}^{-1}$ **Fig. 1a**), rather than
 114 through abrupt or widespread collapse.

115 However, the imbalance between tidal marsh losses and gains has widened over time. Annual gross
 116 losses increased steadily (3.23 ha yr^{-2} ; 95% CI: $2.52\text{--}4.08 \text{ ha yr}^{-2}$), whereas gross gains remained
 117 comparatively stable. As a result, losses increasingly exceeded gains, contributing to an accelerating net
 118 decline in tidal marsh extent. A 10-year moving-window analysis further shows that loss rates increased
 119 from approximately 50 ha yr^{-1} in the 1990s to 150 ha yr^{-1} in the 2020s (**Fig. 1b**). Thus, although the overall
 120 decline appears modest, the rate of loss is accelerating, indicating increasing vulnerability over time.



121
 122 **Fig. 1 | Trends and annual dynamics of tidal-marsh extent in Canada Pacific and Atlantic coasts**
 123 **(1988–2023).** **a**, Annual tidal-marsh extent, together with the loss trend estimated by Sen's slope (95%
 124 CI), with significance assessed using the Mann–Kendall test ($\alpha = 0.05$). **b**, Acceleration of loss estimated
 125 using a 10-year moving window. Each scatter point represents the annual loss rate calculated for a 10-year
 126 period, beginning with 1988–1997. The trend is also estimated using Sen's slope (95% CI) and Mann–
 127 Kendall test ($\alpha = 0.05$).

Spatial variation and reorganization

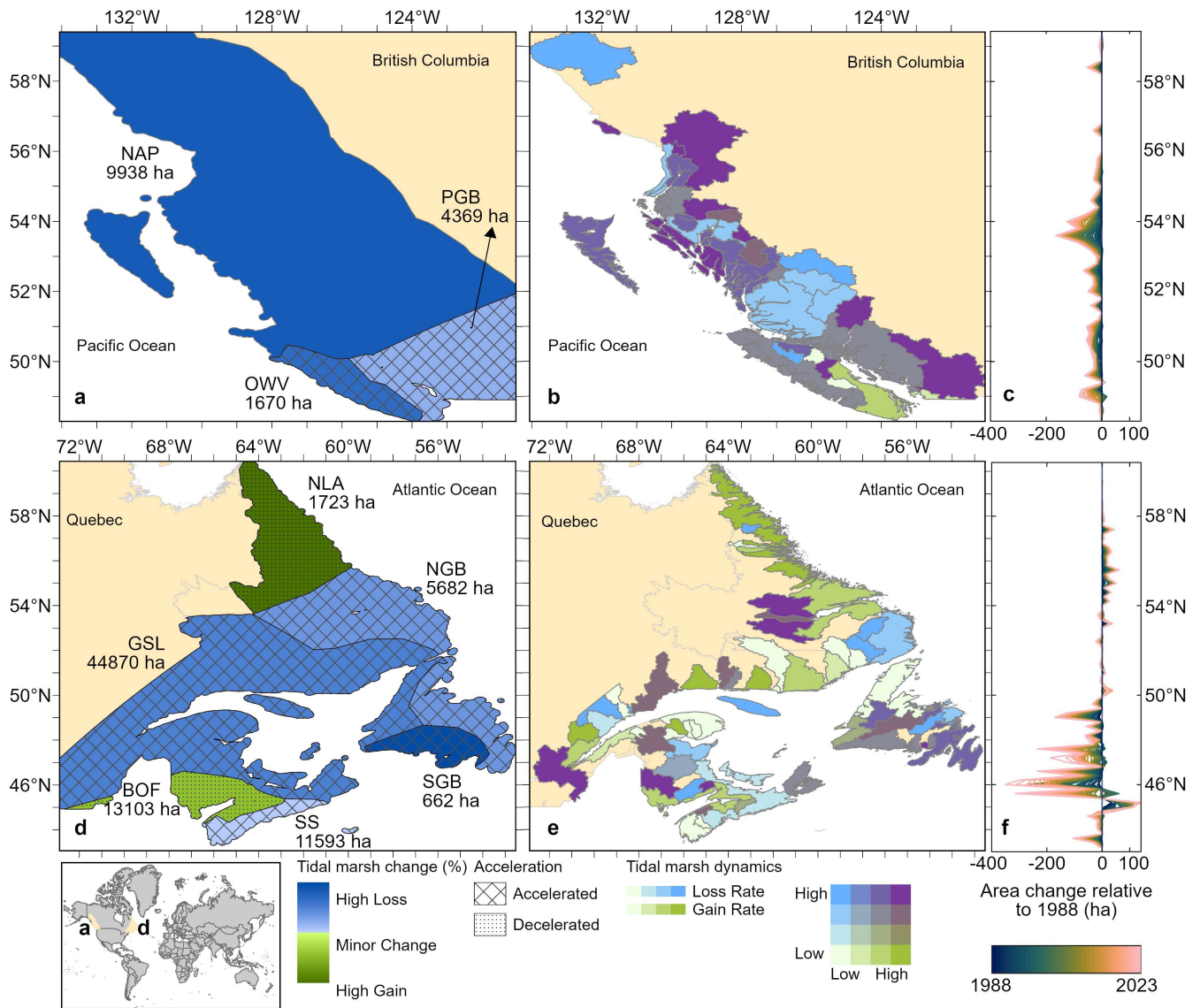
Latitude and ecoregion-level analyses show that tidal marsh change since 1988 varies markedly across Canada's two coasts (**Fig. 2**). Along the Pacific coast, declines were widespread and consistent across all ecoregions (**Fig. 2a**) and latitudes (**Fig. 2c**). Although Pacific marshes represent only one-fifth of Atlantic marsh area, they account for nearly 40% of the total loss. The Oregon–Washington–Vancouver Coast and Shelf (OWV) and North American Pacific Fjordland (NAP) ecoregions exhibited strong declines, with ~10-15% of their overall marsh extent lost in the past four decades (1988-2023). These widespread losses coincide with regions characterized by steep coastal topography with limited accommodation space and constrained sediment supply, conditions that are widely recognized to limit tidal marsh migration and vertical adjustment under sea-level rise^{19,20}.

In contrast, Atlantic marshes show a strong north–south pattern (**Fig. 2d,e,f**). In Northern Labrador (NLA), tidal marshes expanded substantially, reaching about 120% of their 1988 extent. Although these northern marshes (above 54 °N, **Fig. 2f**) account for only about 5% of Atlantic marsh area, their ~440 ha expansion offset nearly one-fifth of the losses occurring elsewhere along the Atlantic coast. Tidal marshes in this region expanded seaward along long stretches of coastline, including into previously unvegetated tidal flats (**Fig. 3c**). This pattern is consistent with falling relative sea level driven by ongoing glacio-isostatic uplift²¹. Farther south, tidal marsh change becomes more mixed but is dominated by slow net loss rate. The general decline is consistent with strong oceanographic and climatic forcing along this section of the northwestern Atlantic²². The Gulf of Maine–Bay of Fundy (BOF, around 45 °N) provides a contrasting case, with a net marsh gain of 392 ha (3.1% of its 1988 extent) by 2023. Although subject to rapid sea-level rise and wave erosion²³ (**Fig. 3a**), this region is characterized by high sediment availability and has experienced substantial restoration efforts, including dike removal and tidal reconnection^{24,25} (**Fig. 3b**).

Across most declining ecoregions, loss rates are increasing over time, whereas the few regions experiencing net gains show signs that expansion is slowing. This dynamic imbalance, featuring accelerating loss and slowing gain suggests that Canada's overall stability masks growing vulnerability.

At finer spatial scales relevant to watershed-level management, basin-level analyses reinforce this pattern of uneven change (**Fig. 2 b,e**). Across 131 hydrological basins²⁶, tidal marsh loss was the dominant trajectory, affecting approximately 60% of basins. Most declines were modest (0–2 ha yr⁻¹), yet many basins exhibit accelerating loss rates (refer to **Extended Data Fig. 3**). Gains were concentrated in a small

subset of basins, primarily in northern Atlantic regions and in restoration-influenced systems. Several basins show high simultaneous gains and losses (**Fig. 2 b,e**), indicating intense marsh turnover rather than net stability. This pattern suggests active spatial redistribution of marsh landscapes, even where total basin area changes little. Because established marshes store large, long-term soil carbon stocks that may be mobilized upon disturbance, their loss is not offset on relevant timescales by newly formed marshes, which - despite potentially higher sequestration rates - have not yet accumulated comparable stocks^{27,28}. Together, these multi-scale patterns demonstrate that Canada's tidal marshes are undergoing continuous spatial reorganization.



167 **Fig. 2 | Spatial heterogeneity and dynamic patterns of tidal marsh change across Canada's Pacific**
168 **and Atlantic coasts (1988–2023).** **a,d**, Net change in tidal marsh area across different ecoregions in
169 Pacific (**a**) and Atlantic (**d**) coasts. Colors represent the relative intensity of loss rate (blue gradient) and
170 gain rate (green gradient), with darker hues indicating higher rates. The crossing and dotted hatching
171 indicate the acceleration or deceleration of the trend, respectively. The lack of hatching means no
172 acceleration of the trend. Labels indicate marsh area (ha) within each ecoregion in 2023. **b,e**, Basin-level
173 tidal marsh dynamics on the Pacific (**b**) and Atlantic (**e**) coasts, showing the combined magnitude of gain
174 and loss rates. **c,f**, Latitudinal reorganization of tidal marshes along the Pacific (**c**) and Atlantic (**f**) coasts.
175 Annual tidal marsh area change relative to 1988 is aggregated into 0.2° latitude bins. Colored lines
176 represent individual years from 1988 (dark blue) to 2023 (light pink). Positive values indicate net
177 expansion relative to 1988, whereas negative values indicate net loss. The world map shows the location
178 of Canada Pacific and Atlantic coasts.

179 Abbreviations: BOF, Gulf of Maine/Bay of Fundy; GSL, Gulf of St. Lawrence–Eastern Scotian Shelf;
180 NAP, North American Pacific Fjordland; NGB, Northern Grand Banks–Southern Labrador; NLA,
181 Northern Labrador; OWV, Oregon–Washington–Vancouver Coast and Shelf; PGB, Puget Trough–
182 Georgia Basin; SGB, Southern Grand Banks–South Newfoundland; SS, Scotian Shelf. Note: Ecoregion
183 boundaries may extend beyond areas that currently support tidal marsh.

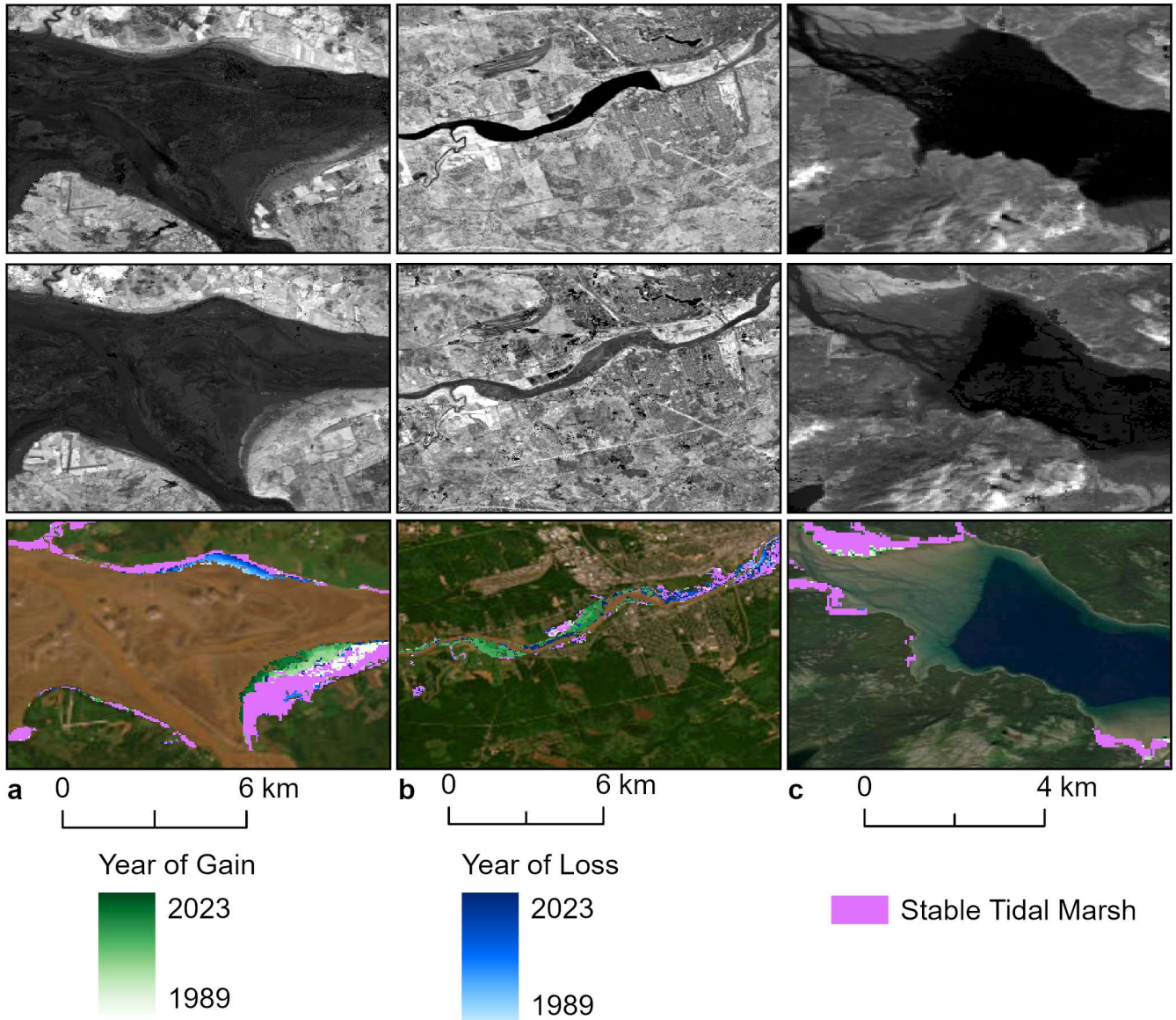


Fig. 3 | Representative examples of tidal marsh loss and gain across Canada (1988–2023). **a**, Tidal marsh loss associated with marsh-edge erosion, alongside localized marsh expansion (Masstown, Cobequid Bay, 45.37°N, 63.49°W); **b**, Tidal marsh gain following dike removal and tidal reconnection (Moncton, Bay of Fundy, 46.06°N, 64.81°W); and **c**, Seaward marsh expansion associated with glacial uplift (Labrador, 57.50°N, 62.54°W). For each site, the top and middle rows show Landsat annual composites from 1988 and 2023, respectively, using NIR band with identical display stretches. The bottom row shows stable tidal marsh (pink), gain (green), and loss (blue) during 1988–2023, with color gradients indicating the year of change. Refer to the online interactive map for details at: <https://xiucheng.projects.earthengine.app/view/canadamarsh>.

Disproportionate loss in low human pressure areas

Despite long-standing policy regulations during the Landsat era limiting direct conversion of tidal marsh in Canada⁹, the continuous loss trend depicted in this study suggests that marsh persistence may remain exposed to other threats, such as relative sea-level rise and coastal erosion, alongside indirect human pressures such as hydrological alteration, infrastructure development and reduced sediment delivery^{3,29,30}. To examine associations with surrounding human activities, we integrated our annual tidal marsh distribution and change maps with the Global Human Modification (GHM) index¹⁶, which ranges from zero (minimal human influence) to one (high modification). We matched each annual marsh pixel location and detected gain or loss to the nearest available GHM observation in time. We grouped marsh area and marsh change into 0.05 increments of the GHM index to assess how tidal marsh distribution and dynamics vary across different levels of surrounding landscape modification.

Most of Canada's tidal marshes are located within relatively undeveloped coastal landscape (**Fig. 4a**). In 2020, approximately 57% of total tidal marsh areas occurred in areas surrounding $\text{GHM} < 0.2$, compared with 64% in 1990. In contrast, only a small fraction of marsh area occurs in highly modified landscapes, with less than 4% of tidal marshes located where $\text{GHM} > 0.7$.

Tidal marsh net loss in Pacific and Atlantic Canada (1988-2023) did not increase monotonically with human modification (**Fig. 4b&c**), contrary to expectations that tidal marsh vulnerability should scale positively with cumulative human pressure due to coastal development and habitat conversion³¹⁻³³. Instead, when expressed as a proportion of marsh area within each GHM class, loss rates were highest at both ends of the modification spectrum (**Fig. 4b**). Tidal marshes around intense human activities ($\text{GHM} > 0.85$) exhibited elevated proportional losses with a cumulative loss rate of 10-20% from 1988-2023, but similarly high proportional declines were also observed in the least modified environments ($\text{GHM} \leq 0.05$). However, proportional loss alone did not determine net outcomes. In highly modified landscapes ($\text{GHM} > 0.7$), marsh losses were largely offset by gains, resulting in near-balanced net change. In contrast, marshes located in low- and intermediate-modification settings ($\text{GHM} < 0.6$) exhibited sustained net losses, as gains consistently failed to compensate for losses. Because the majority of Canada's tidal marsh area is concentrated in low-modification environments, these classes contributed the largest absolute net losses nationally (**Fig. 4c**). Approximately 4,000 ha (40% of the total loss) of tidal marsh loss occurred in areas with $\text{GHM} < 0.05$, of which only about half was offset by gains. Thus, the

greatest cumulative net loss in recent decades occurred not in the most heavily modified settings, but in relatively undeveloped coastal regions.

This spatial contrast is particularly evident along the Pacific coast. At the basin scale (Fig. 2b), the few basins exhibiting tidal marsh gains are concentrated in the Salish Sea, where human modifications are relatively high. In contrast, most basins along the less modified northern Pacific coast show declining tidal marsh extent.

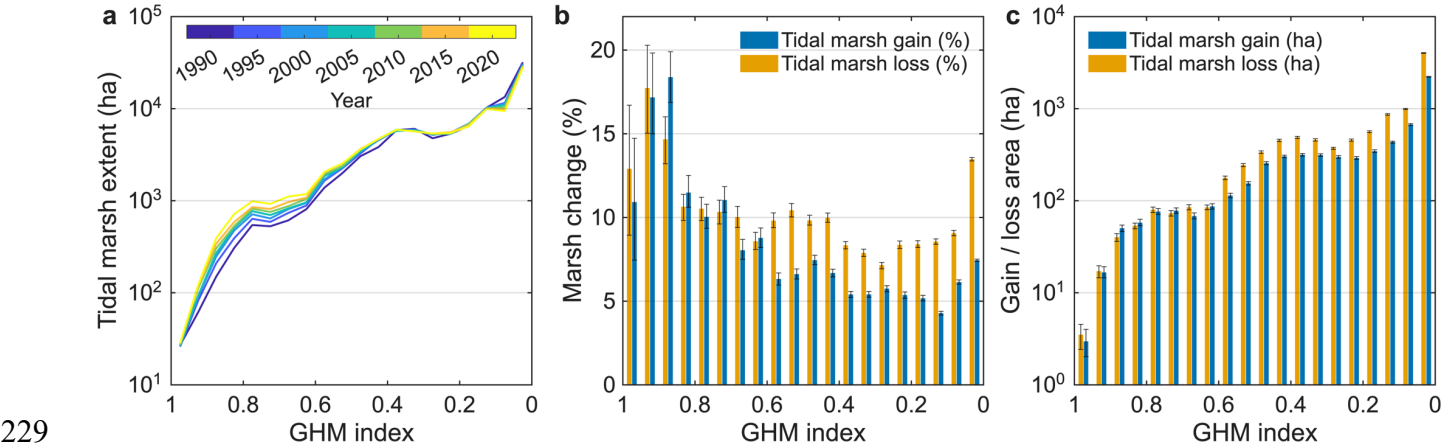


Fig. 4 | Tidal marsh dynamics across levels of human modification. **a**, Distribution of mapped tidal marsh extent across the Global Human Modification (GHM) index at five-year intervals from 1990 to 2020. **b**, Percentage of tidal marsh gain and loss within each GHM bin during 1989–2023. **c**, Absolute tidal marsh gain and loss area (ha) within each GHM bin during 1989–2023. GHM values are grouped into 0.05-wide bins, ranging from 1 (high modification) to 0 (minimal modification). Panels **a** and **c** use logarithmic y axes. Error bars in **b** and **c** show 95% percentile confidence intervals obtained by bootstrapping mapped gain and loss pixels separately.

Advancing tidal marsh protection under global biodiversity targets

We examined how the expansion of Protected and Conserved Areas (PCAs)³⁴ relates to tidal marsh persistence under accelerating environmental change. Tidal marshes located in PCAs have expanded substantially across Canada over the past four decades (Fig. 5a). Prior to the 1990s, less than 5% of Canada’s tidal marsh extent was located within designated PCAs. Protection coverage increased steadily thereafter, with a marked acceleration beginning in the mid-2000s following the establishment of new marine and terrestrial protected areas. By 2023, more than 25% of Canada’s tidal marsh extent was included within PCAs, placing tidal marsh ecosystems close to the national 30 by 30 target¹¹.

To evaluate whether this rapid expansion in protected coverage translated into enhanced tidal marsh persistence, we implemented a quasi-experimental, basin-level Before After Control Impact (BACI) framework^{35–37}. To isolate the effect of protection status, we conducted basin-level comparisons in which tidal marsh change inside PCAs was evaluated against contemporaneous change in tidal marshes outside PCAs within the same hydrological basin. PCAs established in the same basin and year were grouped into a single PCA-basin-year event. Pre- and post-establishment trajectories were compared using the longest available symmetric observation windows, with a minimum window length of seven years (**Extended Data Fig. 5**), to ensure consistent temporal baselines.

Of the 89 PCA-basin-year events analyzed, 38 (42.7%) showed positive BACI responses, indicating an increase in PCA advantage from before to after establishment. These events represented 37.8% of the tidal-marsh area inside PCAs included in the analysis (**Fig. 5b**). The category-level analysis revealed contrasting post-establishment trajectories (**Extended Data Fig. 6**). Among PCA polygons with 25 years of observations, IUCN category IV (habitat/species management areas, where active management may be used) maintained approximately stable tidal-marsh area (+0.1%), whereas categories I–III (with differing conservation objectives and restrictions on human activities) showed declines of approximately 2–5%. These differences highlight variation among management categories, although they do not isolate the effects of specific management actions. Although PCAs have substantially expanded tidal-marsh conservation coverage, the absence of a consistent detectable improvement in marsh persistence suggests that designation alone may be insufficient and should be complemented by habitat-specific conservation and management measures.

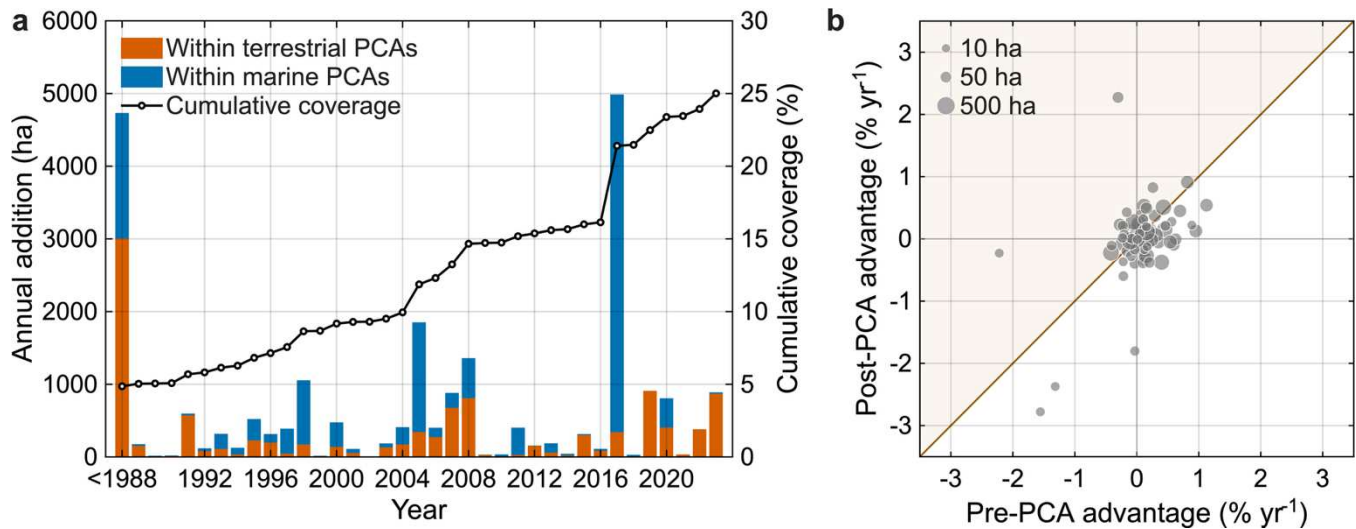


Fig. 5 | Expansion of protected and conserved areas (PCAs) and associated tidal marsh change. a, Annual increase in mapped tidal marsh area included within marine and terrestrial PCAs, with the cumulative proportion of tidal marsh coverage in PCAs shown on the right y-axis. **b,** Basin-level comparison of tidal-marsh change rate advantage inside versus outside PCAs before and after PCA establishment. Each point represents one basin-level PCA establishment comparison; marker size indicates tidal marsh area within PCAs. The 1:1 line indicates no change in PCA advantage after establishment, and points above the line indicate improved post-establishment performance.

Discussion

Stability masks accelerating vulnerability

This study provides the first spatially and temporally consistent annual record of tidal marsh extent and change across Canada Pacific and Atlantic coasts over nearly four decades, resolving inconsistencies among previous snapshot-based assessments^{5,18,38,39}. In a system where net extent change is small over this period, such as Canada's tidal marshes, uncertainties inherent to post-classification change detection can exceed the signal of real change, leading to amplified inconsistencies among estimates (refer to Supplementary Figure S1). By applying a dense time series change-detection framework, we establish a consistent national baseline and methodology for evaluating long-term tidal marsh dynamics.

We show that although approximately 90% of Canada's tidal marsh area remained stable over the study period, substantial spatial reorganization occurred, including net losses along relatively undeveloped coastlines and offsetting gains and losses in regions with intense human activity. As a result, between 1990 and 2020, cumulative losses amount to only ~0.1% per year of total marsh area, which is

287 substantially lower than rates reported in major North American hotspots, particularly along the U.S. Gulf
288 Coast⁴⁰, where annual loss rates approach ~0.4% per year.

289 However, our moving-window analysis reveals a clear acceleration in the rate of decline since the
290 early 1990s, with annual loss rates tripling over the past three decades. Similar acceleration has been
291 documented in the conterminous United States⁴⁰, suggesting a broader North American pattern of
292 increasing tidal marsh loss across contrasting coastal settings. If this accelerating trend persists, future
293 losses could increase disproportionately. Based on trend-based scenario extrapolation from 1990,
294 Canada's tidal marsh area is projected to decline by ~ 8.7–10.6% by 2050 and ~22.9–31.7% by 2100, a
295 period during which national commitments to biodiversity conservation and nature-based climate
296 solutions are expected to be realized ⁴¹. The Southern Grand Banks–South Newfoundland represents a
297 particularly vulnerable ecoregion, projected to retain only ~80% of its current marsh extent by mid-century,
298 while the Pacific coast may lose ~10% of its marsh area by 2050.

299 Thus, by resolving where and when tidal marsh change occurs, our framework reveals that apparent
300 national stability conceals two emerging vulnerabilities: an accelerating rate of loss and a growing spatial
301 imbalance between gains and losses. Although gains partially offset losses and maintain near-constant
302 total area, spatial replacement does not imply functional equivalence ^{42,43}. Although tidal marshes are
303 naturally dynamic ecosystems ³³, natural tidal marshes store deep, long-accumulated soil carbon and
304 support complex habitat structure, their loss, even when balanced by numerically area-equal gains
305 elsewhere, may result in a net reduction in ecosystem function ^{27,28,44}. For example, the loss of long-
306 established tidal marshes can mobilize soil organic carbon that has accumulated during centuries to
307 millennia of wetland persistence, whereas newly formed or restored marshes begin sequestering carbon
308 from relatively low initial stocks ^{45,46}. Consequently, the ~8,912 ha of established marsh lost over our
309 study period, only partially offset by ~5,395 ha of newer marsh gains, likely represents a massive,
310 unquantified net deficit in Canada's blue carbon inventory⁴⁷. By treating newly formed marshes as
311 functional equivalents to deeply established ecosystems, current 'no net loss' policies are masking this
312 hidden deficit. Stability in extent, therefore, should not be interpreted as stability in ecosystem function,
313 carbon balance, or climate mitigation capacity.

314 **The paradox of unmanaged decline**

315 Contrary to expectations, tidal marsh loss since 1988 is not concentrated in Canada's most heavily
316 modified coastlines, but instead occurs disproportionately in regions with low human modification. While

317 historically human activities have led to extensive marsh loss in highly developed regions, much of this
318 loss likely occurred prior to the Landsat observation era, meaning that contemporary patterns reflect
319 landscapes already shaped by long-term human modification^{6,8}.

320 Marshes in highly modified coastal regions face well-documented threats associated with coastal
321 development, including hydrological alteration, sediment disruption and nutrient loading ^{32,33}. However,
322 these regions also exhibit substantial marsh gains, including restoration and sediment management ^{31,33,48},
323 resulting in relatively balanced net change, creating highly engineered but area-wise stable landscapes.
324 Importantly, these landscapes likely experienced substantial marsh loss prior to the 1980s^{6–8}, leaving a
325 reduced but actively managed marsh extent within the current observation period. In this context,
326 developed coastlines often provide greater opportunities for restoration and sediment management ^{49–51},
327 which can partially offset ongoing losses. While our analysis does not directly quantify the effectiveness
328 of specific interventions, the apparent stability of marsh extent in these regions may reflect continued
329 management rather than intrinsic ecosystem resilience.

330 In minimally modified coastal regions, however, losses are less frequently offset by gains. Here,
331 marsh trajectories likely reflect the capacity of ecosystems to adjust naturally to environmental change in
332 the absence of substantial human intervention. Relative sea-level dynamics, sediment availability,
333 geomorphic constraints on landward migration, and wave-driven erosion appear to shape outcomes in
334 these settings ^{52–56}. Where natural accretion or migration cannot keep pace with changing coastal
335 conditions, persistent net loss can occur even under low direct human pressure.

336 This contrast highlights a critical asymmetry: while highly modified coastlines may maintain marsh
337 extent through active management, minimally disturbed regions may experience ongoing decline in the
338 absence of intervention. Restoration and management efforts are disproportionately concentrated near
339 populated coastlines ⁵⁷, where historical conversion creates restoration needs and shoreline protection
340 delivers immediate societal benefits⁵⁸. In contrast, restoration in remote regions remains limited due to
341 higher implementation costs and reduced monitoring capacity, meaning ecological degradation may
342 persist longer without active response. Our basin-level analyses also show spatial variation in the modelled
343 contributions of environmental variables (Supplementary Figs. S3 and S4). These findings highlight the
344 need to assess threats and management needs across different coastal settings, rather than assuming that
345 limited human modification alone ensures marsh persistence.

Protected areas alone do not necessarily prevent marsh decline

Our analysis reveals that PCAs have substantially expanded to include a larger share of Canada's tidal marshes, contributing directly to the 30 by 30 target under the Kunming-Montreal Global Biodiversity Framework¹¹. However, the mean rate of tidal marsh area change within PCAs remained negative after establishment, although trajectories varied among sites. This suggests that expanding formal protection alone may not be sufficient to ensure marsh persistence.

The availability of a dense, multi-decadal annual time series enabled trajectory-based evaluation of protection effectiveness, consistent with recommendations that conservation outcomes be assessed through changes in trend rather than simple before–after differences³⁵. Our outcome aligns with broader evidence that protected areas often deliver limited or context-dependent ecological benefits when the dominant drivers of change are not directly addressed^{34,59,60}. Several factors likely contribute to this protection bias. Direct conversion of tidal marshes has already been strongly constrained in Canada for decades through federal and provincial regulations, most notably the *Federal Policy on Wetland Conservation* (1991)⁹. Because these regulatory policies apply both inside and outside PCAs, tidal marshes outside protected boundaries are not unmanaged landscapes^{61,62}. Moreover, most PCAs encompassing tidal marshes were established to protect broader marine or terrestrial ecosystems rather than tidal marshes specifically. Many primarily regulate extractive activities (e.g., fishing, resource extraction) or terrestrial land use, but designation alone does not necessarily address the threats affecting tidal marsh persistence, such as relative sea-level rise, sediment supply constraints, geomorphic limits on migration, nutrient enrichment and excessive goose grazing^{34,63,64}.

Substantial marsh losses along low-human-pressure coastlines further highlight the limitations of conservation measures focused primarily on restricting local human activities. This emphasizes the importance of aligning conservation strategies with the scale and nature of threats affecting marsh persistence, including those operating beyond protected-area boundaries⁶⁵.

From static area-based protection to dynamic coastal adaptation

Ultimately, Canada's tidal marsh trajectory serves as a critical global warning: maintaining a stable national footprint is not synonymous with ecological or climate resilience. Furthermore, our analysis challenges the expectation that remote coastlines should be relatively secure³³; instead, these relatively low-modification environments are quietly losing ground, while heavily modified coastlines maintain an engineered equilibrium. Consequently, expanding spatial protections to meet the 30 by 30 global target

376 may risk creating coastal ‘paper parks’ if protected-area designation is not paired with management actions
377 that support marsh persistence and recovery.

378 To truly safeguard these vital ecosystems, conservation must urgently pivot from drawing static
379 boundaries on a map to deploying dynamic, process-based management. Area-based protections can limit
380 direct disturbance, but they do not necessarily maintain tidal exchange, sediment delivery, suitable
381 elevation, or landward accommodation space that tidal marshes require⁶⁴. Complementing static
382 protections with spatially targeted restoration and adaptive coastal management may therefore become
383 increasingly important for enabling marsh migration and sustaining vertical adjustment under rising
384 seas^{20,48,54,66,67}. Specifically, conservation resources should be deployed based on the surrounding
385 landscape context. Where marsh expansion is constrained by dikes, roads, shoreline infrastructure, or
386 altered tidal exchange, active interventions can help restore the conditions needed for marsh recovery.
387 Site-level studies in the upper Bay of Fundy (Atlantic Coast around 45°N) show that managed realignment
388 and tidal reconnection after dike breaching promoted rapid sediment deposition, vegetation recovery, and
389 carbon accumulation ^{24,68}. Similarly, long-term assessments of created tidal marshes in the Fraser River
390 Estuary show that restoration persistence depends strongly on-site elevation, location, design, and
391 maintenance⁵⁷. Leveraging both natural geomorphic opportunities, including regions experiencing relative
392 sea-level fall due to glacio-isostatic uplift (Atlantic Coast >54°N), and targeted restoration in constrained
393 or vulnerable settings will be critical to ensuring that Canada’s tidal marshes continue to deliver lasting
394 ecological benefits as coastal pressures intensify.

395

396 **Methods**

397 **Mapped area and Input Data**

398 Our analyses include the whole coastal landscapes along the Atlantic and Pacific coasts of Canada,
399 covering an area of approximately 244,405 km². The Arctic coast of Canada is not included in the present
400 study because the temporal coverage and observational density of Landsat imagery differ substantially
401 from those of the Atlantic and Pacific regions ⁶⁹, precluding consistent long-term time-series analyses
402 across all coasts. These coastal landscapes were delineated based on elevation and proximity to the
403 shoreline, including all areas with elevations below 10 meters based on the NASADEM and extending up
404 to 10 km seaward from the coastline. This definition captures the full extent of intertidal and nearshore
405 environments potentially supporting tidal marsh ecosystems.

406 Canada's tidal marshes along the Atlantic and Pacific coasts occur in contrasting geomorphic and
407 climatic settings, spanning diverse biogeographic regions and strong gradients in temperature, relative
408 sea-level change, and human pressure that shape marsh vulnerability and resilience. In Atlantic Canada,
409 particularly around the Bay of Fundy, extensive marsh areas were diked and drained for agriculture
410 historically, whereas recent decades have seen local restoration and managed realignment initiatives ²⁵.
411 Elsewhere in Atlantic Canada, including the Gulf of St. Lawrence and Newfoundland and Labrador, tidal
412 marshes are generally smaller, naturally formed and strongly shaped by local geomorphology and cold-
413 climate processes ⁷⁰. On Canada's Pacific coast, marshes are more fragmented, constrained by steep
414 topography and increasingly affected by urbanization and infrastructure development ⁷¹.

415 Notably, much of Canada's tidal marsh landscape, particularly in historically developed regions of
416 the Atlantic coast and in parts of the Pacific coast, was substantially altered prior to the satellite
417 observation era through land reclamation, drainage, and coastal development associated with European
418 settlement, industrial expansion, and urbanization ⁶⁻⁸. As a result, the time series analyzed in this study
419 (1988–2023) captures tidal marsh dynamics within a post-alteration landscape, rather than a pre-
420 disturbance baseline.

421 To quantify the extent and long-term changes of tidal marshes, we used a comprehensive time series
422 of 41,563 Landsat images spanning the period 1985–2024. The final product and analysis, however, cover
423 only the period from 1988 to 2023, when the model is robust for time-series analysis, with the initial and
424 final years used for model initialization and validation^{40,72}. All available Landsat 4–8 Collection 2 Surface
425 Reflectance data were obtained from the U.S. Geological Survey (USGS) archive, filtered for scenes with

cloud and cloud-shadow cover < 100 %. For each image, we used six spectral bands, including blue, green, red, near-infrared (NIR), and two shortwave infrareds (SWIR1 and SWIR2), as well as the Quality Assessment (QA) band to support cloud and shadow masking ⁷³.

Because tides exert strong control over short-term water-level fluctuations and can influence the apparent spectral signatures of intertidal areas, we accounted for the tidal stage at the time of each image acquisition. Water-level height predictions were derived from the Empirical Ocean Tide (EOT20) global model ⁷⁴, which provides high-resolution tidal height estimates based on a Generic Mapping Tools (GMT) land-sea mask. For each Landsat observation, we extracted the predicted tidal elevation at the corresponding acquisition time and location. In areas not directly covered by the tidal model (e.g., upland pixels or enclosed inlets), the tidal level of the nearest valid ocean pixel was assigned to ensure spatial continuity.

Tidal marsh dynamics from dense time series model

We developed a national-scale framework to monitor tidal marsh dynamics across Canada's Atlantic and Pacific coasts from 1988 to 2023 using all available Landsat archives (41,563 images). Our workflow integrates the DECODE (Detection and Characterization of cOastal tiDal wEtland Change) dense time series algorithm ¹⁵ with supervised land-cover classification to generate spatially and temporally consistent annual tidal marsh extents at 30 m resolution.

Remote sensing of intertidal ecosystems is complicated by variability in tidal stage, which alters vegetation exposure and surface reflectance across acquisitions. Conventional mapping approaches often rely on image composites or low-tide image selection ^{5,75,76}. However, such time-slice methods can introduce temporal inconsistencies when used to infer change. To address this, DECODE leverages dense pixel-level Landsat observations and explicitly incorporates tidal water level at acquisition time within a harmonic regression framework.

For each pixel, DECODE fits a harmonic model to historical spectral observations, including a tidal-water-level regressor to account for short-term inundation effects. The fitted model (Eq. 1) predicts future expected spectral values and compares them to subsequent new observations. A change is detected when six consecutive new observations deviate significantly from model predictions, indicating a persistent shift in spectral response due to land surface state shift. This approach ensures that regular tidal inundations do not produce sustained and consistent deviations, thereby isolating true ecological and geomorphic changes from internal tidal fluctuations. As a result, DECODE directly detects tidal marsh state changes without

456 differencing classification maps and divides each pixel's trajectory into distinct stable or transitional states
 457 through time. The timing of change occurrence is determined at a temporal interval of Landsat clear
 458 observations. This framework provides a continuous, observation-based record of tidal marsh footprint
 459 from 1985 to 2024 at 30-meter spatial resolution.

$$460 \quad \hat{\rho}_{i,x} = a_{0,i} + \sum_{k=1}^3 \left\{ a_{k,i} \cos \left(\frac{2k\pi}{T} x \right) + b_{k,i} \sin \left(\frac{2k\pi}{T} x \right) \right\} + c_{1,i}x + c_{2,i}w \quad (1)$$

461 Here, $\hat{\rho}_{i,x}$ represents the predicted reflectance or spectral index value of variable i at x Julian date.
 462 The subscript i refers to the modeled input variables, including six Landsat surface reflectance bands and
 463 five derived spectral indices. T denotes the number of days per year ($T=365.25$). k is the temporal
 464 frequency of harmonic components. The coefficients $a_{0,i}$ captures the overall mean value of the time series,
 465 while $a_{k,i}$ and $b_{k,i}$, describe the intra-annual seasonal variability representing three harmonic terms,
 466 respectively. The term $c_{1,i}$ represents inter-annual trend components. The coefficient $c_{2,i}$ quantifies the
 467 influence of tidal variation, and w is the tidal height predicted by the EOT20 model at the time of each
 468 Landsat acquisition.

469 Each temporal segment was described by the harmonic model coefficients, and the root mean square
 470 error (RMSE), depicting temporal–spectral characteristics while minimizing noise from tidal fluctuations.
 471 These coefficients and RMSE values were then used as predictor variables for Random Forest
 472 classification. We collected training datasets separately for the Pacific Coast and Atlantic Coast and built
 473 separate random forest classifiers due to each coast's distinct landscape characteristics. Training data were
 474 collected through visual interpretation of historic high-resolution imagery from Google Earth, Landsat
 475 time series, and ancillary land-cover databases, such as Canadian National Wetland Inventory⁷⁷,
 476 ShoreZone aerial images⁷⁸ and cover maps, and global tidal marsh products.

477 Five primary coastal cover categories were mapped, including tidal marsh, tidal flat, open water
 478 (including eelgrass and kelp forests), water–land interface (e.g., beaches and shorelines), and low-
 479 elevation uplands (e.g., cropland, pasture, developed, forests, and non-tidal marsh wetlands). Because
 480 subclasses within these categories exhibit distinct spectral signatures, training points were first selected
 481 for each subclass and then merged into broader categories in final maps. In total, approximately 30,000
 482 training samples were collected for the Pacific coast and 50,000 for the Atlantic coast.

483 Classification was performed on an annual basis, because individual temporal segments may
484 represent transitional cover states undergoing gradual cover conversions under long-term and chronic
485 stressors. For example, the progressive landward migration of tidal marsh into adjacent forests due to
486 saltwater intrusion will present as a gradual land cover change with a slope. For each segment, 120
487 predictor variables were derived using the harmonic model, including the model coefficients (ρ , a_1 , b_1 , a_2 ,
488 b_2 , a_3 , b_3 , c_1 , c_2 , and RMSE) computed across the seven Landsat spectral bands and five wetland-related
489 spectral indices. The annual overall value (ρ) was calculated as $\rho = a_0 + c_1x$, where x is the Julian date on
490 July 1st, allowing annual variation to be incorporated into the classification process. Annual cover maps
491 were generated by applying the trained Random Forest classifiers to the time-series predictors for each
492 year from 1988 to 2023.

493 All annual maps were subsequently postprocessed with object-based spatial rules to eliminate noise
494 and ensure topological consistency. A minimum mapping unit (MMU) of four Landsat pixels (0.36 ha)
495 was applied. In addition, we removed isolated tidal marsh patches whose minimum distance to open water
496 exceeded a threshold based on patch size. This threshold, measured in pixels, was set equal to the number
497 of pixels in the patch, up to a maximum of 100 pixels⁴⁰. This step reduced “salt-and-pepper” noise and
498 improved spatial continuity of mapped wetlands across the coastal landscape.

499 To estimate classification uncertainty, we followed the “Good Practice” recommendations⁷⁹ for land
500 cover accuracy assessment, applying an unbiased area estimator to adjust mapped areas and compute 95 %
501 confidence intervals (CIs) (refer to Supplementary Table S3). A stratified random sample of 900
502 independent reference pixels was drawn across the study area, stratified by five land cover categories (i.e.,
503 tidal marsh, tidal flats, open water, land-water interface, and low-elevation uplands) (refer to
504 Supplementary Figure S5 & S6). Each reference sample represents both a spatial location and a defined
505 period at our annual product from 1988 to 2023. Reference labels were assigned through visual
506 interpretation of the full Landsat time series and Google Earth ancillary high-resolution imagery. A
507 confusion matrix was then constructed and converted into unbiased estimates of accuracy and area
508 proportions using a post-stratified estimator. For tidal marsh, the user’s accuracy was $84.00 \pm 5.89\%$ and
509 the producer’s accuracy was $92.08 \pm 8.21\%$, and F_1 score of approximately 0.88. The low omission error
510 and moderate commission error, indicating that the mapped tidal marsh area was slightly overestimated
511 approximately 9.6% relative to the area-adjusted estimate. We used area-adjusted estimates for national
512 and coastal marsh extent time series, and mapped areas for the GHM and PCA analyses.

513 **Spatial-temporal dynamics**

514 Of the changed tidal marsh, to investigate the geographic heterogeneity and spatial reorganization,
515 we monitored the tidal marsh changes in ecoregion level, hydrological basin, and latitude degrees. Nine
516 Marine Ecoregions of the World (MEOW) ⁸⁰ cover the study is used. To characterize regional dynamics,
517 we quantified both the long-term trend (ha yr^{-1}) and strength (ha yr^{-2}) of the tidal marsh extent for each
518 ecoregion using the Theil–Sen estimator and a 10-year moving window approach. Ecoregions along the
519 Pacific coast, which account for 17% of the total extent of Canada’s tidal marshes, all ecoregions
520 experienced declines in tidal marsh extent.

521 We quantified temporal trends in tidal marsh extent using the Theil-Sen slope estimator and the Mann-
522 Kendall (MK) statistical test at a 95% confidence interval ⁸¹. These non-parametric approaches estimate
523 linear and monotonic change. To evaluate whether tidal marsh dynamics exhibited acceleration or
524 deceleration over time, we employed a 10-year moving window analysis ^{82,83}. With each 10-year period
525 from 1988-1997 to 2014-2023, we calculated the short-term Theil-Sen slope trends, along with a second-
526 order Theil-Sen slope with MK test to quantify the temporal shifts of these short-term trends. This two-
527 tier framework reveals whether tidal marsh ecosystems are approaching stabilization or undergoing
528 compounding decline or gain. Assuming that the historical pattern of change would continue, we
529 extrapolated tidal marsh extent to 2100 using the rate of change and the acceleration estimated across the
530 1988–2023 record. Confidence bounds from the historical trend estimates were used to construct slower-
531 and faster-loss scenarios.

532 To characterize spatial heterogeneity in these temporal trends, we aggregated pixel-level estimates into
533 hydrological subbasins derived from HydroBASINS level 6 dataset ²⁶, resulting in 131 subbasins with
534 mapped tidal marsh areas across Canada’s Pacific and Atlantic coasts. Each subbasin served as an
535 independent spatial unit that preserves hydrodynamic and sediment connectivity. Within each unit, the
536 median Sen’s slope and MK significant test were computed to represent basin-scale marsh trends. We also
537 summarize the tidal marsh extent across nine ecoregions (**Fig. 2a&b**) to examine regional contrasts under
538 similar geomorphic and climate conditions. The subbasin and ecoregion analyses enabled assessment of
539 both local variability and large-scale spatial coherence in Canada’s tidal marsh dynamics.

540 **Human modifications and tidal marsh dynamics**

541 To explore the influence of human modifications on spatial-temporal patterns of tidal marsh extents,
542 we overlaid our annual tidal marsh maps with the Global Human Modification (GHM) v3 database. Our

use of GHM was informed by two aspects of the Canadian tidal marsh context: conservation policies aimed at limiting direct marsh conversion, and the potential for surrounding human activities to influence marsh persistence indirectly through altered hydrology, sediment delivery, nutrient enrichment, and pollution. We therefore used GHM to characterize the surrounding anthropogenic setting and examine its association with tidal marsh change.

GHM quantified cumulative human modifications through eight anthropogenic stressor layers (i.e., agriculture, built-up, energy production and mining, biological resource use, human accessibility, natural system modification, pollution, transportation and service corridors). The dataset provides human pressures with a continuous index from 0 to 1 at 300 m spatial resolution at five-year intervals from 1990 to 2020. Each cell covers approximately 100 Landsat pixels, providing landscape context for marsh changes mapped at 30 m. For coastal marsh pixels without valid GHM coverage, we assigned the nearest valid terrestrial GHM value to represent adjacent human pressure, under the assumption that anthropogenic influence on tidal marshes is highly related to adjacent land-based activities. For each tidal marsh gain or loss record, we extracted the GHM value closest in time to the detected change event (e.g., GHM 2000 applied to changes in 1998-2002). This provided an estimate of surrounding human pressure around the time of change, although the effects of human activities on tidal marshes can be long-term and cumulative.

We grouped tidal marsh extent, gain and loss into 0.05-wide GHM bins to quantify how the magnitude and direction of marsh change vary along the anthropogenic pressure gradient. Absolute gains and losses (ha) were quantified as the total marsh area gained or lost within each GHM bin over the study period, identifying which human-pressure levels accounted for the largest areas of change. Relative gain and loss rates (%) were calculated by normalizing total gain or loss area within each GHM bin by its mean marsh extent across the seven GHM observation years. These rates describe proportional change over the study period, allowing comparison of change intensity among bins with different marsh extents. To represent indirect human pressure at a larger spatial scale, we averaged GHM values across the hydrological basin containing each marsh location. Marsh gains and losses were then grouped by basin-mean GHM using 0.025-wide bins (**Extended Data Fig. 4**).

Tidal marsh in protected and conserved areas

To evaluate whether formal protection altered tidal marsh trajectories, we used the Canadian Protected and Conserved Areas Database (CPCAD, 2024 release), which provides the boundaries, establishment

573 years and IUCN management categories of protected and conserved areas (PCAs). We implemented a
574 quasi-experimental Before–After–Control–Impact (BACI) design with basin-level controls to assess
575 changes in marsh trends following PCA establishment, aligning with recommended time-series
576 approaches for impact evaluation^{35–37}.

577 Annual tidal marsh extent was overlaid with the PCA boundaries, and marsh areas within PCAs
578 established in the same year and hydrological basin were aggregated. Tidal marshes outside all mapped
579 PCA boundaries within the same basin served as controls to account for shared regional influences,
580 including anthropogenic and environment variables⁸⁴. Each comparison used the longest available
581 symmetric observation window before and after establishment within 1988–2023, excluding the
582 establishment year. A minimum of seven annual observations was required in each period (refer to
583 **Extended Data Fig. 5**), restricting eligible establishment years to 1995–2016. Protected and outside-PCA
584 marsh areas were each required to reach at least 10 ha in both periods.

585 For each observation window, we estimated Sen’s slope of log-transformed annual marsh area and
586 converted it to an annual relative change rate (% yr⁻¹). Identical calculations were performed for protected
587 and outside-PCA marshes within the same basin. The BACI contrast was implemented in two steps. First,
588 we quantified the difference in change rate between protected and unprotected marshes separately for the
589 pre- ($D_{pre} = Trend_{inside,pre} - Trend_{outside,pre}$) and post-establishment (D_{post}) periods. We then
590 calculated the change in this contrast following designation with $\Delta D = D_{post} - D_{pre}$. A positive response
591 ($\Delta D > 0$) indicates that marsh trajectories inside PCAs became more favorable relative to those outside
592 PCAs following establishment.

593 To investigate differences in tidal-marsh trajectories among management categories, we tracked marsh
594 area for up to 25 years after PCA establishment. We distinguished four IUCN management groups: I,
595 combining strict nature reserves (Ia) and wilderness areas (Ib); II, national parks; III, natural monuments
596 or features; and IV, habitat/species management areas⁸⁵. We included PCAs established between 1988
597 and 2022 that contained tidal marsh at establishment. Marsh trajectories were aligned by PCA legacy,
598 defined as the number of years since establishment, and tracked for up to 25 years. Annual marsh area
599 was normalized to its value at establishment, giving an initial index of 1. For each legacy year, category-
600 level mean indices and percentile ranges were calculated from sites with available observations, weighted
601 by marsh area at establishment. The 1988–2023 trend in total marsh area outside all mapped PCA

boundaries provided a reference trajectory. The analysis did not adjust for differences in location, establishment history or coastal conditions among categories.

Evaluation of consistency among tidal marsh datasets

We compared tidal marsh extent and change from this study with four global products within the Canadian study domain. Extent comparisons used the 2020 maps from Worthington et al. (2024)⁴ and Zhang et al. (2024)¹⁸. Change comparisons included Murray et al. (2022)¹, Campbell et al. (2022)⁵, Zhang et al. (2024) and this study, using binary change/no-change maps over approximately comparable periods around 2000–2020. We assessed product performance against visually interpreted reference samples drawn from inter-product disagreement areas. These comparisons therefore characterize performance within disagreement areas rather than overall map accuracy. Product descriptions, comparison periods, reference-sample interpretation and analyses of disagreement sources are provided in Supplementary Information Section 1.

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802 **Data availability**

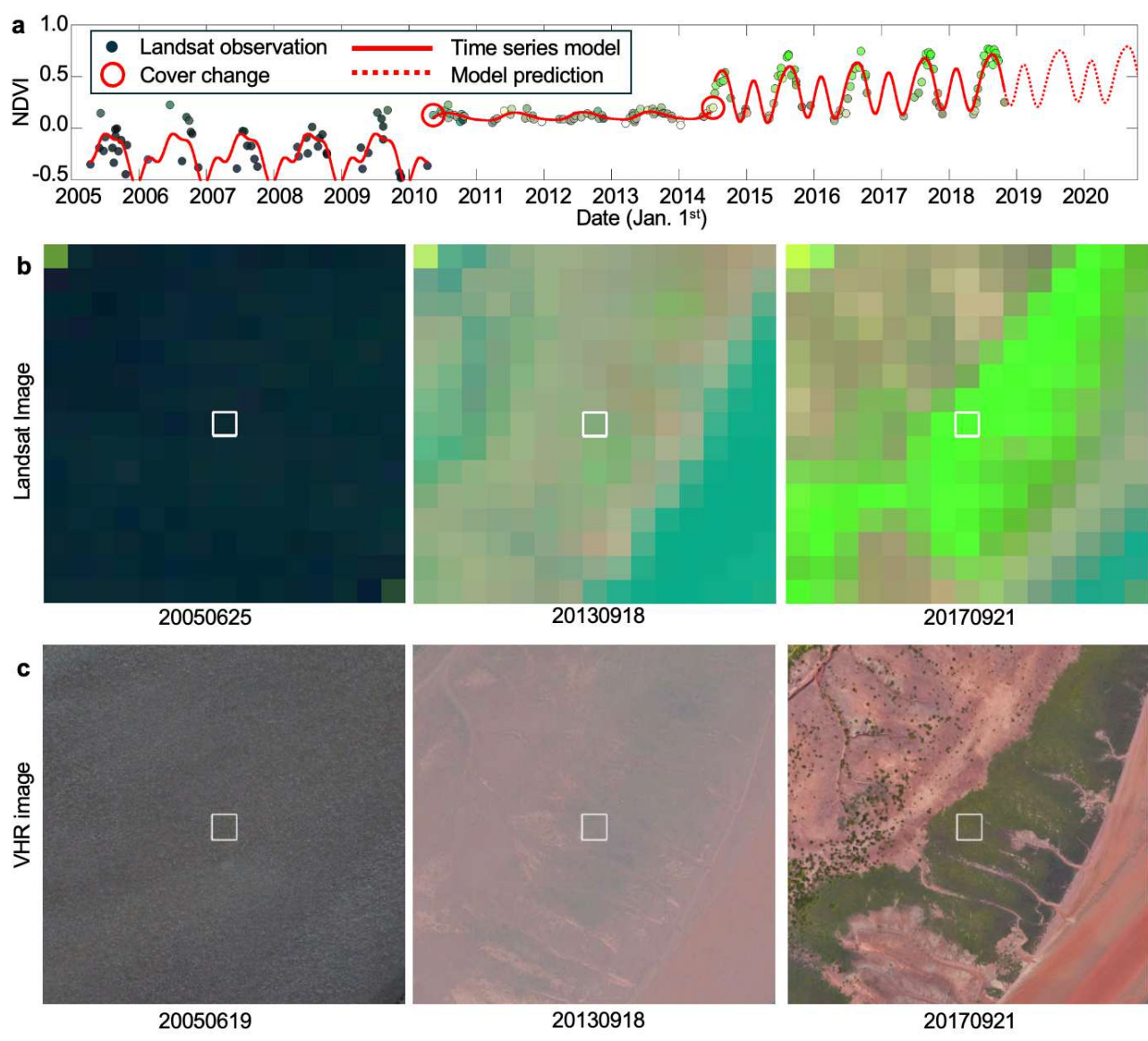
803 All data used in this study were obtained from open data sources. The Landsat Collection 2 data were
804 downloaded from USGS <https://earthexplorer.usgs.gov/>. Tide predictions were obtained from global
805 ocean tide models (EOT20) developed at DGFI-TUM <https://www.seanoe.org/data/00683/79489/>. The
806 NASADEM elevation dataset is available at
807 https://doi.org/10.5067/MEaSURES/NASADEM/NASADEM_HGT.001. Global Human Modification v3
808 dataset are from <https://gee-community-catalog.org/projects/ghm-v3/>. Canadian Protected and Conserved
809 Areas Database is from Environment and Climate Change Canada (ECCC) at
810 [https://www.canada.ca/en/environment-climate-change/services/national-wildlife-areas/protected-](https://www.canada.ca/en/environment-climate-change/services/national-wildlife-areas/protected-conserved-areas-database.html)
811 [conserved-areas-database.html](https://www.canada.ca/en/environment-climate-change/services/national-wildlife-areas/protected-conserved-areas-database.html). Tidal marshes annual extent, loss and gain, and change derived from our
812 DECODE approach and supporting our analyses are available at
813 <https://xiucheng.projects.earthengine.app/view/canadamarsh>.

814 **Code availability**

815 The custom MATLAB code written for the approach and analyses is available via GitHub at
816 <https://github.com/xiuchengyang/CanadaTidalMarsh>.

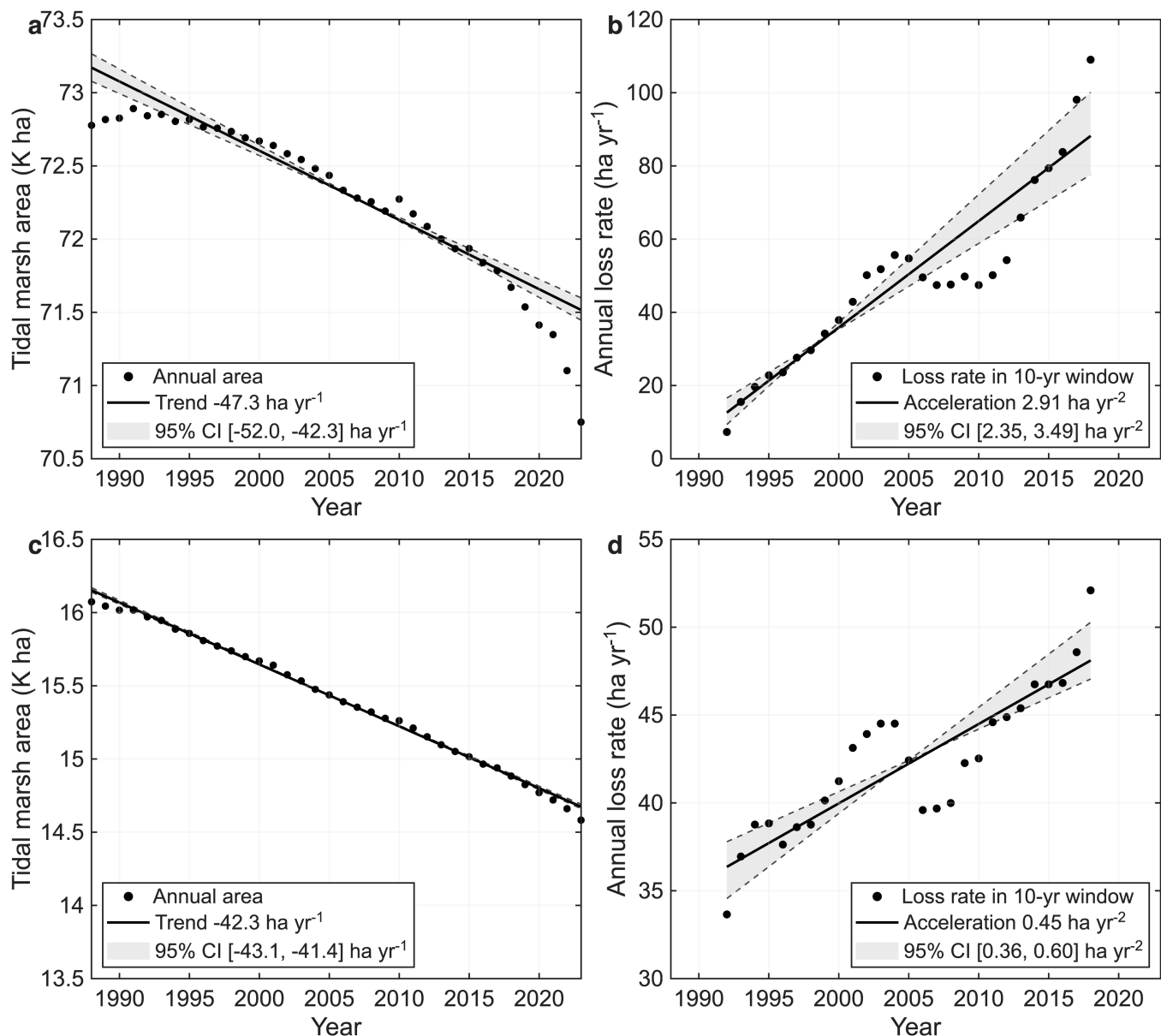
817 **Acknowledgment**

818 We gratefully acknowledge funding and research support from the Natural Sciences and Engineering
819 Research Council of Canada's (NSERC) Alliance grant program (grant numbers: ALLRP 571068-21 and
820 ALLRP 602706-24), Oceans North, World Wildlife Fund Canada, and the Mitacs Accelerate grant
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822 (www.bluecarboncanada.ca).



824

825 **Extended Data Fig. 1 | DECODE time-series detection of tidal-marsh restoration in the upstream**
826 **Petitcodiac River.** a, NDVI trajectory for a restored site upstream of the Petitcodiac River Causeway
827 (64.830451° W, 46.063183° N), where tidal reconnection following the Petitcodiac River restoration
828 project allowed re-establishment of intertidal conditions and subsequent marsh development. Black dots
829 show Landsat observations for the target pixel; the red solid line shows the DECODE model fitted from
830 historical observations, and the red dashed line shows the model prediction. A change is detected when
831 new observations significantly diverge from the forecast, triggering segmentation of the temporal
832 trajectory and re-fitting for the new state. This example shows the transition from open water (in 2005) to
833 tidal flat (in 2013) and vegetated tidal marsh (in 2017) after restoration. b,c, Landsat and very-high-
834 resolution (VHR) images acquired before, during, and after restoration confirm the observed land-surface
835 transition. The dynamic modeling procedure for the DECODE time series model (a) is illustrated in
836 **Supplementary Video S1.**



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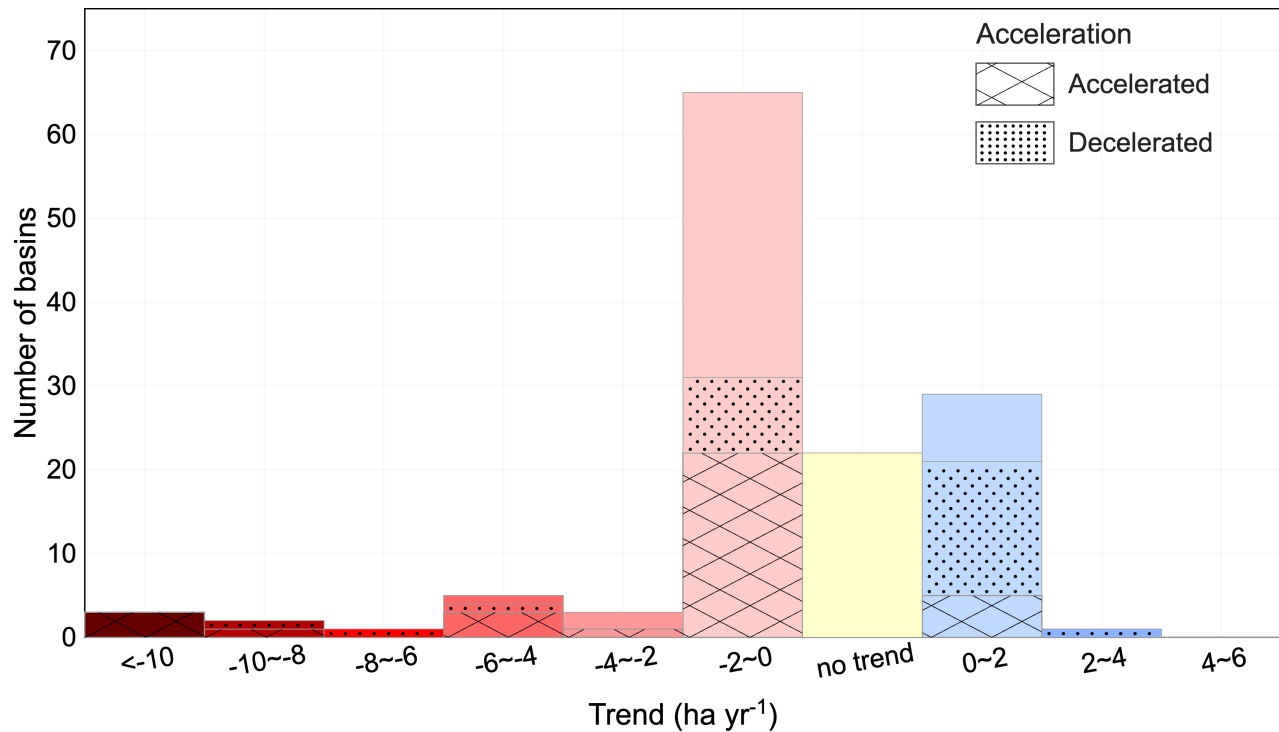
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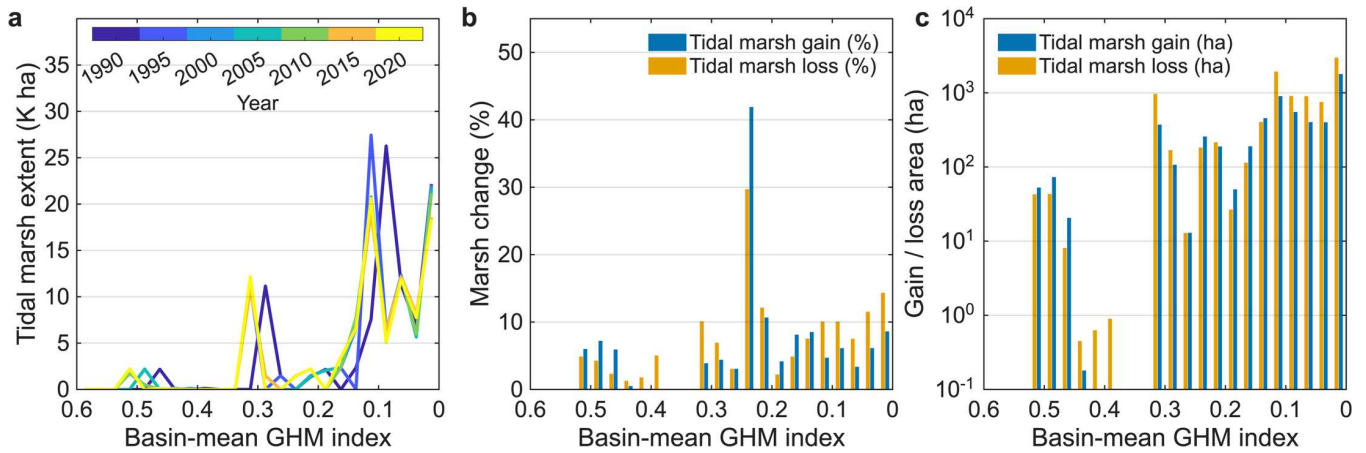
Extended Data Fig. 2 | Long-term decline and accelerating loss of tidal marsh area on Canada's Atlantic and Pacific coasts (1988–2023). **a,c**, Annual tidal marsh extent (ha) and Sen's slope trend for the Atlantic (**a**) and Pacific (**c**) coasts. Points represent annual mapped area adjusted using the whole-area correction ratio. Solid lines show the Sen median trend estimate, dashed lines indicate 95% confidence intervals, and shaded envelopes denote the fitted confidence band. **b,d**, Ten-year moving-window estimates of annual loss rate (ha yr $^{-1}$) and corresponding Sen trend for the Atlantic (**b**) and Pacific (**d**) coasts. Points represent the absolute value of decadal loss rates calculated from rolling 10-year windows. Solid lines indicate the acceleration (Sen slope; ha yr $^{-2}$), and dashed lines show the 95% confidence intervals. All trends were estimated using the Theil–Sen estimator with Kendall's tau significance testing ($\alpha = 0.05$).



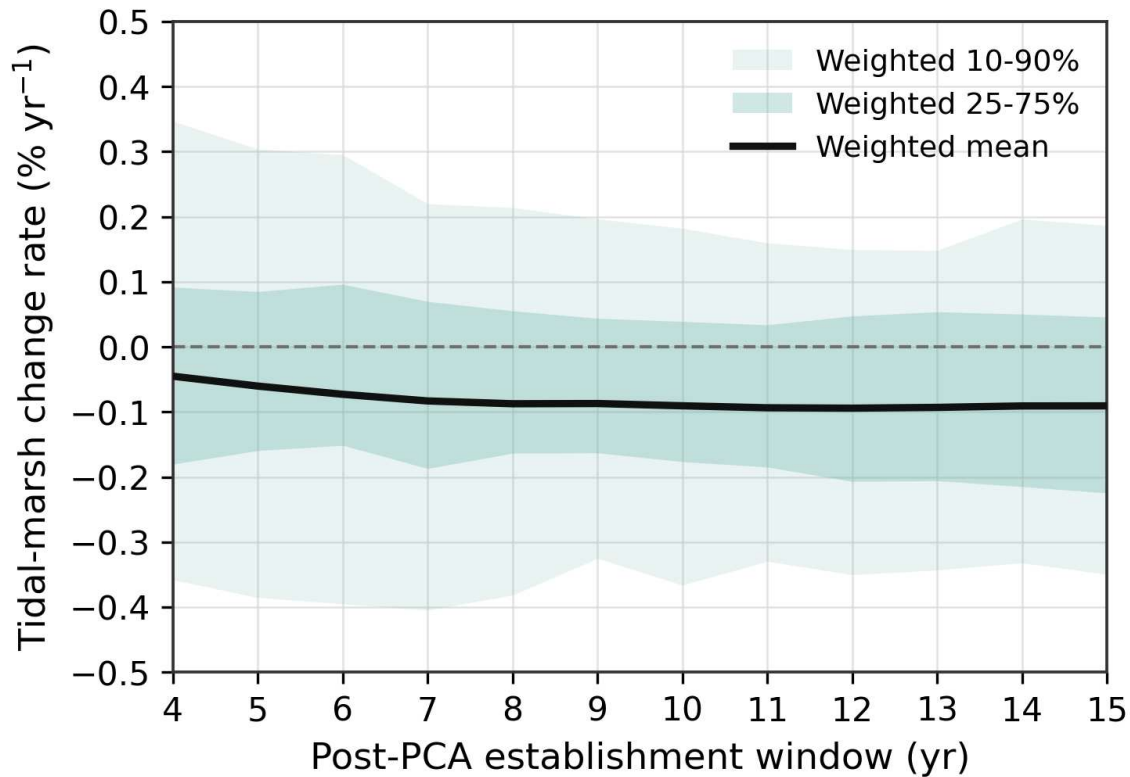
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849 **Extended Data Fig. 3 | Distribution of tidal marsh area trends across Canadian hydrological basins**
850 **(1989–2023).** Histogram showing Sen’s slopes of annual tidal marsh area across 131 hydrological basins.
851 Negative values indicate net marsh loss and positive values indicate net gain. The “no trend” category
852 denotes basins without a statistically significant trend (Mann–Kendall test, $\alpha = 0.05$). Among basins with
853 significant trends, cross-hatched and dotted segments indicate significant acceleration and deceleration,
854 respectively, in the rate of loss or gain, assessed from trends in successive 10-year moving-window slopes.
855 Unhatched segments within the loss and gain bars indicate no statistically significant acceleration or
856 deceleration.

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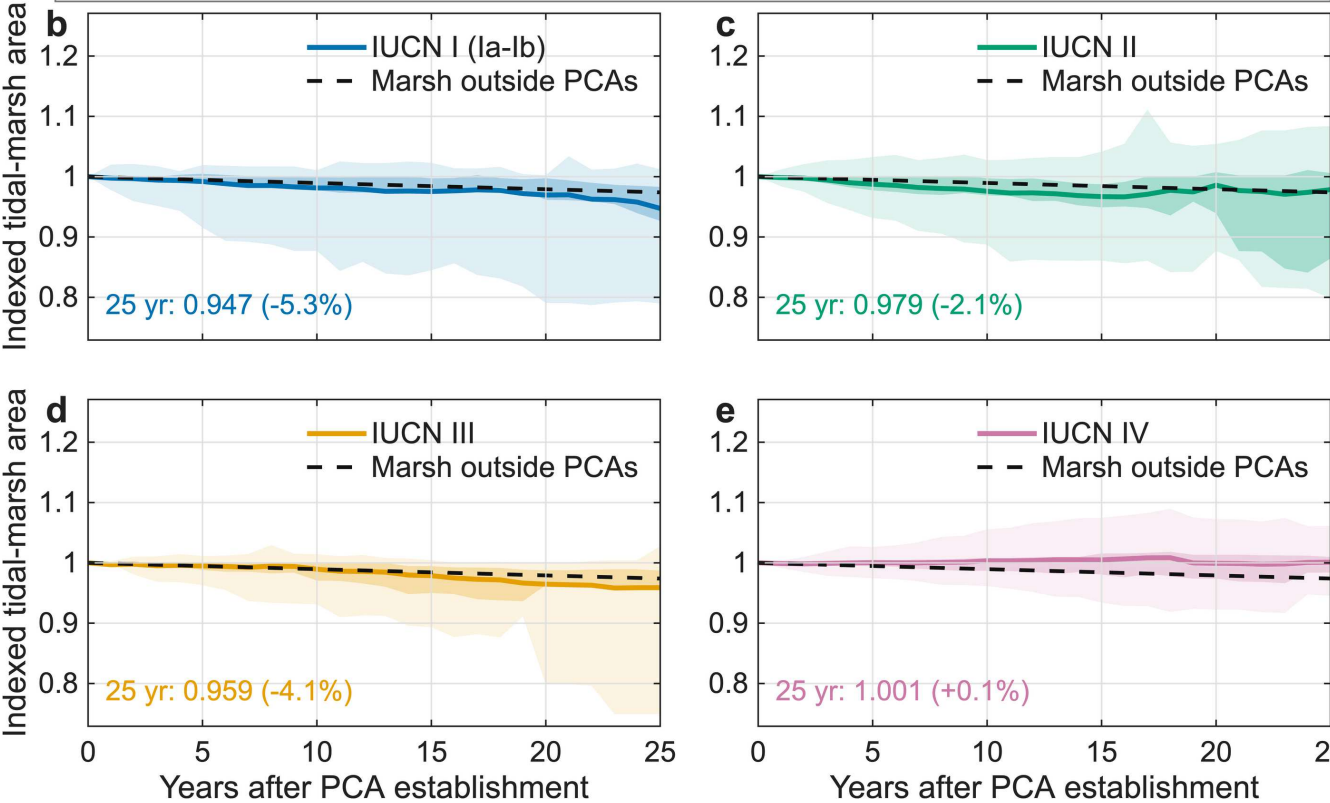
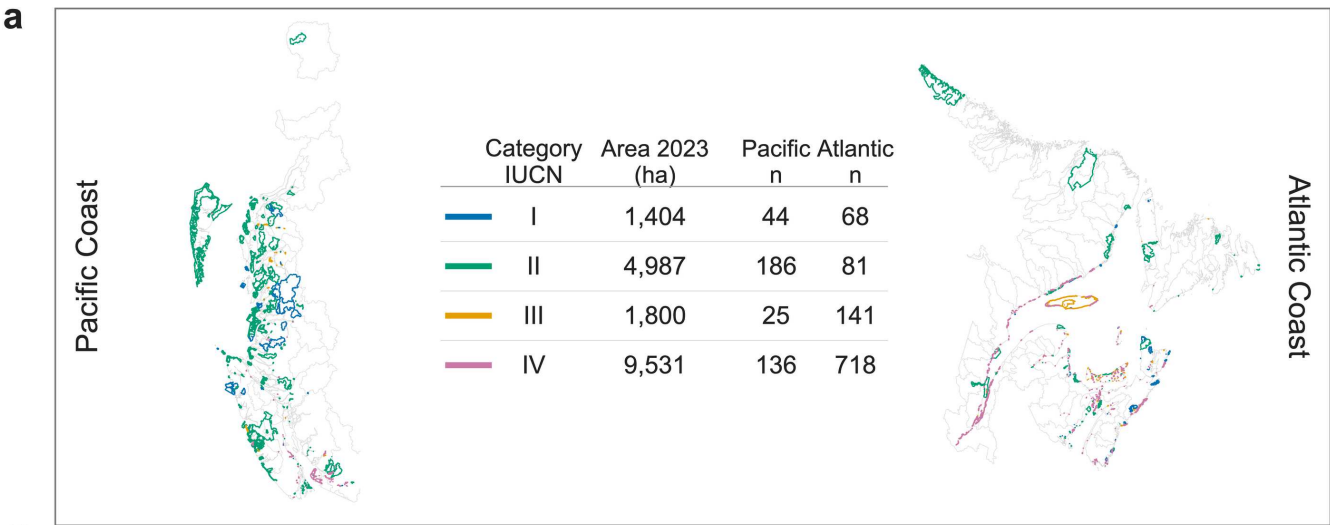


Extended Data Fig. 4 | Tidal-marsh dynamics across basin-level mean human modification. a, Distribution of mapped tidal marsh extent across the basin-mean Global Human Modification (GHM) index at five-year intervals from 1990 to 2020. **b,** Percentage of tidal marsh gain and loss within each basin-mean GHM bin during 1989–2023. **c,** Absolute tidal marsh gain and loss area (ha) within each bin during 1989–2023. Basin-mean GHM values are grouped into 0.025-wide bins and displayed from 0.6 (higher modification) to 0 (minimal modification). Panel c uses a logarithmic y axis, with zero-area bins omitted.



867

868 **Extended Data Fig. 5 | Sensitivity of tidal marsh change rates to observation-window length.** Post-
 869 establishment change rates were estimated using Sen's slope of log-transformed annual marsh area over
 870 the first 4–15 years after PCA establishment, using the same 199 PCA polygons across all windows.
 871 Slopes were converted to annual relative change rates (% yr⁻¹). Each polygon contained at least 10 ha of
 872 tidal marsh at establishment. The black line shows the weighted mean; darker and lighter shading indicate
 873 the weighted 25th–75th and 10th–90th percentile ranges among PCA polygons, respectively. All
 874 summaries are weighted by tidal-marsh area in the establishment year.



Extended Data Fig. 6 | Tidal-marsh trajectories within protected and conserved areas (PCAs) by IUCN management category. **a**, PCA boundaries containing mapped tidal marsh during 1988–2023 along the Pacific and Atlantic coasts, colored by IUCN category. The inset table reports 2023 marsh area and the number of marsh-overlapping PCAs. **b–e**, Post-establishment marsh trajectories for IUCN categories I–IV, respectively, indexed to 1 in the establishment year. Colored lines show establishment-area-weighted mean trajectories; shaded bands indicate the 25th–75th and 5th–95th percentile ranges. Dashed lines show reference trajectories derived from the 1988–2023 trend in total marsh area outside all mapped PCA boundaries.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Yangetal2026MainCAMarshSupplementary.pdf](#)
- [SupplementaryVideoS1.mp4](#)