

Hard armouring outperforms a biomass-based living shoreline on a high-energy, ice-influenced sandstone coast: a one-year controlled comparison at Augustine Cove, Prince Edward Island, Canada

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Abstract

Living shorelines are increasingly promoted as ecologically preferable substitutes for hard armouring, but the great majority of the performance evidence comes from low-energy, microtidal, ice-free estuarine settings in the mid-Atlantic and southeastern United States. Whether that evidence transfers to high-fetch, seasonally ice-affected, friable-bedrock coasts is largely untested. We exploited an unusual natural experiment on the south shore of Prince Edward Island (PEI), Canada, where a single 320 m property presents three contiguous, comparably exposed coastline sections: a 2009 limestone-conglomerate armour stone seawall, a brush-and-biomass living shoreline installed in August 2015, and an unmanaged control. Bluff-edge retreat was quantified over one year (September 2015 – September 2016) using a peg-line survey at eight monitoring stations and shoreline delineation of four georeferenced sUAS orthomosaics along transects spaced at 5 m ($n = 61$ usable transects). Mean bluff-edge retreat differed significantly among sections (Kruskal–Wallis $H = 16.09$, $p < 0.001$). The armour stone section retreated 0.06 ± 0.07 m (mean $\pm$ SE; $n = 20$), a value not distinguishable from zero (Wilcoxon $p = 0.56$), whereas the living shoreline (0.50 ± 0.08 m; $n = 25$) and the unmanaged control (0.45 ± 0.07 m; $n = 16$) both retreated significantly ($p < 0.001$) and did not differ from one another ($p = 1.00$ after correction). The Hodges–Lehmann median difference between the living shoreline and the armour stone was 0.42 m. Archival shoreline analysis showed that the section subsequently armoured had been the fastest-eroding part of the property before 2009 (0.15 m yr^{-1} versus $0.01\text{--}0.02 \text{ m yr}^{-1}$) and the slowest afterwards, while the transect immediately downdrift of the wall recorded the highest post-installation rate on the property (0.75 m yr^{-1}), a pattern consistent with flanking. A site revisit in January 2017 found the western third of the living shoreline structurally removed by winter storms. We conclude that, in this single-site, first-year case study and in this wave climate, the biomass-based living shoreline design delivered no measurable erosion benefit relative to no intervention. The result should not be read as a general indictment of nature-based shoreline protection, but as evidence that design typologies developed for sheltered estuarine fetches cannot be transplanted uncritically to open-coast Gulf of St. Lawrence conditions, and that wave-energy screening should precede installation. These findings carry direct implications for coastal conservation planning and permitting decisions in Atlantic Canada, where nature-based shoreline designs are increasingly promoted without regionally validated siting criteria.

1. Introduction

Coastal societies confronting erosion and relative sea-level rise face a narrow menu of responses, primarily retreat, accommodate, or defend. Where defense is chosen, the choice between hard engineered structures and nature-based alternatives has become one of the more consequential decisions in applied coastal management, because it determines not only the erosion trajectory of the defended parcel but also the ecological character of the shore and the erosional burden transferred to neighbours.

The case against hard armouring is now substantial and largely uncontested in its broad outline. Shoreline hardening is extensive with over 22,000 km, roughly 14% of the shoreline of the contiguous

United States, has been hardened, and many major coastal cities have hardened more than half of their shores (Gittman et al., 2015). A meta-analysis of 54 studies found that seawalls supported 23% lower biodiversity and 45% fewer organisms than natural shorelines, although riprap revetments and breakwaters were not statistically distinguishable from natural shores on those metrics (Gittman et al., 2016). Reflective structures modify nearshore sediment dynamics, contributing to sediment deficits and to reductions in beach width in adjacent unprotected segments (Bernatchez and Fraser, 2012), and the long-running debate over whether and how strongly seawalls accelerate adjacent-beach erosion (Basco, 2006) has never resolved into a general rule, in part because the effect is site-specific and difficult to isolate from ambient variability.

The case for living shorelines has developed largely in parallel. Living shorelines, broadly shoreline stabilization approaches that incorporate natural habitat elements, with or without a low structural sill, have accumulated an encouraging performance record. In North Carolina, marsh sites with and without sills sustained less damage than bulkheads during a Category 1 hurricane, with 76% of surveyed bulkheads damaged in the most exposed region and no detected damage to alternatives (Gittman et al., 2014). Rock-sill living shorelines proved more resilient than both hardened shorelines and natural marshes during Hurricane Matthew, maintaining landward elevation over two years without repair (Smith et al., 2018). Across North Carolina more generally, living shorelines have been shown to be effective erosion control (Polk and Eulie, 2018), and, following Hurricane Florence, they experienced significantly less lateral erosion than unprotected control segments (Polk et al., 2022). A scoping review of the field documented both the rapid growth of the literature and its persistent terminological and geographic unevenness (Smith et al., 2020), and a broader assessment of eco-engineering efficacy concluded that comparative trials of nature-based versus artificial structures under matched environmental conditions remain the central evidentiary gap (Morris et al., 2018).

That gap is the motivation for the present study, and it has a specific geography. Nearly all of the strong comparative evidence originates in the Chesapeake Bay, the Albemarle–Pamlico system, the Gulf of Mexico, or comparable sheltered estuarine settings. They range from microtidal to mesotidal, low to moderate fetch, dominated by fringing *Spartina* marsh, and ice-free. The design guidance that has grown up around that evidence, including the wave-energy classification schemes issued by state agencies and widely reproduced in practitioner manuals, is calibrated to those conditions. Prince Edward Island, Canada is not those conditions.

Prince Edward Island's coast is developed almost entirely on Permo-Carboniferous red sandstone and mudstone, friable enough that bluff faces can be excavated by hand. The Province has one of the highest measured erosion rates in Canada at an average of 0.28 m yr⁻¹ between 1968 and 2010, rising to 0.40 m yr⁻¹ between 2000 and 2010 (Webster and Brydon, 2012). Relative sea level at Charlottetown has risen on the order of 32–36 cm over the past century (Shaw, 2001). Fetches on the Northumberland Strait shore routinely exceed 15 km and reach 35 km or more, an order of magnitude above the 3.2 km threshold at which Chesapeake-derived guidance classifies a shoreline as high energy. Critically, Prince Edward Island sits at the low-latitude margin of seasonal sea ice. The southern Gulf of St. Lawrence has

experienced a statistically-significant decline in ice-season length, and modelling indicates that the transition from low ice concentration to open-water winter conditions increases nearshore sediment transport by 85%, with a total increase of approximately 180% across the full range from high ice concentration to open water (Manson, 2022). The winter storm season, historically damped by nearshore ice and an ice foot, is progressively becoming a period of unattenuated wave attack on unfrozen, saturated bluff faces.

The consequences of that combination were made vivid by post-tropical storm Fiona on 23–24 September 2022, which produced offshore significant wave heights above 8 m and a storm surge on the order of 2 m, drove 12–17 m of foredune retreat at monitored sites in Prince Edward Island National Park with volumetric losses of 28–76 m³ m⁻¹ (George et al., 2024), thinned an ocean-side foredune by an average of 12.3 m and reduced total island volume by 12% at Hog Island (Cantelon et al., 2024), and, in a provincial-scale landcover assessment, was associated with more than 51 km² of coastal land loss and 11 km² of dune loss (approximately 3.5% of the 1,798 km² Prince Edward Island coastal zone). Fiona occurred after the field campaign reported here, but it frames its relevance. Decisions about shoreline defence typology on this coast are being made under a rapidly steepening hazard curve, frequently by individual landowners and volunteer watershed groups without engineering support.

Against that background, this paper reports what is, to our knowledge, the first controlled field comparison of hard armouring, a biomass-based living shoreline, and an unmanaged control on a single Gulf of St. Lawrence property. The specific objectives were to (i) quantify one year of bluff-edge retreat behind each of the three treatments using two independent measurement approaches; (ii) test whether the differences among treatments are statistically distinguishable from measurement noise; (iii) place the single-year result in the context of five decades of archival shoreline change at the same eight stations; and (iv) assess whether adjacent-segment (flanking) erosion is detectable downdrift of the seawall. A companion paper (MacDonald et al., in prep.) treats the methodological intercomparison in detail. In this paper, the authors focus on the management-relevant performance question. Because the choice between armouring and nature-based protection is typically adjudicated through municipal or provincial planning and permitting processes rather than through engineering review alone, we frame the results throughout in terms of their implications for coastal conservation planning and management, rather than as a purely technical performance comparison.

2. Study area

2.1 Regional setting

The study site lies at Augustine Cove on the south (Northumberland Strait) shore of Prince Edward Island, Canada (46.210° N, 63.590° W), within the coastal compartment extending from Rice Point to Seacow Head and including the depositional shoal at Tryon Head (Davies, 2011). For this compartment, mean annual significant breaking wave height is 0.11–0.20 m and maximum significant breaking wave height 1.01–2.00 m, with net littoral drift directed eastward (Davies, 2011). The tidal range at nearby

Borden-Carleton is 2.36 m. At the Borden weather station, the closest provincial station, approximately 8.7 km distant, mean wind speed is 5.93 m s^{-1} with a modal direction of 270° (Prince Edward Island Wind Atlas, 2017). Annual mean wind speeds in 2015 and 2016 were 12.8 and 14.0 km h^{-1} respectively, with maximum recorded gusts of 94.9 km h^{-1} in both years (Jardine, 2016, 2017).

Fetch was estimated from mapping as approximately 17 km to the nearest land to the southwest (Cape Tormentine, New Brunswick) and approximately 37 km due south. Under the Maryland Department of Natural Resources classification, widely used in living-shoreline siting guidance and adopted in the Chesapeake Bay Foundation's practitioner materials, a fetch of 3.2 km or greater defines a high-energy environment. Augustine Cove exceeds that threshold by a factor of five to eleven. We note explicitly that the Chesapeake classification was not developed for a coast with seasonal ice and a 2.36 m tidal range, and we return to this transferability problem in Section 5. Nonetheless, on the criterion that practitioners actually apply, this site is unambiguously high energy.

Three storm events during the peg-line measurement interval were identified from the Borden-Carleton record. The first had 55.6 mm of rain with gusts to 56 km h^{-1} on 23 November 2015; the second was a province-wide snow and rain event on 3 December 2015 (12.7 mm, gusts to 55 km h^{-1}); and, most significantly, the third brought 15.2 mm of rain with gusts to 88 km h^{-1} on 29 March 2016 (Jardine, 2016).

2.2 The three treatment sections

The property (Camp Abegweit, a seasonal children's camp) presents approximately 320 m of coast divided into three contiguous sections separated only by a 30 m graded beach access (Fig. 1).

Section 1 – Armour stone ($\approx 84 \text{ m}$). A limestone-conglomerate seawall installed in 2009 at a reported cost of approximately CAD25,000. Individual stones are 0.5–1.0 m in height and width building a wall that follows the arc of the coastline. Photographic records of construction show a comparatively engineered installation, including grading of the bank slope and a rampart behind the wall. This is a higher standard than the ad hoc placement common on private Prince Edward Island properties. Limestone conglomerate is the dominant armour material on Prince Edward Island and must be imported as the Province has no competent hard bedrock. No maintenance or repair was reported between installation and the study period. The bank behind this section is notably less steep than behind the other two sections and the ground surface is maintained as mown lawn.

Section 2 – Living shoreline ($\approx 135 \text{ m}$). Installed in August 2015, one month before monitoring began, by a commercial ecological landscaping contractor at a reported cost of approximately CAD20,000. The design is a brush-and-biomass typology rather than a marsh-and-sill typology. The bank was regraded toward an angle of repose; logs were placed along the toe; staked hay bales connected by twine were run along the base; native woody species including wild rose (*Rosa* spp.) and dogwood (*Cornus* spp.) were planted into the cliff face to develop stabilizing root systems; and tree branches, additional hay and seaweed were used to build a brush wall covering exposed soil, finished with a nutrient-rich slurry. In

summer 2016, following disputes over the design's effectiveness, the local watershed group modified the structure, principally by reorienting horizontally placed logs into shore-normal positions and re-tying biomass. This modification occurred between our third and fourth surveys and is treated explicitly as a confounder in Sections 4 and 5.

Section 3 — Unmanaged control (≈ 70 m). No deliberate protection was implemented. Several naturally fallen trees are present which may afford incidental toe protection or, alternatively, destabilize the bank through root-plate disturbance. Vegetation is dense and unmanaged.

The three sections share the same compartment, aspect, tidal regime, wind climate, lithology and storm history, and are separated by tens of metres rather than kilometres. This is the principal strength of the design in that it approximates a matched-condition comparative trial of the kind Morris et al. (2018) identified as the field's outstanding need. Its principal weakness, that pre-treatment erosion rates were not identical across the three sections, is addressed directly in Section 4.3.

3. Methods

3.1 Definition of the coastline indicator feature

Following Boak and Turner (2005), a coastal indicator feature must be specified before change can be measured. We adopted the seaward edge of land along the top of the cliff or bluff (Boak and Turner's bluff-top/cliff-top indicator), consistent with the protocol used in the concurrent Prince Edward Island provincial monitoring programme (Clark, 2016). Where overhanging land was present at the cliff edge, measurements were referenced not to the seaward limit of the overhang but to the point vertically above the position at which the intact bank face begins, since the overhang does not represent the true position of the coastline.

3.2 Peg-line survey

On 17 September 2015, eight pairs of 1 m rebar pegs were installed perpendicular (90°) to the coastline: two pairs behind the armour stone, three behind the living shoreline, and three behind the control. Front pegs were set 10 m from the bluff edge, with back pegs 10 m landward (5 m where vegetation obstructed a longer baseline). The back peg establishes a reproducible bearing so that the same transect is remeasured regardless of operator. Pegs were capped with stamped metal identification caps and driven flush in mown areas and left proud (approximately 30 cm) in vegetated areas. Positions were recorded with a recreation-grade Global Positioning System (GPS) to enable relocation (Table 1 of the source dataset). This is the established Prince Edward Island provincial protocol, refined by Clark (2016) from the 1984 Department of Community and Cultural Affairs network, which by the time of this study had grown to over 100 stations province-wide. Measurements were made from the centre of the front peg to the bluff edge with a steel tape laid as level as vegetation allowed.

Only two peg pairs could be installed behind the armour stone as the property owner requested that the eastern end of that section be left clear because of proximity to the children's beach access. Re-measurement was carried out on 29 April 2016, deliberately in advance of the summer reconstruction of the living shoreline, giving a 225-day (7.4 month) peg-line interval.

3.3 sUAS surveys and shoreline delineation

Four sUAS surveys were flown between 17 September 2015 and 9 September 2016 (358 days). Ground control points (locally fabricated wooden targets) were distributed near the corners of each survey block, with additional points within, and their positions fixed with a Trimble Geo7x receiver operating on a networked real-time kinematic correction service at 2 cm accuracy. Four ground control points are sufficient for accurate georeferencing in this configuration (Douterloigne et al., 2010), but we used five to eight. Imagery was processed in Pix4D Mapper Pro to orthomosaics and digital surface models with ground control points manually referenced. Ground sampling distance ranged from 1.29 to 2.96 cm. Full platform specifications, processing parameters, and accuracy assessments are reported in a companion methods paper (MacDonald et al., in prep.). The relevant results are that orthomosaic horizontal residuals against independently surveyed ground control point centres averaged 0.03 m (range 0.01–0.06 m) and that repeat elevations at five stable sample points across the four DSMs agreed to within an average of 0.10 m.

Coastlines were delineated manually in ArcGIS at 1:50 display scale on each orthomosaic. A generalized baseline was then drawn and shore-normal transects generated at 5 m intervals, yielding 22, 30 and 18 transects across the armour stone, living shoreline and control sections respectively. Transects at which delineation was unreliable (principally where blurred vegetation or overhanging foliage obscured the bluff edge) were excluded a priori, leaving 20, 25 and 16 usable transects (61 total). Intersections between each delineated coastline and each transect were generated and inter-flight distances measured. Negative values (apparent seaward advance) were retained rather than truncated, in order to preserve an unbiased estimate of the error distribution.

3.4 Archival shoreline change

Provincial coastlines digitized from 1968, 2000 and 2010 aerial photography (Webster and Brydon, 2012) were imported into ArcGIS together with the peg coordinates. Distances between successive coastlines were measured along the bearing defined by each front–back peg pair and divided by the interval length (32 and 10 years respectively) to give annualized rates. Because the seawall was installed in 2009 and provincial photography is acquired on a decadal cycle, the 2000–2010 epoch straddles installation and cannot isolate the post-installation signal. It is interpreted accordingly.

3.5 Statistical analysis

Distributions of transect-level change were non-normal and, in the armour stone section, approximately symmetric about zero. Non-parametric methods were therefore used throughout. Differences among the three sections in total annual change were tested with a Kruskal–Wallis test followed by pairwise Mann–

Whitney *U* tests with Bonferroni correction ($\alpha = 0.05$, three comparisons). Effect sizes are reported as rank-biserial correlations and as Hodges–Lehmann median differences. Whether each section’s change differed from zero was tested with Wilcoxon signed-rank tests. Structure across the three inter-flight intervals within each section was tested with Friedman tests on the repeated transect measurements. Paired change in archival rates between epochs was tested with a Wilcoxon signed-rank test across the eight stations. Analyses were performed in Python 3 (SciPy).

4. Results

4.1 Peg-line survey

Over the 225-day interval from 17 September 2015 to 29 April 2016, mean bluff-edge retreat was 0.04 m behind the armour stone (individual values 0.08 and 0.00 m), 0.21 m behind the living shoreline (0.00, 0.25, 0.38 m) and 0.38 m behind the control (0.37, 0.57, 0.19 m). The ordering (armour stone < living shoreline < unmanaged) matches the a priori expectation derived from the literature. With two and three stations per section, these values are not amenable to inferential testing. They are reported as an independent, ground-truthed corroboration of the transect results below, and, importantly, as the only measurements in the study capable of resolving undercutting, which is invisible to nadir imagery. At stations behind the living shoreline and the control, accounting for undercutting added as much as 0.20 m to the recorded retreat.

4.2 Shoreline delineation

Total change over the 358-day interval differed significantly among sections (Kruskal–Wallis $H = 16.09$, $p = 3.2 \times 10^{-4}$). Summary statistics are given in Table 1.

Table 1
Bluff-edge change (m, positive = landward retreat) between 17 September 2015 and 9 September 2016 from delineated sUAS orthomosaics.

Section	<i>n</i>	Mean ± SE	95% CI	Median	IQR	Range	Transects with net advance
Armour stone	20	0.058 ± 0.070	−0.088 to 0.204	0.030	−0.19 to 0.25	−0.41 to 0.79	9 (45%)
Living shoreline	25	0.495 ± 0.077	0.336 to 0.655	0.550	0.19 to 0.68	0.03 to 1.82	0 (0%)
Unmanaged control	16	0.449 ± 0.066	0.307 to 0.590	0.465	0.26 to 0.60	0.00 to 1.03	0 (0%)

Three features of Table 1 carry the paper’s central result.

First, the armour stone section did not retreat detectably. Its 95% confidence interval spans zero, its median is 0.03 m, and a Wilcoxon signed-rank test cannot reject the null hypothesis of no change ($p = 0.56$). Nine of twenty transects recorded net seaward advance, which is what an error distribution

centred near zero should look like, a point developed in the companion methods paper (MacDonald et al., in prep.).

Second, both unarmoured sections retreated unambiguously. The living shoreline (Wilcoxon $p = 1.2 \times 10^{-5}$) and the control ($p = 6.5 \times 10^{-4}$) both differ from zero, and neither recorded a single transect of net advance in 25 and 16 measurements respectively.

Third, and most consequentially for management, the living shoreline and the unmanaged control are statistically indistinguishable from one another (Mann–Whitney $U = 207.5$, $p = 0.85$; Bonferroni-adjusted $p = 1.00$; rank-biserial = 0.04; Hodges–Lehmann median difference = 0.02 m), while both differ strongly from the armour stone (living shoreline versus armour stone: $U = 94.0$, adjusted $p = 1.1 \times 10^{-3}$, rank-biserial = - 0.62, Hodges–Lehmann difference = 0.42 m; control versus armour stone: $U = 55.0$, adjusted $p = 2.6 \times 10^{-3}$, rank-biserial = - 0.66, Hodges–Lehmann difference = 0.41 m). In its first year, at this site, the living shoreline performed as though nothing had been installed.

4.3 Seasonality and the maintenance confounder

Decomposing the annual signal into the three inter-flight intervals (88, 137 and 133 days) reveals contrasting temporal structure (Table 2).

Table 2
Mean bluff-edge change by interval, with rates normalized to interval length.

Section	17 Sep – 14 Dec 2015 (88 d)	14 Dec 2015–29 Apr 2016 (137 d)	29 Apr – 9 Sep 2016 (133 d)	Friedman p
Armour stone	-0.003 ± 0.029 m (- 0.03 mm d ⁻¹)	+ 0.051 ± 0.022 m (+ 0.37 mm d ⁻¹)	+ 0.010 ± 0.041 m (+ 0.07 mm d ⁻¹)	0.040
Living shoreline	+ 0.227 ± 0.050 m (+ 2.58 mm d ⁻¹)	+ 0.046 ± 0.024 m (+ 0.34 mm d ⁻¹)	+ 0.222 ± 0.050 m (+ 1.67 mm d ⁻¹)	0.002
Unmanaged control	+ 0.208 ± 0.076 m (+ 2.37 mm d ⁻¹)	+ 0.182 ± 0.052 m (+ 1.33 mm d ⁻¹)	+ 0.058 ± 0.033 m (+ 0.44 mm d ⁻¹)	0.305

The control section shows the expected pattern for an ice-influenced Gulf coast with 87% of annual retreat occurring during the 225-day cold-season window between the first and third surveys, at rates of 2.37 and 1.33 mm d⁻¹, falling to 0.44 mm d⁻¹ over the summer. The armour stone shows no meaningful seasonal signal at any point.

The living shoreline departs from both. It lost ground rapidly in the first 88 days (2.58 mm d⁻¹, the highest rate recorded anywhere in the study), was comparatively stable through the deep-winter interval (0.34 mm d⁻¹, indistinguishable from the armour stone in the same window), and then lost ground rapidly again over the summer (1.67 mm d⁻¹), a period during which the control section was nearly dormant. Only 55% of its annual retreat occurred in the cold season.

We interpret the autumn signal as genuine structural failure. The installation was one month old at the start of monitoring, biomass had not consolidated, and planted material had not established root systems. This is precisely the vulnerability window that regional practitioner guidance anticipates, which stresses spring planting to maximize the growing season and continuous vegetative or biomass cover over exposed soil through winter (Ecology Action Centre, 2014). An August installation on this coast provides roughly six weeks before the autumn storm season.

The summer signal is confounded. The reconstruction undertaken by the watershed group between the third and fourth surveys involved repositioning heavy logs resting on the bluff edge, and the monitoring lead maintained contact with the volunteer responsible in order to flag this risk. Some fraction of the 0.22 m recorded in that interval is therefore likely to be maintenance-induced rather than wave-induced. We cannot partition it. Two observations bound the interpretation. First, the confounder inflates the living shoreline estimate and therefore cannot explain the finding that the living shoreline failed to outperform the control, because removing it would move the living shoreline mean toward, not below, the control mean. Second, the necessity of intrusive mid-life reconstruction is itself a performance attribute of the design rather than an external nuisance, a point we develop in Section 5.3.

4.4 Archival shoreline change, 1968–2010

Annualized retreat rates at the eight stations are given in Table 3.

Table 3
Archival retreat rates (m yr⁻¹) derived from 1968, 2000 and 2010 provincial coastlines.

Station	1968–2000	2000–2010
1 Armour stone west	0.13	0.28
2 Armour stone centre	0.16	0.38
3 Living shoreline west	0.01	0.75
4 Living shoreline centre	0.01	0.27
5 Living shoreline east	0.04	0.32
6 Control west	0.02	0.57
7 Control centre	0.01	0.54
8 Control east	0.01	0.21
Section mean, armour stone	0.15	0.33
Section mean, living shoreline	0.02	0.45
Section mean, control	0.01	0.44

Two results follow. First, retreat accelerated sharply and consistently with the property-wide mean rising from 0.049 to 0.415 m yr⁻¹, an 8.5-fold increase, with every one of the eight stations recording a higher rate in the later epoch (Wilcoxon $p = 0.008$). The 2000–2010 property mean is closely comparable to the provincial mean of 0.40 m yr⁻¹ for the same epoch (Webster and Brydon, 2012). Webster and Brydon linked provincial acceleration to a marked rise in water levels at the Charlottetown tidal gauge after 2004. The concurrent decline in southern Gulf ice-season length (Manson, 2022) provides a second, non-exclusive mechanism.

Second, the pre-treatment ordering was the reverse of the post-treatment ordering. Before 2009, the section that was subsequently armoured was eroding an order of magnitude faster than the rest of the property (0.15 versus 0.01–0.02 m yr⁻¹), which is, of course, why the owners chose to armour it, and it is the section containing the camp's buildings and principal lawn. After 2009, it became the slowest-eroding section on the property. This reversal is the strongest available evidence that the 2015–2016 result reflects treatment effect and not a pre-existing spatial gradient in erosion susceptibility. Had the armour stone section simply been intrinsically stable, it would not have led the property in retreat for the preceding three decades.

4.5 Evidence of flanking

Station 3, the first monitoring station east (downdrift, given eastward net drift) of the seawall, recorded 0.75 m yr⁻¹ between 2000 and 2010, the highest rate of any station on the property in either epoch, and 2.3 times the mean of the armoured section itself over the same interval. In the 1968–2000 epoch, the same station recorded 0.01 m yr⁻¹, among the lowest on the property.

This is consistent with the flanking and end-around erosion long associated with terminated hard structures (Basco, 2006; Bernatchez and Fraser, 2012). We state the limitation plainly as such: $n = 1$, the 2000–2010 epoch straddles installation, and no attempt was made to control for the graded beach access that separates the two sections and which may itself concentrate runoff and foot traffic. The observation warrants targeted investigation rather than inference. It does not by itself establish an adjacent-erosion effect.

4.6 Post-study observation

A site revisit in January 2017, four months after the final survey, found a portion of the living shoreline missing, with damage concentrated on its western side. Given eastward net drift and a prevailing 270° wind direction, the western end is the updrift and most exposed terminus. This observation falls outside the measurement programme but bears directly on the durability question in Section 5.

5. Discussion

5.1 What the result does and does not show

The finding is narrow and should be stated narrowly. A brush-and-biomass living shoreline, installed in August on a coast with 17–37 km of fetch and a 2.36 m tidal range, delivered no measurable reduction in bluff-edge retreat relative to no intervention over its first year, while a competently engineered armour stone seawall on the same property, in the same year, showed no detectable retreat at all.

It does not show that living shorelines fail in the Gulf of St. Lawrence. It does not show that hard armouring is preferable on this coast in any comprehensive sense. The biodiversity costs documented by Gittman et al. (2016), the sediment-budget consequences documented by Bernatchez and Fraser (2012), and our own flanking observation all sit on the other side of the ledger, and none of them were quantified here. And it does not show that the living shoreline would fail in year five as root establishment, biomass consolidation and vegetation succession are cumulative processes, and the fair comparison for a nature-based intervention is a multi-year trajectory rather than a first-year snapshot. Smith et al. (2018) found rock-sill living shorelines gaining structural function over a two-year post-installation window; a design that is weakest when newest is not thereby a failed design.

What the result does show, and what we think is transferable, is that the specific design typology installed here was mismatched to the specific energy environment it was placed in, and that this mismatch was foreseeable at the design stage from information available at the design stage.

5.2 The transferability problem in wave-energy guidance

The living shoreline literature's support is a set of environments - Chesapeake Bay, Albemarle–Pamlico, the northern Gulf of Mexico - that share low to moderate fetch, fringing marsh, and no seasonal ice. The wave-energy classification most commonly used to screen sites, in which 3.2 km of fetch marks the boundary of high energy, originates in that setting.

Applied literally, that criterion classifies most of the Prince Edward Island coast as high energy and would have excluded this site. Applied loosely, or not at all, it permits an installation that failed. But the criterion is also not straightforwardly applicable. Chesapeake Bay has neither the 2.36 m tidal range of the Northumberland Strait nor its seasonal ice regime, and the relevant physical stressor on a Prince Edward Island sandstone bluff is not only wave attack but also freeze–thaw cycling of a saturated friable face, ice scour and ice push during the ice season, and the growing exposure of that face to winter waves as ice cover declines (Manson, 2022). A fetch threshold is a poor proxy for a hazard suite that includes cryogenic weathering.

The practical implication is that Atlantic Canada needs its own siting guidance rather than a borrowed threshold. That guidance would need at minimum to incorporate (i) directional fetch weighted by the wind rose rather than maximum fetch; (ii) the winter ice regime and its trend, including the number of days on which nearshore ice attenuates wave energy and the number on which an ice foot forms; (iii) bluff lithology and height, since a 4–6 m friable sandstone bluff presents a fundamentally different stabilisation problem from a 0.5 m marsh edge; and (iv) the availability of sustained maintenance capacity. Regional practitioner experience already points in this direction. The Ecology Action Centre's

Northumberland Strait installations, which used a comparable typology in a comparable wave climate, were reported as generally successful but with explicit conditions attached regarding spring planting and winter cover (Ecology Action Centre, 2014).

5.3 Design typology, not the living shoreline concept

It is important to distinguish the typology tested here from the typologies that carry the strong performance evidence. The successful North Carolina cases are overwhelmingly marsh plantings with granite or oyster sills, that is, they pair a vegetated surface with a low-crested, wave-dissipating structural element seaward of it (Gittman et al., 2014; Smith et al., 2018; Polk et al., 2022). Notably, Smith et al. (2018) found the sill component to matter. Enhancement was observed at granite-sill sites and not at oyster-bag sites, a difference attributed to the structural stability of the sill.

The Augustine Cove design has no sill. Its structural elements such as logs at the toe, staked hay bales, a brush wall of tree limbs, seaweed infill, are unanchored or lightly anchored biodegradable material intended to buy time while root systems develop. Under 1–2 m breaking waves on a 2.36 m tidal range, with the wave attack point migrating vertically across the structure through each tidal cycle, this is a structurally different proposition from a rock sill. The January 2017 observation of material removal at the exposed western terminus, and the need for a full reconstruction within ten months of installation, are consistent with that reading.

There is also a maintenance-regime distinction that the literature tends to underweight. Practitioner guidance acknowledges that soft approaches require more frequent maintenance than hard structures, and that sustained volunteer or community engagement is effectively a design requirement (Esnard and Mitsova, 2012). At Augustine Cove that requirement was met (a local watershed group did undertake reconstruction) and the reconstruction itself plausibly contributed to bluff-edge loss, because it involved manipulating heavy material resting on a friable bluff edge. A design whose maintenance is erosive is a design whose maintenance burden should be counted as a cost rather than assumed away. This is a specific instance of the more general point made by Morris et al. (2018) that cost-effectiveness comparisons must be conducted against an artificial structure under the same environmental conditions, over the full service life, and must include all ecosystem services on both sides.

5.4 The counterfactual and the cost comparison

The two installations cost approximately CAD25,000 (2009, armour stone, 84 m) and CAD20,000 (2015, living shoreline, 135 m), roughly CAD298 m⁻¹ and CAD148 m⁻¹ respectively before inflation adjustment. On a naive first-year cost-per-metre-of-erosion-avoided basis the living shoreline performs infinitely poorly, since it avoided no measurable erosion. But this framing is misleading in both directions. The armour stone's service life will end, and Prince Edward Island communities have a documented tendency toward reactive rather than planned repair (Jolicoeur and O'Carroll, 2007), so its true whole-life cost is understated by the installation figure. The living shoreline, conversely, may yet perform in years three to ten, and its ecological co-benefits such as habitat provision, maintenance of the land–water interface, sediment permeability, are real even where its erosion performance is not yet demonstrable.

What can be said with confidence is that the decision framework applied at this site was inadequate to the decision. Neither installation appears to have followed a formal wave-energy assessment, a comparison of design alternatives under local conditions, or a monitoring commitment established in advance. That is not unusual as coastal defence decisions on Prince Edward Island are frequently made parcel by parcel, by landowners and volunteer groups, without engineering input and without a mechanism for aggregating outcomes across the province.

5.5 Implications under a steepening hazard curve

Three trends compound the problem this study documents. Relative sea level continues to rise, at a rate of roughly 32–36 cm per century historically at Charlottetown (Shaw, 2001) and projected to accelerate. Ice-season length in the southern Gulf is declining, with the transition to open-water winters projected to increase nearshore sediment transport by approximately 180% relative to high-ice conditions (Manson, 2022); a change that acts specifically on the winter interval during which, at our control section, 87% of annual retreat already occurs. And storm intensity events of the magnitude of Fiona, which drove 12–17 m of foredune retreat at monitored Prince Edward Island sites in a single night (George et al., 2024) and reduced total island volume at Hog Island by 12% (Cantelon et al., 2024), reset the baseline against which any protection scheme must be evaluated.

Under these conditions, the burden of proof on shoreline protection typologies should rise, not fall. A design that provides no measurable benefit in a year with a maximum recorded gust of 94.9 km h⁻¹ and no named storm cannot be assumed to provide benefit in a Fiona year. Conversely, hard armouring, whatever its ecological costs, is not a permanent solution either. It fixes a shoreline position against a rising sea, transfers energy downdrift, and, as our station 3 observation hints and the wider literature documents (Basco, 2006; Bernatchez and Fraser, 2012), may accelerate the erosion of the neighbours who did not choose it.

The honest management conclusion is therefore not “armour instead” but that on high-energy Prince Edward Island shorelines, the realistic menu is narrower than landowners are often led to believe, and that setback and managed retreat deserve more weight in the conversation than they currently receive. This is the position the provincial visualization and outreach programme has taken with communities directly (Fenech et al., 2017), and our results support it.

5.6 Implications for coastal conservation planning and permitting

The performance gap documented here has a direct bearing on how coastal conservation planning and permitting bodies evaluate shoreline-protection applications. On Prince Edward Island, as in much of Atlantic Canada, decisions about armouring versus nature-based protection are typically made parcel by parcel through provincial permitting processes or, on private land absent a permitting trigger, with no external review at all. Neither pathway currently requires the kind of site-specific wave-energy screening

that this study suggests would have flagged the mismatch between the installed typology and the local hazard regime before construction began.

For coastal conservation planners, three practical implications follow. First, permitting and advisory frameworks for nature-based shoreline protection should require, at minimum, a directional fetch and ice-regime assessment before approval, rather than relying on a generic best-practices checklist developed for a different coastal setting. Second, because a design's first-year performance may understate its eventual function, any planning framework that conditions future approvals or funding on short-term monitoring results should build in a multi-year evaluation window rather than a single post-installation inspection. Third, conservation authorities weighing hard armouring approvals should treat flanking risk to neighbouring parcels, not just the applicant's own shoreline, as a standard element of environmental review, given the pattern documented in Section 4.5. None of these recommendations require new legislative authority as they are changes to the technical content of an existing permitting and planning process.

5.7 Limitations

Six limitations bound the inference. (i) The study covers one year with a single replicate of each treatment; treatment and location are perfectly confounded within the property, and we rely on the archival reversal reported in Section 4.4 to argue that pre-existing gradients do not explain the result. We emphasize that, with treatment and location perfectly confounded within a single property, this study constitutes a well-instrumented single case rather than a replicated experiment. Its relative-performance findings should be treated as hypothesis-generating for the region, to be tested against additional sites, rather than as a general design rule. (ii) The living shoreline was one month old at the start of monitoring, so this is a test of first-year performance, which is the phase in which a nature-based design should be expected to perform worst. (iii) The summer reconstruction confounds the third interval, in a direction that inflates rather than deflates the living shoreline's measured retreat. (iv) Nadir imagery cannot resolve undercutting. The delineation therefore systematically underestimates retreat at the two steep-banked sections and, because the armour stone section has a gentler bank, this bias is unequal across treatments and works against the armour stone rather than for it. (v) The armoured section is mown lawn, which delineates more reliably than dense unmanaged vegetation, a differential data-quality issue treated fully in the companion paper (MacDonald et al. in prep.). (vi) Surface runoff was not measured and may contribute to bluff-edge loss independently of wave attack. The mown, graded armour stone section and the vegetated control differ in runoff behaviour in ways we did not quantify.

6. Conclusions

On a single high-fetch, seasonally ice-influenced sandstone property on the south shore of Prince Edward Island, one year of monitoring at 61 transects and eight ground stations produced four findings.

1. At this single site, an armour stone seawall installed in 2009 showed no bluff-edge retreat distinguishable from measurement noise over the year 2015–2016 (0.06 ± 0.07 m; Wilcoxon $p =$

0.56).

2. At the same single site, a brush-and-biomass living shoreline installed in August 2015 retreated 0.50 ± 0.08 m, statistically indistinguishable from the 0.45 ± 0.07 m recorded at an adjacent unmanaged control (adjusted $p = 1.00$), and significantly worse than the armoured section (adjusted $p = 0.001$; median difference 0.42 m).
3. Archival analysis showed that the armoured section had been the fastest-eroding part of the property before installation and the slowest afterwards, and that property-wide retreat accelerated 8.5-fold between the 1968–2000 and 2000–2010 epochs, consistent with the provincial trend.
4. The transect immediately downdrift of the seawall recorded the highest post-installation archival rate on the property (0.75 m yr^{-1}), a pattern consistent with flanking but based on a single station.

The policy implication is not that nature-based shoreline protection should be abandoned in Atlantic Canada, but that design typologies validated in sheltered, ice-free estuaries should not be installed on open Gulf of St. Lawrence coasts without local wave-energy screening, a design incorporating a durable wave-dissipating element, spring installation to maximize establishment before the storm season, a funded maintenance commitment, and monitoring designed in from the outset. Region-specific siting guidance for the southern Gulf, incorporating directional fetch, ice-regime trend, bluff lithology and maintenance capacity, is an urgent and tractable need. Embedding these criteria in provincial permitting and coastal conservation-planning frameworks, rather than leaving them to individual landowners and volunteer groups working without engineering or planning support, is the most direct route to closing the gap this case study exposes.

Declarations

Author Contribution

Andrew MacDonald - Conceptualization; Methodology; Managing and annotating data; Verifying results/reproducibility; Formal Analysis; Investigation; Writing – Original Draft; Writing – Review & Editing
Adam Fenech - Conceptualization; Methodology; Formal Analysis; Resources; Writing – Review & Editing; Supervision; Funding Acquisition; Project Administration
Xander Wang - Conceptualization; Writing – Review & Editing; Supervision
Pedro Quijon - Conceptualization; Writing – Review and Editing; Supervision
Graham Whitelaw - Writing – Review and Editing;

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Data Availability

The data that support the findings of this study are stored at the UPEI Climate Research Lab, and are available with the permission of the UPEI Climate Research Lab as long as attribution is provided.

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Figures

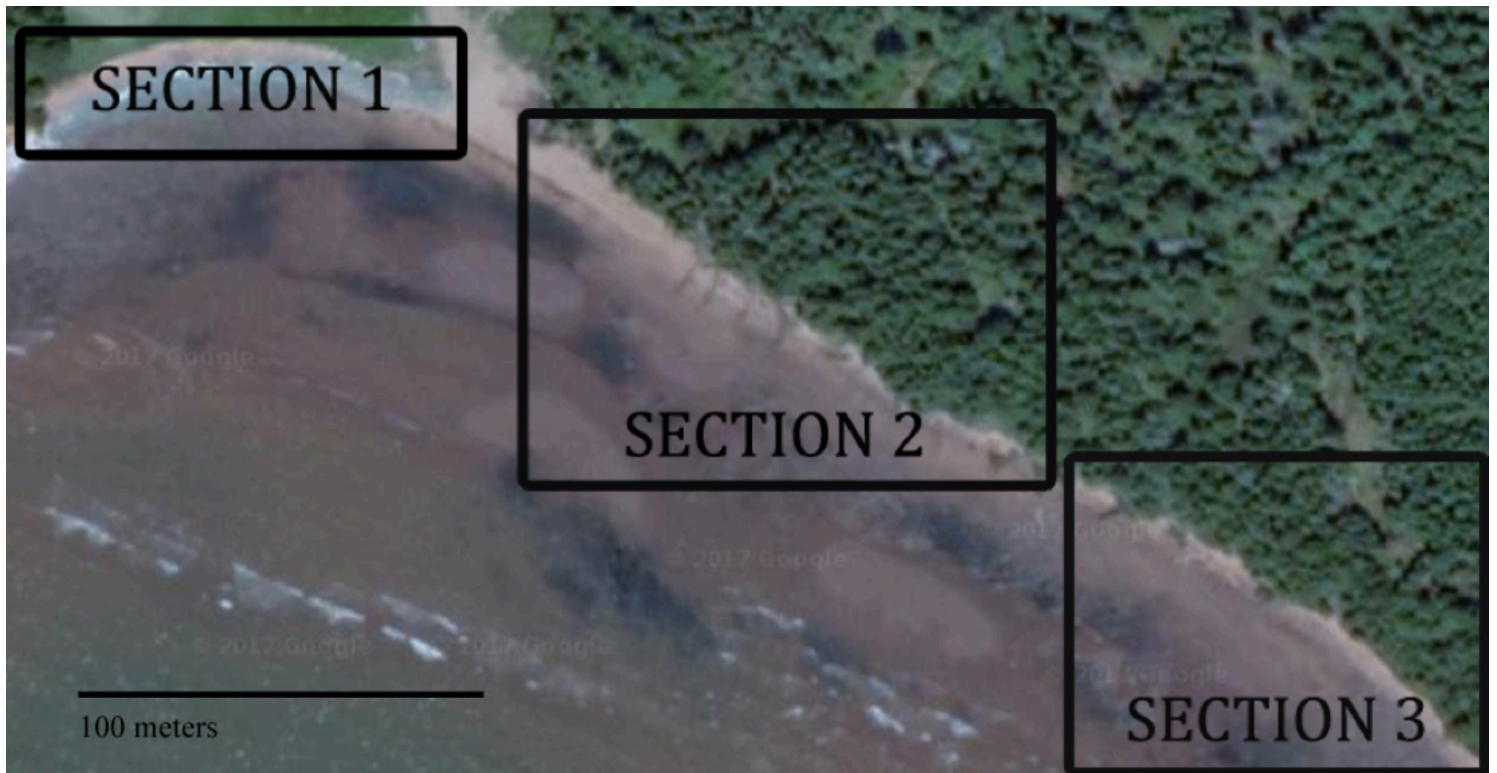


Figure 1

Three sections of studied coastline at Augustine Cove, PE, Canada. Section 1 is protected by armour stone, Section 2 is protected by a living shoreline, and Section 3 is unprotected (control site).