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Eelgrass ecosystem collapse and social-ecological regime shift driven by hydropower development and climate change

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A list of authors and their affiliations appears at the end of the paper

Global declines in coastal habitats and wildlife have devastating consequences for Indigenous Peoples. In some places, hydropower development has environmental impacts that contribute significantly to coastal habitat loss. As development is rejuvenated for the carbon-neutral transition, mitigation of further coastal habitat impacts depends on assessing the relative and interactive effects of climate change and hydropower development. Here, we follow a detection and attribution framework to understand the collapse and limited recovery of a social-ecological system including eelgrass (*Zostera marina, shikaapaashkw*), geese (*Branta* spp., *nisk* and *iyiwaapuwaau*), and Cree (*Eeyou*) in subarctic eastern James Bay, Canada (Eeyou Istchee). Informed by historical observations, Indigenous knowledge, and scientific research, we attribute the collapse of eelgrass and shifts in the associated social-ecological system to ecological effects of hydroelectric development (1978-1996), which degraded local environments causing eelgrass declines. Climate-driven extreme events (1998 onward) compounded losses and ecological feedbacks extended eelgrass declines all along the coast. Eelgrass recovery today appears limited by poor water clarity, altered sediments, hydrologic changes from development, and a new climate regime. Eeyou have adapted by shifting their relationships with the coastal habitat. Comprehensive assessments for hydropower developments should explicitly consider coastal social-ecological dynamics and the possible compounding impacts of climate change.

Coastal habitats have supported human communities for hundreds of thousands of years. Coastlines provide food, shelter, and access to marine and freshwater environments that define the culture, livelihoods, and identities of Indigenous Peoples who have lived along marine shorelines for countless generations[1]. The destruction and loss of coastal habitats worldwide during the past century[2] thus has gravely affected both social systems and ecosystems[3]. Coastal habitat protection, management and restoration can contribute to climate mitigation and adaptation[4,5], biodiversity conservation[6], and Indigenous self-determination. However, the interaction of local and global environmental change to cause habitat loss and prevent habitat recovery[4] is a critical knowledge gap compromising current coastal restoration efforts and preventing true cost accounting of various development activities.

Seagrasses are foundation species in many coastal ecosystems. They provide critical habitat for marine and semi-aquatic wildlife, such

e-mail: zouzou.kuzyk@umanitoba.ca; melanie.leblanc@niskamoon.org

as waterfowl, and the reliable, nearshore wildlife harvesting opportunities in seagrass ecosystems have been particularly important for many coastal Indigenous Peoples' food security and cultural continuity (cf.[5–9]). Recently, seagrass ecosystems have also gained attention because of their tendency to accumulate carbon ("blue carbon"), in addition to being biodiversity hotspots. Protecting and restoring degraded seagrass ecosystems may thus contribute to numerous benefits for both Indigenous and non-Indigenous coastal communities, as well as for the ecosystems themselves[10–12].

Many seagrass populations around the globe have massively declined in the past century. Few have fully recovered to their historical depth and spatial extents, although North Atlantic eelgrass lost to widespread wasting disease in the 1930s is considered naturally recovered in many areas, and recovered as a result of active restoration in other areas[13,14]. Incomplete recovery of degraded seagrass ecosystems is often characterized by lower shoot density[15], reduced depth extent[16], and/or reduced spatial extent[16–18] of meadows relative to historical observations, as well as reduced usage by wildlife and ecological functions such as carbon storage[19]. The reasons for failure to fully recover can be unclear, especially when proximate causes of declines and related environmental conditions have improved[18–21].

Among the potential ultimate causes of ecological changes in seagrass ecosystems are local and regional land use and development activities in watersheds that alter riverine fluxes of freshwater, nutrients, and sediment, and cause localized deterioration of water quality and poor water column light conditions due to elevated concentrations of suspended sediments[13,14]. Sedimentation is a well-recognized stressor because it can disrupt the natural feedback loops that keep seagrass meadows healthy: i.e., excess sediment makes water more turbid, reducing light availability and consequently slowing seagrass growth[22,23]. Dams are well-known drivers of changes to downstream river flows, nutrient ratios, and sediment loads[24–26]. However, explicit consideration of how seagrass ecosystems may be impacted by dam construction and operation is lacking. Sixty-three percent of the world's very long rivers are no longer free flowing[27], and many of the remaining rivers are planned for impoundment[28]. Most studies on the ecological impacts of hydroelectric development focus on river and reservoir systems[25–27], while impacts on coastal ecosystems remain unclear.

Here, we present a synthesis of recent evidence and transdisciplinary knowledge[29] to reveal how a social-ecological system connecting eelgrass (*Zostera marina*, *shikaapaashkw*), geese (*Branta* spp., *nisk* and *iyiwaapuwaau*), and Cree (Eeyou) in subarctic eastern James Bay, Canada (Eeyou Istchee) has been compromised by the effects of local hydroelectric development compounded by climate change. The evidence presented includes diverse forms of knowledge including Eeyou Indigenous Knowledge shared in interviews, long-term eelgrass monitoring data collected over 30 years, and recent research conducted in the region by the authors.

We apply a detection and attribution process[30], increasingly emphasized in global change assessments[31], to synthesize evidence and infer the causes of the eelgrass social-ecological system collapse in Eeyou Istchee (Fig. 1). This approach, centered on a causal model linking eelgrass health to environmental drivers, pressures, and biological feedbacks (Fig. 2), integrates scientific records, recent fieldwork, and Eeyou knowledge. To reflect the strength of inference and uncertainty, we use terms such as likely, very likely, and may have caused, depending on the weight of evidence. We present this case because large-scale ecological collapses—often linked to past development—are widespread, yet traditional scientific methods alone have struggled to explain or guide responses to them[32]. This study provides an example showing that attribution can be done even after significant time has passed and with limited quantitative data, especially when supported by partnerships between scientists and local knowledge holders.

Results

Components and collapse of an eelgrass-goose-Eeyou system

In northeast James Bay, a coastal marine social-ecological system was centered around eelgrass and the harvest of geese in the eelgrass habitat prior to and during the 1970s, when waterfowl was a vital source of food for north coast Eeyou, as it had been for time immemorial[5,33,34]. Tens of thousands of migrating Canada Geese (*Branta canadensis*) and Atlantic Brant (*Branta bernicla horta*) visited the eelgrass meadows each fall[35]. At the time, eastern James Bay supported the largest expanse of eelgrass *Zostera marina* meadows in North America[36]. Harvest surveys conducted in the 1970's documented the annual harvest of more than 50,000 Canada Geese and 6000 Brant by Eeyou hunters living in the coastal communities[37].

This eelgrass ecosystem collapsed in the late 1990s[5,33,38,39]. The collapse was rapidly observed and reported by land users from coastal traplines (i.e., land areas stewarded by a family, where they hold hunting and trapping rights) and by Cree First Nations of Eeyou Istchee. Coinciding with the eelgrass collapse, Eeyou observed a major reduction in the migratory visits of geese during fall, and a corresponding decline in hunting success[33]. The Eeyou formally reported the changes to Canadian Parliament in 2008, and the change was acknowledged by Fisheries and Oceans Canada[32], but no scientific study of the change was initiated by government, academic or industry researchers for a 20-year period.

Coastal Eeyou in Chisasibi (formerly Fort George) associated the loss of eelgrass with hydroelectric development of the La Grande River (LGR)[5,39,40]. Environmental monitoring reports prepared for Hydro-Québec (the Crown corporation that owns and operates the hydroelectric complex) stated that the decline was most likely linked to natural causes such as wasting disease, climate change, and isostatic rebound[33,38]. Nevertheless, Eeyou continued to push for an investigation[5,39]. In 2017, a formal collaboration began between the Eeyou and a team of university-based researchers with a mandate to i) consider Indigenous and scientific knowledge as distinct but equal sources of information[29] and ii) seek to identify what caused the eelgrass decline, including the role (if any) of putative drivers, including La Grande Complex hydroelectric power development (Fig. 1, inset).

Presently, with eelgrass meadows still sparse and discontinuous along the coast[15], and coastal waters frequently murky[15], the fall goose distribution is not predictable[41,42]. The Eeyou note a social-ecological regime shift marked by increasingly disordered and less productive hunts, leading to the erosion of traditional knowledge[43].

Detection of eelgrass change

During the past 40 years, eelgrass underwent a massive decline along the east James Bay coast and failed to fully recover. Eeyou remember eelgrass as consistently widespread and abundant along the north coast of James Bay before the late 1990s[5,39,40,44] (Fig. S1). During the 1980s, the Chisasibi First Nation coastal community noted localized eelgrass declines in some traplines near the LGR, but no changes were observed in other coastal communities located away from the influence of the LGR plume. Scientific observations in the 1970s[44] and 1991[36] found eelgrass to be present between depths of 0.5 and 4.0 m, with shoots up to 2.5 m long, biomass in places >1000 g dw m^{-2}, and an estimated areal coverage of ~250 km^2. Eelgrass monitoring at six sites near LGR after 1981 noted localized eelgrass losses but no site-wide changes until 1999, when biomass measured at six monitoring sites decreased by about 90% (Fig. 3). Chisasibi Eeyou noted that eelgrass had ceased to be seen frozen in the ice or as beach wrack and deep eelgrass beds had disappeared completely. A survey of eelgrass cover across 87 sites distributed all along the coast, including areas not influenced by the LGR plume[33,38], indicated an 88% decrease in the 'dense' eelgrass cover class (> 50%) between 1996 and 1999 (Fig. 3, inset)[15]. During 2017–2021, shoot density and cover were still substantially lower than in the 1970s – early 1990s, with no shoots longer

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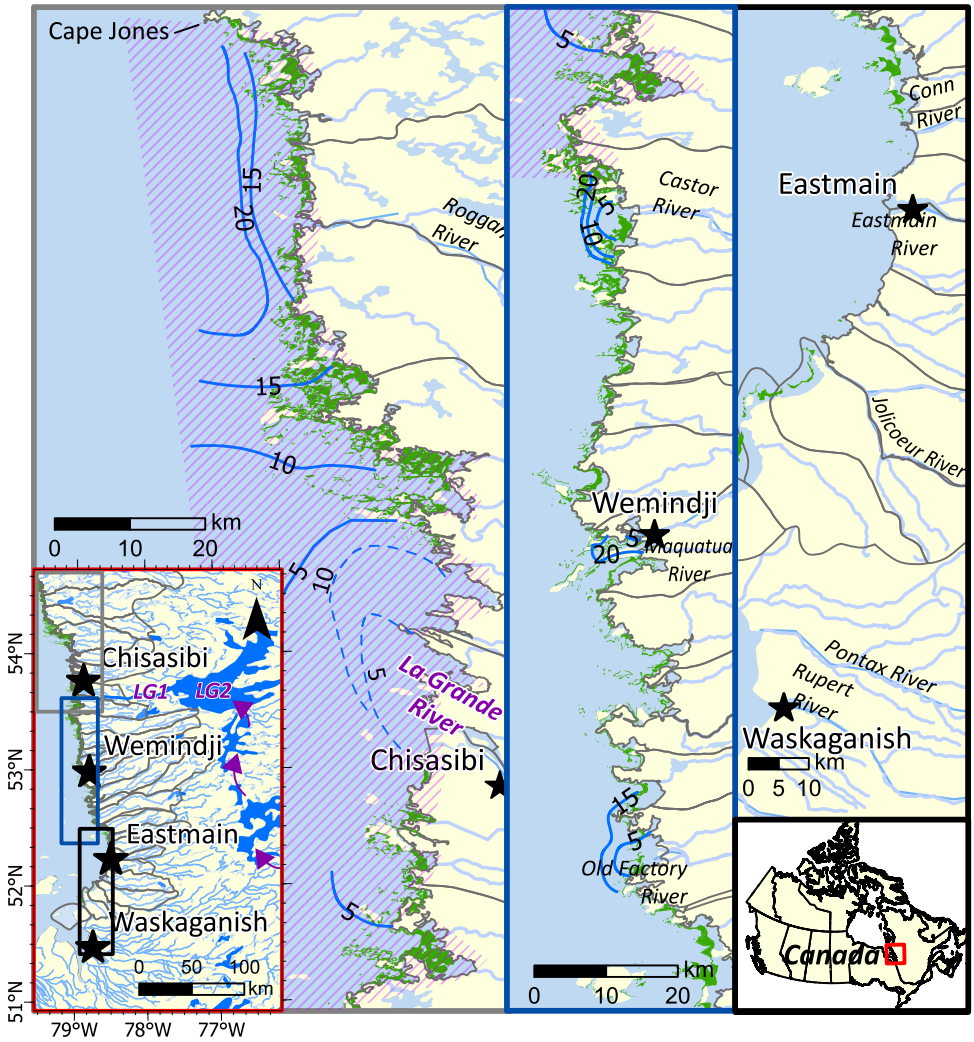

Fig. 1 | Map of the coastal area of Eeyou Istchee in northern Québec, east coast of James Bay, Canada, over three panels arranged north to south. Green shading shows historical eelgrass distribution. Gray lines delineate traplines, which are land areas stewarded by a family that holds associated hunting and trapping rights. Contours of surface salinity show the change in the winter freshwater plume of La Grande River (LGR) between pre-development (dashed lines) and 2017–2021 (solid lines). The broader region of freshwater influence of the LGR in winter is shown by pink hatching. Inset map shows northward river re-routing (arrows) for the La Grande Complex. LGR flow, regulated by dams and powerhouses (e.g., LG2, LG1), enters James Bay at Chisasibi. Map created using ArcGIS® software by Esri and Esri Basemap. Copyright © Esri. All rights reserved. Additional data sources: Government of Canada (2013), https://open.canada.ca/data/en/dataset/be0165a8-ad5d-4adb-a27a-2d4117c3967c; Government of Quebec (2020), https://www.donneesquebec.ca/recherche/dataset/base-de-donnees-geographiques-et-administratives, and Fisheries and Oceans Canada (2009), https://open.canada.ca/data/en/dataset/c9ab948f-5009-4dbc-9129-2f6e373f17f6.

than 1.0 m and cover generally sparse or discontinuous (Fig. S2)[15,45]. Beds were generally patchy and limited to shallow areas (< 2 m) (Fig. S3).

Detection of environmental changes

Development of the "La Grande Complex" over three phases increased winter river flows ten-fold causing an enlarged freshwater plume and first increasing then decreasing sediment fluxes to the coastal habitat[43,46,47]. The complex consists of 11 power generating stations, 74 generating units, and nine reservoirs. During Phase I (1973–1985), four rivers, including the Eastmain River, were partially diverted into the La Grande River (LGR) watershed, increasing its flow. Peak LGR discharge shifted from spring to winter, with February flow rising from 520 m^3 s^{-1} in 1975 to 1750 m^3 s^{-1} in 1980, and 3000 m^3 s^{-1} in 1984[46]. Annual discharge from the Eastmain River after diversion dropped to about 10% of historical values. In Phase II (1987–1996), additional reservoirs and generation stations were added to the La Grande Complex, including La Grande-1 (LG1), <40 km from the bay, with a design flow of 5950 m^3 s^{-1}[43]. In Phase III (2002–2013), partial diversion of the Rupert River further increased the average annual LGR discharge to 3782 m^3 s^{-1}, about double its pre-development discharge and nearly half the total discharge to James Bay[48] (Fig. 4; Tables S1 and S2). In recent years, high winter discharges were sustained at ~4800 m^3 s^{-1} continuously throughout the January–March period[47].

Eeyou from coastal traplines near Chisasibi witnessed several environmental changes associated with LGR development including coastal freshening, riverbank erosion, and sediment release into the bay, the latter linked to murkier water and seabed hardening in the eelgrass habitat[45]. According to oceanographic studies, the ten-fold increase in winter LGR discharge also increased by ten-fold the size of the under-ice freshwater plume along the coast, as indicated by a salinity of 5 in Fig. 1. This increase in the freshwater plume from ~120 km^2 to ~1200 km^2 extended it into eelgrass habitat 30–40 km north and south of the river mouth[46,47]. The area of noticeable freshening of surface waters from winter LGR discharge, referred to as the LGR sector, stretched north to Hudson Bay (near Cape Jones)[46,47]. The winter LGR export of nitrate, the limiting nutrient in the bay's oligotrophic marine waters, increased more than 10-fold, at the expense of

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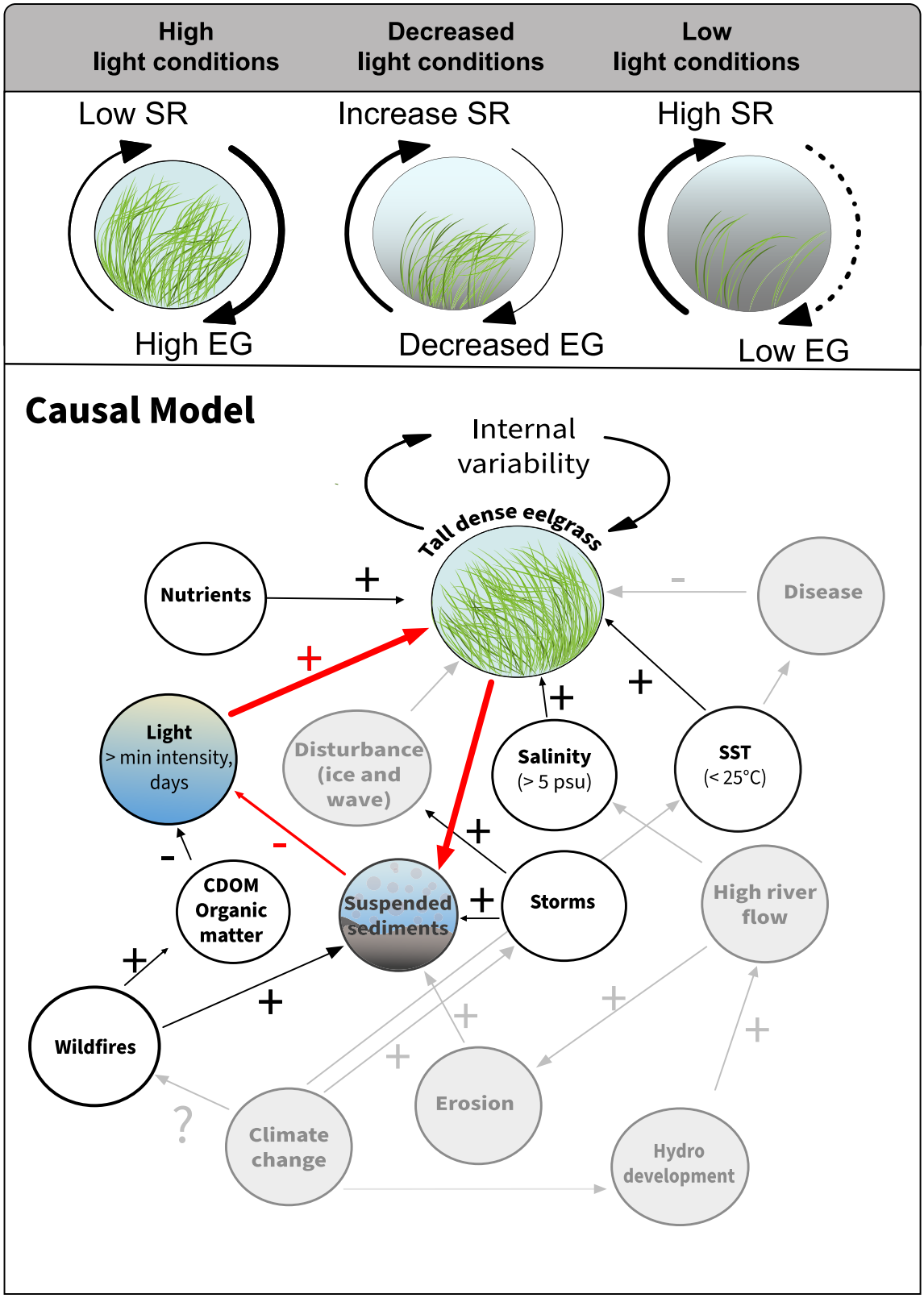

Fig. 2 | Schematics of the Eelgrass-sediment-light (ESL) feedback mechanism and causal model for effects attribution. Top panel shows relationship between sediment resuspension (SR) and eelgrass growth (EG). Causal model (lower panel) relates eelgrass health to direct and indirect effects, both positive (+) and negative (−), of driver and pressure variables (open ovals) on eelgrass. Red arrows highlight the ESL feedback mechanism. Some drivers are grayed out, indicating lack of effect pre-1980. Internal variability represents biological features that contribute to the resilience of the eelgrass plants (e.g., eelgrass genetic diversity, growth strategy, seed banks) and fundamental habitat traits such as water depth gradient.

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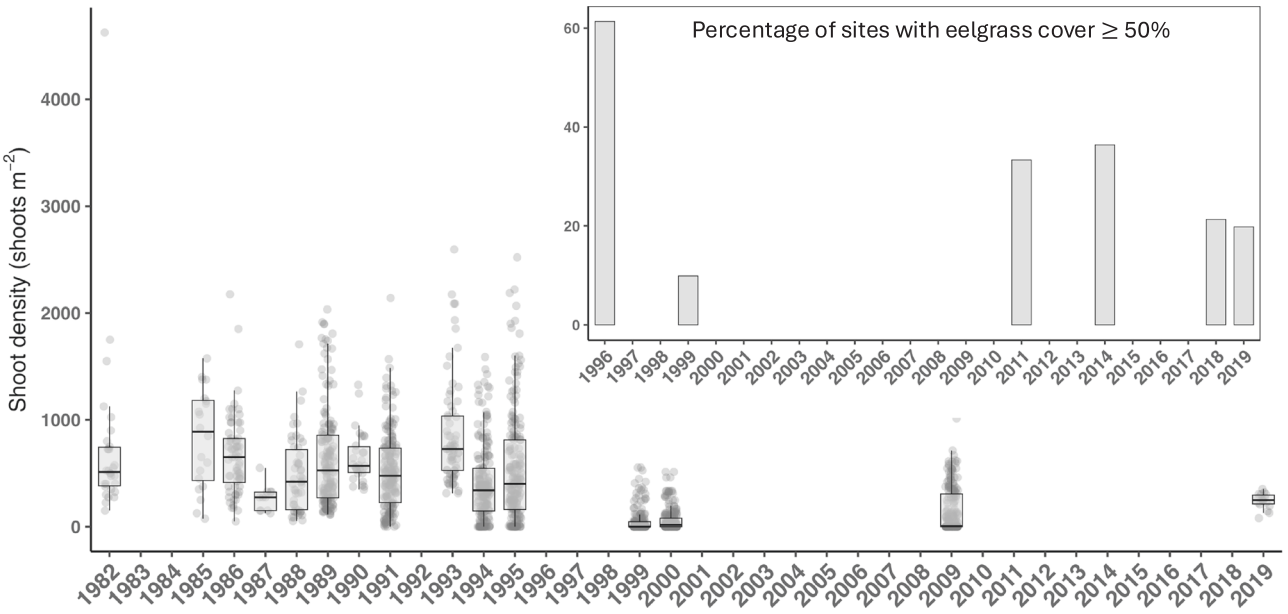

Fig. 3 | Eelgrass shoot density (raw data (dots) and boxes showing mean ± standard error) from Hydro-Québec monitoring (1982–2009) and this project (2019). Inset shows eelgrass cover surveyed all along the coast at 11-91 sites depending on year. Absence of a bar indicates no data collected.

nitrate delivery during spring and summer[48,49]. Reservoir flooding led to increased downstream fluxes of dissolved and particulate organic matter[48,50,51] and, together with riverbank erosion, caused a four-fold increase in annual sediment exports from LGR during 1979–1991, including annual releases of ~1,000,000 t y^{-1} fine silt and clay[50].

Discharge from the Eastmain River after diversion dropped to about 10%, which weakened its influence along the coast. The diversion limited the Eastmain watershed to the coastal plain near the bay dominated by marine clays, silts, and peat bogs. Suspended particulate matter (SPM), colored dissolved organic matter (CDOM), and nutrients increased in Eastmain River water but because of reduced flow, the overall influence of the river decreased[43]. The Eastmain estuary experienced higher surface salinity, weaker stratification, and altered circulation after the diversion[51].

The marine climate in northeast James Bay changed abruptly in the late 1990s. Coastal Eeyou have remarked on the way climate change is transforming coastal ecosystems and mention, in particular, loss of sea ice[45]. Climate scientists detect a transition in the mid-1990s after 1996 from a relatively stable regime of seasonal ice and surface-water temperature extremes in the broader Hudson Bay region to much greater fluctuations from year to year[52]. In northeast James Bay, due in part to a strong El Niño, the winter of 1997/1998 was exceptionally warm with low snow cover. Warm air temperatures continued into spring and the regional sea ice broke up in mid-May of 1998 about one month earlier than the mean breakup date during 1982–1997 (Fig. 4B). With ice clearing from northeast James Bay in late May, a spring storm (Figure S4) produced a sediment-rich LGR freshwater plume that was transported northward (Figure S5). Rapid warming of ice-free surface waters led to unseasonably high sea surface temperatures (SSTs) throughout June-October 1998 (Fig. 4C). In total, five high-SST events lasting a total of 79 days occurred during that period that meet the definition of a marine heat wave (MHW; SST exceeding 90th percentile of the baseline for five consecutive days or more (Fig. 4D))[53]. Prior to the five 1998 MHWs, there were only two MHWs in Eeyou Istchee coastal waters for the entire 1982–1997 period.

Although an exceptional year individually, 1998 is even more notable as a change-point year, meaning that the northeast James Bay system has not returned to pre-1998 conditions in the subsequent 25+ years. Using a Pettitt change-point test, 1998 is a clear change point for sea ice breakup, MHW frequency, and May-July 10-m windspeeds. For June-October SSTs, 1996 is the stronger change-point year; like the other three parameters, there is no significant trend before or after the change point. Thus, since the late 1990s, James Bay has experienced windier springs, earlier sea ice breakup, and hotter, longer, and more frequent MHWs[53]. Furthermore, what used to be extreme is now the norm: for example, in the warmest year prior to 1996 (1984), the median June–October SST in northeast James Bay was only 4.2 °C, whereas an average year now (post-1996) has a median June-October SST of 5.4 °C (Fig. 4C). Notably, climate change is not the primary driver for change in river discharge in northeast James Bay. LGR development resulted in a change-point year of 1985 for discharge. Significantly higher discharge since 1998 (130 km^3 y^{-1}) compared to 1951–1985 and 1986–1997 (Fig. 4A) may be a function of regulation combined with (inter)decadal variability within the climate system.

Water clarity decreased along the Eeyou Istchee coast both at local and regional scales during recent decades. Eeyou report that coastal marine water changed from transparent blue to murky brown in Chisasibi between 1986 and the early 1990s and a decade later in Wemindji[45]. Eeyou from both these communities historically could see the bottom (seabed) at depths of 6 m or more, while the southernmost coast around Eastmain and Waskaganish was traditionally marked by colored and turbid water. During 2017–2021, Secchi disc depths along the coast were typically 2 m or less (Fig. S6) and photosynthetically active radiation (PAR) at the seabed (2–4 m) was very low due to light attenuation by a combination of turbidity and CDOM. Four factors are suspected of contributing at various scales to the decreased water clarity in Eeyou Istchee (Fig. 5):

Browning of James Bay waters likely has occurred, based on satellite images that show an increase in absorption by CDOM (a_g(440 nm)), between 1998 and 2021 throughout eastern James Bay surface waters, particularly during the month of June after 2010 (Fig. S7). Thus, the increase in CDOM on a coast-wide scale likely explains in part the increased murkiness witnessed by Eeyou in all coastal communities over the past 20 years[45]. The observed coastal browning is likely related to a general increase in river discharge into the bay since the late-1980s[54] and rising concentrations of dissolved organic carbon (DOC) and CDOM in river water, coherent with regional trends of increasing DOC and CDOM over the past three decades that have been reported for inland waters across northern Canadian landscapes[55]. Earlier sea ice melt and retreat may also play a role.

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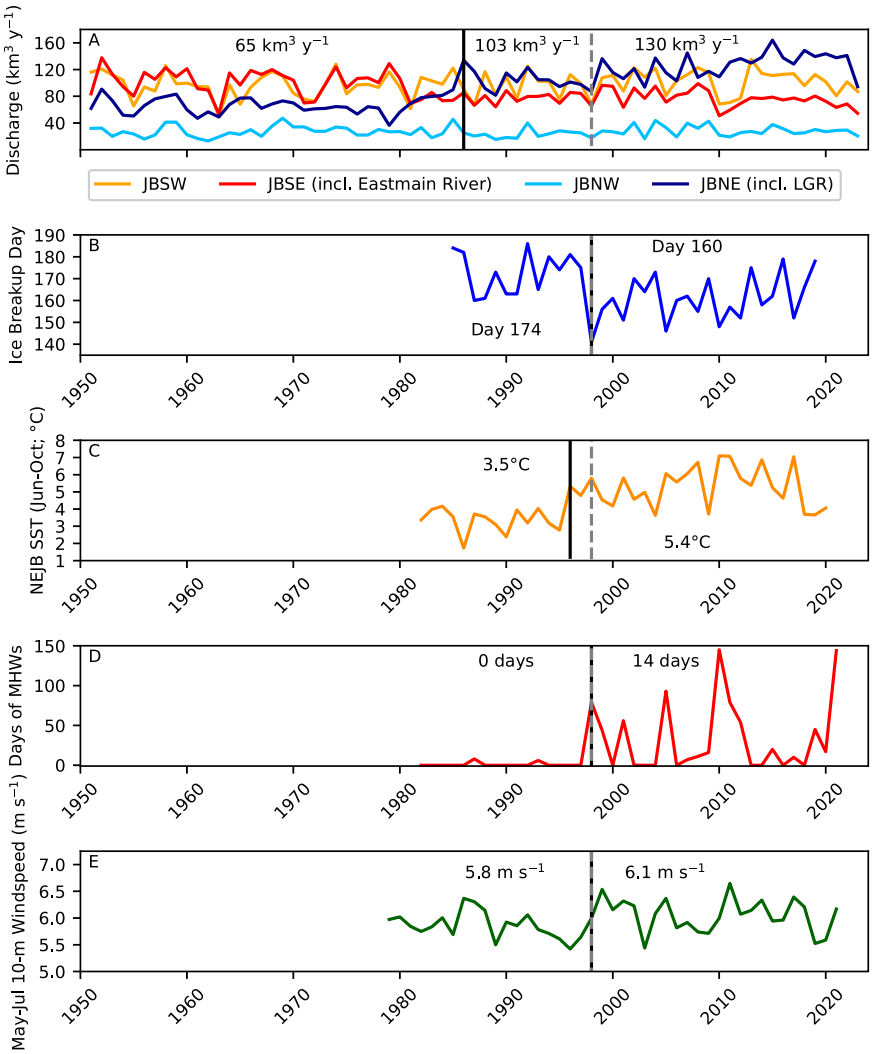

Fig. 4 | Time series for environmental parameters over 1951–2021. A estimated annual freshwater discharge for the large watershed sectors of James Bay (JB) (northeast JB (JBNE), southeast JB (JBSE), northwest JB (JBNW), southwest JB (JBSW)); **B** ice breakup date (day of year) in northeast James Bay, **C** average sea surface temperatures (SST, °Celsius) for June-October along the northeast coast of James Bay; **D** total days of marine heat waves (MHWs); and **E**) average 10-m windspeed from May–July. Vertical black solid line marks the strongest change-point year based on a Pettitt test, and the vertical gray dashed line indicates 1998 – the best overall change-point year. The median values for each distinct period are also recorded; each pair of medians is significantly different based on a two-sided Mann–Whitney test ($p < 0.05$; see Tables S1 and S2 for details.). For plot A, JBNE discharge is used for Pettitt and Mann–Whitney tests.

Excess sediment and organic matter released from LGR during the four phases of development likely dispersed with the river plume and deposited at and beyond the plume fringes, where current velocities decrease and salinity increases, while another part may have been trapped in eelgrass beds. Both Eeyou and monitoring teams got the impression of increased turbidity along the coastline in 1985, compared to previous years when the water was clearly transparent, even in windy weather. Sediment core data obtained in the LGR sector show high inventories of a watershed soil erosion tracer, ^{137}Cs[56], and buried organic matter that could represent a source of nutrients for algal mats (e.g., *Cladophora sericea* and a host of epiphytic microalgae) that seem to have become more abundant in the shallow bays. Presently, the LGR as it emerges from the last reservoir LG1 is characterized by lower concentrations of nutrients, DOC, and SPM, and lower fluxes of these constituents during the growing season compared to before development; this is due mostly to the retention of particulates within the upstream reservoirs and the shifting of discharge into winter[48,49]. However, there is an additional, unquantified but potentially significant SPM flux due to bank erosion in the lowest reach of the river[43,57] that could result in events of high riverine delivery of suspended materials, likely at times of peak river discharge during winter. Nutrient release from sediments due to degradation of previously buried organic matter has not been quantified.

Sediment destabilized after loss of eelgrass meadows, exacerbated by more extreme weather and longer open-water season, likely is being recycled in the nearshore area, contributing to a coastal turbid fringe. Eeyou use the word “aayoshtinuukticj” to describe how large eelgrass meadows with long shoots that reached the surface at low tide historically calmed the waters in the bays[5]. With today’s shorter shoots and lower shoot density (Fig. 3) comes a decrease in the calming effect. Sediment core geochemical profiles show that previously stored sediment was destabilized and eroded after loss of the eelgrass meadows, releasing carbon, nitrogen, and other elements; furthermore, surviving eelgrass beds are not trapping much sediment on an ongoing basis, leading to increased water turbidity[23,58]. Sediment nutrients that go unused by eelgrass may stimulate increased presence of algal mats, as seen in Danish coastal waters[59]. Wave-driven sediment resuspension may be exacerbated by increased spring wind velocities and the lengthening of the ice-free season. High-resolution satellite imagery shows that turbid waters

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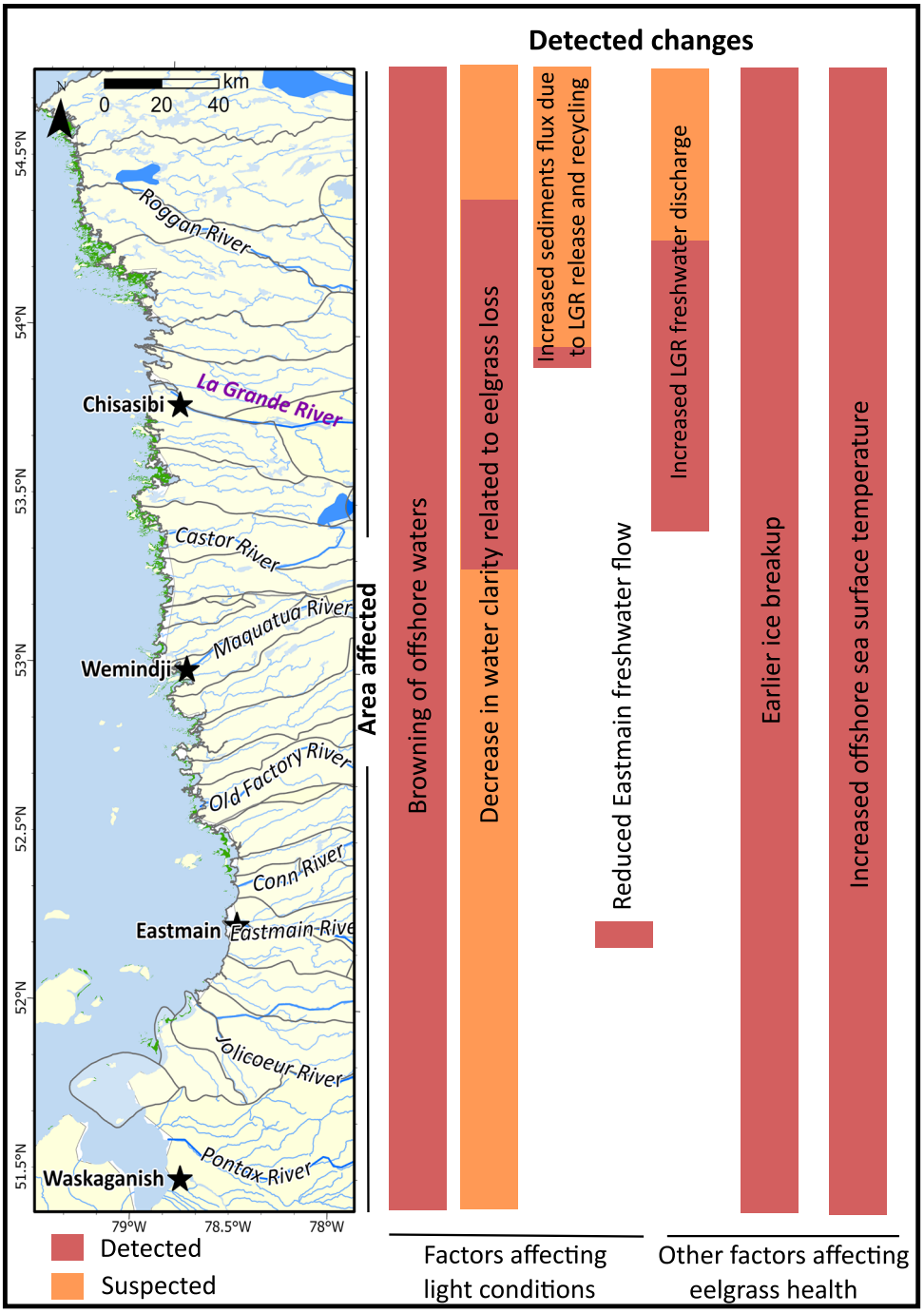

Fig. 5 | Conceptual graphic summarizing spatial extent of detected and suspected environmental factors affecting eelgrass health along the Eeyou Istchee coast. Left: overview map of coastline with trapline delineations in gray and major rivers. Eelgrass extent in 1996 and previous years shown in green. Right: Bars showing spatial extent (north–south) of detected and suspected changes in light conditions and other aspects relevant to eelgrass health. Map created using ArcGIS® software by Esri and Esri Basemap. Copyright © Esri. All rights reserved. Additional data sources: Government of Canada (2013), https://open.canada.ca/data/en/dataset/be0165a8-ad5d-4adb-a27a-2d4117c3967c; Government of Quebec (2020), https://www.donneesquebec.ca/recherche/dataset/base-de-donnees-geographiques-et-administratives, and Fisheries and Oceans Canada (2009), https://open.canada.ca/data/en/dataset/c9ab948f-5009-4dbc-9129-2f6e373f17f6.

with SPM concentrations up to 30 mg L^{-1} can be pervasive in the nearshore waters along the coastline (Fig. S8).

Attribution of changes in eelgrass to changes in drivers

We use the causal model (Fig. 2) to synthesize evidence for strong relationships between changes in eelgrass health and environmental conditions. We structure the analysis around four time periods related to the eelgrass crash, recognizing the evolution of the role of the Eelgrass-sediment-light (ESL) feedback as eelgrass declined. We do not attribute any large-scale changes in eelgrass to the Eastmain diversion because of the small spatial scale of the known environmental effects (Fig. 5).

Low salinity (< 5), which adversely affects the ability of eelgrass to maintain a positive carbon balance (i.e., net primary production)[60,61], likely started affecting eelgrass growth in the LGR sector when the winter plume enlarged in the 1980s. Negative effects on carbon balance may particularly jeopardize eelgrasses in high-latitude environments, which require substantial carbohydrate reserves to survive long

light-limited winters[62,63]. The tolerance of eelgrass to low salinity varies across populations but salinity ≤5 consistently reduces eelgrass productivity and survival[60,61]. Thus, it is very likely that expansion of the LGR winter plume from ~120 km^2 to ~1200 km^2 reduced eelgrass winter survival and early spring growth in the affected area.

Reduced water clarity during the growing season likely started affecting eelgrass growth in the LGR sector when reservoir flooding and bank collapse increased sediment and organic matter releases in the 1980s. High sediment and organic matter loads can directly reduce water clarity or indirectly (via the ESL feedback) reduce water clarity by smothering eelgrass shoots or causing problems associated with decaying organic matter that impact eelgrass growth. Eelgrass needs clear waters for growth because it has a higher light requirement than both macroalgae and phytoplankton, with an average minimum light requirement of ~20–30% of surface irradiance[60]. We suspect that light started to decrease in parts of the LGR sector when hydroelectrical development started, due to a combination of excess sediment and organic matter releases from LGR and reduced flocculation from the additional freshwater. Local eelgrass losses would have released previously stored sediments and nitrogen[64], likely exacerbating the poor water clarity and starting to shift the eelgrass ecosystem toward a regime shift (Fig. 6E).

Eelgrass growth all along the coast was likely affected by the climate shift and extreme events starting in 1998. The early ice breakup, unseasonably high SSTs and prolonged MHWs in the early part of the 1998 growing season (May, June, and July) may have caused eelgrass to experience extreme negative carbon balance leading to poor growth and/or high mortality. Experimental studies have shown that unusually warm winter-to-spring conditions when light is still limited can have severe effects on eelgrass by accelerating the consumption of energy reserves, which are low following winter, and by triggering early flowering[65].

Eelgrass recovery likely has been limited by suboptimal water column light levels, partly due to browning and partly from turbidity, combined with a new, more variable, climate regime. An experiment that determined ex situ production-irradiance curves for eelgrass from two Eeyou meadows and collected in situ light data during summer 2021 (continuous measurements of PAR) found suboptimal light conditions for eelgrass growth[66]. The growing season in James Bay is short, and eelgrass plants need to build up substantial carbon stores during that period to survive the long under-ice period. Because suboptimal water column light levels threaten the ability of eelgrass to build up these stores, we suspect that light limitation has limited eelgrass recovery in the region.

Discussion

Indigenous Eeyou hunters in James Bay, subarctic Canada, have observed many changes in the coastal environment as they adapt to shifts and changes in local and regional conditions that impact the goose hunt[40]. Pairing this Indigenous understanding with scientific data in a detection and attribution approach, we conclude that the cumulative effects of hydroelectric development in the region and on the La Grande River, in particular, over >20 years gradually overcame the natural resilience of the eelgrass ecosystem, setting the stage for a regional ecosystem collapse triggered by extreme climate events in 1998. The loss of eelgrass cover and biomass has not reversed decades later, nor have the massive flocks of geese returned to using the coastal habitat along the northeast coast (Fig. 6).

Considering how the biophysical conditions in the LGR sector of the eastern James Bay coast were modified during the more than two decades of hydroelectric development, including lower salinity and higher sediment and organic matter inputs, it is surprising that most of this sector's eelgrass meadows resisted major biomass losses until the late 1990s[15,33,45]. This initial resilience of the eelgrass ecosystem in the face of major environmental changes can be understood by considering how aspects of seagrass meadows, themselves, combine with features of the surrounding biological and biophysical environment to determine resilience[67]. We suspect that the vast extent (> 250 km^2) and healthy state of the eelgrass in the 1970s before development[5,7,15,33,44,45] (Fig. 3) and stable regional marine climate[43,53] (Fig. 4) helped maintain the stabilizing ESL feedback loop and hence strong eelgrass growth despite the potentially destabilizing effects of the 1980s salinity changes and increased suspended sediment loads. The ESL feedback has been identified as critical to eelgrass meadow resilience in North America and Europe yet has been considered in very few ecosystem models[68]. In a physical setting like James Bay, where fine-grained sediments are abundant, coastal areas are low-lying, and isostatic rebound rates are among the highest in the world[69], we believe the ESL feedback was a pivotal feature in this ecosystem's resilience. This resonates with the Eeyou concept of "aayoshtinuukticj", which describes the calming effect of the large, dense eelgrass meadows[5] that previously flourished in sheltered bays all along the northeast James Bay coast[44].

In recent scientific studies and interviews with Eeyou land users, we found indications for deteriorating biophysical conditions in the LGR sector of the eastern James Bay coast during the 1980s-early 90s coinciding with LGR hydroelectric development. Indeed, smaller and isolated eelgrass beds disappeared during the 1980s from locations directly impacted by the expanded LGR freshwater plume[5,33,45]. Changes in sediment properties and eelgrass rhizome condition were noted at some sites. In 1995, with the LG1 dam (40 km inland from the coast) newly completed and discharge reaching ~6000 m^3 s^{-1} for the first time, Chisasibi community members observed pulsed releases of debris and sediment into the bay reflecting new bank erosion along this lowest reach of the river. With these environmental impacts not yet abated, spring 1998 brought several extreme events in the regional marine climate including exceptionally early ice breakup, wind changes, and a series of intense marine heat waves. We believe these events provided a trigger, pushing the already precarious eelgrass ecosystem in the LGR sector past its tipping point and initiating what would become a regional ecosystem collapse[70,71]. Conditions inhibiting good eelgrass growth would have left bare seafloor temporarily vulnerable to sediment resuspension, releasing previously stored sediments and organic matter and likely exacerbating the poor water clarity from the LGR sediment releases. With the ESL feedback thus disrupted by loss of eelgrass, destabilized sediment likely intensified the eelgrass losses that had already begun at local scales in the LGR sector and extended these losses to neighboring areas (cf.[68]), in which eelgrass habitat was not extensive to begin with[44]. Thus, at the center of the Eeyou Istchee eelgrass ecosystem collapse is the crossing of thresholds in the ESL feedback loop—excess sedimentation, loss of density of eelgrass beds, leading to release of trapped sediment and organic matter, producing an even more inhospitable environment for eelgrass growth[22,68]. Rapid transitions of eelgrass ecosystems to alternative stable states dominated by exposed sediments and algal mats instead of seagrass are well documented[21,23,67,71,72]. This alternative state resembles the Eeyou Istchee eelgrass ecosystem seen today, which has short shoots, vast expanses of bare sediment, increased quantities of algal mats, and waters that are often turbid during the short summer growing season due to resuspended sediments. Exacerbating the low light availability, climate change has increased the ice-free season increasing annual wave action, and seabed shoaling has raised sediments previously deposited in deeper eelgrass beds (2–4 m) into the zone of wave action.

The early ice breakup and MHW events of May-June 1998 were signs of exceptional conditions in northeast James Bay and unprecedented for the second half of the last century[73]. They occurred unseasonably early, when James Bay eelgrass has low energy reserves after surviving beneath the ice cover for six months[36]. It is possible that the immediate impacts of these events were physical damage and eelgrass mortality, from which recovery lagged because of low

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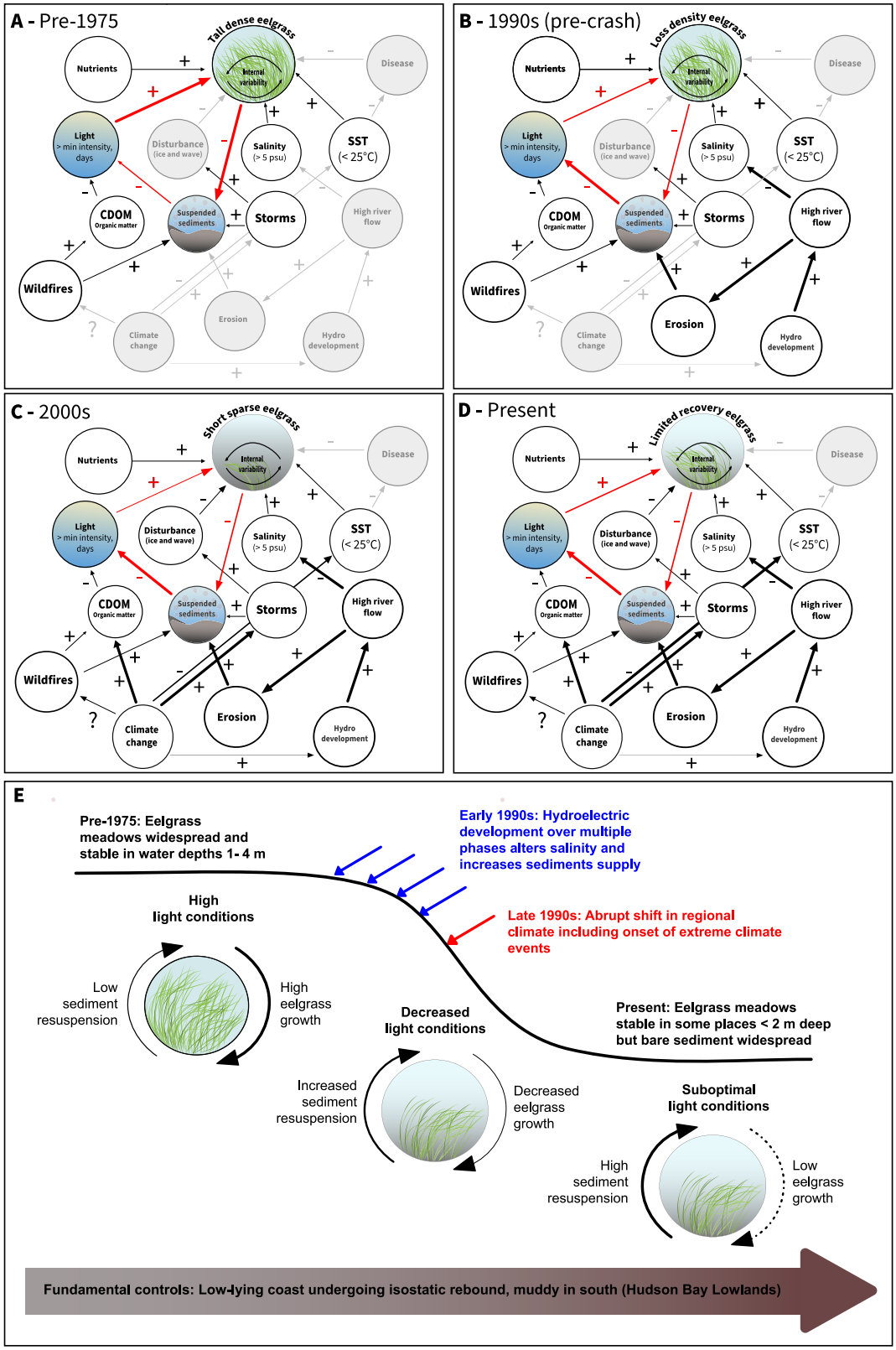

Fig. 6 | Causal model illustrating temporal sequence of events in which Eeyou Istchee eelgrass health declined stepwise because of repeated stressors that disrupted the Eelgrass-sediment-light (ESL) feedback loop (highlighted in red). Panel **A** shows natural state pre-1975. In panel **B**, hydroelectric development has begun to increase river flows and hence sediment erosion while lowering salinity. There is a loss of density in local eelgrass beds. In panel **C**, suspended sediments increase and light decreases due to short sparse eelgrass and greater storm and ice disturbance. Climate change has increased CDOM, further decreasing underwater light. In panel **D**, eelgrass show limited recovery in a coastal habitat with these altered environmental conditions. Panel **E** shows a conceptual model attributing change in eelgrass ecosystem in Eeyou Istchee to cumulative effects of hydro-electric development, which gradually overcame the natural resilience of the eel-grass ecosystem, setting the stage for a regional ecosystem collapse triggered by extreme climate events in 1998.

biomass production and germination rates[74,75]. Eelgrass in Eeyou Istchee today is characterized by low genetic diversity, compared to populations in the northeastern United States, and Atlantic and Pacific Canada[76]. This may reflect eelgrass colonizing James Bay after deglaciation or could have come about more recently and reflect a population bottleneck following the decline. Regardless, this large "genomic offset" implies that the northeast James Bay eelgrass population is more vulnerable to climate change than better-studied populations in temperate regions.

There are remarkable similarities between the Eeyou Istchee scenario, and the ecological regime shift observed along the Swedish west coast after the loss of eelgrass beds, where increased sediment resuspension and proliferation of drifting algal mats prevent both natural recovery and human restoration of eelgrass[77]. However, an important distinction between the two events is that the Eeyou Istchee regime shift affected eelgrass ecosystem estimated to cover 250 km^2, whereas the Swedish west coast shift affected an area of 0.4–2 km^2. A similar dramatic shift from eelgrass to bare sediments happened in the 1930s in the Dutch Wadden Sea after the construction of a large dam and "wasting disease"; despite restoration attempts this ecosystem never fully recovered[20,23]. High concentrations of fine sediment and organic matter can increase turbidity for a long time following disturbance, and eelgrass growth in deeper habitats, below depths of ice scour, is challenged both by low light conditions and a short growing season at high latitudes, perhaps making it sensitive to temporary declines in water quality[78]. In the present conditions of Eeyou Istchee, the biophysical features of the coastal environment remain altered by hydroelectric dam operations[48,57]. Some places have hard and disturbed sediments[56], algal mats are abundant, and there are recurring early ice breakup events and marine heat waves[15,53].

For the eelgrass-goose-Eeyou social-ecological system, after more than 20 years, goose usage of the coastal habitat remains low[41,42,79]. Altered migration routes mean that fewer geese fly along the Eeyou Istchee coast and those that do, fail to stop, likely not attracted by (or even seeing) the short sparse eelgrass that remains, even in former heavy-use areas[5,39,41,42,79]. Coastal Eeyou are adapting to these environmental changes, as they have adapted to past changes[43]. However, it remains to be seen whether eelgrass ecosystem services such as provision of fish habitat and 'blue carbon' burial could be restored. Climate change is also known to be affecting air temperatures and vegetation patterns in the eastern James Bay watersheds; in summer 2023, there were intense forest fires, bringing possible effects on water quality that we cannot yet predict (cf.[80]).

In Eeyou Istchee, reconstructing a posteriori the events and likely causes of the massive eelgrass-goose-human system collapse required drawing upon local Eeyou knowledge with multidisciplinary scientific approaches. The full story of what unfolded was not discoverable with only the toolkit of natural sciences; it required iterative work and collaboration across communities to uncover[29]. Yet the exercise offers unprecedented understanding of the local and global causes of an environmental catastrophe in Canada's northern landscapes. Collaborations with impacted communities supported the attribution of ecological change to drivers occurring at very different scales and thereby requiring multiple means of detection[81]. In Québec, as elsewhere, new hydropower development is being considered on a scale not seen since the 1970s, alongside other types of developments (mining, ports, etc.). It is vital that future impact assessments proceed differently, considering coastal ecosystems, employing multiple knowledge systems, and trying to anticipate how climate change may compound other impacts.

Methods

Statistics and reproducibility

This study was co-designed with Indigenous Cree (Eeyou) First Nation partners through processes developed under research agreements with Niskamoon and the project steering committee[29]. Eeyou land users conducted fieldwork along the coast between January 2016 and August 2021 and participated in several iterations of data analysis, interpretation, and review. Details on the interweaving of Eeyou knowledge and science through informal channels are given in Fink-Mercier et al.[29] and the project's final report[82], which is published online at https://doi.org/10.34992/4K4Z-TF96. Through formal interviews, Eeyou participated in recording their knowledge between July 2019 and June 2022 including 27 coastal traplines and 66 semi-structured and participatory mapping interviews. The study engaged 95 Eeyou land users, including tallymen and elders. Thus, Indigenous knowledge was central to this study, influencing planning, data collection, analysis, synthesis, result presentations, and final reports, alongside Western science.

Statistical analyses of scientific data were conducted in accordance with standards in each field. For eelgrass shoot density, sample size reflected availability of past monitoring data (1982 to 2009). Using generalized additive mixed models (GAMMs; R-package gamm4), we tested for temporal trends in eelgrass shoot density assuming a negative binomial error distribution. No data were excluded from the analyses[15]. The Investigators were not blinded to allocation during experiments and outcome assessment. For analysis of environmental time series, a Pettitt test (a non-parametric test for change points) and two-tailed Mann–Whitney test (assessing difference in medians) around the best change point year of 1998 were applied. The null hypothesis was no step change ($p < 0.05$ comparing before/after 1998 for all variables). Experiments were used to test the nutrient and light limitation hypotheses. In the former, we experimentally manipulated plot-level water column nutrient concentration in situ at two sites and compared eelgrass growth in manipulated and control quadrats[66]. At each site, we set up 3 parallel transects at least 5 m from the edge of the meadow using SCUBA and randomly assigned experimental treatments to 25 × 25 cm quadrats every 5 m along each transect. To assess the ability of eelgrass to grow under low light conditions, we used 8 whole, randomly selected shoots collected from within the experimental array at each site to construct production–irradiance (PI) curves[66].

Ethics and inclusion statement

The knowledge of the Eeyou is well suited to detecting change as their harvesting activities rely on observations of their environment at multiple scales[40,42,45]. The Indigenous knowledge component of this study was community-driven, with input from Eeyou land users, eelgrass ecologists, waterfowl experts, and the project's steering committee[29]. Eeyou engagement in every step of the research was specified in the formal research agreements between the Eeyou organizations and the universities, and these terms were adhered to by the university researchers. These agreements specified protocols for returning all data to the communities and respecting privacy of material in interviews, consistent with established FAIR and CARE principles.

The Behavioral Research Ethics Board of the University of British Columbia approved the components of this research that relied on formal interviews with Eeyou people (H20-02942)[45]. This work fully complies with the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans (TCPS 22018). The ethical obligations surrounding informed consent in research involving Indigenous Peoples align with Article 9.1 of the TCPS. Additionally, this study adhered to the principles outlined in individual Research and Information Sharing Agreements executed between the principal investigator and the respective First Nations Governments.

Eelgrass abundance, nutrient content and depth delineation

To compile information on eelgrass biomass and density in Eeyou Istchee, Hydro-Québec monitoring reports were reviewed and all raw observations were compiled[15]. Eelgrass biomass monitoring was a main method of monitoring. Six eelgrass beds within the LGR sector were

monitored for shoot density and biomass by Hydro-Québec between 1982 and 2009 to assess the impacts of La Grande development. Eelgrass biomass was assessed at a larger number of locations along the coast in 2019. Eelgrass cover monitoring was the second method employed between 1999 and 2019[15]. Cover classes were assigned according to four abundance classes (Fig. S2).

To assess eelgrass beds depth range, we conducted side-scan sonar surveys using an autonomous underwater vehicle (AUV) at seven coastal locations in 2019. The AUV was equipped with a Klein side-scan sonar, a conductivity and temperature sensor, and a 10-beam Doppler velocity logger (DVL) for underwater navigation and AUV to the seafloor distance measurement[81]. A square grid of 20 × 20 m was overlaid on the side-scan sonar imagery and each grid cell classified by eye as one of: bare seabed, patchy eelgrass, or continuous eelgrass. Water depths along the survey lines were retrieved and sorted into depth bins for each of the classified areas to produce histograms of the water depth distribution of the eelgrass.

To assess energy reserves and nutrient limitation, we measured eelgrass C content in the roots and N in leaves in 2019, respectively. To assess contribution of water column and sediment nutrient sources, we also analyzed the N isotopic ratio ($\delta^{15}N$) in eelgrass shoots[83].

To test if light and nutrient levels in the water limit eelgrass growth, we conducted experiments on eelgrass from two beds south of Chisasibi. For nutrient limitation, we manipulated water column nutrient concentrations and compared eelgrass growth in high-nutrient (manipulated) and ambient-nutrient (controlled) conditions at each site[66]. SCUBA divers measured eelgrass growth rates using a standard protocol. For light limitation, we collected shoots from each eelgrass bed, brought them to a field laboratory, and manipulated light levels. Evidence of light limitation was obtained by comparing eelgrass light requirements with light records from sampling sites.

Remote sensing of ice breakup and sea surface temperature

To compare with eelgrass metrics, times series of environmental variables were compiled and examined[15]. Mean daily sea surface temperatures of June (°C) for James Bay were obtained from the Group for High Resolution Sea Surface Temperature (GHRSST) product 'AVHRR_OI-NCEI-L4-GLOB-v2.1', which provides continuous daily record of SST on a 0.25° spatial grid from 1982 to 2019. The regional annual ice breakup dates were determined from regional ice charts produced by the Canadian Ice Service. Regional sea-level pressure and wind fields at hourly temporal resolution and 0.25° spatial resolution were acquired from the fifth-generation reanalysis (ERA5) of the European Center of Medium-Range Weather Forecasts[84,85]. Annual freshwater discharge was estimated for the large watershed sectors of the JB from 1951 to 2021[86].

Marine heat wave (MHW) frequency, duration, and intensity for 1982 to 2021 for eastern James Bay were described using the SST dataset from the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) system[53]. This system generates high-resolution (1/20° grid), daily, global, gap-filled SST fields derived from satellite and in situ data. MHW events were defined by five days of sustained warming above the 90th percentile for a 40-year baseline period (1982-2021) for at least five consecutive days[87].

Ocean color remote sensing

Concentrations of optically active biogeochemical compounds, i.e., colored dissolved organic matter (CDOM) and suspended particulate matter (SPM) in the bay were assessed through satellite remote sensing. Regionally tuned empirical algorithms were used to compute CDOM absorbance (a_g(400 nm)) and SPM concentrations based on in situ reflectance, CDOM, and SPM data collected in 2018 and 2019 within the scope of the CHCRP[88]. For the analysis of long-term changes to CDOM, data from the Moderate-resolution Imaging Spectroradiometer onboard the Aqua satellite (MODIS-Aqua) were atmospherically corrected using a modified version of SeaDAS v8[89]. For the estimation of SPM concentrations, data from the MultiSpectral Imager (MSI) onboard Sentinel-2 (atmospherically corrected using ACOLITE[90]) was used. Log-transformed values for satellite derived SPM concentrations were mapped to evaluate the spatial variability along the coast as observed by Sentinel-2A MSI on August 8, 2016.

In situ water parameters

To compare the extent of the La Grande River plume to pre-development extent, we carried out a detailed study of the plume when the LGR discharge averaged 4800 $m^3\ s^{-1}$ in the winters of 2016 and 2017[47]. Salinity was measured using a conductivity-temperature-depth probe (CTD) and recorded continuously from January to April using ice-deployed moorings. Additionally, discrete CTD profiles were taken all along the coast in all four seasons from 2017 to 2021, and water samples were collected and analyzed for salinity[49,91].

To assess the seasonal availability of nutrients in coastal surface waters, nitrate and phosphate were measured in water samples from the LGR sector during early winter, late winter, and summer (2016 and 2017)[49], and from sites distributed all along the eastern coast of James Bay during winter (2018, 2019 and 2020), spring (2018 and 2019), summer (2018, 2019 and 2021), and fall (2017 and 2018)[91]. Sampling stations were located within 25 km of the shore.

Sediment cores

To assess whether erosion had occurred, sediment cores up to 58 cm in length were collected across six Chisasibi traplines between 2017 and 2021 using a gravity corer and push corer as described previously[56]. The sediment cores were sectioned immediately and subsections analyzed to obtain profiles of the natural radioisotope ^{210}Pb and the artificial radionuclide ^{137}Cs, which is expected to be present in coastal sediments continuously deposited since ca. 1954[56].

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The in situ water salinity, $\delta^{18}O$, and nutrients data generated in this study have been deposited in the CanWIN data repository hosted by the University of Manitoba, Center for Earth Observation Science under the Eeyou Coastal Habitat accession code [https://doi.org/10.34992/6354-e007]. The ice core salinity and $\delta^{18}O$ data are in the same repository [https://doi.org/10.34992/zd7j-jq80]. The CTD and mooring data from 2016-2017 are also in this repository [https://doi.org/10.34992/cd02-8a75] as are the CTD and mooring data from other years of the study [https://doi.org/10.34992/2enm-0h29]. Sediment core data generated in this study have been deposited in CanWin [https://doi.org/10.34992/a2j8-fa74]. Eelgrass data generated in this study are deposited in the Dryad digital repository [https://doi.org/10.5061/dryad.37pvmcvpk]. River biogeochemical data are available online [https://doi.org/10.5683/SP3/7EQN2S]. Sentinel-2 data is available through the Copernicus Programme and the Copernicus Browser. MODIS data can be accessed via the NASA OB.DAAC. Data from interviews with Indigenous land users that support the findings of this study are available under restricted access to maintain the privacy and confidentiality of the research contributors from the Cree Nation where it was gathered. Access to this information can be obtained by contacting E. Rabbitskin (ernie.rabbitskin@niskamoon.org) or M. Leblanc (melanie.leblanc@niskamoon.org) at Niskamoon Corporation.

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Author contributions

Z.A.K. led the synthesis of results and wrote the manuscript with significant input from M.O., M.L., P.d.G. and M.H.; Ideas and/or results were also contributed by J.E., S.B., F.N., C.J.I., P.d.G., U.N., M.G., M.H., M.d.M., N.S.K., and C.F.-M. Data were processed and displayed by D.W., S.B., C.P., M.S., M.L., C.F.-M., M.G., and A.C.; J.E., Z.A.K., F.N., S.B., M.L., U.N., M.G., C.F.-M., A.G., M.S., C.P., K.D., N.S.K., M.d.M., P.d.G. and C.J.I. completed fieldwork and helped present results in communities. E.R. coordinated the research teams for fieldwork and community meetings and outreach when involved in multi-region collaborations involving local researchers and reviewed results. M.D. contributed to research design and results synthesis. All authors edited the manuscript for clarity and accuracy.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Zou Zou A. Kuzyk or Mélanie Leblanc.

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Zou Zou A. Kuzyk[1] ✉, Mélanie Leblanc[2,3] ✉, Jens Ehn[1], Alex Crawford[1], Chris Peck[1], Alessia Guzzi[1], Madelyn Stocking[1], C. Julián Idrobo[2], Nicole S. Knight[2], Kaleigh Davis[2], Marc Dunn[3], Ernie Rabbitskin[3], Simon Bélanger[4], Fanny Noisette[4], Michel Gosselin[4], Caroline Fink-Mercier[4], Urs Neumeier[4], Daniela Walch[4], Michaela de Melo[5], Paul A. del Giorgio[5], Murray Humphries[6] & Mary I. O'Connor[2,7]

[1]Centre for Earth Observation Science, University of Manitoba, Winnipeg, MB, Canada. [2]Department of Zoology and Biodiversity Research Centre, University of British Columbia, Vancouver, BC, Canada. [3]Niskamoon Corporation, Chisasibi, QC, Canada. [4]Université du Québec à Rimouski (UQAR), Rimouski, QC, Canada. [5]Université du Québec à Montréal (UQAM), Montréal, QC, Canada. [6]McGill University, Montréal, QC, Canada. [7]Santa Fe Institute, Santa Fe, NM, USA. ✉e-mail: zouzou.kuzyk@umanitoba.ca; melanie.leblanc@niskamoon.org