Aquaculture
September 2014, Volume 433 Pages 450-457
http://dx.doi.org/10.1016/j.aquaculture.2014.07.006
http://archimer.ifremer.fr/doc/00202/31287/

Influence of suspended mussel lines on sediment erosion and resuspension in Lagune de la Grande Entrée, Îles-de-la-Madeleine, Québec, Canada

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Abstract :

Downward fluxes of organically rich biodeposits under suspended mussel lines can cause benthic impacts such as changes in benthic community structure or microbial mat production. Quantifying sediment erosion in these coastal ecosystems is important for understanding how fluxes of organic matter and mussel biodeposits contribute to benthic–pelagic coupling. Critical shear velocity (u*crit), erosion rates and particle size distributions of resuspended sediment were measured at four stations distributed along a transect perpendicular to a mussel farm in Lagune de la Grande Entrée, Îles-de-la-Madeleine (Quebec, Canada). Stations were selected underneath the outer-most mussel line (0 m) and at distances of 15, 30 m and at a reference station (500 m) further along the transect. Shear velocity was measured using a calibrated portable Particle Erosion Simulator, also referred to as the BEAST (Benthic Environmental Assessment Sediment Tool). Undisturbed sediment cores obtained by divers were exposed to shear stress to compare differences between stations. Erosion sequences indicated no significant differences in u*crit between stations, but there were significant differences in erosion rates beneath mussel lines compared to other stations. Erosion rates were the highest in cores from beneath mussel lines, but paradoxically had the lowest u*crit. Mean erosion rates at u*crit varied between 25 and

47 g m^{-2} min^{-1} and critical erosion thresholds varied between 1.58 and 1.73 cm s^{-1}, which compare with intensive mussel culture sites elsewhere in eastern Canada. Significant differences existed in biotic and abiotic properties of sediments which could explain variation in maximum erosion rates within and between stations. Particle sizes measured by videography of resuspended sediment at different shear velocities ranged from 0.2 to 3.0 mm. Quantifying sediment erosion from intact marine sediments helps to improve our mechanistic understanding of these processes, and the BEAST further contributes to predictive capability in benthic–pelagic coupling modeling.

Highlights

► An erosion device was used to quantify sediment near cultured mussels. ►Erosion rates were significantly higher beneath mussel lines. ►Critical shear velocities compared to other studies in eastern Canada ►The BEAST contributes to our understanding of benthic–pelagic coupling.

Keywords : Sediment erosion, Shear velocity, Resuspension, Biodeposits, Particle size, Mytilus edulis

1. **Introduction**

Quantification of sediment erosion around coastal aquaculture operations is essential for understanding fluxes of organic rich particu1ate matter. Sedimentation, sinking rates and dispersion of organic and inorganic partic1es (comprising of phytoplankton, sediment, detritus, fecal pellets or resuspended aggregates), is dependent on particle diameter and density, and are highly variable in coastal water colurnns (Andersen et al., 2002; Miller et al., 2002; Nickell et al., 2003; Giles and Pilditch, 2004). Sedimentation is further compounded by filter-feeding bivalves which play an important role in coastal ecosystems through their influence on benthic-pelagic coupling and nutrient cycling (Christensen et al., 2003). Filter-feeding bivalves repackage fine suspended material into larger organic rich biodeposits (feces and pseudofeces) that sink more rapidly than their constituents, increasing fluxes of organic matter to the benthos, depending on water depth, currents and resuspension (Chamberlain et al., 2001). While dynamics of mussel biodeposition (resuspension and disaggregation) is poorly quantified, enhanced sedimentation under mussel culture is well documented (e.g., Hatcher et al., 1994; Callier et al., 2006).

Bottom sediment resuspension is affected by biostabilization, porosity, organic content, grain size, and bioturbation (Miller et al., 2002; Nickell et al., 2003; Giles and Pilditch, 2004; Walker and Grant, 2009). Quantifying sediment resuspension is important for understanding sediment erosion thresholds (critical shear velocity, u_{*crit}) and fluxes generated by currents or waves becomes an important predictive tool in coastal ecosystem management. Quantifying sediment transport is possible when erosion thresholds are known, although few calibrated data exist for sediment entrainment rates (Tolhurst et al., 2000; Grant et al., 2013), especially those influenced by mussel biodeposits or microbial mats (Walker and Grant, 2009). Sediment stability (defined as increased erosion threshold) is often associated with biostabilizing microbial mats, including diatoms and/or bacteria which can physically bind cohesive and non-cohesive sediment particles via the excretion of extracellular polymeric substances (Grant et al., 1986; Grant and Gust, 1987; Tolhurst et al., 2002). Alternatively, bioturbation can destabilize sediments by increasing porosity or by grazing on stabilizing organisms (Gerdol and Hughes, 1994). Sediment erosion thresholds are therefore difficult to predict, due to varying biotic and abiotic influences. Moreover, erosion thresholds are difficult to measure for undisturbed sediments, requiring substantial effort using laboratory or field flume quantification (Widdows et al., 1998).

Downward fluxes of organic biodeposits under suspended mussel culture operations has been reported to have local adverse benthic impacts, decreasing biodiversity and increasing sulfate reduction leading to anaerobic conditions (see review by McKindsey et al., 2011). Whilst some modeling studies have considered erosion and dispersion around mussel aquaculture sites (Giles et al., 2009; Wiese et al., 2009), combined field

measurements of sediment erosion rates from suspension-feeding bivalves has rarely been investigated (Widdows et al., 1998; Miller et al., 2002; Giles and Pilditch, 2004; Walker and Grant, 2009). Recent studies associated with mussel aquaculture in Lagune de la Grande Entrée (LGE) have documented benthic impacts associated with biodeposition, including nutrient and particle fluxes (Callier et al., 2006, 2009; Richard et al., 2006, 2007a, 2007b). Ecosystem models of aquaculture carrying capacity on the basis of mussel grazing have also beeen conducted there (Grant et al., 2007; Filgueira et al., 2012). However, the fate of biodeposits through dispersion and resuspension events remains unclear in LGE (Callier et al., 2006; Weise et al., 2009). This is especially important if benthic microalgae are resuspended as an additional mussel food source (Frechette and Grant, 1991).

We re-designed and calibrated a portable erosion chamber called the 'Benthic Erosion Assessment Sediment Tool' (BEAST) (Grant et al., 2013) to measure erosion in undisturbed sediment cores in an attempt to field verify biodeposit dispersion model predictions in LGE. The following objectives were undertaken: (1) quantify erosion thresholds, erosion rates, and resuspended particle size distributions along a SW transect perpendicular to a mussel line in the direction of main current flow; (2) determine sediment organic quality; and (3) compare erosion features to a separate study by Callier et al. (2006) who measured downward fluxes of biodeposits and spatial extent of dispersion investigated via sediment traps located along the same transect.

2. Methods

2.1. Study site

This study was conducted below and adjacent to a mussel farm in LGE, Îles-de-la-Madeleine, Quebec, in August 2004. Îles-de-la-Madeleine are in the Gulf of St. Lawrence in eastern Canada, with LGE (58 km^2) located in the northeast of the largest island (47° 37' N, 61° 31' W). Mean currents are weak (<5 cm s^{-1}) occasionally increasing to 10 cm s^{-1} during strong wind events, resulting in a well-mixed water column (Koutitonsky et al., 2002). A deep navigation channel (8 m) separates LGE into a shallow (1-3 m) sandy area to the west and a deeper (5-7 m) muddy basin to the east where the mussel farm is located (Fig. 1). Blue mussels, *Mytilus edulis* L. are cultured using longlines with continuous socking looping between floats and the farm has operated since the 1980s, currently producing 180 t yr^{-1} in a farm area of 2.5 km^2 (Weise et al., 2009).

2.3. Sediment sampling stations

Triplicate intact sediment samples were collected in Plexiglas™ cores (11.2 cm I.D.) by SCUBA divers for erosion experiments and particle size distribution from stations along a SW transect perpendicular to a mussel line along the direction of main current flow (i.e., underneath a mussel line to a reference station). Sampling stations were located 0, 15 and 30 m from the mussel line. A reference station was selected at a sandy site located 500 m further along the transect (Fig. 1). Three additional sediment cores were collected from each station for determination of sediment physical properties, using sub-cores over the 0-1 cm depth horizon with truncated 5 mL plastic syringes for measurement of grain size, percent organic matter (%OM), percent total organic carbon (%TOC) and C:N ratios.

2.4. Sediment properties

Sub-samples were stored at -20C in pre-weighed plastic scintillation vials until analysis. Triplicate thawed samples were wet sieved with tap water through 63-2000 μm sieves. Sub-samples of <63 μm suspended sediment were collected and filtered through GF/F filters for analysis of %OM. For %OM, filter residues and sediments were oven dried at 60°C for 3 d to constant weight, followed by ashing in a furnace oven at 520°C for 24 h before re-weighing. Sediment texture distribution was determined using GRADISTAT (Blott and Pye, 2001). Sediments were ananlyzed for C:N ratios using a CHN elemental analyzer (Perkin-Elmer 2400) (Walker, 2005).

2.5. Sediment erosion thresholds and erosion rates

Sediment erosion thresholds and erosion rates were determined on triplicate cores from each station using the BEAST with methods that have been reported elsewhere in greater detail (Walker et al., 2008; Walker and Grant, 2009; Grant et al., 2013). Briefly, cores were filled with approximately 1 L of seawater overlying a 30 cm sediment column and stored in a dark water bath (10°C) to equilibrate before erosion was performed. The plunger disc was inserted into the core liner, and oscillation imposed for 2 min. intervals at equivalent shear velocities of 0.9-2.6 cm s^{-1}. Onset of sediment erosion was detected via turbidity and digital imaging. Initial particle movement is detected as erosion of flocs, while the sediment surface remains intact. Critical shear velocity is defined as a more generalized failure of the bed. We have used these categories previously (Grant et al., 2013), finding them to be more applicable to our BEAST erosion sequences than the Type I and II terms classically used (Tolhurst et al., 2000).

Turbidity in erosion chamber was monitored using % transmission as a proxy for sediment concentration with an *in situ* fiber-optic spectrophotometer (Brinkmann PC 800 colorimeter, 670 nm). The fiber-optic probe was zeroed with filtered seawater and calibrated using thawed frozen sediment samples covering a range of concentrations from all stations. Sediment slurries were filtered through GF/F to determine suspended particulate matter (SPM) concentrations.

Sequences of sediment erosion and erosion activity at the sediment bed were recorded visually using a mini-DV camcorder (Canon ZR45 MC) and analyzed following protocols from our previous studies (Walker et al., 2008). Digital still images were obtained at 1 min. intervals using video capture software (Pinnacle Studio version 8, Pinnacle systems). Particle size analysis of images was determined with SigmaScan Pro version 5 (SPSS Inc.) image analysis software. Particles could only be discriminated at lower shear velocities before SPM concentrations became too turbid. Minimum particle sizes measured using estimated spherical diameter (ESD) was 200 μm.

Erosion rates were calculated according to Walker and Grant (2009). The spectrophotometer gave linear responses to SPM concentrations of sandy sediments at all stations covering concentrations from 0-7700 mg L^{-1}, so that each % transmission unit represented a specific SPM concentration. Erosion rates were calculated for each time interval based on this linear relationship with respect to sediment core surface area (98 cm^2).

2.7. Statistical analysis

Significant differences were determined using Minitab to perform one-way analysis of variance (ANOVA) followed by Tukey's test at the $P<0.05$ level (unless indicated otherwise).

3. Results

1.1.Sediment properties

Sediment grain size composition and significance tests for %TOC, %OM and C:N ratios are shown in Fig. 2. Sediments were comprised of silty sand at 0 m or fine sand at remaining stations. Median grain sizes (D_{50}) at 0 m were 90 μm, with similar slightly coarser sizes at 15 and 30m, increasing to 180 μm at 500 m. Percent TOC and %OM varied between stations with lowest values measured at 500 m. This was expected of the coarser sediment found in the far field. However, the 0m farm sediments were finest, yet lower in %OC them the more distant farm sites. The 15 and 30m sediments were not significantly different in organic or carbon content. Sediment C:N ratios were 7-8 at 15, 30, and 500m, but significantly higher at 0m with a values of 12. This may reflect more degraded sedimentary organic material arising from mussel feces.

3.2. Erosion experiments

Observations of erosion sequences show consistent behaviour of the three variables (Fig. 3). Shear stress is applied in consistent linear manner. Turbidity remains constant or diplays a slow increase as flocs are resuspended until the initiation of more general erosion, and then shows a steep increase (declining % transmission). Erosion rate provides an instantaneous measure of sediment dynamics that remains at a low level until

the onset of general erosion when it displays a marked increase. The shapes of these curves are used to distinguish important differences between stations. Specifically, turbidity curves in cores from beneath mussel lines, experienced sharp transitions to erosion once protective organic rich carpets were disrupted at this station (Fig. 3). This was in contrast to other stations, where transitions to erosion were more gradual, probably due to larger grain sizes and the absence of mats. Critical shear velocity (u^*_{crit}) was reached between 1.58-1.73 cm s^{-1} at all stations. Mean erosion rates at u^*_{crit} varied between 25-47 g m^{-2} min^{-1} at 30 m and 0 m, respectively.

The behaviour of both turbidity and erosion rate are variable in the chamber experiments, and few consistent differences between stations can be observed. In some cases, an increase in turbidity occurred well before the general erosion threshold, indicating that the accumulation of surface flocs accounts for sunstantial resuspension. As expected, the onset of general erosion occurs at the peak of erosion rate, and afer a rapid increase in this rate. The only consistent spatial difference is that in cores from the mussel farm, initial floc movement began at a lower speed than at reference sites. Otherwise, metrics such as the erosion threshold and the erosion rate at this threshold are variable enough to obscure spatial differences.

Cores from 0 m appeared to have a shallow light brown oxidized layer which penetrated <1.5 cm, although according to Callier et al. (2008) these sediments were largely anoxic up to a depth of 10 cm below the surface. Before onset of erosion the water column remained clear, but with increasing shear stress, larger particles (>0.4 mm) began lifting. The first phase of erosion was observed when turbidity began to increase at

1.40 cm s^{-1}. As further stress was applied, the bed failed and the second phase of erosion was observed (u^*_{crit} = 1.58 cm s^{-1}), with the suspension becoming fully turbid. Shear stress at u_{*crit} was sufficient to lift larger particles (upto 2 mm) and maintain them in suspension.

Cores from 15 m contained deeper light brown surface layers between 0.5-2 cm. The second phase of erosion, occurred at u_{*crit} of 1.73 cm s^{-1} and shear stress was sufficient to lift particles between 0.2-1 mm. Cores from 30 and 500 m stations contained a shallow light brown surface layer between 0.6-1 cm deep and the second phase of erosion occurred at u_{*crit} of 1.67 cm s^{-1} and 1.72 cm s^{-1}, respectively with particles between 0.2-3 mm.

Decreasing % transmission values had tight linear relationships with SPM concentration measured by filtration and gravimetry (R^2 = 0.93-0.99), corresponding to mean SPM concentrations of between 2931 to 7763 mg L^{-1} (Fig. 4a). Mean erosion rates were recorded up to 47 ±2.9 g m^{-2} min^{-1} at 0 m and only 25 ±2.5 g m^{-2} min^{-1} at 30 m from the mussel line and were significantly different (P<0.01) (Fig. 4b). There were no obvious relationships between critical shear stress and erosion rates across stations (R^2 = 0.29) (Fig. 4c). Frequency of resuspended particle sizes, with increasing shear velocity, ranged from 0.1-3.0 mm for all stations and for all erosion thresholds (Fig. 5). Image analysis of particles sizes became difficult >u* of 1.7 cm s^{-1}, due to increasing turbidity. Particles <200 μm were below levels of detection for this method and are not shown. Overall, there appears to be subtle differences in particle size distributions across stations, with more particles resuspended at lower shear velocities at 0 m compared to 500 m.

4. Discussion

One of the primary impacts of mussel culture is enhanced biodeposition of fecal and pseudofecal material (Cranford et al., 2009). Many studies have documented environmental effects due to this increased sedimentation including impacts associated with eutrophication, e.g., sediment hypoxia, increased sulfate reduction, and greater effluxes of ammonium (Danovaro et al., 2004; Hartstein and Rowden, 2004; Callier et al., 2007, 2008; Richard et al., 2007a, 2007b; McKindsey et al., 2011). Among the resultant biotic responses to organic loading are the development of microbial mats, and decline in benthic invertebrate biodiversity due to their sensitivity to sulfide concentrations (Pearson and Rosenburg, 1978; Hatcher et al., 1994; Chamberlain et al., 2001).

Several studies have shown that increasing biodeposition from bivalve culture may lead to changes in sediment composition, resulting in muddy, anaerobic sediments (e.g., Hatcher et al., 1994). In our study, the finest sediment was found at the mussel lines, mirroring size fractions reported by Callier et al. (2006, 2008). Sediment at the longlines also had the highest C:N suggesting that the biodeposits are degraded from grazing and digestion. Callier et al. (2008) did not report any significant difference between other sediment characteristics (including %OM) or benthic communities along the same transect. Taken together these studies and the present work suggest that the LGE farm had little effect on the local environment. The lack of localized impacts in LGE was perhaps influenced by wind induced resuspension in this shallow water site (Koutitonsky et al., 2002).

Critical erosion thresholds of sediments at all stations occurred when shear velocities reached between 1.58-1.73 cm s^{-1}, which compare favorably with field

measurements made at intensive mussel culture sites in Prince Edward Island, Canada (Walker and Grant, 2009). Analysis of sediment erosion sequences indicated there were no significant differences in sediment u^*_{crit} between stations and there was as much inter- as intra-station variation, although the limited replicates used in this study probably highlighted the relatively high intra-station variation. More studies using additional cores to perform erosion sequences would likely decrease the intra-treatment variability of our erosion thresholds and may potentially highlight significant differences along the transect. There were however significantly higher erosion rates beneath mussel lines (47 g m^{-2} min^{-1}), where fluxes of organic matter to sediments were high due to increased biodeposition, compared to 30 m (25 g m^{-2} min^{-1}). A simple explanation is that there is similar fine material in a background of sand at each site. This produces a similar threshold for erosion based on a visual criterion or change in turbidity. However, the erosion rate is greater at the longlines, because there is more of the fine material available to erode. If shear velocity is estimated as 5% of free stream (Gordon et al., 2004), then even the higher range of currents measured in the vicinity of the farm are below critical shear velocity.

Our erosion sequences clearly show two phases of erosion, an initial phase (surficial) and a second phase (critical erosion). According to Tolhurst et al. (2000) cohesive sediments erode in several phases, as a function of depth of the eroded layer. We demarcated the distinction between phases of erosion on the basis of surficial layer events, where the first phase of erosion (i.e., flocs, biofilms, surface mm of sediment) was compared to the second phase of erosion (i.e., failure of sediment surface to cm-scale depths and a sharp increase in turbidity) (Grant et al., 2013).

Initially, in all cores, except for those collected beneath mussel lines (0 m), there was little or no change in turbidity, with only a few small particles eroding from the surface (first phase of erosion). However as turbidity began to increase, erosion rates increased dramatically until a second phase of erosion was achieved whereby further increases in shear stress did not appear to increase erosion rates. Although sediment concentration and particle size maybe difficult to correlate at high shear velocities (due to poor visibility in cores), they are both dependant on turbulent shear (Walker et al., 2008). At low shear velocities in erosion sequences using sediment cores collected from beneath suspended mussel lines it appeared that larger aggregates were resuspended first (Fig. 5). For example, in our recent studies on microbial mats, sediments which were initially biostabilized against erosion due to an 'armoring' effect, the onset of erosion was abrupt once these mats failed, resulting in the resuspension of large mat fragments (Walker and Grant, 2009).

Much of the feces biodeposition, from mussel culture may have become incorporated into these sediments and the method used here for sediment grain size analysis may have resulted in the destruction of these bio-aggregates. This may have underestimated the binding effects of the microbial mats and may therefore, not correlate well with sediment erodibility, particularly for sediments beneath mussel lines which had the highest erosion rates. Studies by Fugate and Friedrichs (2003) noted that biological aggregations initially resisted turbulent breakup in sediment erosion studies in Chesapeake Bay, but Paterson (1989), found that sediments underlying biofilms (once exposed), were more easily eroded than the biostabilized layer itself. A similar response in sediment stability was observed by Walker and Grant (2009) around mussel culture

sites in Tracadie Bay, where mean erosion thresholds of 1.74 cm s^{-1} and erosion rates of 47 g m^{-2} min^{-1} were recorded. These results compare favorably with erosion rates and thresholds reported in this study, as erosion experiments on cores containing large areas of eelgrass, *Zostera marina* initially resisted erosion, but when turbulent breakup did occur, large fragments above the sediment bed were observed.

Erosion rate calculations respond to small changes in turbidity at each time step and are a sensitive indicator of instantaneous resuspension. As the first phase of erosion began, a steep rise in erosion rate was observed. With increased stress, more scouring of unconsolidated material occured and during the second phase of erosion, the rate began to decrease as the bed eroded to more consolodated sediments yielding fewer and larger particles. These observations reiterate previous studies which demonstrate that there are multiple erosion thresholds, dependent on sediment texture and the vertical distribution of shear strength (Tolhurst et al., 2000).

Erosion rates around mussel culture sites in this study were higher than those reported by Giles and Pilditch (2004), that found organic rich biodeposits from mussels were easily eroded at thresholds <1 cm s^{-1}. Again, this was probably due in part to biostabilization of microbial mats, the presence of eelgrass and the textural properties of sediments beneath mussel lines in LGE. Normally in natural sediments fecal material reduces sediment stability (Andersen et al., 2002), but in this study biodeposits probably contributed to microbial mat biomass.

Several physical and biological properties of the sediment surface were measured in order to determine a suitable quantitative predictor of the erodibility of sediment (e.g., grain size, %OM content, %TOC and C:N ratios). There were also other contributions to

organic enrichment in LGE, such as the presence of large amounts of detritus (e.g., eelgrass) and microbial mats revealed from diver observations and evidenced in several core samples. The accumulation of fine particles in the sediment at these sites may be influenced by limited tidal exchange, removal of biodeposits by feeding mussels during wind-induced resuspension events, and subsequent biostabilization of the fine fraction at the sediment-water interface by microbial mats, and the construction of a navigation channel in the 1980's which probably changed the hydrodynamics of the lagoon. The physical characteristics of the sediments at these stations, and others along the transect in LGE have previously been described by (Callier et al., 2006, 2007), who reported no difference in sediment %OM between 0 and 15 m from the mussel line. Also they found no difference in the depth of the sediment oxic layer between 0 and 15 m from mussel line, where sediments were reduced and blackened with a sulfide layer, however, the 30 m station was more oxidized. There was also no difference in abundance of infauna, wet weight biomass and diversity of species between the three stations at 0, 15 and 30 m (Callier et al., 2007).

Callier et al. (2006) reported that measured deposition of mussel biodeposits were fairly localized along the transect in LGE, albeit with some inter-annual variation, and was in broad agreement with modeled biodeposit settling rates by Weise et al. (2009). However negative benthic impacts were more diffuse along the same transect. The amount of organic enrichment along the transect in this study was fairly uniform except at the reference station, which may partly explain the lack of significant differences observed in erosion sequences between stations. However, the amount of %TOC and %OM was highest at 30 m from the mussel line, suggesting that dispersal via the

dominant current flow direction (with current velocities sometimes exceeding u^*_{crit} values measured here), was responsible for transporting material. The lowest erosion thresholds (but highest erosion rates), were recorded directly below the mussel line, where the increased deposition of organically rich biodeposits may have already caused changes in the sediment textural properties but not the benthic community structure (Callier et al., 2006). This contrasts to the increases in grain size observed further along the transect, where slightly higher erosion thresholds were observed.

Our work in modeling the role of resuspension in benthic-pelagic coupling is limited by accurate estimates of erosion characteristics, whose prediction is often mired in complex biophysical interactions (Grant et al., 2013; Walker et al., 2008). This is particularly true of erosion studies with microbial mats where armoring is so important to the erosion process close to mussel aquaculture sites (Walker and Grant, 2009). The use of the BEAST as a proxy for quantifying sediment erosion demonstrates its practical capability to provide quantitative field measurements of transport parameters from undisturbed marine sediments to improve our mechanistic understanding of these processes, and further contributes to predictive capability in modeling of benthic-pelagic coupling. Future applications using this device could include environmental effects monitoring to improve habitat and ecosystem management of potential changes in benthic ecosystems near coastal aquaculture operations. More studies are required in order to fully understand the effects of sediment erosion and resuspension from the impacts of biodeposition from mussel aquaculture in these shallow coastal sites.

Acknowledgements

We thank MAPAQ and B. Hargrave for collaboration and C. Éloquin and associates for permission to use their site. Funding was provided by Aquaculture Collaborative Research and Development Program (ACRDP), Société de Dévelopment de l'Industrie Maricole (SODIM) and Fisheries and Oceans Canada. We thank B. Schofield and M. Merrimen for fabrication of the BEAST which formed part of the equipment necessary for the Canadian Arctic Shelves Exchange Study (CASES), a Research Network funded by the Natural Sciences and Engineering Research Council of Canada (NSERC).

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Figure legends

Fig. 1. Mussel farm (grey rectangles) in Lagune de la Grande Entrée (LGE), Îles-de-la-Madeleine, Canada. Sampling stations distributed along a SW transect aligned with major current flow 0, 15 and 30 m from mussel farm. A reference station was located 500 m further along the transect.

Fig. 2. Sediment properties at LGE stations: (a) %TOC; (b) Proportion of mean sediment grain sizes. Silt and sand are sub-divided into very fine (vf), fine (f), medium (m), coarse (c), and very coarse (vc) fractions. D_{50} values (μm) are indicated; (c) %OM determined from a sub-sample of <63 μm SPM collected and filtered through GF/F filters; (d) C:N ratios from 0-1cm sediment horizon. Significant differences determined by one-way ANOVA followed by Tukey's test; within each measured attribute, stations with same letters were not significantly different and stations with different letters were significantly different (P<0.05). Plotted values are means ±SE (n = 3).

Fig. 3. Erosion sequences showing shear velocity (○), turbidity (% transmission) (●) and erosion rate (grey circles) performed on sediment cores using the BEAST at increasing distances from a mussel line: (a) 0 m; (b) 15 m; (c) 30 m and (d) 500 m. Onset of erosion is indicated by vertical solid line (i.e., turbidity begins to increase). Onset of significant erosion (i.e., critical shear velocity) is indicated by the vertical dashed line which distinguishes between different phases of erosion.

Fig. 4. SPM concentrations at lowest % transmission (a); peak erosion rate (b); shear velocity at critical shear stress (u_{*crit}) (i.e., second phase of erosion) (c). Significant differences were determined by one-way ANOVA followed by Tukey's test; within each measured attribute, sites with same letters were not significantly different and sites with

different letters were significantly different ($P<0.05$ for SPM concentrations) and ($P<0.10$ for erosion rate and shear velocity). Plotted values are means ±S.E. ($n = 3$).

Fig. 5. Frequency of particle sizes (ESD, mm) resuspended from sediment cores under different erosion thresholds. Sampling stations: 0, 15, 30 and 500 m subjected to u* between, 0.90-1.79 cm s^{-1}. Total number (n) of particles assessed at a given shear velocity is indicated above each histogram.

Fig. 1.

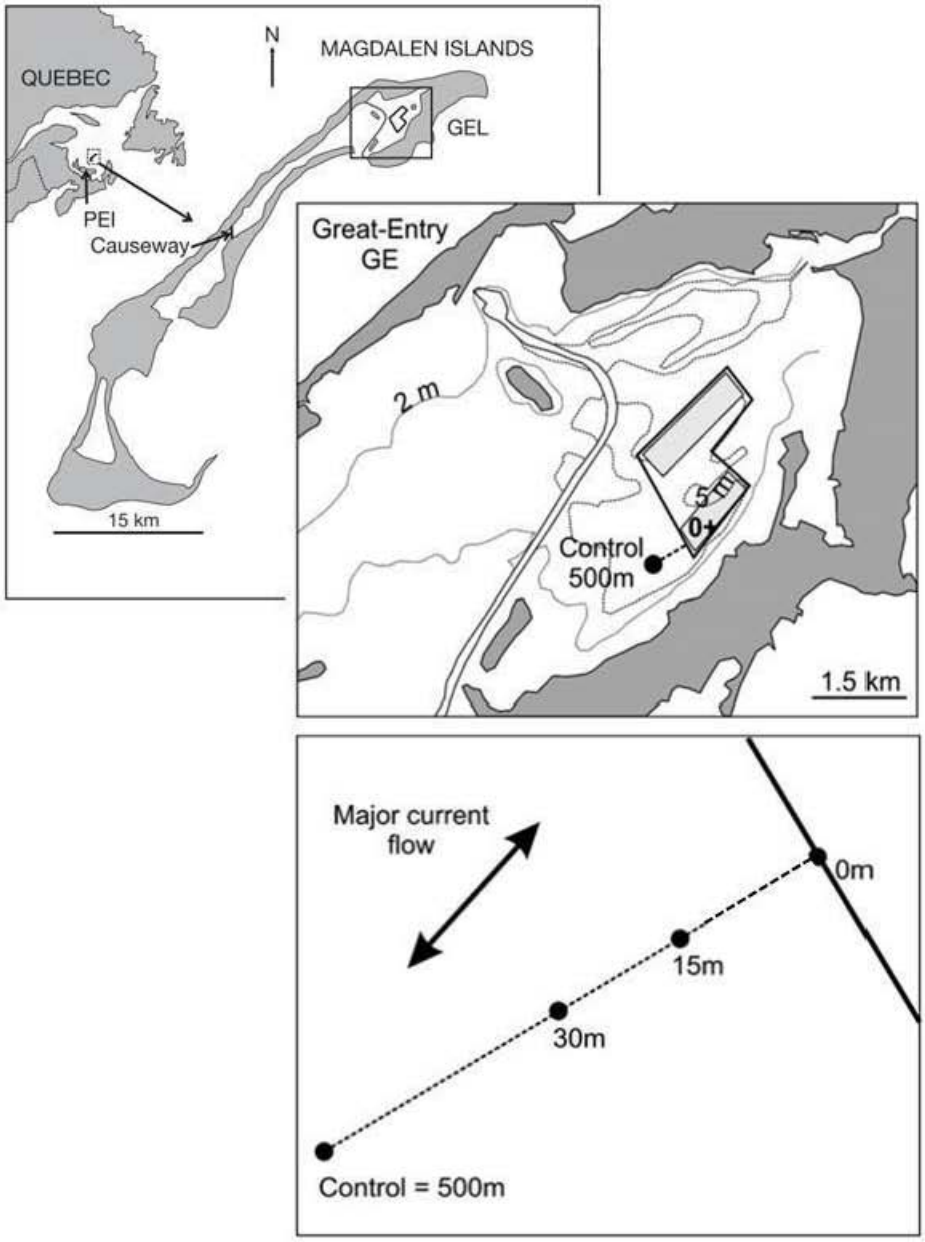

N
MAGDALEN ISLANDS
QUEBEC
GEL
PEI
Causeway
15 km
Great-Entry
GE
2 m
5 m
0+
Control
500m
1.5 km
Major current
flow
0m
15m
30m
Control = 500m

Fig. 2.

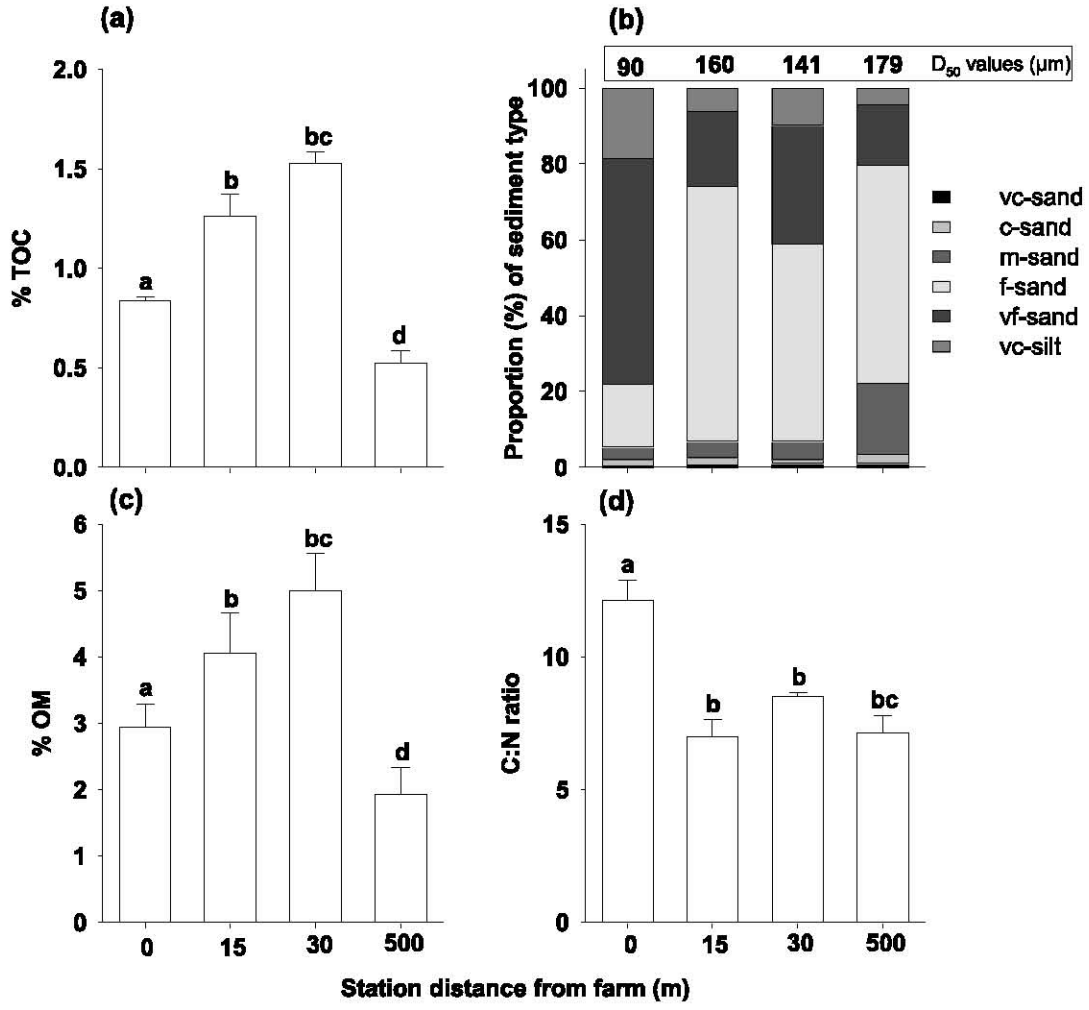

(a)
% TOC
2.0
1.5
1.0
0.5
0.0
a
b
bc
d
(b)
90
160
141
179
D50 values (µm)
Proportion (%) of sediment type
100
80
60
40
20
0
vc-sand
c-sand
m-sand
f-sand
vf-sand
vc-silt
(c)
% OM
6
5
4
3
2
1
0
a
b
bc
d
(d)
C:N ratio
15
10
5
0
a
b
b
bc
0
15
30
500
Station distance from farm (m)

Fig. 3.

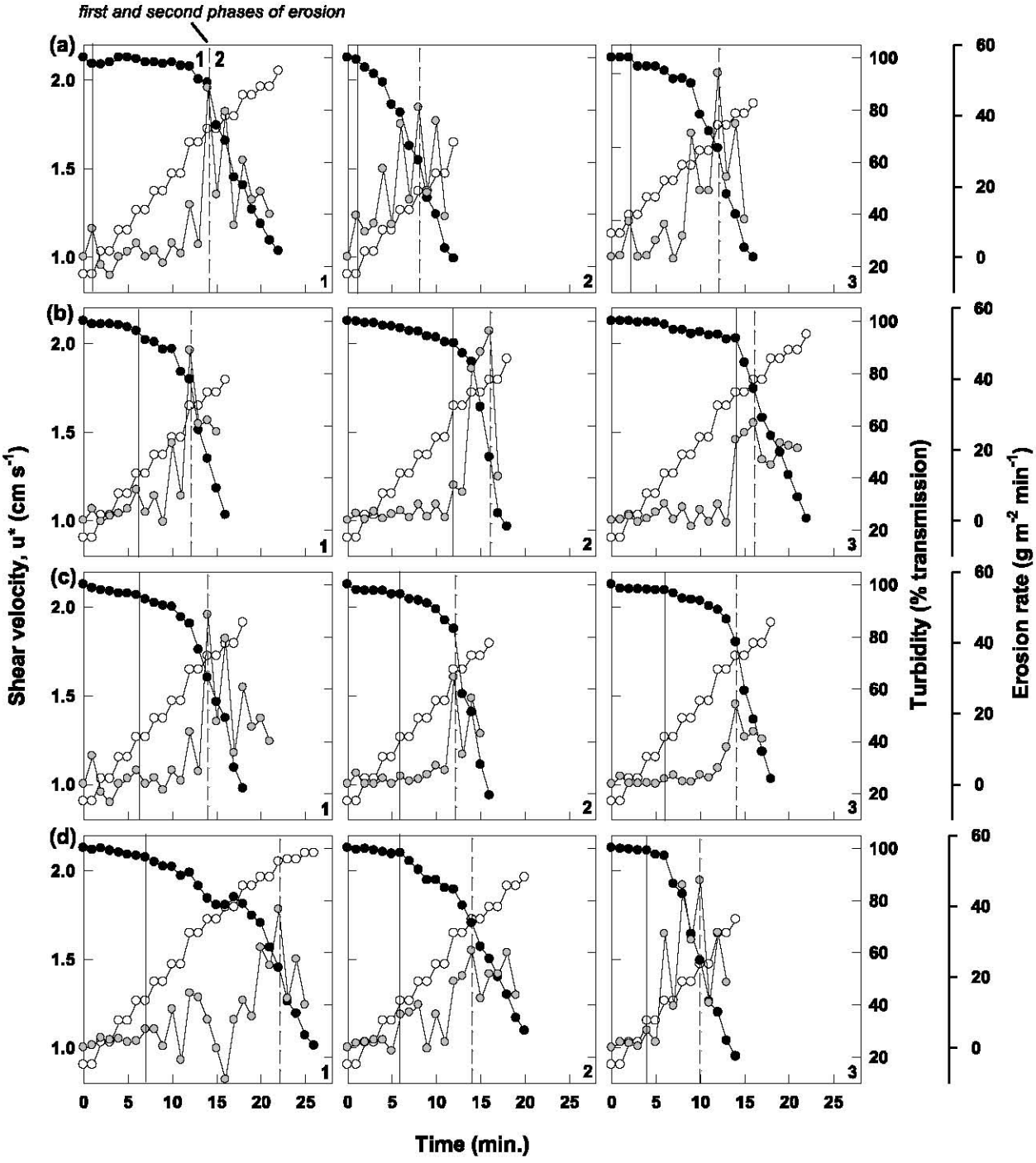

first and second phases of erosion
(a)
(b)
(c)
(d)
1
2
3
Shear velocity, u* (cm s-1)
Turbidity (% transmission)
Erosion rate (g m-2 min-1)
Time (min.)

Fig. 4.

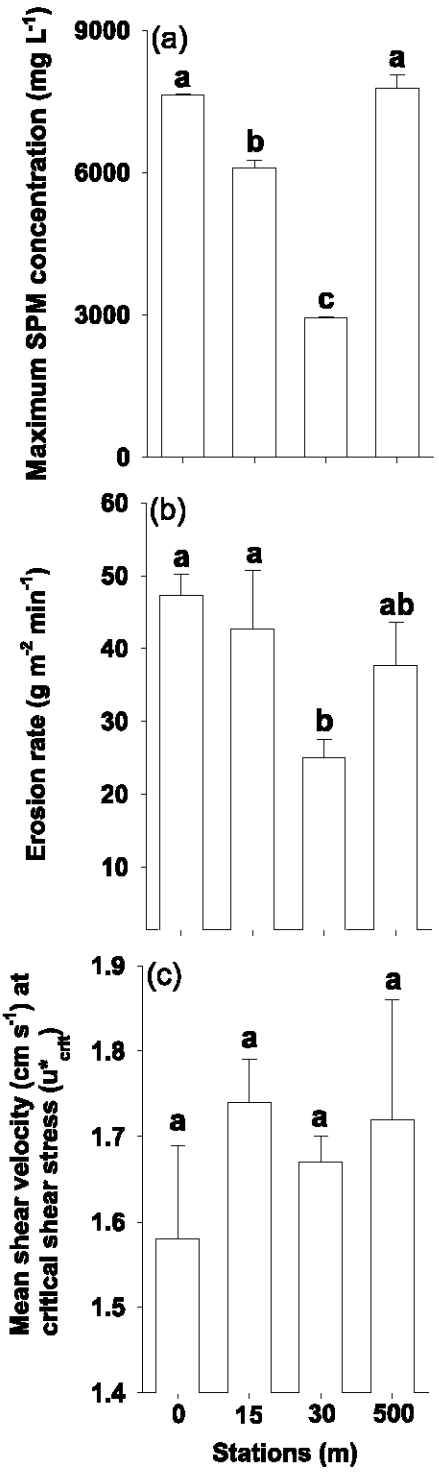
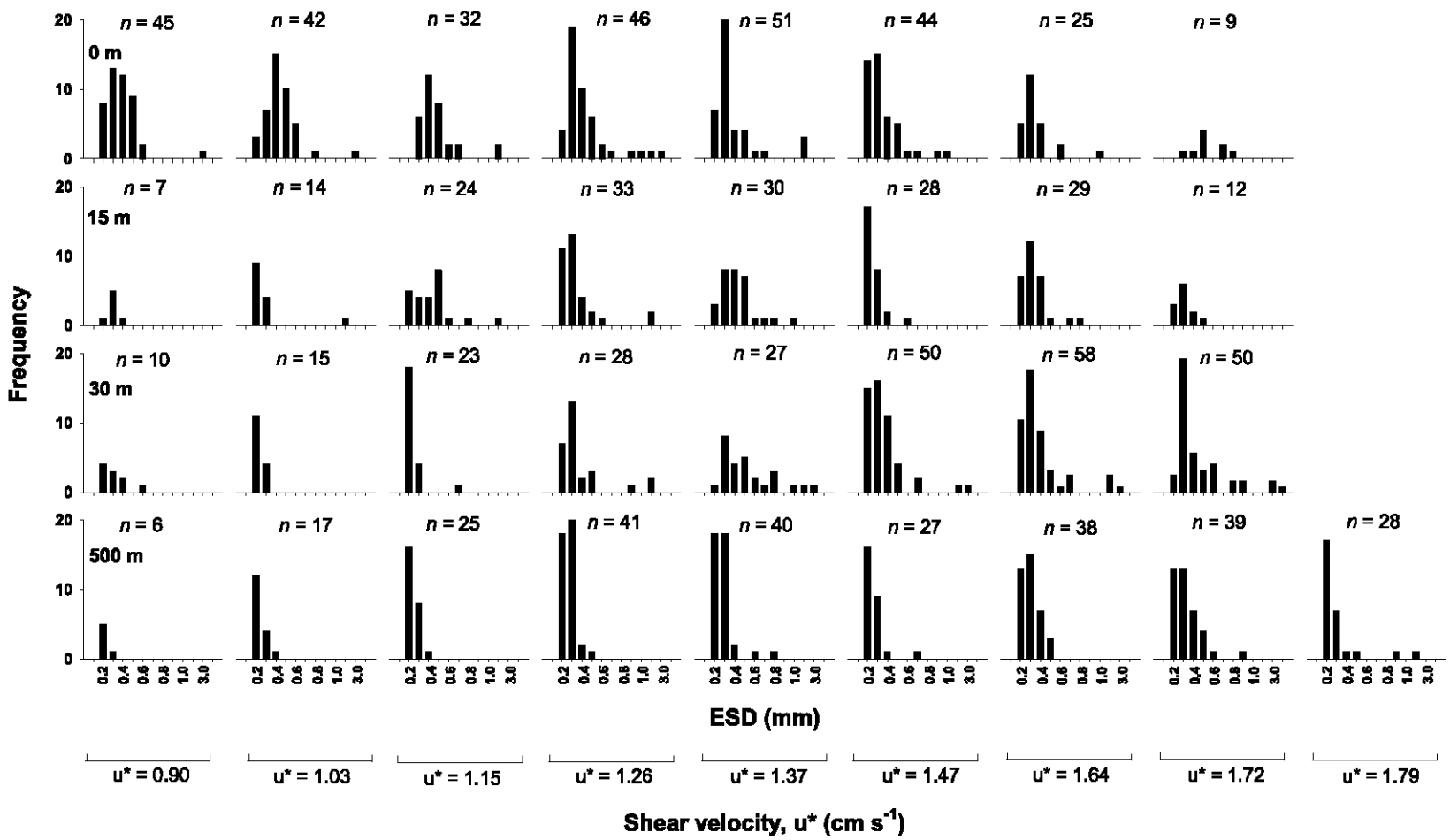

(a)
Maximum SPM concentration (mg L-1)
9000
6000
3000
0
a
b
c
a
(b)
Erosion rate (g m-2 min-1)
60
50
40
30
20
10
a
a
b
ab
(c)
Mean shear velocity (cm s-1) at critical shear stress (u*cnt)
1.9
1.8
1.7
1.6
1.5
1.4
a
a
a
a
0
15
30
500
Stations (m)

Fig. 5.


n = 45
n = 42
n = 32
n = 46
n = 51
n = 44
n = 25
n = 9
0 m
n = 7
n = 14
n = 24
n = 33
n = 30
n = 28
n = 29
n = 12
15 m
n = 10
n = 15
n = 23
n = 28
n = 27
n = 50
n = 58
n = 50
30 m
n = 6
n = 17
n = 25
n = 41
n = 40
n = 27
n = 38
n = 39
n = 28
500 m
Frequency
0
10
20
0.2
0.4
0.6
0.8
1.0
3.0
ESD (mm)
u* = 0.90
u* = 1.03
u* = 1.15
u* = 1.26
u* = 1.37
u* = 1.47
u* = 1.64
u* = 1.72
u* = 1.79
Shear velocity, u* (cm s-1)