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Green sea urchins (*Strongylocentrotus droebachiensis*) as potential biomonitors of metal pollution near a former lead-zinc mine in West Greenland

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Abstract In this study, metal accumulation in green sea urchins (*Strongylocentrotus droebachiensis*) was investigated near the former Black Angel lead-zinc mine in Maarmorilik, West Greenland. Sea urchins (n = 9–11; 31–59 mm in diameter) were collected from three stations located at < 1 km, 5 km, and 12 km (reference site) away from the former mine site, respectively. After collection, tissue of the sea urchins was divided into gonads and remaining soft parts (viscera) before subjected to chemical analyses. Focus was on eight elements found in elevated concentrations in the mine waste (iron, copper, zinc, arsenic, silver, cadmium, mercury and lead). Sea urchins at the mine site contained significantly more copper, mercury and lead compared with the reference site for both the gonads and viscera, while the latter also contained significantly more iron, zinc and silver. Arsenic and cadmium were not significantly elevated in sea urchins at the mine site. Most elements were found in higher concentrations in the viscera compared with the gonads. For comprehensive monitoring of metal pollution at mine sites, a diverse selection of monitoring organisms is necessary. The study shows that green sea urchins accumulate selected metals and can be used as a monitoring organism for mining pollution, at least for iron, copper, zinc, silver, mercury and lead. However, the results also show that green sea urchins are less likely to reflect small environmental changes in loading of most metals (except iron, copper and silver) and for arsenic compared to suspension feeders such as blue mussels.

Keywords Environmental monitoring · Monitoring organisms · Metals · Mining · Arctic

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Introduction

Dispersion and bioaccumulation of metals is a well-known environmental concern associated with mining due to the inherent toxicity of many metals (Lottermoser 2010). Monitoring of bioavailable metal loading from past and present mining activities is therefore important in order to evaluate the impact and, if needed, address mitigation actions. Monitoring programmes typically include a suite of monitoring organisms abundant at the site of interest, which effectively can accumulate metals and other pollutants and therefore act as sentinels of pollution. Compared with environmental samples such as water and sediment, monitoring organisms provide information on the bioavailable metal fractions, offer time-integrated information and can reflect metal loading from different sources depending on trophic level, habitat and feeding strategy of the specific organism. To design adequate monitoring programmes, detailed knowledge of the bioaccumulation potential of pollutants in a range of potential monitoring organisms is important. In that way, monitoring programmes can be designed according to the abundance of organisms at the site of interest and the pollutants of concern.

Sea urchins have previously been shown to accumulate metals (Bohn 1979; Sadiq et al. 1996; Deheyn et al. 2005; Ahn et al. 2009) and can serve as sentinels of pollution (Dafni 1980; Aspholm and Hylland 1998). Sea urchins are bottom-dwelling herbivores feeding mainly on macro-algal material (seaweed; Lemire and Himmelman 1996; Hernández-Almaraz et al. 2016). Sea urchins are also an important prey item for predatory organisms at higher trophic levels such as fish, seals and birds, and are considered to contribute significantly to the transfer of pollutants like metals to higher trophic levels (Ahn et al. 2009). Most studies on metal accumulation in sea urchins have focused on toxic effects on reproduction and embryo development using lab-based experiments (Geraci et al. 2004; Kobayashi and Okamura 2004, 2005; Gopalakrishnan et al. 2008), while few studies have targeted metal accumulation in natural populations (Bohn 1979; Ahn et al. 2009; Hernández-Almaraz et al. 2016).

In Greenland, environmental monitoring of the marine environment near mine sites has mainly been focused on mussels, seaweed and fish as monitoring organisms (Søndergaard et al. 2011a; Søndergaard 2013). Sea urchins have not previously been evaluated for this purpose despite high abundance in many places around Greenland. With the aim to extend the range of potential monitoring organisms suitable for environmental monitoring near Greenland mine sites, this study was initiated to evaluate the bioaccumulation potential of metals (including arsenic) in sea urchins (*Strongylocentrotus droebachiensis*) found near the former Black Angel lead-zinc mine in West Greenland, which is regarded as a heavily polluted area (Søndergaard et al. 2011a). A range of other environmental samples/parameters (seafloor sediment, dissolved metals in seawater, seaweed and mussels) were collected at the same sites as the sea urchins and analysed for comparison. Green sea urchins (*S. droebachiensis*) have a wide geographic distribution and are abundant in subtidal systems in the North Atlantic, the North Pacific and the Arctic Ocean (Lemire and Himmelman 1996; Ahn et al. 2009). Due to the widespread geographical abundance of green sea urchins and sea urchins in general, conclusions from this study are likely to have wider applications for the use of sea urchins as biomonitors of metal pollution, also in areas extending beyond the Arctic.

Methodology

Site description

The Black Angel mine at Maarmorilik in West Greenland, was in operation between the years 1973 to 1990. The ore consisted of lead (4%), zinc (12%) and silver (30 ppm) in the sulphide minerals galena and sphalerite in addition to mainly dolomite and pyrite. During the mining period, a total of 11 million tonnes ore was extracted resulting in 590,000 tonnes lead concentrate (i.e. consisting of 70% lead, 420 ppm silver) and 2,327,000 tonnes zinc concentrate (58%) (Thomassen 2003).

Tailings from the ore processing contained elevated concentrations of a range of metals, mainly iron (Fe), copper (Cu), zinc (Zn), arsenic (As), silver (Ag), cadmium (Cd), mercury (Hg) and lead (Pb). A total of 8 million tonnes of tailings was disposed in the small fjord Affarlikassaa (named the A-fjord from here on out). The A-fjord is partly separated from the outer fjord Qaamarujuk by a sill at the fjord mouth. Waste rock from excavation of the mine tunnels, which also contained elevated metal concentrations, was deposited on the mountain slopes. The largest of the waste rock dumps comprising roughly 400,000 tonnes of rock was partly removed in 1990 as part of the mine closure and placed on top of the tailings in the A-fjord in an effort to reduce the pollution. Both tailings and waste rock, as well as residues from the area of the mining town, turned out to be significant sources of pollution to the surrounding area (Johansen et al. 2010). Elevated concentrations of metals have been observed in seawater, sediment and a number of species in both the terrestrial and marine environment (Larsen et al. 2001; Elberling et al. 2002; Johansen et al. 2010; Søndergaard et al. 2011a; Søndergaard et al. 2011b; Sonne et al. 2014). More than two decades after mine closure, the area is still regarded as highly polluted (Søndergaard et al. 2014).

Sampling

Sampling was conducted at three stations with different distances to the mine (Fig. 1) in August 2017: Station 1 is located in the A-fjord in close vicinity to the mine;

station 2 and station 3 are located 5 km and 12 km away from the mine towards the open coast. Station 3 is regarded as a reference site with no or minimal impact from the mine.

Green sea urchins (c. 10 individuals per station) were collected at depths between 1 and 10 m using nets (either attached to a pole or dragged across the sea floor from a boat), put into polyethylene bags and frozen. In addition to sea urchins, samples of seaweed (*Fucus vesiculosus*) and blue mussels (*Mytilus edulis*) were collected from the same sites along with seafloor sediment and measurements of labile dissolved metals in the seawater. Blue mussels (c. 10 individual per site) and seaweed were collected from shore at low tide. For seaweed, the fresh growth tips (growth of the year) were cut from the rest of the plants using stainless steel scissors and sampled. A total of three replicate seaweed samples were collected from each site, each representing growth tips of c. 10 individuals. Sea bottom sediment was collected using an Ekman grab sampler and the upper c. 5-cm layer sampled from three different spots and pooled into one bag. Measurements of labile dissolved metal concentration in the seawater was done using DGT sampling devices (i.e. Diffusive Gradients in Thin films; www.dgtresearch.com) suspended in the water column c. 3 m above the bottom and deployed from 2 to 11 August 2017 using a buoy setup as described in Søndergaard et al. (2014).

Sample preparation

In the laboratory, the sea urchins were weighted and the shell (commonly referred to as the 'test') diameters measured (Table 1). The shells were then cut open and the gonads, and the viscera (i.e. the remaining soft parts) were carefully taken out using a plastic tweezer, put into separate polyethylene bags and weighted. Samples of sea urchins were collected on an individual basis. Blue mussels were divided into size groups according to their shell length and the 4–6-cm group were sampled for the purpose of the study. The soft part of the mussel was cut out from the shell using a stainless steel scalpel and pooled together into one bag. Subsequently, samples of sea urchins, seaweed and blue mussels were frozen, freeze dried and homogenized. Seafloor sediment was freeze dried using a ScanVac Coolsafe freeze drier and sieved to < 63 μm in size prior to analyses.

Chemical analyses

Freeze-dried subsamples of biota (c. 300 mg) were microwave-digested (Anton Paar Multiwave 3000) in Teflon bombs in 4 ml/4 ml Merck Suprapure HNO_3/MilliQ water. Freeze-dried subsamples of sediment (c. 200 mg) were digested in a mixture of 0.25 ml/0.75 ml/3 ml Suprapure HNO_3/HCl/HF in Berghof bombs at 120 °C for 4 h, then diluted with MilliQ water and the HF was neutralised by boric acid. DGT samplers were rinsed, dismantled and treated as described in Søndergaard et al. (2014). Digestion solutions were diluted with MilliQ water and analysed for 60+ elements of which eight selected elements representing the most important pollutants in the area are reported here: Fe, Cu, Zn, As, Ag, Cd, Hg and Pb. Analyses were performed using an Agilent 7900 ICP-MS. In addition, a Milestone Direct Mercury Analyzer (DMA-80) was used for analyses of Hg in seaweed and sediment due to their relatively low Hg concentrations. The analytical quality was checked by analysing blanks, duplicates and the certified reference materials (CRMs) DOLT-5, DORM-4 and TORT-3 (for biota) and MESS-4, PACS-2 and HISS-1 (for sediment). The recovery percentages for the CRMs were 82–107% for biota and 79–114% for sediment for the elements listed above. The detection limits for each element were set as three standard deviations (SD) on blank samples analysed along with the samples.

Data treatment

Element concentrations in gonads and viscera of the sea urchins were compared statistically between sites using a Student *t*-test in Microsoft Excel software. Also, element concentrations in gonads versus viscera were compared for all samples. Prior to the *t* test, an *F*-test was conducted to test the probability for equal variances in the data sets.

Dependence between element concentration and the shell diameter of the sea urchins was investigated at each site using linear regression analyses in Microsoft Excel software and the Linest function. Finally, the correlation between element concentrations in all the samples was investigated using the Linest function.

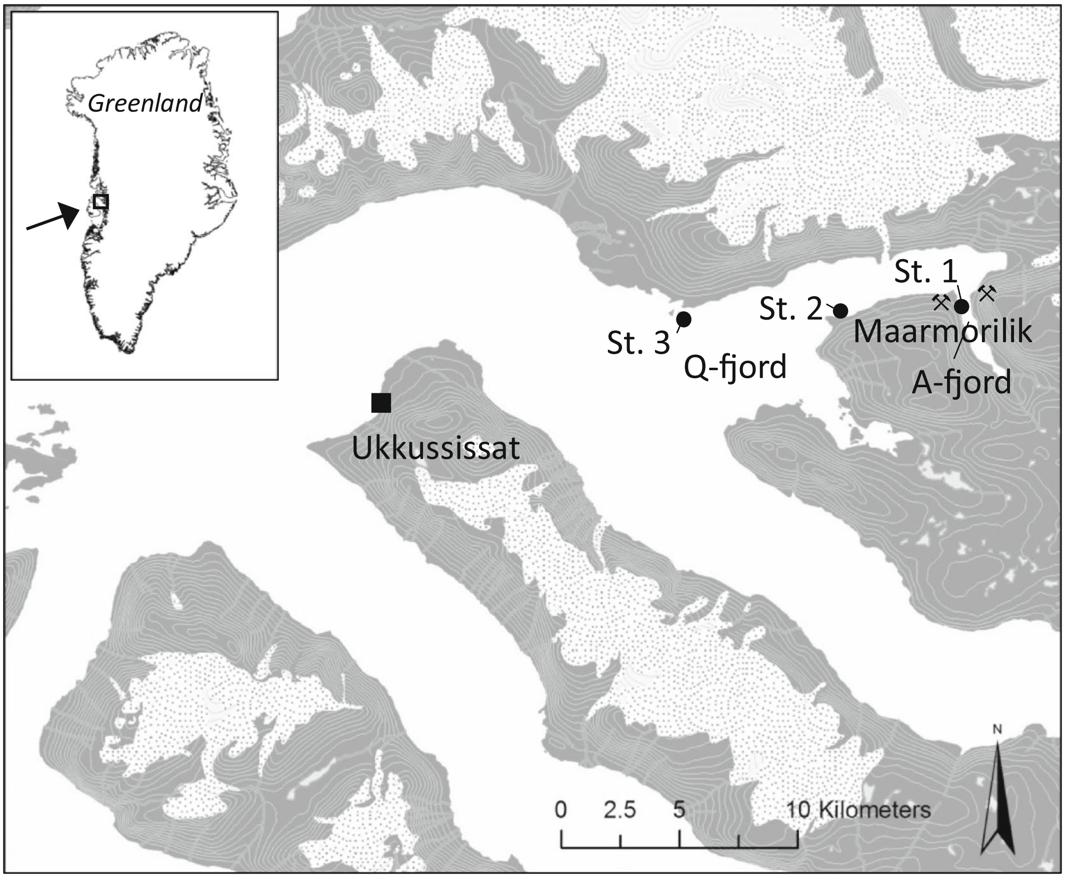

Fig. 1 Map of the area near the former Black Angel lead-zinc mine in Maarmorilik, West Greenland, and location of the three sampling stations. Station 1 is located at the mine site (most polluted) and station 2 and station 3 (reference) are located 5 and 12 km away, respectively. The location of the fjords Affarlikassaa (named the A-fjord) and Qaamarujuk (named the Q-fjord) is also shown

Results

Metal concentrations in viscera and gonads of green sea urchins

Concentrations of Fe, Cu, Zn, As, Ag, Cd, Hg and Pb in the viscera and gonads of green sea urchins from the three stations near the Black Angel mine are shown in Table 2. All elements were present in concentrations above the detection limit at all sites.

Concentrations of Fe, Cu, Ag and Pb were all significantly ($p < 0.05$) higher in the viscera compared with the gonads, whereas no significant differences were observed for Zn, As, Cd and Hg. For the viscera, concentrations of Fe, Cu, Zn, Ag, Hg and Pb were significantly higher in sea urchins at station 1, situated in close

Table 1 Number, shell diameter and weight of the green sea urchins (*S. droebachiensis*) sampled at the three sampling stations near the former Black Angel lead-zinc mine in Maarmorilik, West Greenland

	n	Diameter, range (mm)	Diameter, mean ± SD (mm)	Total wet weight (g)	Gonad wet weight (g)	Viscera wet weight (g)
Station 1	9	31-37	34 ± 2	11.4 ± 0.8	0.98 ± 0.46	2.61 ± 0.68
Station 2	9	35-59	40 ± 8	21.4 ± 17.4	1.22 ± 1.52	5.03 ± 6.39
Station 3	11	34-56	43 ± 6	27.8 ± 11.5	1.35 ± 0.95	6.02 ± 3.65

Table 2 Element concentrations (± one standard deviation (SD)) in the viscera and gonads of green sea urchins (*Strongylocentrotus droebachiensis*) at the three sampling stations near the former Black Angel lead-zinc mine in Maarmorilik, West Greenland. Below are corresponding element concentrations in seaweed growth tips (*Fucus vesiculosus*), blue mussels (*Mytilus edulis*), sea flour sediment and seawater (as measured by the DGT technique). Values for biota and sediment are in mg kg^{-1} dry wt. Seawater is in μg DGT-labile metal l^{-1}. *n* = number of samples.

	n	Fe	Cu	Zn	As	Ag	Cd	Hg	Pb
Sea urchins (viscera)									
Station 1	9	13400 ± 3560	14.3 ± 2.4	111 ± 34	7.49 ± 0.83	0.166 ± 0.037	0.52 ± 0.15	0.055 ± 0.010	34.9 ± 18.4
Station 2	9	3880 ± 3530	7.56 ± 2.53	74.4 ± 19.4	8.48 ± 2.06	0.128 ± 0.041	0.95 ± 0.22	0.045 ± 0.014	9.61 ± 7.96
Station 3	1	6750 ± 3250	8.68 ± 2.16	63.9 ± 14.0	7.79 ± 1.26	0.125 ± 0.042	0.74 ± 0.25	0.027 ± 0.006	5.45 ± 2.23
Sea urchins (gonads)									
Station 1	9	6610 ± 3860	10.2 ± 3.7	95.7 ± 35.1	6.59 ± 1.18	0.068 ± 0.034	0.37 ± 0.11	0.042 ± 0.014	14.2 ± 8.8
Station 2	9	2160 ± 3060	5.67 ± 2.61	73.8 ± 36.1	7.70 ± 1.80	0.089 ± 0.056	0.95 ± 0.43	0.048 ± 0.031	5.40 ± 6.88
Station 3	11	3730 ± 3000	5.21 ± 1.44	87.1 ± 67.8	7.73 ± 0.99	0.051 ± 0.023	0.53 ± 0.16	0.024 ± 0.006	2.71 ± 1.78
Seaweed									
Station 1	3	231 ± 82	2.04 ± 0.40	106 ± 2	60.5 ± 4.5	0.144 ± 0.004	0.858 ± 0.032	0.0046 ± 0.0003	1.64 ± 0.31
Station 2	3	423 ± 350	2.41 ± 0.74	26.4 ± 3.3	41.4 ± 2.0	0.133 ± 0.009	0.701 ± 0.083	0.0043 ± 0.0006	0.87 ± 0.30
Station 3	3	522 ± 267	3.22 ± 0.89	33.7 ± 7.1	41.0 ± 1.7	0.137 ± 0.016	0.709 ± 0.078	0.0072 ± 0.0011	1.13 ± 0.35
Blue mussels									
Station 1	1a	1190	9.31	233	12.2	0.056	3.392	0.135	80.1
Station 2	1a	879	14.5	141	9.46	0.021	1.945	0.127	27.7
Station 3	1a	1510	7.07	112	11.1	0.035	1.763	0.119	23.0
Seafloor sediment									
Station 1	1	64500	75.4	1410	40.5	1.360	4.907	0.538	2410
Station 2	1	29800	39.1	175	8.93	0.116	0.622	0.043	72
Station 3	1	21700	21.1	58	4.56	0.016	0.139	0.008	21
Seawater (DGT)									
Station 1	1	1.05	< 0.150	0.848	ND	< 0.001	0.020	ND	0.107
Station 2	1	0.908	0.305	1.48	ND	< 0.001	0.016	ND	0.059
Station 3	1	0.734	< 0.150	0.543	ND	< 0.001	0.014	ND	0.017

[a] Blue mussel samples were pooled samples of c. 10 individuals of 4–6 cm in length from each site. < xxx = < Detection limit (determined as 3 SD on blanks). *ND* not determined

vicinity to the mine, compared with sea urchins at station 3 that is regarded as a low-/unpolluted reference site (Table 2 and Fig. 2; $p < 0.05$). Also, concentrations of Hg were significantly ($p < 0.001$) higher in the viscera at station 2 compared with station 3. For the gonads, concentrations of Cu, Hg and Pb were significantly ($p < 0.01$) higher at station 1 compared with station 3. Concentrations of Hg were also significantly ($p < 0.05$) higher at station 2 compared with station 3. No significantly higher concentrations of neither As nor Cd in the viscera or gonads were observed at station 1 compared with station 3.

Within each site, the relation between element concentration in the gonads and viscera versus size (shell diameter) was investigated using linear regression statistics. In the gonads, no significant correlation was observed between element concentration and size for any of the elements. In the viscera, a significant ($p < 0.05$) positive correlation was only observed for Fe at station 1 ($r^2 = 0.53$) and for Cu and Pb at station 3 ($r^2 = 0.53$ and 0.43, respectively).

For all samples, correlations between elements in the viscera and gonads, respectively, were investigated using the linear regression statistics and the results are shown in Table 3. Generally, the viscera had a higher correlation between the elements than the gonads. In the viscera, Fe, Cu, Zn, Ag and Pb all showed a high

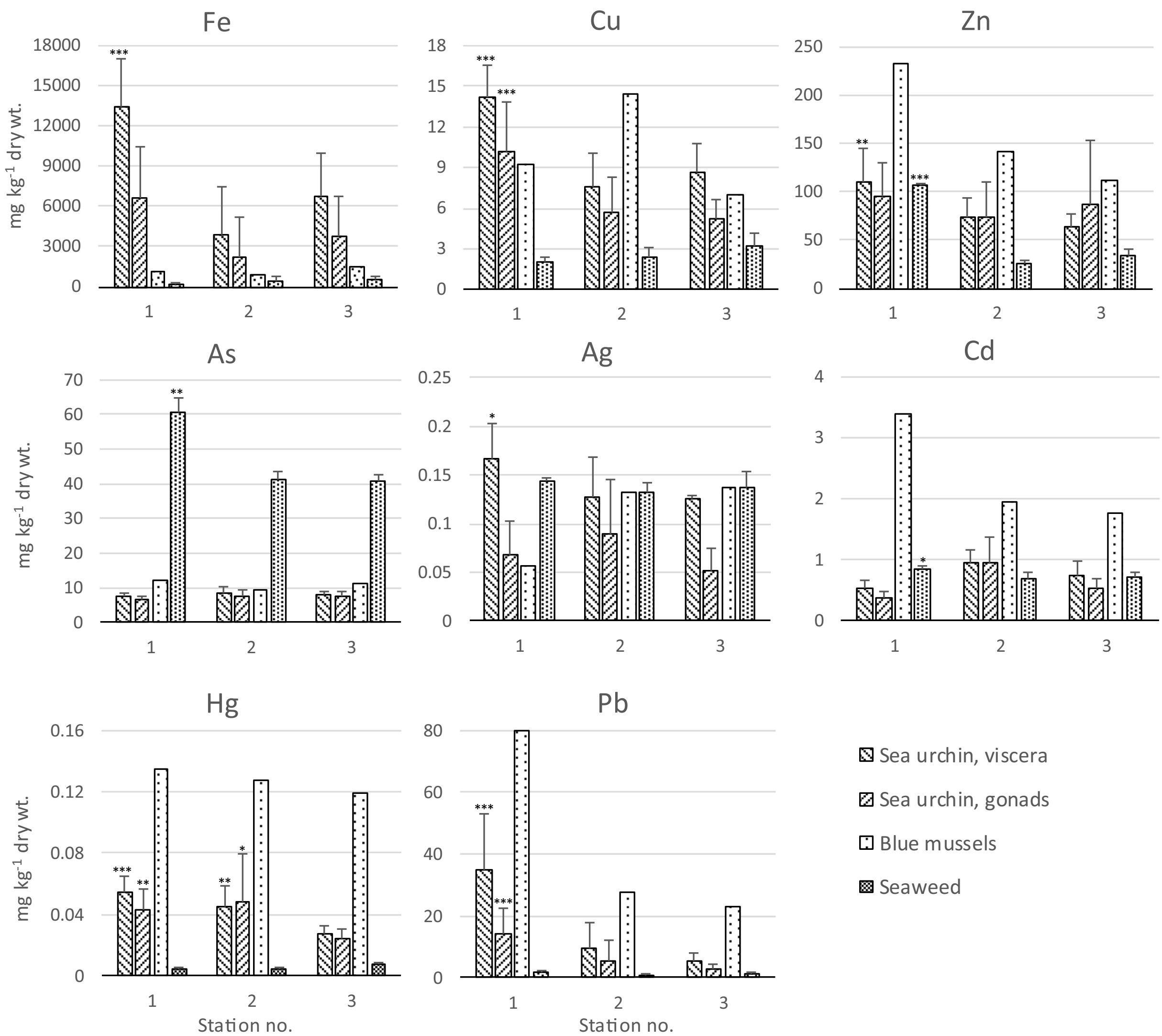

Fig. 2 Element concentrations (+ one standard deviation) in the viscera and gonads from green sea urchins (*Strongylocentrotus droebachiensis*), soft parts of blue mussels (*Mytilus edulis*) and growth tips of seaweed (*Fucus vesiculosus*) at 3 sampling stations near the former Black Angel lead-zinc mine in Maarmorilik, West Greenland. Asterisks above the element concentration in sea urchin viscera and gonads or seaweed at station 1 or station 2 indicate that the concentration of that element was significantly higher (*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$) compared with station 3 used as a reference site. For blue mussels, only one composite sample was analysed per station, which did not allow for a statistical comparison between sites.

correlation with each other ($r^2 = 0.34$–0.84; $p < 0.001$). In the gonads, Fe, Cu and Pb ($r^2 = 0.63$–0.68; $p < 0.001$) and Cd and Hg ($r^2 = 0.35$; $p < 0.001$) showed a high correlation with each other.

Metal concentrations in green sea urchins compared with other environmental samples

Concentrations of Fe, Cu, Zn, As, Ag, Cd, Hg and Pb in seaweed, blue mussels, seafloor sediment and seawater from the three stations near the Black Angel mine are shown in Table 2. Seafloor sediment showed a clear gradient in concentrations of all the elements with concentrations decreasing from station 1 to station 2 to station 3. For seawater, dissolved labile element concentrations as measured by the DGT technique showed a less pronounced gradient in metal concentrations during the measurement period compared with seafloor sediment. For example, dissolved labile Pb in

Table 3 Correlation matrix (r^2 values) between elements in the viscera and gonads of green sea urchins (*Strongylocentrotus droebachiensis*) collected from 3 sites near the former Black Angel lead-zinc mine in Maarmorilik, West Greenland

Viscera								
Fe	–							
Cu	0.84***	–						
Zn	0.35***	0.42***	–					
As	0.10	0.03	0.02	–				
Ag	0.11	0.16*	0.42***	0.00	–			
Cd	0.31**	0.24**	0.01	0.06	0.03	–		
Hg	0.04	0.15*	0.33**	0.02	0.16*	0.01	–	
Pb	0.54***	0.54***	0.80***	0.03	0.34***	0.09	0.30**	–
	Fe	Cu	Zn	As	Ag	Cd	Hg	Pb
Gonads								
Fe	–							
Cu	0.68***	–						
Zn	0.03	0.01	–					
As	0.01	0.00	0.09	–				
Ag	0.00	0.02	0.02	0.02	–			
Cd	0.03	0.01	0.01	0.18*	0.24**	–		
Hg	0.02	0.18*	0.01	0.19*	0.12	0.37***	–	
Pb	0.67***	0.63***	0.06	0.00	0.04	0.01	0.07	–
	Fe	Cu	Zn	As	Ag	Cd	Hg	Pb

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

seawater decreased only by a factor of six from 0.107 to 0.017 μg l^{-1} from station 1 to station 3 whereas Pb in seafloor sediment decreased by a factor of more than 100 from 2410 to 21 mg kg^{-1}. The other metals measured as dissolved labile metals in the seawater showed either a smaller gradient than Pb or no decreasing concentration gradient.

Concentrations of elements observed in the viscera and gonads of green sea urchins at the 3 stations are shown in Fig. 2 along with corresponding element concentrations in blue mussels and seaweed. Blue mussels and seaweed are used as key monitoring species near mines in Greenland. Compared with blue mussels, sea urchins contained more Fe and Ag but less Zn, Cd, Hg and Pb. Concentrations of Cu and As were at approximately the same level in sea urchins and blue mussels. Compared with seaweed, sea urchins contained more Fe, Cu, Zn, Hg and Pb but less As. Concentrations of Ag and Cd were at approximately the same level in sea urchins and seaweed.

Discussion

Green sea urchins as potential biomonitors of metal pollution in Greenland

The results show that green sea urchins accumulated Fe, Cu, Zn, Ag, Hg and Pb in highest concentrations at the most polluted station (station 1) closest to the mine site. Concentrations of these metals were clearly elevated in seafloor sediment at this station and are considered pollutants directly related to the mining activities. This shows that green sea urchins can be used as biomonitors of pollution, at least for dispersion and biological uptake of these metals. No consistent significant correlation between concentrations of the metals and size of the sea urchins was observed. A significant correlation was observed between Fe concentrations in the viscera and size at station 1 and Cu and Pb concentration in the viscera and size at station 3. However, this correlation was not consistent between stations. This indicates that it is not critical to account for potential size differences in the sea urchins, at least not for the size interval in this study (shell diameter range of 31–59 mm). A significant correlation between Fe, Cu, Zn, Ag and Pb in the viscera of the sea urchins from all sites indicates that these metals both come from the same source and are subject to the same degree of metabolic regulation (or lack thereof) within the sea urchins. Compared with concentrations in similar species of sea urchins reported in Bohn (1979) and Ahn et al. (2009) and shown in Table 4, concentrations of Cu, Zn, As and Cd were within or near the same range, whereas concentrations of Fe and Pb in this study were much higher. The Bohn (1979) study was conducted near a Pb/Zn ore deposit area on Baffin Island in Canada, and the Ahn et al. (2009) study was carried out in Kongsfjorden, Svalbard in Norway, which is an area with relatively low metal levels currently used as a reference site for Arctic climate variability. For Fe, concentrations up to 18,400 mg kg^{-1} dry wt. were measured in green sea urchins in this study in comparison with concentrations up to 845 mg kg^{-1} dry wt. in Bohn (1979). For Pb, concentrations up to 77 mg kg^{-1} dry wt. were measured in this study in comparison with concentrations up to 0.49 mg kg^{-1} dry wt. in Ahn et al. (2009). These differences in Fe and Pb concentrations are considered to be caused by the high levels of Fe and Pb in the environment near the Black Angel mine and by a limited ability of the green sea urchins to regulate these elements.

Higher concentrations of Fe and Pb and most other elements in the visceral mass compared with the gonads in the sea urchins may indicate that significant metal amounts are taken up via the diet (Ahn et al. 2009). Higher concentrations in the viscera could also be influenced by partially digested stomach and intestine contents, which could overestimate the metal concentration of the tissue. Sea urchins are known to feed primarily on macro-algae (seaweed) (Lemire and Himmelman 1996; Hernández-Almaraz et al. 2016). However, the gradient in accumulated Fe, Cu, Zn, Hg and Pb in sea urchins in this study did not reflect a similar gradient of these metals in *F. vesiculosus* seaweed. A similar lack of correlation between metal concentrations in green sea urchins and seaweed was also observed in Ahn et al. (2009). Ahn et al. (2009) hypothesised the presence of other pathways of metal transfer to the sea urchins than algae, more specifically metal-laden lithogenic particles coming from glacial run-off. This study supports the hypothesis by Ahn et al. (2009) that transfer of metals from metal-laden particles within the habitat of the green sea urchins plays an important role for bioaccumulation of metals in the sea urchins. The food availability was assumed to be approximately the same at the 3 stations since the sea urchins were equally abundant. Spatial variations in element concentrations near anthropogenic pollution sources in other species of sea urchins (i.e. *Paracentrotus lividus* and *Lytechinus variegatus*) have been investigated in recent studies (Scanu et al. 2015; Alves et al. 2018; Rouane-Hacene et al. 2018; Ternengo et al. 2018). In those studies, elevated concentrations of a number of elements were observed near pollutions sources and those species were proposed as biomonitors for the elements Fe, Cu, Zn, As, Cd and Pb (and for additional elements not included in this study).

Blue mussels and seaweed (*Fucus* spp.) are widely used as key monitoring organisms for mining pollution in Greenland due to their ability to bioaccumulate pollutants such as metals from different sources and their widespread geographical abundance (Søndergaard et al. 2014). Bioaccumulation of metals in suspension feeders such as blue mussels can be considered a proxy for metals dissolved in the seawater and metals bound to particles suspended in the water column that is ingested by the mussels (Rainbow 1995). Bioaccumulation of metals in algae such as seaweed can be regarded as a proxy for the metals dissolved in the seawater only (Rainbow 1995). Sea urchins being mainly herbivores can take up metals dissolved in the seawater and metals contained the diet (mainly algae) and presumably also metals bound to particles that is ingested. Bioaccumulation of metals in sea urchins can therefore be considered a proxy for the metal loading from these sources. In terms of metal sources, the metal accumulation in sea urchin is therefore considered closely related to those of the blue mussels since they exist in approximately the same habitat. Compared with blue mussels, green sea urchins were found to accumulate less Zn, As, Cd, Hg and Pb per weight unit but more Fe (and Cu and Ag at some sites). Green sea urchin may therefore potentially be less sensitive as monitoring/indicator organisms for measuring changes of bioavailable Zn, As, Cd, Hg and Pb loading in the environment compared with blue mussels but potentially more sensitive to detect changes of Fe, Cu and Ag loading. Specifically, green sea urchins showed a significantly higher Fe, Cu and Ag loading at the mine site, which was not reflected in the blue mussels, presumably due to the blue mussel's ability to regulate the Fe, Cu and Ag. For most metals of environmental importance (Zn, Cd, Hg and Pb), blue

Table 4 Comparison of the range in element concentrations (mg kg^{-1} dry wt.) in *Strongylocentrotus* spp. in this study with values for the same sea urchin species from other Arctic areas.

Element	This study		Ahn (2009)		Bohn (1979)	
	Gonad	Viscera*	Gonad	Whole tissue	Gonad	Whole tissue
Fe	276–13100	275–18400	32–133	80–582	185–285	305–845
Cu	2.3–14	4.0–18	1.2–3.3	1.7–3.9	3.3–9.0	2.4–3.3
Zn	31–248	40–185	20–134	26–120	96–184	29–39
As	4.7–10	5.2–12	8.2–24	9.0–26	6.8–16	3.4–4.2
Ag	0.01–0.20	0.06–0.23	–	–	–	–
Cd	0.23–1.8	0.34–1.4	0.52–1.6	0.78–2.8	0.9–1.5	1.2–1.8
Hg	0.02–0.12	0.02–0.08	–	–	–	–
Pb	0.33–33	2.7–77	0.03–0.08	0.06–0.49	–	–

*Viscera: whole tissue minus the gonad

– not available

mussels are considered a more sensitive biomonitor species than green sea urchins. However, blue mussels are not always abundant near mine sites in Greenland and sea urchins are more abundant than blue mussels at some sites. Consequently, green sea urchins may potentially serve as a valuable biomonitor and component in monitoring programmes, especially if suspension feeders such as blue mussels do not exist at the monitoring site.

Conclusion

This study shows that green sea urchins accumulate selected metals in both the gonads and viscera and can be used as a monitoring organism for mining pollution depending on the metals of concern. However, the results also show that sea urchins are less likely to reflect small environmental changes in metal loading for most metals compared with suspension feeders such as blue mussels. Green sea urchins are widely abundant in both temperate and arctic waters and may be a valuable supplement to traditional key monitoring species in environmental monitoring programmes, e.g. near mining areas in Greenland. This is especially relevant if suspension feeders such as blue mussels are not present at the monitoring site.

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