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Beach-cast as biofertiliser in the Baltic Sea region-potential limitations due to cadmium-content

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ABSTRACT

Macroalgal mass blooms and accumulating beach-cast are increasing problems in many coastal areas. However, beach-cast is also a potentially valuable marine bioresource, e.g. as a biofertiliser in coastal agriculture. One limiting factor in use of beach-cast as a fertiliser is uncertainty regarding the cadmium (Cd) concentration depending on beach-cast composition and location. In this study, chemical analyses were performed on beach-cast from Burgsviken Bay off Gotland, in the Baltic Sea. The results revealed large variations in cadmium concentration depending on sampling location and beach-cast composition, with levels ranging between 0.13 and 2.2 mg Cd/kg dry matter (DM). Of 15 beach-cast samples analysed, one had a cadmium content above the Swedish statutory limit for sewage sludge biofertiliser (2 mg Cd/kg DM) and four had values above the limit suggested by the Swedish Environmental Protection Agency for 2030 (0.8 mg/kg DM). Species-specific analysis revealed that eelgrass (*Zostera marina*) contained significantly higher cadmium concentrations than filamentous red algae species (*Ceramium* and *Polysiphonia* spp.). Avoiding eelgrass-rich beach-cast by seasonal timing of harvesting and monitoring differences in cadmium concentrations between harvesting sites could thus facilitate use of beach-cast as biofertiliser.

1. Introduction

An increasing number of macroalgal mass blooms have been reported around the world, causing changes in food webs and loss of ecosystem functions and ecosystem services (Andersen et al., 2017; O'Neill et al., 2015; Potter et al., 2016; Xing et al., 2015). At the same time, attention is turning to the potential of marine bioresources as a possible solution in meeting predicted future demand for fuels, food and raw materials (Burgess et al., 2018; Duarte et al., 2009; Gentry et al., 2017; Wei et al., 2013). It has been suggested that food, energy and material production and flows need to be more resource-efficient, by releasing fewer nutrients and less carbon dioxide (Kennedy et al., 2015; Rockström et al., 2017). Food production systems today are dependent on fossil fuels and linear flows of nutrients, which result in large amounts of nutrients being transported from land to sea. This nutrient load leads to eutrophication, changes in environmental conditions and possibly also abrupt changes in marine biota. The Baltic Sea is a living example of how marine systems can change due to several decades of increased nutrient load. During the twentieth century, the total nitrogen load to the Baltic Sea increased by about three-fold and the total phosphorus load increased by about five-fold. As a result, biological production in Baltic Sea water has doubled, water transparency has decreased and anoxic conditions and deposition of anoxic sediments on the sea floor have increased (Kautsky and Kautsky, 2000). Abundance of the key macroalgae species in the Baltic Sea, bladderwrack (*Fucus vesiculosis*), has declined, while abundance of opportunistic filamentous algae species such as *Ceramium* spp. and *Polysiphonia* spp. has increased (Isæus et al., 2004; Kautsky and Kautsky, 2000; Risén et al., 2014). Long-term reductions in total nutrient load to the Baltic Sea have been achieved during the last 30 years but, due to accumulated effects, recovery processes in the Baltic Sea are slow, although some improvements have been reported (Andersen et al., 2017).

One specific side-effect of eutrophication is the occurrence of blooms of macroalgae and other macrophytes, resulting in piles of decaying biomass along the coastline (so-called beach-cast). Recent studies have examined the bioresource potential of beach-cast and the ecosystem services affected (mainly positively, but some negatively) along Swedish coastlines through harvesting and managing beach-cast biomass (Blidberg and Gröndahl, 2012; Risén et al., 2013, 2014, 2017). On the Swedish island of Gotland in the Baltic Sea, use of beach-cast has been very important over centuries for improving the nutrient status and overall quality of agricultural soils (Eskeröd, 1962; Linné, 1741).

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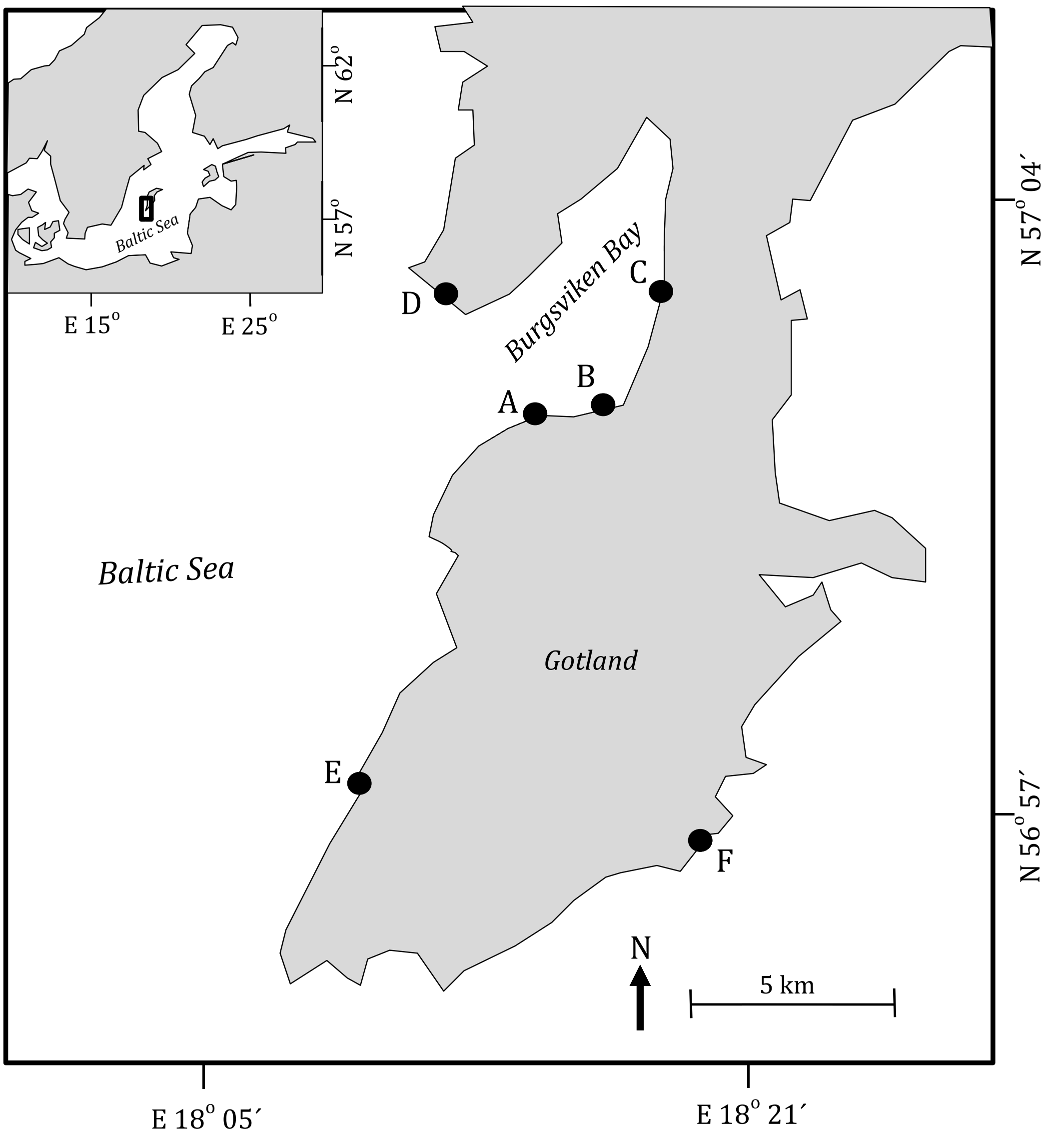

Fig. 1. Sampling sites in southern Gotland. Sites A-D in Burgsviken Bay; A (Valar), B (Burgsvik Port), C (Käldehagen), D (Näsudden). Reference site E is located in Kettelvik, 12 km south of Burgsvik; and reference site F in Holmhällar, 12 km south-east of Burgsviken (only used for species-specific sampling).

This practice was once particularly important in the north and south of the island, where the soils are naturally dry and nutrient-poor, as seaweed compost contributes structure and nutrients and increases the water retention properties of the soil. The use of beach-cast fertiliser more or less ceased with the introduction of mineral fertiliser during the 1950s. Today, the piles of decomposing beach-cast on beaches are a nuisance for local residents and visiting tourists. There is also growing demand for biofertiliser among farmers, sparking an interest in exploiting the beach-cast biomass that accumulates on Gotland. One simple solution (in line with traditional agricultural practices on Gotland) is to use the beach-cast as a fertiliser and soil conditioner in fields near the beaches. In a study in Trelleborg, south-west Sweden, local residents showed strong willingness-to-pay for non-market values of cleaning the beaches and using the beach-cast as a bioresource (Risén et al., 2017). In the Burgsviken Bay area of south-west Gotland, a local initiative called 'Save Burgsviken Bay' was started in 2011 by a non-government organisation called *Forum Östersjön*, together with local residents, to work on recovery/protection of the bay from eutrophication impacts. Several hands-on projects were initiated to reduce total nutrient pressure from the surroundings of the bay and restore marine and coastal habitats within the area. One of the projects involved removal of beach-cast from the beaches and using it as a fertiliser in agricultural fields or in energy crop (*Salix* spp.) plantations (Larsson, 2016).

However, the use of beach-cast as fertiliser also poses some severe challenges. One is uncertainty about the cadmium (Cd) level in the beach-cast. Cadmium can cause endocrine malfunctions in humans and is also a known carcinogen linked to certain types of cancer (Pan et al., 2010). A recent plan for reducing cadmium accumulation in European soils suggests regulating the maximum permitted cadmium concentration per kg phosphorus (P) in all mineral fertilisers. The new rules, if implemented, would initially permit a total cadmium level of 60 mg Cd/kg P in phosphorus fertilisers, but the limit would then be lowered to 40 mg/kg P after three years and 20 mg Cd/kg P after nine years (Smolders, 2017).

The goal of both the EU and Sweden is to lower the cadmium content in agricultural soils in the future. The cadmium content in the Baltic Sea has been strongly affected over time by anthropogenic sources such as industry and agriculture (Lodenius, 2016). It is well known that algae and submerged vascular plant species can accumulate cadmium and other heavy metals (Bonanno and Orlando-Bonaca, 2018; Lyngby and Brix, 1982). A study on the north-east coast of Öland, an island in the southern Baltic Sea, showed relatively high cadmium content in beach-cast and also in edible plants grown in beach-cast compost (Greger et al., 2007). Those authors concluded that use of beach-cast compost for agricultural crops destined for direct human consumption should be avoided. However, that study represented only a snapshot of cadmium content in beach-cast on Öland, while much of the rest of the Baltic Sea region has not been investigated and thus there is a lack of general information on cadmium content in Baltic biomass (see Bisther, 2015) and variables that may affect cadmium content. Understanding the limitations of beach-cast and exploring methods to overcome these will enable its use as a fertiliser, supporting local communities and agriculture with local, sustainable fertilisers.

This study was performed in Burgsviken Bay off Gotland in the Baltic Sea, to examine cadmium content in beach-cast and potential use of beach-cast as a biofertiliser in the Burgsviken Bay area. The objectives of this study were to examine the cadmium content of beach-cast along the coastline of Burgsviken Bay (1) and to analyse the contribution of different macrophyte species to the cadmium content in beach-cast at the study site (2).

2. Materials and methods

2.1. Site description

The study area of Burgsviken Bay off Gotland is located in the centre of the Baltic Sea (Fig. 1), where the average ocean salinity is about 7 ppu (Feistel et al., 2010). The bay is 9 km long and 4 km wide with a total shoreline of 19 km, an average depth of 2–4 m and a maximum depth of 7 m in the centre of the bay. A soft benthic habitat dominates, but the sediments vary from mud, sand or silt to stones. The total catchment area is 32.2 km^2, stretching from the coastline towards the centre of the island in mostly agriculture-dominated land. Most human settlements in the area are situated along the inner eastern coast of the bay, in and between the small villages of Burgsvik and Fide (Fig. 1).

The selection of sampling sites was based on two criteria: i) Beach-cast harvesting had to be possible (reachability, sediments, slope etc.); and ii) the sites had to represent a geographical range from the inner, more sheltered part of the bay to more exposed sites closer to the mouth of the bay (Sites A-D, Fig. 1). Reference sites outside the bay were used for comparisons with the sites in the bay. One reference site (site E) was used for species mixture sampling conducted in 2015. Two reference sites (site E and site F) were used for species-specific sampling conducted during 2016. Site F was added due to the great variation in cadmium concentration observed in the beach-cast samples from 2015. Both these reference sites have a historical record of beach-cast harvesting and both are located on the peninsula Sudret at the southern tip of Gotland, site E (Kettelvik) on the west coast and site F (Holmhällar) on the east coast.

2.2. Spatial variability in cadmium in beach-cast species mixtures

Beach-cast containing a mixture of natural species was collected for chemical analyses in October 2015 at sites A-D and reference site E (Fig. 1). At each site, three beach-cast samples were collected from three randomised 1 dm^2-plots along the outermost part of the beach-cast pile, closest the sea (freshest beach-cast). Samples containing approximately 1 dm^3 of macrophyte tissue were collected (≅ 0.375 kg fresh weight ≅ 0.075 kg dry weight). The analytical laboratory used 1 g of dried tissue from each sample for the chemical analysis (see detailed description below). Average spatial coverage of four species/groups of species was estimated as percentage abundance for each sampling plot by visual estimation by two independent observers. The four species/species groups represented those most commonly found in the area: the vascular species eelgrass (*Zostera marina*), the common red algae *Furcellaria lumbricalis*, filamentous red algae as a group (including *Polysiphonia* spp. and *Ceramium* spp.) and a lumped group including less frequent algae and plants such as *Fucus vesiculosis*, *Cladophora glomerata* and *Potamogeton pectinatus.*

2.3. Cadmium accumulation in macrophytes

Samples from five different species/species groups of macrophytes abundant in beach-cast were collected during September 2016 at sites A-D and reference sites E-F in or close to the Burgsviken Bay area (see Fig. 1). Differences in macrophyte abundance in the beach-cast banks resulted in variations in the number of samples collected per species. Sampling covered the three main species/species groups *Zostera marina* (n = 15), *Furcellaria lumbricalis* (n = 5) and filamentous red algae (n = 9), as well as *Fucus vesiculosis* (n = 4) and *Potamogeton pectinatus* (n = 4).

To examine cadmium accumulation in different tissue parts of *Zostera marina*, three individual plants were collected (one at each of the sites A (Valar), B (Burgsviken Port) and C (Käldehagen) (see Fig. 1). Aboveground biomass (leaves) and belowground biomass (roots and rhizomes) were assessed by separating the plants into two fractions, leaves and rhizomes with roots.

2.4. Chemical analysis

All chemical analyses were performed by the accredited laboratory Eurofins Environment Sweden AB (Lidköping, Sweden. Macrophytes samples were mixed into a slurry of which 5–8 gr were collected and weighed to register fresh weight. Dry mass was then calculated according to standards (SS-EN 12880:2000) after drying in an oven for 20 h at 105 °C. For the cadmium analysis, samples were dried at 40 °C and homogenized before weighing. For analysis 0.9 gr of the sample was collected and digested with 8 ml HNO_3 and 2 ml H_2O_2 in a microwave at 180 °C for 20 min. Cadmium analysis was then conducted by inductively coupled plasma–mass spectrometry technique (ICP-MS, methodological reference NMKL No. 161 1998 mod./ICP-MS).

Kjeldahls nitrogen was analysed using 1.4 gr of slurry and following the treatment from instructions for the standard SS-EN 13342 using Kjetab catalyst and sulfuric acid in a Kjeltec Auto Analyzer. Samples for phosphorus analysis was prepared over 30 min using a multi shaker set at 1800 rpm. For each sample between 2 and 5 gr of the slurry was used and water was added to a total volume of 25 ml. After shaking and filtering the samples were analysed by KONE instrument according to reference method SS-EN ISO 6878: 2005. Measurement uncertainty for the different analyses was estimated as follows: DM (10%), Cd (20%), N (10%), P (15%). Uncertainty levels was calculated based on 10 repeated measurements per sample.

2.5. Statistical analysis

All statistical analyses were performed using the IBM SPSS Statistics 24 software. Non-parametric statistical methods were used because of non-normally distributed data and small sample size. For analyses of overall differences in cadmium content in beach-cast mixture samples from different locations, Kruskal-Wallis analysis was used. For analysis of correlations between inventoried abundance of species/species groups in the mixture and the cadmium content in these mixtures, Spearman rank correlation was used. Wilcoxon's paired rank test was used to compare the cadmium content in filamentous red algae and eelgrass (*Zostera marina*) based on data obtained in the cadmium analyses of specific macrophytes.

3. Results

3.1. Spatial variability in cadmium and nutrients in beach-cast

All beach-cast samples except one (A1, Valar) showed cadmium levels below the current Swedish permissible level of 2 mg Cd/kg DM

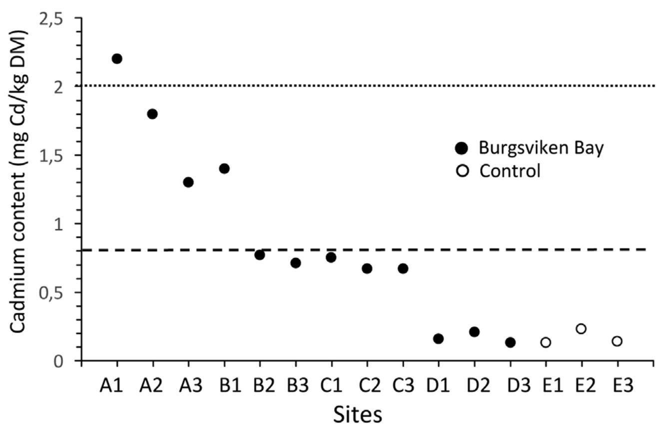

Fig. 2. Cadmium content in beach-cast collected at sites A-E in southern Gotland. The dotted line indicates the current Swedish limit on cadmium in biofertiliser/sewage sludge (SFS, 1998:944). The dashed line indicates the Swedish EPA suggested cadmium level for biofertiliser/sewage sludge by 2030 (Swedish-EPA, 2013).

for sewage sludge as biofertiliser (SFS 1998: 944) (Fig. 2).

Eleven of the 15 samples had also values below 0.8 mg Cd/kg DM, which is within the long-term limit proposed by the Swedish Environmental Protection Agency (EPA) for the year 2030. Although most samples showed relatively low cadmium levels there was large variation between sites, with high levels at site A (1.3–2.2 mg Cd/kg DM), intermediate levels at sites B and C (0.67–1.4 mg Cd/kg DM) and low levels at site D (0.13–0.21 mg Cd/kg DM). The reference site E outside Burgsviken Bay also showed low values (0.13–0.24 mg Cd/kg DM). The difference in cadmium levels between sites was significant according to the Kruskal-Wallis test, independent of whether a reference site was included in the analysis (all sites A-E, $p = 0.015$, adjusted $H = 12.302$, $df = 4$; sites A-D (reference site excluded) $p = 0.023$, adjusted $H = 9.55$, $df = 3$).

The phosphorus level in fresh beach-cast samples varied between 1700 and 3400 mg/kg dry matter (DM), and the nitrogen level varied between 13000 and 38000 mg/kg DM. Regarding cadmium/phosphorus mass ratio, only two of the 15 samples were found to be below the recently suggested maximum level of 60 mg Cd/kg P for chemical fertiliser (Smolders, 2017). Chemical fertiliser was chosen for comparison, since there is currently no statutory permissible level for beach-cast biofertiliser. The six samples with the lowest Cd/P mass ratio were found at site D and the reference site E (Table 1). The other nine

Table 1
Concentrations of phosphorus (P), nitrogen (N), cadmium (Cd) and dry matter (DM) and Cd/P mass ratio in beach-cast collected at sites A-E in the Burgsviken Bay area of Gotland in the Baltic Sea. *Reference site E.

Site	P	N	Cd	Cd/P ratio	Dry matter
	(mg/kg DM)	(mg/kg DM)	(mg/kg DM)	(mg Cd/kg P)	[%]
A1	3400	33000	2.2	647	9.8
A2	3500	38000	1.8	514	7.2
A3	3700	31000	1.3	351	13.3
B1	2400	20000	1.4	583	35
B2	2200	29000	0.77	350	7.6
B3	2000	21000	0.71	355	19.7
C1	1600	13000	0.75	469	45
C2	2100	16000	0.67	319	45.1
C3	1700	16000	0.67	394	41.8
D1	2600	34000	0.16	61	20.7
D2	2600	31000	0.21	80	24.1
D3	3300	32000	0.13	39	20.3
E1*	1900	25000	0.13	68	23.9
E2*	2100	28000	0.23	109	20.5
E3*	3000	24000	0.14	47	22.2

Table 2
Spearman rank correlation coefficient (ρ) between cadmium (Cd) concentration, Cd to phosphorus mass ratio (Cd/P) and abundance of different algae species/species groups. Probability values and level of significance are also shown (*$P < 0.05$, **$P < 0.01$).

Species/Species group	Cadmium		Cd/P	
	ρ (Rho)	*P*	ρ	*P*
Zostera marina	0.442	0.099	0.581	**0.023***
Red algae	- 0.353	0.197	- 0.102	0.718
Furcellaria lumbricalis	- 0.64	**0.010***	- 0.664	**0.007****
Lumped group of species	0.462	0.083	0.229	0.411

samples from the three remaining sites A-C in Burgsviken Bay all showed relatively high Cd/P mass ratio of between 319 and 647 mg Cd/kg P (Table 1).

The concentrations of cadmium in beach-cast showed some significant correlations with abundance of different species/species groups at the collection site (Table 2). High abundance of *Furcellaria lumbricalis* was correlated with low cadmium levels in beach-cast, while high abundance of *Zostera marina* was positively correlated with high cadmium content in beach-cast. For the red algae group and the lumped species group, the plots were scattered and showed no correlation between species abundance and cadmium concentrations in beach-cast.

All sampling plots with high abundance of *Zostera marina* showed relatively high cadmium/phosphorus mass relationship (> 300 mg Cd/kg P). Sampling sites with low estimated abundance of *Zostera marina* had in general low Cd/P values.

3.2. Cadmium levels in macrophyte species/species groups

The average cadmium level was higher in *Zostera marina* samples (median 2.1 mg/kg DM) than in the red filamentous algae group, *Potamogeton pectinatus, Fucus vesiculosis and Furcellaria lumbricalis* (median 0.25 mg/kg DM) (Fig. 3). In general, the cadmium levels in *Zostera marina* exceeded the permissible level of 0.8 mg Cd/kg DM proposed by the Swedish-EPA (2013) for 2030 and some individual samples also exceeded the current Swedish limit for sewage sludge biofertiliser of 2 mg Cd/kg DM. All other groups showed low values of cadmium. *Zostera marina* samples had significantly higher cadmium levels than the filamentous red algae-group in direct comparisons by Wilcoxon's paired rank test ($z = 2.023$, $p = 0.043$; based on average values from sites A, B and D-F because filamentous red algae were

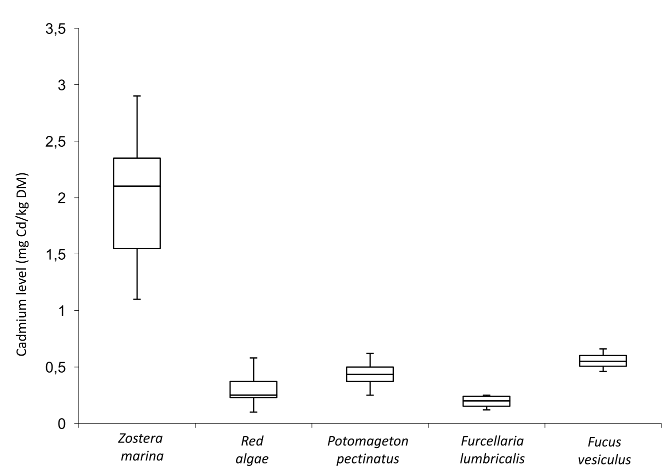

Fig. 3. Cadmium content in macrophytes collected at Burgsviken Bay, Gotland. Boxes show 75% confidence interval and median, error bars indicate min-max values.

Table 3
Cadmium concentration in leaves and rhizomes of *Zostera marina* from site sites A (Valar), B (Burgsviken Port) and C (Käldehagen).

t	A	B	C	Mean
Leaves (mg Cd/kg DM)	1.9	2.2	1.6	1.9
Rhizomes (mg Cd/kg DM)	0.42	0.57	0.49	0.49

absent at site C).

Additional analysis of tissues from three *Zostera marina* plants indicated that all samples of leaf tissue had a higher cadmium content (average 1.9 mg/kg DM) than the rhizome tissue samples (average 0.49 mg/kg) (Table 3), although the small sample size (n = 3) precluded statistical analysis.

4. Discussion

Chemical analyses of beach-cast from the Burgsviken Bay area revealed large variations in cadmium content between different samples and different sites. Most samples (14 out of 15) were found to contain concentrations below the current Swedish permissible level of 2 mg Cd/kg DM for sewage sludge biofertiliser. The cadmium to phosphorus mass ratio was found to be relatively high on average, with only two out of 15 samples being below the proposed (not yet accepted) permissible ratio for fertilisers (60 mg Cd/kg P) (Smolders, 2017). Low cadmium levels were found in samples from site D (Näsudden) on the outer side of the bay and in samples from reference site E (also an exposed site). The abundance of *Zostera marina* seemed to be related to high cadmium concentrations and high Cd/P mass ratio in beach-cast, while *Furcellaria lumbricalis*-rich beach-cast had low Cd/P ratio and low cadmium levels.

The relationship between species composition and cadmium concentrations in beach-cast was confirmed by the results of chemical analyses of separate species/species groups, where both filamentous red algae and *Furcellaria lumbricalis* showed low cadmium levels. *Zostera marina* samples, on the other hand, had high concentration of cadmium, which explains why high abundance of *Zostera marina* in the beach-cast species mixture in general gave a higher concentration of cadmium.

An earlier study at Bödabukten on the east coast of Öland (about 80 km west of Burgsviken Bay) showed high concentrations of cadmium in algae beach-cast species, e.g. 1.1–3.2 mg Cd/kg DM for *Furcellaria lumbricalis* and 4.3–4.7 mg Cd/kg DM for *Polysiphonia* (Greger et al., 2007). That study also found that vegetables grown in algae beach-cast had a high cadmium content, leading to the conclusion that beach-cast/algae compost should only be used mixed with other fertilisers as manure and only for the cultivation of non-edible crops. The Bödabukten study found three-to four-fold higher cadmium values than observed in the present study, which raises questions about the importance of local variations in beach-cast composition and in heavy metal concentrations limiting use as biofertiliser. The geographical variation in cadmium concentrations in beach-cast is largely unknown, although some preliminary patterns for the Baltic Sea have been reported (Bergström, 2012). Several variables are suggested to affect the cadmium content in macroalgae and seaweed, for example water and sediment concentrations of cadmium, phylogeny, morphology, tissue age and seasonality (Bonanno and Orlando-Bonaca, 2018; Malea and Kevrekidis, 2014). However, we did not monitor these variables in the present study.

Algae are frequently suggested to act as accumulators of heavy metals, with red algae in particular reported to accumulate cadmium for example (Cullinane and Whelan, 1982). However, high cadmium concentration in the Burgsviken Bay beach-cast seemed to be correlated with high abundance of eelgrass (*Zostera marina)* and not with high abundance of macroalgae (Table 2, Fig. 3). Seagrass species such as *Zostera marina* are also known to accumulate cadmium, either by uptake from sediment in the roots or directly from seawater in the leaves (Campanella et al., 2001; Lyngby and Brix, 1982). The cadmium level in eelgrass analysed in the present study was clearly higher than the recommended 0.8 mg Cd/kg DM proposed by the Swedish EPA for 2030 (Swedish-EPA, 2013), and one sample even exceeded the current limit for biofertiliser of 2 mg Cd/kg DM. There was a significant difference between the cadmium concentration in *Zostera marina* (mean 2.0 mg/kg DM) and that in the filamentous red algae (mean 0.36 mg/kg DM). *Furcellaria lumbricalis*, *Potamogeton pectinatus* and *Fucus vesiculosis* also had low values (< 0.8 mg/kg DM).

Cadmium concentrations were higher in *Zostera marina* leaves than in the roots in all three samples compared (Table 3). This indicates that bioaccumulation occurs in the leaves of *Zostera marina*, as also shown in earlier studies (Govers et al., 2014; Lyngby and Brix, 1982). There seems to be no general pattern for this leaf-rhizome difference in heavy metal concentrations in different seagrass species (Govers et al., 2014). Higher cadmium level in Z*ostera marina* leaves can be the result of either cadmium accumulation from sediment to leaves via rhizomes or cadmium uptake directly from the water body (Lyngby and Brix, 1982; Malea et al., 1994). Seagrass leaves grow from the meristem at the base of the plant (younger tissue), which means that heavy metal concentrations are higher in older tissue at the tips of the leaves (Campanella et al., 2001). Tissue age and species longevity are thus important for explaining cadmium content in plant material. Moreover, a number of other factors are suggested to be important for metal uptake, such as: species-specific bioaccumulative capacity, seasonal variation, morphology, growth pattern and cadmium concentration in sediment or and open water. The cadmium level in biomass may also be affected by chemical interactions between metals (e.g. cadmium and zinc).

Earlier studies have also reported large differences in bioaccumulation abilities between different species within taxonomic groups such as spermatophytes and rhodophytes (Govers et al., 2014; Malea and Kevrekidis, 2014; Schlacher-Hoenlinger and Schlacher, 1998). There are thus no reliable indicator species for larger taxonomic groups. This is one reason why more information is needed about cadmium uptake and concentration, both in different macrophyte species and also as affected by local geographical and environmental circumstances.

Since abundance of eelgrass explained the high cadmium content in beach-cast in the Burgsviken Bay samples, separating eelgrass and algae fractions (either by sorting or using different harvesting times) could be a viable way to obtain a beach-cast biofertiliser with low cadmium content. The eelgrass fraction could be used as a fertiliser in *Salix* energy crop plantations, since it has been shown that *Salix* can accumulate cadmium from agricultural soils (Greger and Landberg, 2015). The algae fraction of the beach-cast could be used as a biofertiliser in fields in the Burgsviken Bay area. In the past, beach-cast fertiliser has been important in northern (Fårö) and southern (Sudret) Gotland, but knowledge of harvesting, composting and using beach-cast fertiliser in agriculture has largely been lost. Local farmers are interested in using this resource, but they lack knowledge on cadmium levels in beach-cast and accumulation in different vegetables and in different soils. In a pilot study within the project 'Save Burgsviken Bay' in which edible plants were cultivated in beach-cast compost (50% beach-cast, 50% food waste compost), nearly all vegetables tested in the study (bean, cucumber, carrot, parsley, parsnip, pea, late-season potato) had cadmium levels below the permissible EU level. The only exception was early-season potatoes, which had levels slightly higher than the permissible limit (Larsson, 2016). Another pilot study on beach-cast fertilised fields in Fårö, Gotland (Weber-Qvarfort, 2016) and a study in northern Öland (Greger et al., 2007) found that some types of edible plants produced had higher than recommended cadmium levels, while other plants had low or acceptable levels. The varying degrees of cadmium uptake by different edible plant species is another area in need of further research, so that more precise recommendations can be provided for farmers.

The Swedish EPA and the European Union are working to reduce cadmium concentrations in agricultural fields and in foods. They are also working to achieve a circular economy, including more effective recycling of phosphorus in rural and urban systems. The knowledge gaps in research and indecisive political frameworks concerning phosphorus retention and heavy metal regulations are currently preventing a shift towards increased use of renewable biofertilisers. A few studies have examined the effects of beach-cast harvesting on marine ecosystems (Malm et al., 2004; Orr et al., 2014), but more research is also needed within this field before beach-cast harvesting is encouraged on a larger scale.

We suggest that the following three areas of improvement be prioritised in future work on use of beach-cast as a biofertiliser in the Baltic Sea region: i) A clearer picture is needed of the variation of heavy metal concentrations in beach-cast, with particular focus on cadmium in different beach-cast substrates. The importance of site, species composition, time of harvest, biofertiliser management, field application etc. should be determined. ii) A better understanding is needed of metabolic processes within beach-cast plant species affected by cadmium, uptake of cadmium by different agricultural plants and the variables affecting cadmium accumulation and losses from cultivated soils. iii) A programme is needed at regional (county) level to monitor macrophyte blooms along the coast of the Baltic Sea (species composition, total beach-cast biomass) and to sample and analyse the beach-cast for its concentrations of cadmium, arsenic and other potentially harmful heavy metals and toxic substances.

We believe that improvements in these three key areas would strengthen and encourage many of the local initiatives and ongoing management projects on Gotland and in other places around the Baltic Sea. In the long run, improved beach-cast management could contribute positively to nutrient recovery, soil improvement and increased coastal ecosystem services in the region.

5. Conclusions

Chemical analyses of beach-cast from Burgsviken Bay on Gotland showed large variations in cadmium content depending on sampling site. Higher abundance of *Zostera marina* in natural beach-cast was positively correlated with cadmium level and species-specific cadmium analysis also showed higher cadmium content in *Zostera marina* than in the other main species/species groups tested. Thus, in this study, *Zostera marina* explained high cadmium concentrations in natural beach-cast. Separating *Zostera marina* from the other macrophytes in beach-cast in the Burgsviken Bay area could be a potential solution to lower the cadmium content and make beach-cast more suitable for use as biofertiliser. However, before implementation this approach would require practical and technical solutions for sorting and harvesting beach-cast and more data on the potential decrease in cadmium concentration that can be achieved by sorting beach-cast species.

Declarations of interest

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