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Heavy metal transfer from composted macroalgae to crops

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Abstract

Marine macroalgal compost may be used as fertiliser in agriculture and horticulture. However, macroalgae may accumulate heavy metals, thereby rendering compost made from it unsuitable for food crop production. Our aim was to determine whether the edible parts of crop plants grown in various macroalgal composts contain elevated concentrations of heavy metals. Compost of seaweed beach-cast containing up to 85% red macroalgae and experimentally produced red and brown-algal (*Fucus serratus*) composts, respectively, were used in cultivating vegetables. The vegetables produced were compared with ones cultivated in composted horse manure and in soil in terms of transfer of cadmium (Cd), and in some cases also of copper (Cu), lead (Pb), and mercury (Hg) from the different substrates to the edible parts of the plants. Effects of the composted material on biomass production and seed germination were also examined. Concentrations of Cu, Hg, and Pb were not elevated in either of the composts or in the crop plants compared with limit values for cultivated plants and soil. However, the concentration of Cd in the composts and crop plants was greater than the limit values for arable soil and cultivated plants, respectively. Furthermore, more Cd was transferred to the plants grown in red-algal than in brown-algal (*F. serratus*) compost, despite the fact that the brown-algal (*F. serratus*) compost had a higher Cd concentration. The Cd concentrations in lettuce and oats cultivated in the seaweed composts exceeded official EU limit values, while the concentrations in root vegetables and leguminous plants were lower than the limit values. Cultivation in composted red macroalgae increased the biomass production of all vegetables except beans, compared with cultivation in the other substrates. However, the germination frequency was lower for seed sown in composted red and brown algae than for seed sown in soil. We conclude that although cultivation of food crops directly in composted macroalgae (specifically, composted red algae) would enhance yields, it is not recommended. Instead, macroalgal compost could be used in smaller amounts on agricultural soils as a valuable nutrient source for non-food crop cultivation.

Keywords: Cadmium; Crop plant; *Fucus*; Heavy metal; Macroalgal compost; Red alga

1. Introduction

The use of marine macroalgae as fertiliser in crop production has a long tradition in coastal areas all over the world (Stephenson, 1968). Over 250 years ago, von Linné (1745) had already reported the extensive agricultural use of the perennial brown macroalgae, *Fucus vesiculosus* L., on the large Swedish island of Öland, in the Baltic Sea. Seaweed cast continued to be so valuable to farmers, even in the early 1900s, that the authorities had to regulate its use (Weibull, 1919). In many countries, seaweed and beach-cast are still used in both agriculture and horticulture (Verkleij, 1992; Zodape, 2001). The positive effect of these substances on crop growth is even greater than would be expected from the nutrients they supply, and this effect may be caused by growth hormones in the macroalgae (Crouch and Vanstaden, 1991, 1992, 1993). Besides supplying nutrients, using composted macroalgae improves the soil structure by increasing the humus content (Haslam and Hopkins, 1996).

To the best of our knowledge, no data have been presented concerning possible heavy metal contamination occurring by fertilizing the soil with macroalgae, although it is well documented that heavy metals, which bind to the polysaccharides in the cell walls of algae (Zolotukhina and Gavrilenko, 1991), can be accumulated by macroalgae. Red algae in particular may concentrate heavy metals by a factor of 10^4 from seawater, which commonly has a very low heavy metal concentration (Wahbeh and Mahasneh, 1985). The accumulation of heavy metals by macroalgae depends on both the total surrounding metal concentrations and the availability of the metals, which increases with decreasing seawater salinity. This has been suggested by,

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for example, Steinhagen-Schneider (1981) as a reason for the 10-times-higher cadmium concentration in *F. vesiculosus* growing in the brackish central Baltic Sea (∼7‰ salinity) than in the North Sea (∼30‰ salinity).

Eutrophication of the Baltic Sea has led to an increase in the growth of filamentous macroalgal species over the past 60 years, while the amount of *F. vesiculosus*, traditionally used as an agricultural fertiliser in south-eastern Sweden, has declined (Cedervall and Elmgren, 1990). In shallow water in the archipelagos, brown filamentous macroalgae of the genera *Pilayella* and *Ectocarpus* are today abundant (Lotze et al., 2000; Vahteri et al., 2000), while the macroalgal community along the open coasts mainly consists of red macroalgal species of the genera *Polysiphonia*, *Ceramium*, and *Rhodomela* (Wallentinus, 1979). In late summer and autumn, large quantities of these filamentous macroalgae become detached from the substrate, accumulating along the open coasts and as drifting mats in shallows among archipelagos in the area (Norkko and Bonsdorff, 1996a,b; Norkko, 1998). According to Malm et al. (2004), up to 6900 tonnes fresh weight of beach-cast per km of shoreline per year is found on the island of Öland in Sweden. Removing the macroalgae from the beaches may, however, result in a waste disposal problem on land. It would thus be of both economic and environmental interest to use the beach-cast as fertiliser, partly replacing the use of commercial fertilisers in coastal areas (Jöborn et al., 2001).

This research investigated the concentrations of cadmium (Cd), copper (Cu), mercury (Hg), and lead (Pb) in macroalgal beach-cast from the Baltic Sea, on the island of Öland, and in compost made from red and brown algae, and determined the transfer of these metals into food crops. The investigation was performed in four steps. First, the concentrations of Cd, Cu, Pb, and Hg were analysed in algae collected from four different types of fresh beach-casts along the east coast of the island of Öland in the Baltic Sea. In the second step, the transfer of Cd, Cu, Pb, and Hg from composted beach-cast to crops was determined in a greenhouse experiment. Since we found that only the Cd concentrations and the transfer of Cd to crops exceeded the threshold values for arable soil and cultivated plants established by national and European authorities the third and forth steps only examined Cd. In the third step, beach-cast and manure were compared in terms of Cd concentrations and transfer of Cd to various crops in field cultivation. In the fourth step, the objective was to compare various substrates in terms of Cd concentrations and the transfer of Cd to crops; the substrates were composted red filamentous algae, composted brown seaweed (*Fucus serratus* L.), and soil. This experiment was performed in a greenhouse.

2. Materials and methods

2.1. Species composition of beach-cast

The species composition of the beach-cast at Böda, situated on the east coast of Öland, Sweden (N57″13′52 E17″05′47), was estimated in September 1999. Beach-cast from three other sites – northern, central, and southern – 70 km apart on the east coast of Öland, were also analysed. At each site, 1-kg samples were collected along 500 m of shoreline at five sites approximately 100 m apart, 0.5 m above the water line. The samples were sorted by species, and the biomass of the dominant species was determined by measuring the fresh weight. The proportions of the two filamentous red macroalgal species present in the beach-cast, i.e. *Polysiphonia fucoides* (Hudson) Greville and *Rhodomela confervoides* (Hudson) P.C. Silva, were estimated by sorting 100 g (FW) of filamentous macroalgal biomass from each sampling site, using a stereomicroscope. From these data, the proportion of each species as a percentage (fresh weight per m^2) of the beach-cast was calculated. The sorted beach-cast material was used in analysing the Cd, Cu, Pb, and Hg concentrations in each species.

2.2. Plant cultivation in beach-cast compost

2.2.1. Greenhouse experiment (experiment one)

The sandy beaches at Böda have been cleaned of beach-cast regularly over the past 20 years by owners of waterfront property. The material has been dumped in large piles in the forest close to shore, where it has been left to decay. Five kilograms of this composted algal material was collected from the bottoms of four different 3-year-old piles. From photographs and from interviews with workers responsible for the beach cleaning, the initial composition of the composted material in all piles was estimated to be over 90% filamentous red algae. Four boxes ($0.1\,m \times 0.3\,m \times 0.5\,m$) were filled with $15\,dm^3$ of these composted materials, each box containing compost from a single compost pile. As controls, four similar boxes were filled with commercially available compost, Weibulls ekologiska plantjord, from Svalöf-Weibull AB (Sweden). The parameters of both substrates in terms of pH, organic content, nutrients (NPK), salinity, and water-extractable anion concentration are presented in Table 1.

Twenty oat plants (*Avena sativa* L. cv. Kattgräs) and 20 pea plants (*Pisum sativum* L. cv. De Grace, low) were grown from seed in each of the four composts produced from the beach-casts and in each of the four soil samples. The cultivation was done in a greenhouse (set for 22 °C, RH ≈ 70%) equipped with supplementary high-pressure 230V, 240 W sodium lamps (Kema Europa, Amsterdam, The Netherlands), giving a photon flux density of $500\,\mu mol\,m^{-2}\,s^{-1}$ for 12 h of each 24-h cycle. The plants were harvested after approximately 2 months of growth, by which time the ears and pods had developed. After harvest, the aboveground plant material and growth substrate were analysed for Hg, Pb, Cu, and Cd as well as organic matter content.

2.2.2. Field experiment (experiment two)

A field experiment was performed in Böda in summer 2000. The same beach-cast compost (from Böda) as was used in the greenhouse experiment was used in this experiment. The material was spread out forming a square $10\,m^2$ and 0.5 m thick. As a standard of reference for the beach-cast compost, an equally large square of composted horse manure (comprising barley straw and horse faeces in equal proportions) was also used (for substrate parameters, see Table 1). The two squares were each

Table 1
pH, organic (%) and macronutrient content (%), salinity, and anions (Cl, Br, and SO_4) of the extractable fraction of the different substrates used in the experiments ($n = 1$, 5 samples pooled)

Experiment/substrate	pH	Organic matter content (%)	S (‰)	N ($g\,kg^{-1}$)	P ($g\,kg^{-1}$)	K ($g\,kg^{-1}$)	Cl ($g\,kg^{-1}$)	Br ($mg\,kg^{-1}$)	SO_4 ($mg\,kg^{-1}$)
Greenhouse experiment in beach-cast									
Control soil	5.12	64.2	0.1	6.7	0.8	1.4	37	1	650
Beach-cast compost	5.21	13.4	2.1	5.1	1.1	4.3	232	580	2916
Field experiment in beach-cast									
Manure	7.57	44.0	0.9	5.1	0.4	1.0	ND	162	930
Beach-cast compost	5.13	29.7	3.7	11.4	2.5	9.5	378	709	4528
Greenhouse experiment in algal compost									
Control soil	5.07	66.9	0.1	6.4	0.6	1.5	41	1	576
Red-algal compost	5.45	66.1	2.9	27.1	1.1	2.1	1260	940	18241
Brown-algal (*F. serratus*) compost	6.56	72.6	2.8	20.8	1.5	6.2	2392	452	244

ND = no data.

divided into twenty smaller 0.5 m^2 squares. At the beginning of June 2000, 200 seeds of carrot (*Dacus carota* cv. Nates 4 duke), 100 seeds of red beet (*Beta vulgaris* cv. Liten rund), 200 seeds of lettuce (*Lactuca sativa* cv. Great Lakes 118), five potatoes (*Solanum tuberosum* cv. Asterix), 150 seeds of spinach (*Spinacia oleracea* cv. Matador), and 60 seeds of broad bean (*Vicia faba* cv. Green Hang Down) were sown in these smaller squares, four squares for each species and substrate. The germination frequencies, i.e. the percentages of seeds that germinated, were determined. Plants were harvested at maturity. The leafy vegetables were harvested after 33 days at the beginning of July 2000, while all other species were harvested after 85 days in mid-September 2000. The cadmium content of the substrate and of the edible parts of the vegetables was analysed.

2.3. Plant cultivation in red-algal and brown-algal compost (experiment three)

2.3.1. Preparation of composts

Newly washed-ashore *F. serratus* L. and red macroalgae (*P. fucoides*, 85%; *R. confervoides*, 15%) were collected in May 2000 at five sites on the island of Öland, southeastern Sweden. Forty kilograms each of *F. serratus* and red macroalgae were collected separately at each site, mixed with 10 kg of oat straw (to produce a firmer structure in the final compost), and composted outdoors in 200-L plastic barrels. A total of 10 barrels were used, five for red macroalgae and five for *F. serratus* material. To ensure that the macroalgal material would decompose aerobically, the bottom of each barrel was removed and replaced with a wire mesh (1-cm mesh size), and the barrel was mounted 20 cm above the ground. The barrels were also provided with air through 10 small holes drilled in their walls and five in their lids (3 cmØ). Each barrel was irrigated every week with 10 L of tap water, except for the December 2000–March 2001 period when the compost material was frozen. At the beginning of May 2001, compost was taken from each of the barrels for further use.

2.3.2. Plant cultivation

One box, 10 cm × 30 cm × 50 cm, was filled with compost from each barrel; in addition, five boxes were filled with Weibulls ekologiska plantjord, from Svalöf-Weibull AB (Sweden). The qualities of the composts and soil are presented in Table 1. All boxes were randomly set out in the greenhouse, and in each box, 50 radish seeds (*Raphanus sativus* cv. Round Red Small White Tip 2), 50 lettuce seeds (*L. sativa* cv. Great Lakes 118), or 25 oat grains (*A. sativa* cv. Kattgräs 007) were sown. At maturity, the radishes were harvested after 22 days, the lettuce after 45 days, and oats after 96 days. The Cd contents of the edible parts of the plants were analysed. The germination frequency of these plants and their edible biomass production were also recorded.

2.4. Analysis of organic content and heavy metals

The composted materials, control soils, manure, commonest algal species in the beach-cast (Table 2), and edible parts of the cultivated plants were analysed for Cd, and, in the case of the greenhouse experiment with beach-cast compost and the algal species in the beach-cast, also for Cu, Hg, and Pb concentrations. The algal material that was collected fresh from the outermost part of the beach-cast was carefully washed in filtered seawater to remove sediment and sand particles prior to analysis. The edible plant parts were carefully washed by hand in redistilled water to remove substrate particles. Before analysis, the plant materials from the greenhouse plantings in beach-cast compost were dried to constant weight at 40 °C for 72 h to enable analysis of Hg. A small part of each sample was then dried at 105 °C for 24 h, weighed, and then burned at 600 °C for 2 h to determine the absolute dry weight and organic matter content, respectively. In the two other experiments in which only Cd was analysed, the plant material was dried at 105 °C for 24 h.

Prior to wet digestion, the dried plant and algal materials were crushed with a mortar and pestle, whereas the dried soil and composted algal materials were sieved with a 2-mm mesh. The dried plant and algal samples were wet digested in 65% HNO_3:70% $HClO_4$ (7:3, v/v) in steps up to 225 °C, according to the method described by Frank (1976). For Hg analysis, wet digestion was performed up to 180 °C. The composted algal material and the control soil samples were wet digested in 7 M HNO_3 at 120 °C for 30 min, according to Swedish standard methods SS028 150 and SS028 152. Samples were then anal-

Table 2
Proportions (% fresh weight) of various species in beach-cast, and concentrations of Cd and Cu in red and brown macroalgae in beach-cast at Böda as well as in beach-cast collected at the northern, central, and southern sites along the east coast of Öland, Sweden (collected in September 1999, $n = 5$, ±S.E.)

Species	Proportions (%)	Cd ($mg\,kg^{-1}$ DW)	Cu ($mg\,kg^{-1}$ DW)
Böda			
Polysiphonia fucoids	42.8 ± 14.2	4.3 ± 0.2	12.0 ± 1.7
Rhodomela confervoides	15.4 ± 4.1	3.0 ± 0.1	10.7 ± 0.5
Furcellaria lumbricalis	28.8 ± 16.0	3.2 ± 0.8	11.1 ± 1.1
Fucus vesiculosus	4.1 ± 2.3	–	–
Potamogeton natans	2.0 ± 1.0	–	–
Zostera marina	0.1 ± 1.0	–	–
Mytilus edulis	6.4 ± 4.4	–	–
Northern site			
Polysiphonia fucoids	43.0 ± 18.5	3.9 ± 0.3	11.8 ± 2.2
R. confervoides	29.0 ± 5.8	2.9 ± 0.1	9.7 ± 0.9
Furcellaria lumbricalis	15.0 ± 20.8	2.4 ± 1.2	10.5 ± 1.2
Central site			
Polysiphonia fucoides	85.0 ± 6.9	4.7 ± 0.6	16.6 ± 4.0
R. confervoides	12.0 ± 5.2	2.3 ± 1.2	11.5 ± 4.3
Southern site			
P. fucoides	81.0 ± 2.9	4.3 ± 0.9	21.6 ± 3.8
R. confervoides	17.0 ± 4.6	1.9 ± 1.1	13.0 ± 2.7
Furcellaria lumbricalis	3.0 ± 1.7	1.1 ± 0.2	7.1 ± 2.8
Fucus serratus	1.0 ± 0	3.9 ± 1.9	6.7 ± 0.9

The concentrations of Hg and Pb were in all cases under the detection limits, which were 0.002 mg Hg kg^{-1} DW and 0.1 mg Pb kg^{-1} DW.

ysed for Cd, Cu, Pb, and Hg by means of atomic absorption spectrophotometry (SpectrAA-100; Varian Inc., Palo Alto, CA, USA) using the flame technique for Cu, the furnace technique (GTA-97; Varian Inc.) for Cd and Pb, and the hydride vapour-generation technique (VGA-77; Varian Inc.) for Hg. *Phalaris arundinaceae* L. (NJV 94-4, SLU) was used as reference material. Standards were added to the samples to eliminate interaction with the sample matrix.

2.5. Calculations and statistical treatment

The concentrations of the metals in the materials were related to the 105 °C DW. The transfer factor was calculated according to the following formula:

$$\text{transfer factor} = \frac{\text{metal concentration in edible plant parts (mg kg}^{-1}\text{ DW)}}{\text{metal concentration in substrate (mg kg}^{-1}\text{ DW)}} \qquad (1)$$

The statistics were calculated using Statistica 5.5 for Windows. The homogeneity of variance was tested using Cochran's test, and data were transformed when necessary. Significant differences at $p \leq 0.05$ were analysed using Tukey's honest significant difference (HSD) test using JMP version 2 (SAS Institute Inc., 1989).

3. Results

Red macroalgae comprised over 85% of the fresh weight of the beach-cast (Table 2). The most common red-algal species was *P. fucoides*, followed by *R. confervoides* and *Furcellaria lumbricalis* wherever the beach-cast was collected along the east coast of Öland. Relatively small amounts of brown and green macroalgae, aquatic angiosperms, and invertebrates were found as well. The heavy metal contents of the dominant macroalgal species of these beach-cast samples consisted of approximately 1–5 mg Cd kg^{-1} DW, 7–22 mg Cu kg^{-1} DW, <0.002 mg Hg kg^{-1} DW, and <0.1 mg Pb kg^{-1} DW. *P. fucoides* dominated the biomass of the beach-cast and had the highest concentrations of Cd and Cu. Among the red macroalgal species, *P. fucoides*, *R. confervoides*, and *F. lumbricalis* contained similar Cd concentrations. The concentration of metals in the beach-cast algae of a given species did not differ significantly between collection sites.

The nutrient levels in the different substrates varied considerably (Table 1). Both beach-cast compost from the field experiment as well as the red-algal and *F. serratus* compost contained higher N, K, and P levels than the manure or soil did. Also, the salinity as well as the Cl and Br in the leachate from the substrate were higher in all composts based on algae than from the soil or manure. The SO_4 concentration was much higher in the leachate from the red-algal compost than from all other treatments; it was also higher in the leachate from beach-cast compost than from the soil or manure.

The concentrations of Hg, Pb, Cu, and Cd in plants and substrate in the greenhouse experiment (experiment one) with beach-cast compost and soil are presented in Table 3. In soil and composted beach-cast, the Hg and Pb concentrations were <0.01 and <0.5 mg kg^{-1} DW, respectively, while oats and peas grown in the soil and composted beach-cast both contained <0.002 mg Hg kg^{-1} DW and <0.1 mg Pb kg^{-1} DW. No significant difference in Cu concentration was found between plants cultivated in soil and in beach-cast compost or between oats and

Table 3
Cd and Cu contents and biomass in soil, composted beach-cast, and aboveground parts of peas and oats after cultivation for 2 months in soil and beach-cast compost from the east coast of Öland, Sweden ($n = 4$, ±S.E.)

Soil and plant species	Biomass (g)	Cd		Cu	
		mg kg^{-1} DW	TF	mg kg^{-1} DW	TF
Soil cultivation					
Soil	–	0.29 ± 0.05	–	8.37 ± 1.42	–
Oats	3.22 ± 0.08	0.04 ± 0.01 a	0.15 ± 0.03 a	4.44 ± 1.38 a	0.65 ± 0.33 a
Peas	3.13 ± 0.33	0.08 ± 0.02 a	0.32 ± 0.08 a	4.76 ± 0.25 a	0.67 ± 0.12 a
Beach-cast compost cultivation					
Beach-cast compost	–	1.04 ± 0.26*	–	3.93 ± 1.14*	–
Oats	3.12 ± 0.34	0.60 ± 0.12* b	0.70 ± 0.13 b	3.21 ± 0.73 a	1.39 ± 0.41 b
Peas	3.09 ± 0.44	0.17 ± 0.04* a	0.26 ± 0.09 a	4.46 ± 1.13 a	1.33 ± 0.12 b

Different letters (a and b) in the same column indicate a significant difference between data at $p < 0.005$ according to Tukey's HSD test. The concentrations of Hg and Pb were in all cases under the detection limits, which were 0.002 and 0.01 mg Hg kg^{-1} DW and 0.1 and 0.5 mg Pb kg^{-1} DW for plants and substrate, respectively.
* Significant difference, $p < 0.05$, from cultivation in commercial soil for each metal.

peas. The transfer factor for Cu was, however, higher in beach-cast compost than in soil for both species (two-way ANOVA, $p = 0.001$). The compost produced from beach-cast material, mainly comprising *P. fucoides*, contained significantly more Cd than the soil did. Both oats and peas contained significantly more Cd when grown in the beach-cast compost than when grown in the control soil (two-way ANOVA, $p < 0.001$). Oats accumulated significantly more Cd than peas did when grown in the beach-cast compost (two-way ANOVA, $p = 0.001$), but not when grown in soil. The transfer factor was higher in beach-cast than in soil for oats; however, no difference between substrates was found for peas.

The concentration of Cd in plants and substrate in the field experiment (experiment two) with beach-cast compost and manure is presented in Table 4. Beach-cast compost contained significantly more Cd than the composted horse manure did, and the Cd concentrations in the edible parts of plants was higher for plants cultivated in beach-cast compost than in composted horse manure, though not significantly for spinach. In addition, the transfer of Cd from substrate to edible plant parts was always higher from beach-cast compost than from composted horse manure in all vegetables including spinach. An especially high transfer factor in beach-cast compost was found for lettuce. In beach-cast compost, lettuce accumulated significantly more Cd in its edible parts (one-way ANOVA, $p < 0.001$) while broad beans (one-way ANOVA, $p = 0.05$) accumulated less Cd than the other crop species did.

The beach-cast compost contained both red macroalgae and *F. serratus*, and our intention in experiment three was also to compare the Cd transfer to crops from compost made of each type of algae separately as well as from soil. The compost produced from red macroalgae (Tukey's HSD, $p = 0.01$) and from *F. serratus* (Tukey's HSD, $p = 0.007$) both contained significantly more Cd than did the soil (Table 5). The Cd concentration and transfer of Cd to the edible parts of the cultivated plants increased more in all species when grown in both types of algal composts than when grown in soil, and, as found in the field study, lettuce accumulated the highest concentrations. Compost produced from the brown algae *F. serratus* had a significantly higher Cd concentration than did compost produced from red algae. However, although the difference was not significant, there was a tendency for plants cultivated in the *F*. serratus compost to have a lower Cd concentration than did plants grown in red-algal compost. The transfer factor was also higher for lettuce and oats grown in the red-algal compost.

The germination frequency (i.e. percent of sown seeds that germinated) of the seed of various plant species did not differ depending on whether seed was sown in beach-cast compost or composted horse manure (Table 6). However, comparing sowings in red-macroalgal and *F. serratus* composts with sowings

Table 4
Content of cadmium in manure, beach-cast compost, and edible parts of various vegetables after cultivation for 36 days (lettuce and spinach) and 85 days (carrot, broad bean, potato, and red beet) in a field experiment

Plant species and substrate	Cd concentration (mg kg^{-1} DW)		Transfer factor	
	Manure	Beach-cast compost	Manure	Beach-cast compost
Substrate	0.42 ± 0.01	1.00 ± 0.23*	–	–
Carrot	0.03 ± 0.01	0.87 ± 0.12*	0.06 ± 0.03	0.92 ± 0.12*
Broad bean	0.01 ± 0.01	0.14 ± 0.02*	0.01 ± 0.01	0.15 ± 0.04*
Lettuce	0.05 ± 0.02	3.15 ± 0.47*	0.13 ± 0.03	3.65 ± 1.06*
Potato	0.01 ± 0.01	0.30 ± 0.07*	0.01 ± 0.01	0.30 ± 0.03*
Red beet	0.03 ± 0.01	0.99 ± 0.11*	0.08 ± 0.01	1.13 ± 0.30*
Spinach	0.09 ± 0.02	0.78 ± 0.30	0.22 ± 0.06	0.86 ± 0.41*

The transfer factor is indicated ($n = 3$, ±S.E.).
* Significant difference, $p < 0.05$, from cultivation in manure for each plant species.

Table 5
Content of cadmium in soil, red-algal compost, *F. serratus* compost, and edible parts of various crops after cultivation in greenhouse

Plant species and substrate	Cd concentration (mg kg^{-1} DW)			Transfer factor		
	Soil	Red-algal compost	*F. serratus* compost	Soil	Red-algal compost	*F. serratus* compost
Substrate	0.26 ± 0.02	3.48 ± 0.89*	5.86 ± 1.70*,#	–	–	–
Lettuce	0.02 ± 0.01	2.04 ± 0.45*	0.98 ± 0.37*	0.08 ± 0.01	0.85 ± 0.24*	0.26 ± 0.14#
Radish	0.01 ± 0.01	0.36 ± 0.13*	0.30 ± 0.06*	0.01 ± 0.01	0.09 ± 0.02*	0.08 ± 0.02
Oats	0.01 ± 0.01	0.21 ± 0.02*	0.06 ± 0.01*	0.03 ± 0.02	0.07 ± 0.01	0.01 ± 0.01#

Significant difference, $p < 0.05$, *from cultivation in soil, #between the two composts for each plant species. The transfer factor is indicated ($n = 5$, ±S.E.).

Table 6
Percent germination and biomass of edible parts of various vegetables after cultivation for 36 days (lettuce and spinach) and 85 days (carrot, broad bean, and red beet) in manure or beach-cast compost in the field experiment ($n_{germination} = 2$, $n_{biomass} = 3$, ±S.E.)

Plant species	Germination (%)		Biomass (g DW)	
	Manure	Beach-cast compost	Manure	Beach-cast compost
Carrot	22 ± 8	24 ± 7	1.7 ± 0.3	3.4 ± 0.6*
Broad bean	10 ± 2	15 ± 3	10.6 ± 2.6	3.3 ± 0.8*
Lettuce	16 ± 3	16 ± 4	0.5 ± 0.1	1.6 ± 0.3*
Red beet	66 ± 12	67 ± 10	4.0 ± 1.0	7.2 ± 1.6
Spinach	11 ± 2	26 ± 4	0.5 ± 0.1	1.3 ± 0.2*

* Significant difference, $p < 0.05$, from cultivation in manure for each plant species.

in soil, differences were found for lettuce and radishes but not oats (Table 7). Lettuce seed sown in red-macroalgal compost (Tukey's HSD, $p = 0.03$) and in *F. serratus* compost (Tukey's HSD, $p = 0.04$) had a significantly lower germination frequency than did lettuce seeds sown in the soil, but there was no significant difference between the germination frequency of lettuce sown in the two types of compost. The percent germination of radish seed sown in red-macroalgal compost was significantly lower than that of radish seed sown in the control soil (Tukey's HSD, $p = 0.04$), while the germination frequency of radish seed sown in *F. serratus* compost was similar to that of radish seed sown in soil.

The biomass production of carrot, lettuce, and spinach approximately doubled when the plants were grown in beach-cast compost rather than in composted horse manure (Table 6), while the biomass of broad beans was three times larger for plants grown in the manure than in beach-cast compost. The biomass of both oats and radishes was higher for plants grown in red-macroalgal compost than for plants grown in either the control soil (Tukey's HSD, $p < 0.001$) or the *F. serratus* compost (Tukey's HSD, $p < 0.001$), while the biomass of the lettuce did not differ significantly between plantings in the two substrates (Table 7). Oats, radishes, and lettuce, however, produced equally large biomasses when grown in either *F. serratus* compost or control soil. In the first greenhouse experiment (Table 3), no difference was detected in the biomass production of oats and peas between substrates.

The Cd concentration in lettuce ($[Cd]_{lettuce}$) and transfer factor (TF) of Cd for lettuce cultivated in various substrates (from experiments two and three) was compared (Fig. 1). The $[Cd]_{lettuce}$ and TF were highest in lettuce grown in the beach-cast compost, followed by lettuce grown in the red-algal compost and then in the *F. serratus* brown-algal compost. The Cd concentration in lettuce increased with increasing TF, however, in a saturating manner. The relationship between TF or $[Cd]_{lettuce}$ and the substrate concentration of Cd indicated that both TF and $[Cd]_{lettuce}$ increased at slightly elevated substrate concentrations, but decreased at higher substrate concentrations.

The Cd uptake by lettuce increased with increased salinity of the leachate from the substrate, as indicated shown by the increasing TF and [Cd] in lettuce with increasing salinity (Fig. 2). A similar pattern was found in relation to increasing [Br] in the leachate, while both TF and $[Cd]_{lettuce}$ decreased with increasing [Cl] at Cl concentrations above 500 mg kg^{-1}. Increasing pH influenced TF and $[Cd]_{lettuce}$ in the same manner as Cl did, i.e. by decreasing the Cd uptake.

4. Discussion

Red macroalgae comprised over 85% of the beach-cast by fresh weight (Table 2), in line with the findings of Malm et al. (2004). Of this 85%, the red alga *P. fucoides* was the most common; however, the various red-algal species did not differ much in Cd or Cu content. The concentration of Cu of

Table 7
Percent germination and biomass of edible parts of various crops after cultivation for 22 (lettuce), 45 (radish), and 96 (oat) days in soil, red-algal compost, and *F. serratus* compost in greenhouse ($n_{germination} = 5$, $n_{biomass} = 10$, ±S.E.)

Plant species	Germination (%)			Biomass (g DW)		
	Soil	Red-algal compost	*F. serratus* compost	Soil	Red-algal compost	*F. serratus* compost
Lettuce	56.8 ± 12.6	28.4 ± 3.0*	29.2 ± 5.9*	0.15 ± 0.03	0.38 ± 0.09	0.23 ± 0.05
Radish	86.8 ± 5.8	56.4 ± 7.2*	44.0 ± 12.3	0.30 ± 0.03	0.81 ± 0.06*	0.40 ± 0.05#
Oats	77.6 ± 5.2	90.4 ± 4.3	73.6 ± 8.5	1.33 ± 0.14	2.67 ± 0.22*	1.51 ± 0.14#

Significant difference, $p < 0.05$, *from cultivation in soil, #between the two macroalgae composts for each plant species.

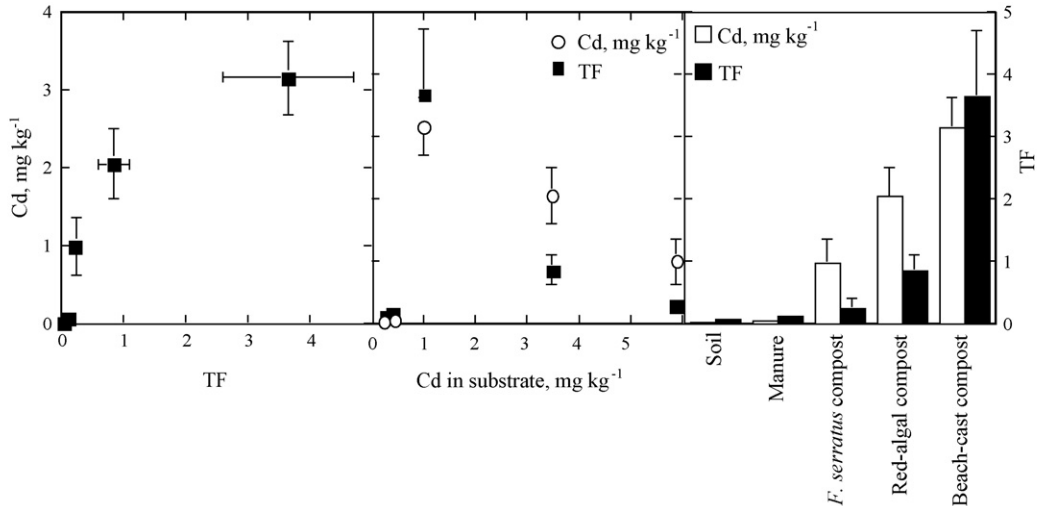

Fig. 1. Relationship between transfer factor (TF, i.e. $[Cd]_{lettuce}$:$[Cd]_{substrate}$) and Cd concentration in lettuce (left), between Cd in substrate and Cd concentration and TF in lettuce (middle), and between Cd concentration and TF in lettuce (right) grown in various composts, soils, and manure. The graphs present data from experiments two and three ($n = 3$, ±S.E.).

7–22 mg kg^{-1} DW and of Cd of 1–5 mg kg^{-1} DW in the algae (Table 2) can be compared with approximately 441 ng Cu L^{-1} and 11 ng Cd L^{-1} in the water of the Baltic proper (Kremling and Streu, 2000). The algae can thus concentrate the Cu and Cd in the seawater by factors of up to 50 and 500, respectively. The beach-cast consisting of not more than up to 4% brown algae (*Fucus* spp.) and *F. serratus* contained less Cu (7 mg kg^{-1} DW) and as high a Cd concentration (4.2 mg kg^{-1} DW) as did the red algae (Table 2). The concentrations of Hg and Pb in the algae were under the detection limit and will therefore not be discussed.

The beach-cast compost used as a substrate for cultivation did not contain higher Cu, Hg, or Pb levels than the soil did. However, compared with Swedish soil (Eriksson et al., 1997), the Cd concentration of the beach-cast compost examined in the present study was elevated (Pais and Jones, 1997). The concentration of Cd in the macroalgal composts greatly exceeded what is acceptable in topsoil (see Table 5), as the average Cd content of Swedish soils is approximately 0.25 mg kg^{-1} DW (Christiansen and Björnberg, 1997). Compost from red algae contained a lower concentration of Cd (3.5 mg kg^{-1}) than did *F. serratus* compost (5.8 mg kg^{-1}); however, beach-cast compost, which contained 85% red algae and up to 4% brown algae, had a lower Cd concentration (1 mg kg^{-1}). The reason for this difference may be the different composting methods used. To have an acceptable Cd level for use in edible crop cultivation, only 10% or less of composted beach-cast should be used to have levels close to those of Swedish soils, i.e. approximately 0.25 mg kg^{-1} DW (Christiansen and Björnberg, 1997).

Cu and Cd enrichment seems not to have occurred during composting, since the concentrations found in compost were in the same range as those measured in fresh macroalgae of the same species (Table 2). The metal concentration in algae was approximately four times higher than in the beach-cast compost. The Cd concentrations did not differ between the red algae and the red-algal compost or between the brown algae and the brown-algal *F. serratus* compost. In other instances, it is common for the metal concentration to increase in compost due to CO_2 loss and mass loss.

The concentrations of Cu, Hg, and Pb in the edible parts of the food crops cultivated in composted beach-cast were not elevated in comparison with the values found by Pais and Jones

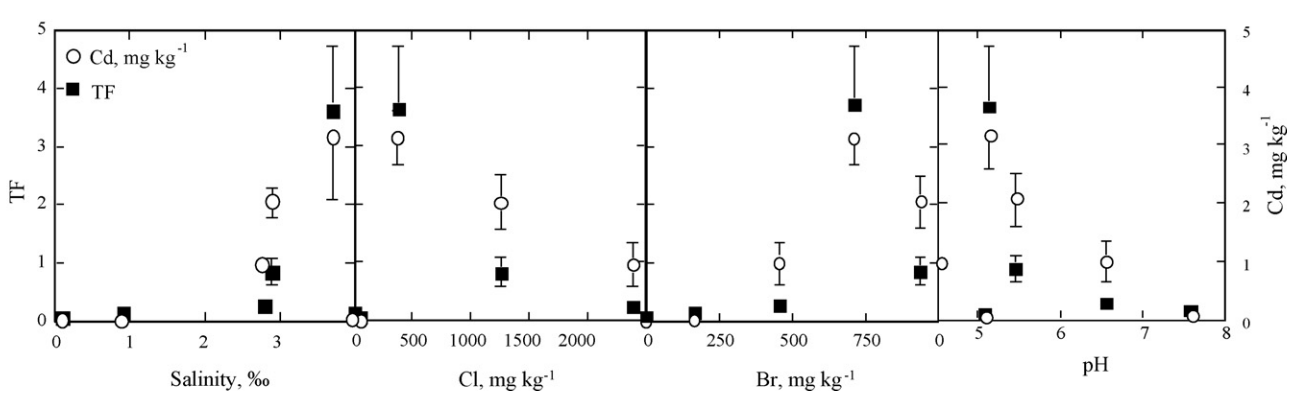

Fig. 2. Influence of salinity, chloride, bromide, and pH on transfer factor (TF, i.e. $[Cd]_{lettuce}$:$[Cd]_{substrate}$) and Cd concentration in lettuce grown in various composts, soils, and manure. The graphs present of data from experiments two and three ($n = 3$, ±S.E.).

(1997). The concentration of Cd in the edible parts of the various food crops was significantly higher for plants grown in the various macroalgal composts than in soil or manure (Tables 3–5). The Cd concentrations in lettuce and oats cultivated in composts exceeded the limit established by the Swedish National Food Administration and the EU Commission, while the Cd concentrations in the edible portions of root vegetables and leguminous plants were lower than the limit values. Among the various species, lettuce had the highest Cd accumulation factor.

The various substrates influenced the availability to and uptake of Cd in plants. The uptake of Cd was not positively related to the Cd concentration in the substrates (Fig. 1), and the highest uptake in lettuce was found in lettuce growing in beach-cast compost, which had a lower Cd concentration than either the red-algal of the *F. serratus* compost. This could be because of the high salinity of the water released from the beach-cast compost, as it has been shown that Cd uptake from soil increases with increasing Cl concentration (Weggler et al., 2004). However, the present research found that Cd uptake decreased with increasing Cl concentration (Fig. 2), and instead there was a possible positive relationship between Br and Cd uptake (Fig. 2). On the other hand, there is more than one difference between the various substrates, and it is impossible to find just one factor influencing the Cd uptake. The transfer factor for the edible portions of various plant species was also higher in the red-algal than in *F. serratus* compost, indicating that Cd may be less strongly attached to the polysaccharides in red algae than to those in, for example, *F. serratus*.

Not only Cd concentration, but also germination frequency and biomass production were influenced by cultivation in macroalgal compost. The lower germination frequency of seed sown in composted red macroalgae than of seed sown in soil may be explained by the high concentrations of organic compounds, i.e. aliphatic haloketones, brominated phenols, and terpenoids, produced naturally by red algae (Fenical, 1975). Several of these compounds are toxic (Horgen et al., 2000), and Eklund et al. (2004) showed that the red-coloured effluents that leak from decomposed algae have toxic effects. The low germination frequency of lettuce seed sown in *F. serratus* compost may be explained in the same way.

The studied plants grew differently in the various substrates. The most likely reason for these considerable differences in growth is a larger and more available supply of nitrogen in the macroalgal compost (Table 1) than in the other substrates. This assumption is supported by the observation that broad beans, which have the capacity to fix nitrogen (Andreev et al., 2000), were the only cultivated plants that produced a significantly lower biomass in beach-cast compost than in composted manure. The broad been plants cultivated in the composted horse manure had observable bacterial nodules on their roots, while nodules of observable size were lacking on the broad been plants cultivated in the macroalgal compost, a clear indication of nitrogen excess in the macroalgal compost (Qiao and Murray, 1997). The higher salinity of the beach-cast compost (Table 1) explains the reversed growth response of the broad beans compared with those of the other cultivated plant species studied, since it is known that leguminous species are sensitive to high soil salinity (Saadallah et al., 2001).

5. Conclusion

High cadmium concentration is the reason for not growing edible plants in pure beach-cast compost. However, it should be noted that instead of pure algal compost being used on its own as a growth medium, it can be used in smaller amounts as a nutrient amendment for agricultural soil; this diminishes Cd addition and uptake, as shown in recent field studies. To avoid the Cd problem, it would be better to grow non-food crops in soil treated with macroalgal compost. There is a great need to use the huge amounts of plant nutrients stored in the macroalgal masses drifting in the Baltic Sea; such use could ameliorate the eutrophication of the Baltic Sea, both locally and regionally.

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