Cd accumulation in soil from beachcast application: A long-term prediction of its reintroduction for bio-fertilisation in Gotland, Sweden

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Abstract

The ecological consequences of using beachcast compost as an agricultural resource input merit study. Using beachcast compost as a biofertiliser has multiple positive effects on agroecosystems, while also serving to remedy the negative effects on marine ecosystems caused by excessive beachcast production due to eutrophication. This process thus presents an opportunity to contribute to circular nutrient management and the development of sustainable agricultural, but it may also result in accumulation Cd (Cd) in the soil. In Gotland, Sweden, an example of cross-scale interaction between marine and agricultural domains has emerged from a national policy subsidising beachcast harvesting, which may help reintroduce the historical tradition of using beachcast in agriculture. To estimate potential risks, a field experiment and Cd mass balance were conducted to predict the rate of Cd accumulation, changes in soil Cd fractions, and potential beachcast application methods that avoid Cd soil accumulation. In the scenario where the maximum Cd input from beachcast compost is set to the same threshold as the level established for sewage sludge—0.75 g ha^{-1} year^{-1}—beachcast compost with a Cd content of 1.5 mg kg^{-1} dw (the EU threshold for biofertilisers) could be applied in an amount of approximately 2000 kg ha^{-1} per year (one-tenth of the amount applied in this study). Therefore, the long-term effects of Cd soil accumulation resulting from continuous application of beachcast as fertiliser on agroecosystems cannot be disregarded and are of global relevance.

Keywords: beachcast, biofertiliser, soil, cadmium, accumulation modelling

Introduction

Beachcast (wrecked algae and seaweed washing up on shores) used to be a highly sought-after agricultural and horticultural input in coastal areas worldwide (Aitken & Senn, 1965; Craigie, 2011) until the introduction of chemical fertiliser reduced the dependency on bio-based fertilisers (Larsson & Granstedt, 2010) including beachcast (Illera-vives et al., 2020). However, given the need for future agriculture to support the recycling of nutrients and waste in the form of compost and to encourage locally-appropriate strategies for maintaining soil fertility which are environmentally sustainable (HLPE, 2019), the sustainable utilisation of beachcast as fertiliser is expected to play an important role in agroecosystems in coastal areas in the near future (Emadodin et al., 2020).

The process of re-introducing beachcast in agriculture includes multiple interactions with the environment, as beachcast supplies nutrients, growth-promoting substances, in addition to positively affecting soil texture and water-holding capacity (Craigie, 2011; Emadodin et al., 2020). Despite its multiple positive functions and effects on the ecosystem, however, more knowledge is required before re-introducing beachcast in agriculture, with the main environmental risk factor being Cadmium (Cd) soil accumulation and crop absorption (Franzén et al., 2019; Greger et al., 2007; Michalak et al., 2017; Nabti et al., 2017; Squadrone et al., 2018; Weinberger et al., 2019). As changes in agricultural systems (such as new resource inputs) may significantly affect soil buffering of a contaminant (Mench, 1998), using beachcast compost in agriculture could influence the environment (e.g. changes in Cd fluxes), and have environmental implications that affect the future sustainability of agroecosystems (i.e. potential contamination).

Cadmium is a critical environmental contaminant of crops and soils that can be a risk for animal and human health due to its common environmental bioavailability (Barrow, 2000; de Vries et al., 2002; Römkens et al., 2018). Cd naturally occurs in soil, and is added to soil from atmospheric deposition, but also through the anthropogenic activity of industrialised agriculture, and through the application of chemical fertilisers Cd concentrations have significantly increased (Barrow, 2000). Cd is therefore circulating in larger amounts, and is found in various traditional and alternative biofertilisers and soil amendments (Barrow, 2000). Due to the long residence time of heavy metals in soil, their introduction to agricultural lands via waste fertilisers and soil amendments constitute an long-term risk, and non-linear responses of contaminants to changing environmental conditions requires the analysis of temporal trends (Hesterberg, 1998).

Where soil contaminants are of concern, research approaches should identify specific future scenarios, and then develop countermeasures to lower anticipated risks (Hesterberg, 1998). A justifiable procedure for risk evaluation is calculating Cd fluxes from local inputs/values (considering the above parameters), creating a mass balance (Barrow, 2000; Michaud et al., 2020; Six & Smolders, 2014). For this purpose, the island of Gotland, Sweden provides an excellent case study. A Swedish national policy that funds beachcast removal to curb eutrophication (by decreasing the nutrient load from the sea) is extensively applied on Gotland, and local authorities recently added an agricultural use requirement to receive funding for beachcast removal (Länsstyrelsen Gotland, 2022). Hence, the use of beachcast in agriculture could be expected to increase, and more knowledge regarding ecosystem effects from Cd uptake and accumulation using composted beachcast is relevant to agroecosystem management and agricultural and environmental policies. Given the excessive amounts of beachcast due to eutrophication, the search for a waste-to-resource conversion of this biomass, referred to as "green and golden tides" in Nature (Smetacek & Zingone, 2013), is on.

Consequently, the risk of long-term Cd accumulation from agricultural use of beachcast is of international relevance and is accordingly the aim of this study. With this aim, the Cd concentration in beachcast was correlated with soil accumulation and crop absorption in a 2-year field experiment (2019-2021) located on Gotland, Sweden, investigating: (1) the rate of Cd accumulation in wheat crops and agricultural top soil; (2) the changes of soil Cd fractions and Cd uptake by wheat, as affected by beachcast fertiliser treatment and chemical fertiliser (NPK); and (3) potential scenarios (for beachcast application) to avoid Cd soil accumulation.

Materials and methods

Study area

The island of Gotland is situated in the Baltic Sea (57° 29' N, 18° 32' E). Of the island's total 3135 km^2, 36% of the area constitutes agricultural land. Gotland has a long tradition of using beachcast compost as fertiliser and for soil improvement in agriculture (Franzén et al., 2019), although this practice was abandoned in mainstream agriculture, this resource is still available. Beachcast access is mainly due to the Swedish national policy scheme LOVA (Swedish: Lokala *vattenvårdsprojekt*), which emphasises harvesting beachcast in order to curb eutrophication in the region (Swedish Agency for Marine and Water Management, 2020). When beachcast is harvested as part of the policy scheme on Gotland, the typical procedure involves collecting beachcast in piles slightly offshore to allow it to decompose and rinse (removing salts), with the potential of later using the composted material as fertiliser. The scheme has resulted in an estimated removal of 466 tons of N and 35 tons of P over a decade of harvesting (Söderqvist et al., 2021)—primary macronutrients that could potentially serve as a supply source for agricultural production.

Site description and experimental setup

The field experiment and measurements were conducted during 2019–2020, at Hallfreda, Gotland, Sweden (57° 34' N, 18°24' E). The soil has been classified as loam (USDA soil taxonomy), and the soil pH values are greater than 7. The field experiment was conducted on calcareous soil with a pH of 6.8 and base saturation at 70%, consisting of 44% sand, 32% silt, 22% clay, and 2,3% loam, The mean annual precipitation during 2019–2020 was 610.5 mm for Gotland (Visby) (SMHI, 2020a, 2021) and the mean annual air temperature was 9°C (SMHI, 2019, 2020b).

A three-year crop rotation was used with spring wheat, autumn rapeseed, and winter wheat, according to common practice in the study area. The experiment was laid out in a randomised block design, containing four treatments with four replicates. Each replicate plot was $6 \times 16\ m^2$ in size, separated from neighbouring plots by 0.5-meter-wide pathways, preventing treatments from mixing. The spring wheat (Rosadur) was sown in mid-May 2019 and again in 2020 (550 grains m^{-2}), and the heads were harvested at maturity in mid-August for both years. As for autumn rapeseed and winter wheat, common literature values were used for the modelling.

Selected treatments

The following fertiliser treatments were compared in the study: beachcast compost, chemical fertiliser, and unfertilised soil as control. The composted beachcast material for fertiliser use in this experiment was collected at Augstens, Gotland (coordinates) in December 2019, and placed in a pile approximately 5 × 15 m in size to decompose over the course of 6 months. The species composition was estimated in December 2019, and the majority of the beachcast consisted of Sp. *Furcellaria lumbricalis*. The beachcast compost application was based on historical knowledge of what used to be common practice, theoretically calculated to 20 tons per ha^{-1} and year. Samples of the beachcast compost were analysed by ALS Global (Luleå, Sweden) using coupled plasma–mass spectrometry technique (ICP-MS, methodological reference NMKL No. 161 1998 mod./ICP-MS) to calculate total Cd input from beachcast.

The chemical fertiliser application was consistent with standard practices of the local farmers: YaraMila NPK 24-4-5 (500 kg ha^{-1} yr^{-1}) and YaraBela Axan NS 27-4 (296 kg ha^{-1} yr^{-1}). In the former, Yara (Yara AB, Malmö, Sweden) assured Cd was <12 mg Cd $(kg\ P)^{-1}$ and this maximum content was assumed for the calculations.

The block design and treatment for the spring wheat experiment was repeated in succession for two years.

Sampling and analysis (soil and crops)

Soil samples were collected directly before sowing and after harvesting by pooling 20 cores (25 mm Ø, 0.2 m depth) per plot. All soil samples were initially air-dried and sieved (2mm mesh size). The amount of geochemically-active soil Cd was determined by 0.1 mol L^{-1} HNO_3 extraction (Gustafsson et al., 2003). A dried soil sample of 2.00 g was mixed with 35 mL 0.1 mol L^{-1} HNO_3 in a bottle, equilibrated for 16 hours in an end-over-end shaker, then centrifuged at 3000 rpm for 15 minutes, and finally filtered with a Sartorius filter (0.2 µm). The 0.1 mol L^{-1} HNO_3 extracts were analysed for Cd by ALS Scandinavia AB using ICP-SFMS. (ALS, 2018). The weight of the soil was calculated from the bulk density (1300 kg m^{-3}) and plow depth (25 cm). Easily soluble Cd was determined by 1 mmol L^{-1} $CaCl_2$ soil extraction. A dried soil sample of 5.00 g was mixed with 50 mL 1 mmol L^{-1} $CaCl_2$, equilibrated for 16 hours in an end-over-end shaker, then centrifuged at 3000 rpm for 15 minutes, and finally filtered with a Sartorius filter (0.2 µm). ALS Scandinavia AB analysed the 1 mmol L^{-1} $CaCl_2$ extracts for Cd using ICP-SFMS. All soil pH measurements were made in 0.01 M $CaCl_2$. No significant differences in geochemically-active soil Cd, easily soluble Cd, and Cd content of the wheat grain was detected in field experiment.

Crop samples were collected by randomly hand-shearing and pooling four fistfuls of straw (incl. grain) per plot, resulting in a total of 16 samples. With trace elements as the central focus, precautions were taken during the various handling steps to counteract contamination of all samples prior to performing analyses (Dahlin et al., 2016). The samples were frozen in perforated plastic sample bags and dried at 50°C for 5 hours, followed by hand-threshing in a laboratory to avoid contamination. The Cd content of the wheat grain/kernel was determined using ICP-SFMS, performed by ALS Laboratories.

Cd mass balance: model application

With colloidal transport influencing transport of Cd in soil (Bergen et al., 2023), a model for calculating accumulation was preferred over measuring, using a correction factor of 0.5 in accordance with (Degryse et al., 2003).

Mass balance: model description

The contribution of fertiliser applications to soil Cd is a function of the Cd contents of fertilisers and of application rates, affecting Cd accumulation in soils, as well as its absorption by crops (Eriksson, 2009; Grant & Sheppard, 2008; Six & Smolders, 2014). Additionally, the solubility and mobility of Cd in soils and crops are affected by different physicochemical properties (like pH) which are also strongly influenced by fertiliser sources, as well as choice of crop (Ma et al., 2021). The mass balance of Cd sources and sinks was set up accordingly, with sources consisting of Cd inputs from atmospheric deposition, fertiliser treatments, and outputs from crop offtake and leaching, whereas the sink comprised topsoil accumulation (sorption) (Figure 1). With colloidal transport influencing transport of Cd in soil (Bergen et al., 2023), a model for calculating accumulation was preferred over measuring, using a correction factor of 0.5 in accordance with (Degryse et al., 2003).

Wheat was selected for the experiment, as it is one of the crops that is most sensitive to Cd (Harris & Taylor, 2013), and one of the most commonly grown crops world-wide (FAO, 2021).

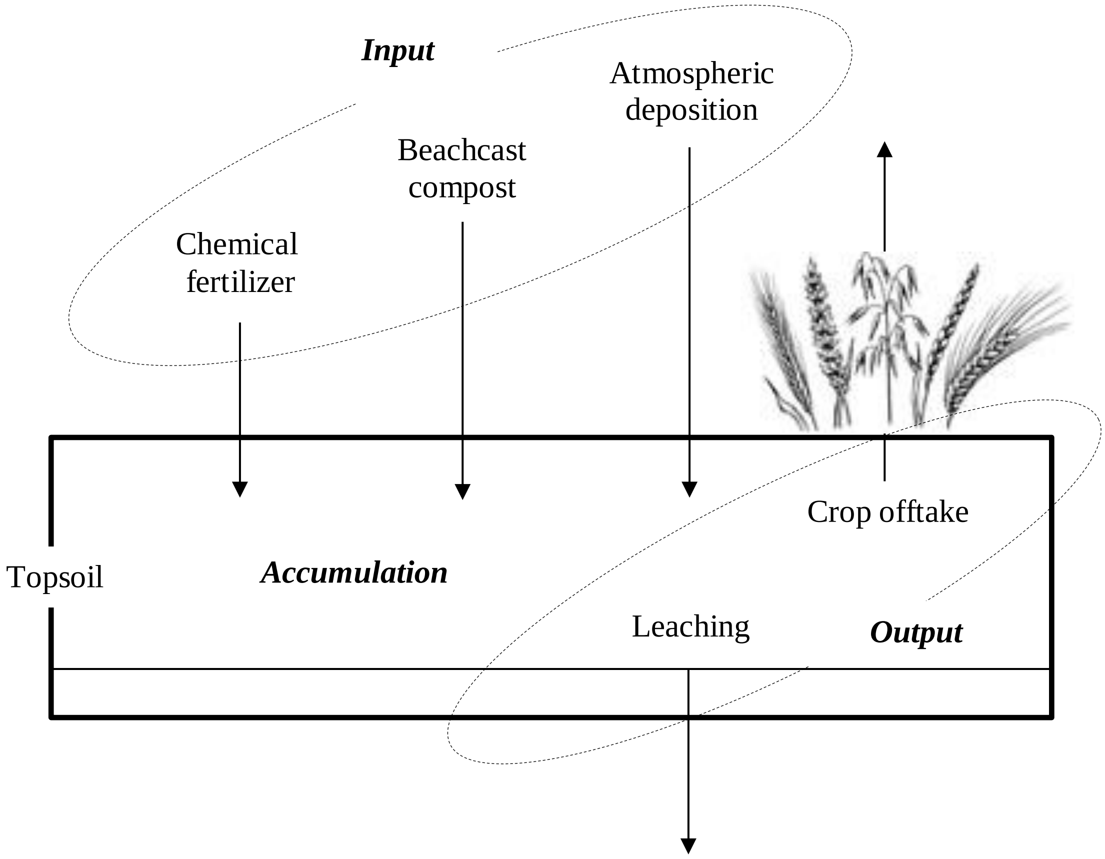

Figure 1. Illustration of the mass balance in inputs, outputs, and accumulation. Inputs include chemical and beachcast fertiliser treatments respectively, as well as atmospheric deposition. The Cd that remains in the topsoil is referred to as 'accumulation', and 'output' consists of plant uptake and leaching/runoff.

Rate of Cd accumulation

The sink, in the form of Cd soil accumulation, is the result of Cd fluxes to and from the sink; e.g., Cd input and Cd output, according to the following equation:

$$\text{Soil Cd accumulation} = \text{Cd input} - \text{Cd output} \qquad (1)$$

In this study, Cd input consists of atmospheric deposition and fertiliser application, and Cd output consists of leaching and crop offtake. Due to the high pH levels in soil in Gotland, Sweden, liming is uncommon and has therefore not been included in the model.

Based on the model description (Figure 1) and Equation 1, long-term Cd changes of the sink ($\mathrm{Cd}_{\mathrm{soil,\,i}}$) were estimated based on the initial Cd content of the soil ($\mathrm{Cd}_{\mathrm{soil,\,i-1}}$), and the yearly accumulation from input (atmospheric deposition and fertiliser application) and output (leaching and crop offtake), according to the following equation:

$$[\mathrm{Cd}]_{\mathrm{soil,\,i}} = [\mathrm{Cd}]_{\mathrm{soil,\,i-1}} + Input - Output \qquad (2)$$

The initial Cd content of the soil ($\mathrm{Cd}_{\mathrm{soil,\,0}}$) was calculated from the average dilute acid-extractable Cd (Cd extracted by 0.1 mol L^{-1} HNO_3) in all treatment plots in the start year of the experiment (2019) and found to be 335 g Cd ha^{-1} yr^{-1} .

Inputs

The annual deposition of Cd to croplands in the studied region was taken from the Meteorological Synthesising Centre–East, and ranged from 0.043–0.08 g ha^{-1} yr^{-1} for the experimental site on Gotland, Sweden (Meteorological Synthesising Centre East, 2022). In the model, we chose a value of 0.06 g Cd ha^{-1} yr^{-1}.

Cd input from beachcast compost and chemical fertiliser treatments was calculated based on the application rate and on the Cd content of the fertilisers. Model parameters with referenced sources for the spring wheat cultivation experiment are presented in Table 1, and parameters for autumn rapeseed and winter wheat are in Table 2.

The Cd content of beachcast varied from 1.6, 1.7, and 2.4 mg Cd kg^{-1} dw, resulting in an average Cd input of 0.67 g Cd $(kg\ P)^{-1}$ (Table 1). Yearly beachcast compost application was assumed to remain constant at this level for autumn rapeseed and winter wheat (Table 2). Research on beachcast compost as a biofertiliser shows that the nutrient and metal contents vary significantly depending on algae and seaweed species composition, composting process, and other parameters, with measured Cd levels ranging from 1.1–3.2 mg kg^{-1} dw (Franzén et al., 2019; Greger et al., 2007; Michalak et al., 2017; Paul, 2018; Villares et al., 2016; Weinberger et al., 2021).

Table 1. Model parameters for the spring wheat cultivation experiment used to predict long-term Cd changes in beachcast compost and chemical fertiliser.

Model parameters for spring wheat *(cultivation experiment)*

Fertiliser treatment	Year	Application rate *(kg P ha^{-1})*	Cd content fertilisers *(mg Cd (kg P^{-1}))*	Yield *(tons WW ha^{-1})* [c]	Water content *(kg kg^{-1})*	Harvest index [d]	Cd_{grain} *(mg kg^{-1})*	TF
Beachcast compost	2019	10 [a]	0.67	2937	0.80	0.5	0.037	0.65
	2020	10		3452	0.79		0.067	
Chemical fertiliser	2019	20	0.012 [b]	5314	0.81		0.057	
	2020	20		5076	0.79		0.047	

[a] The beachcast compost application of 20,000 kg ha^{-1} (WW) corresponds to approximately 10 kg P ha^{-1}.

[b] Data given by the supplier, see text

[c] The yields for the control were: 2520 (in 2019) and 3193 (in 2020) ton ha^{-1}

[d] (Gustafsson et al., 2023)

The annual input from NPK fertiliser resulted in an input of 0.012 g Cd $(kg\ P)^{-1}$ from the chemical fertiliser treatment (Table 1). The same Cd content of the chemical fertiliser was assumed for autumn rapeseed and autumn wheat. For autumn rapeseed, the application rate was set to recommended levels (Yara, 2021), corresponding to 11.4 kg P ha^{-1}, whereas the level for winter wheat was estimated from (Gustafsson et al., 2023) to be 10 kg P ha^{-1} (Table 2).

Table 2. Model parameters used to predict the long-term Cd changes in the two treatments using beachcast compost and chemical fertiliser for autumn rape and winter wheat. Values for grain harvest, harvest index, and Cd content were used to calculate the transfer factor, TF, (of Cd from soil to crop), and thereby $[\mathrm{Cd}]_{\mathrm{crop}}$ (e.g. output through plant uptake/crop harvest).

Model parameters for autumn rape and winter wheat *(literature values)*

Crop	Application rate *(kg P ha^{-1})*		Grain harvest *(kg ha^{-1})*	Harvest index	$\mathrm{Cd}_{\mathrm{grain}}$ *(mg kg^{-1} dw)*	TF
	Beachcast compost	Chemical fertiliser				
Autumn rapeseed	10	11.4 [a)]	2720 [c)]	0.3 [e)]	0.033[g)]	0.5
Winter wheat	10	10 [b)]	6310 [d)]	0.5 [f)]	0.044[h)]	0.5

[a)] (Yara, 2021)

[b)] (Gustafsson et al., 2023)

[c)] (Jordbruksverket, 2020a)

[d)] (Jordbruksverket, 2020b)

[e)] (Diepenbrock, 2000)

[f)] (Gustafsson et al., 2023)

[g)] (Dyrlund Martinsson, 2021)

[h)] (Wångstrand et al., 2007)

Outputs

Cd output from crop offtake $[\mathrm{Cd}]_{\mathrm{crop}}$ was calculated by combining the yield and Cd concentration in each sample. Crop offtake is relatively small compared to other Cd fluxes (Six & Smolders, 2014), and was simplified using the assumption that the Cd concentration in the crop changes proportionally with the soil Cd concentration, commonly referred to as a 'transfer function', or TF. The TF is therefore the ratio of the Cd concentration in the crop and in the soil (calculated on a dry weight basis in this study):

$$\mathrm{TF} = \frac{[\mathrm{Cd}]_{\mathrm{crop}}}{[\mathrm{Cd}]_{\mathrm{soil}}} \qquad (2)$$

In the experiment, $[\mathrm{Cd}]_{\mathrm{crop}}$ from the spring wheat crops/plants was calculated based on the Cd content of the wheat grain/kernel removed via harvesting, with values adjusted to the varying yields and water content between the treatments, as well as between the two years. Because the straw was not analysed in the current study, the total crop Cd (including the straw) was assumed to be three times the level of the wheat kernel, based on results from a parallel study (Gustafsson et al., 2023). In the field trial, the straw was removed from the system and was therefore included in the crop offtake.

TF for autumn rape and winter wheat (the assumed crop rotation) was calculated using literature values. First, average grain harvest (ton ha^{-1}) and harvest indices were used to estimate the total harvest (grain harvest divided by harvest index). Secondly, the average Cd content of each crop was used to calculate the total Cd removed via crop harvest (total harvest time
$\mathrm{Cd}_{\mathrm{crop}}$).

Leaching represents the other output of Cd from the topsoil, and there are different predictive models. For this mass balance, output via leaching was estimated based on the precipitation excess/runoff and $[\mathrm{Cd}]_{\mathrm{solution}}$. The average annual precipitation excess, F, measured in mm (m^2 yr^{-1}), in the area of the experiment (SMHI, 2020c).

$$\text{Leaching} = F \times [\mathrm{Cd}]_{\mathrm{solution}} \tag{3}$$

Output via leaching was calculated using the following equation:

$$[\mathrm{Cd}]_{\mathrm{solution\ 0\text{-}100}} = \left(\frac{[\mathrm{Cd}]_{\mathrm{soil\ 0\text{-}100}}}{K_{\mathrm{F}} \times \{\mathrm{H}^{+}\}^{-0.6}} \right)^{1/0.85} \tag{4}$$

where K_{F} is the Freundlich coefficient, calibrated from the first year's results for $[\mathrm{Cd}]_{\mathrm{solution}}$ and $[\mathrm{Cd}]_{\mathrm{soil}}$ and the measured pH values. The exponent of -0.6 for $\{\mathrm{H}^{+}\}$ was selected based on an average from Six & Smolders (2014) (–0.51) and Temminghoff et al. (1995) (–0.69) with pH as a variable. The Freundlich exponent of 0.85 (1/0.85 when rearranged as in Eq. 4) is based on the results of Christensen (1984) and Temminghoff et al. (1995). Assuming one yield per year, the $[\mathrm{Cd}]_{\mathrm{solution}}$ (µg L^{-1}) was converted to (µg m^{-2}) and eventually g Cd ha^{-1} yr^{-1}, and the annual increase was calculated iteratively from 0 to 100 years using Equation 3. The calculated value of the Freundlich coefficient K_{F} was 0.00127. For the runoff, the average for 2020 of 224.0 mm yr^{-1} was used (2019 was an exceptionally dry year at 130.6 mm yr^{-1}) (SMHI, 2020c). The pH was set to 7.2, which is the average from all treatments and years.

The changes of soil Cd fractions

The mass balance model (Eq. 1) was used to predict future Cd concentrations in soils (for wheat cultivation) for which the mass balance used is dynamic (i.e., the output by leaching and plant uptake/crop offtake changes with changing total soil concentrations) (De Meeûs et al., 2002). Inputs of Cd are assumed to be constant (for the two treatments) over the next 30 years. The long-term change in soil Cd (measured in percentages) was extrapolated from the initial soil Cd concentration ($[\mathrm{Cd}]_{\mathrm{soil,\ 0)}}$) and the soil Cd concentration after a 30-year period and yearly application of the respective fertilisers ($[\mathrm{Cd}]_{\mathrm{soil,\ 30)}}$), using the following equation:

$$\%\ \text{change} = \frac{[\mathrm{Cd}]_{\mathrm{soil,30}} - [\mathrm{Cd}]_{\mathrm{soil,0}}}{[\mathrm{Cd}]_{\mathrm{soil,0}}} \times 100 \tag{5}$$

Model parameters used to obtain the scenario of a crop rotation of spring wheat, autumn rapeseed, and winter wheat are shown in Table 3.

Assumptions

Assumptions include homogeneous soil without vertical variation of soil properties in the topsoil. In accordance with Six & Smolders (2014), a constant relation between soil content and crop offtake was assumed. Surface runoff and erosion were viewed as a redistribution of Cd within the landscape and were therefore excluded in the model. Moreover, the model assumes the Cd soil concentration to be equal to that of the $CaCl_2$ solution. Irrigation is not common practice in the Nordics, wherefore it was not part of the model.

Changes in the organic content of the soil were not included in the model, and consequently, the continuous release of bound-but-soluble Cd due to decomposition of carbon material was not considered. Neither did the model consider the highly calcareous soil, known to decrease crop uptake (Miller et al., 1995). These conservative assumptions were made as a precaution, to not underestimate the potential level of soil Cd accumulation. The Cd levels are deemed low enough to not inhibit crop growth, wherefore a potential decline in biomass for crop offtake was not included in the model.

Results

The results show that the Cd originating from the fertiliser source constitutes the main Cd input of the mass balance. The Cd input from the beachcast treatment amounted to 8.5 Cd ha^{-1} yr^{-1}, or about 20 times the amount from the CF treatment (Table 4, and Figures 2 and 3). The amount of beachcast compost applied was significant, and accordingly, the total input of Cd was substantial. As a reference, the accepted threshold for biofertilisers, including sewage sludge, is 0.75 g ha^{-1} yr^{-1} (Avfall Sverige, 2021).

In a prospective simulation of soil Cd content evolution until year 2100 from a treatment of co-composted green wastes and sludge showed that soil content reached 0.4 mg Cd kg^{-1} in the soil (Michaud et al., 2020). In comparison, the soil Cd content for the beachcast compost treatment in this study was approximately 0.897 mg Cd kg^{-1} in 2090 (Table 4).

The Cd output from crop harvesting in wheat varied between years and treatments due to crop rotation (e.g., varying amounts of chemical fertiliser being applied, and varying transfer factors for the different crops). Moreover, the model predicted a difference between treatments, with an expected increase in crop offtake for the beachcast treatment (Figure 2), and conversely, a slow decrease from CF use (Figure 3). The crop offtake from the beachcast treatment increased from 0.55 to 1.49 g ha^{-1} yr^{-1}, nearly tripling from 2020 to 2090. This was due to the assumed constant relation between soil content and crop offtake, in accordance with Six & Smolders (2014). As for the chemical fertiliser treatment, the higher crop biomass/yield made the Cd offtake from harvest higher than the control, from 0.38 to 0.63 g ha^{-1} yr^{-1} (Table 4). In line with the findings by Bergkvist et al. (2003), the crop offtake was nearly twice as high compared to that of the control.

The output from leaching nearly tripled for the beachcast compost treatment (from 0.57 to 1.60 g ha^{-1} yr^{-1} between 2020 and 2090), but decreased slightly for chemical fertiliser and for the control (Table 4).

Table 4. Mass balance of Cd, in g ha^{-1} yr^{-1}, showing inputs from atmospheric deposition and fertiliser treatments, output from crop offtake and leaching, and soil accumulation for respective treatments (beachcast compost, BC; chemical fertiliser, CF; and control, C).

Mass balance of Cd (g ha^{-1} yr^{-1})													
Cd	**Input +**				**Output –**						**Soil Accumulation**		
Yr.	Atm. Dep.	Fertiliser Treatments			Crop offtake			Leaching					
		BC	*CF*	*Con.*	*BC*	*CF*	*Con.*	*BC*	*CF*	*Con.*	*BC*	*CF*	*Con.*
’19	0.06	8.5	0.22	0	0.55	0.59	0.34	0.56	0.56	0.58	331	333	341
’20	0.06	8.5	0.71	0	0.34	0.38	0.32	0.57	0.56	0.57	338	332	340
’30	0.06	8.5	0.18	0	0.76	0.7	0.58	0.72	0.55	0.56	413	326	331
’50	0.06	8.5	0.71	0	0.55	0.36	0.30	1.02	0.52	0.52	555	314	314
’70	0.06	8.5	0.22	0	0.69	0.35	0.28	1.31	0.50	0.49	687	304	297
’90	0.06	8.5	0.18	0	1.49	0.63	0.49	1.60	0.48	0.46	810	294	282

The results from the model show that the rate of accumulation is equal to a soil Cd level of approximately 555 g ha^{-1} yr^{-1} soil in 2050. At this predicted rate of increase, soil Cd would double in half a century (from 338 g ha^{-1} yr^{-1} in 2020 to 687 g ha^{-1} yr^{-1} in 2070) from continuous beachcast compost when applied at a level of 20 ton ha^{-1} yr^{-1}. Conversely, the model indicates a predicted decrease in soil Cd (accumulation) for both the chemical fertiliser and the control (Table 4 and Figure 4).

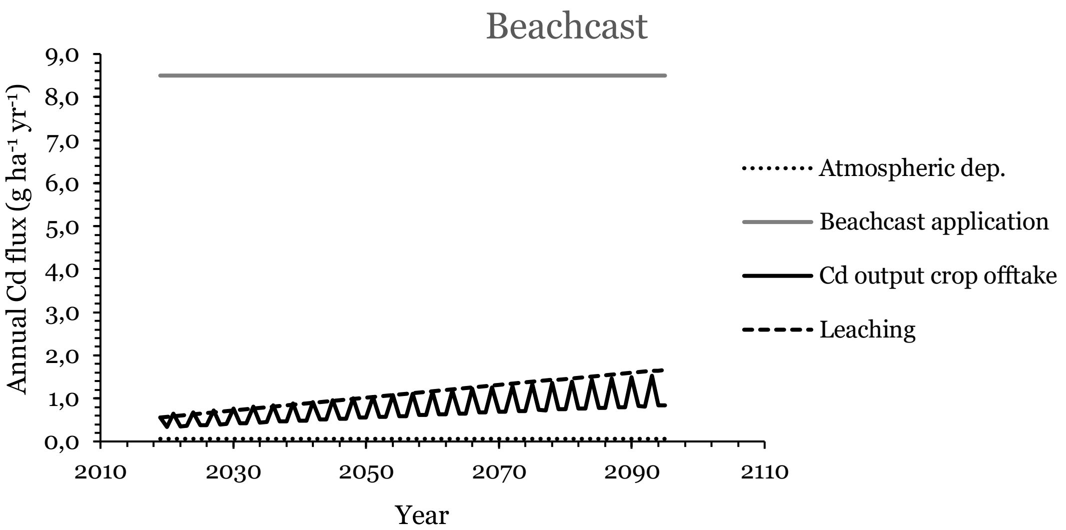

Figure 2. Predicted Cd fluxes in the beachcast compost treatment, in g ha^{-1} yr^{-1}, between 2020 and 2090. The beachcast application is constant at 8.5 g ha^{-1} yr^{-1}.

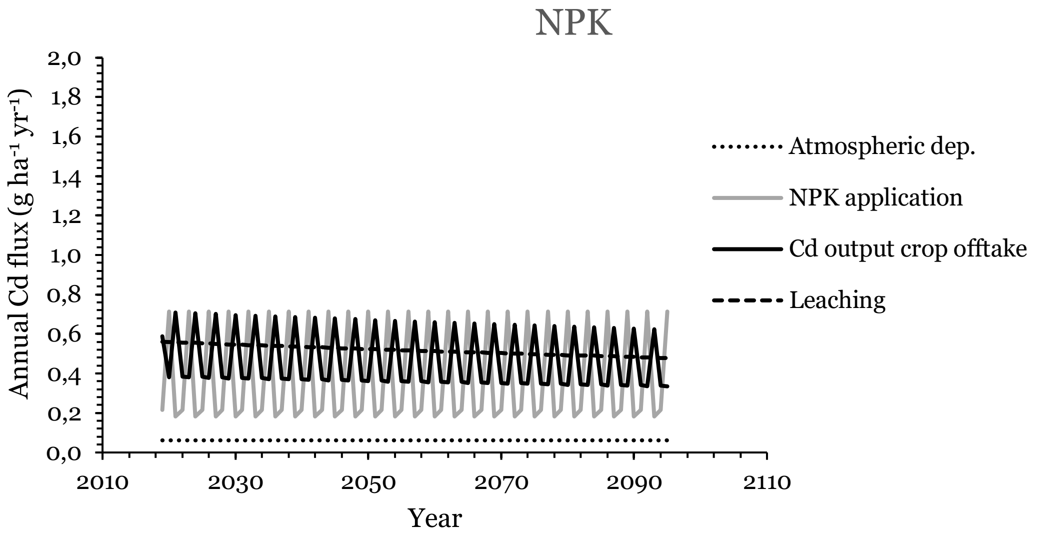

Figure 3. Predicted Cd fluxes in the chemical fertiliser treatment, in g ha^{-1} yr^{-1}, between 2020 and 2090.

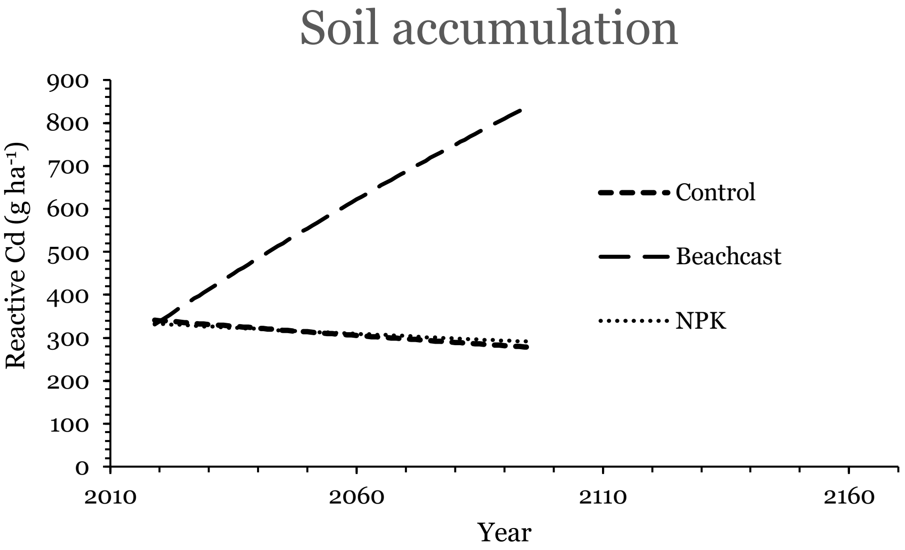

Figure 4. Predicted soil accumulation of reactive Cd in the three treatments, in g ha^{-1} yr^{-1}, between 2020 and 2090.

Soil Cd fractions

In the scenario of applying beachcast compost yearly in the amount of 20 ton ha^{-1} until 2030, Cd concentrations in the agricultural topsoil (in this certain location) are predicted to increase by 25%. Over the long term to 2050, 2070, and 2090, soil Cd is predicted to increase by 68%, 107% and 145%, respectively.

Table 5. Modelled long-term change in soil Cd fractions concentrations after continuous application of beachcast compost and chemical fertiliser until 2030, 2050, 2070, and 2090, respectively.

Changes in $[Cd]_{soil}$ (%)				
Treatments	**Change in soil Cd$_{2030}$** (%)	**Change in soil Cd$_{2050}$** (%)	**Change in soil Cd$_{2070}$** (%)	**Change in soil Cd$_{2090}$** (%)
Beachcast compost	25 %	68 %	107 %	145 %
Chemical fertiliser	–2.0 %	–5.6 %	–8.8 %	–12 %
Control	–2.9 %	–8.0 %	–13 %	–17 %

As a reference, the increase in soil Cd from the chemical fertiliser treatment and the control decreased by 12% and 17%, respectively, between 2030 and 2090.

Scenario generation to avoid accumulation

Scenarios were generated to discern patterns for which beachcast compost could potentially be applied long-term while avoiding Cd soil accumulation; e.g., sustainable use. Considering the crop rotation constant, scenarios were modelled with the following variables: combining a lower (i) Cd content of the beachcast compost, and (ii) frequency of application.
Three scenarios were generated:

(1) Beachcast compost with a Cd content of 1.5 mg kg^{-1} dw, the EU threshold for biofertilisers (EU Fertilising Products and Amending Regulations, 2019) applied yearly at a rate of 20 ton ha^{-1}
(2) Beachcast compost with a Cd content of 1.5 mg kg^{-1} dw applied every 7–9 years at a rate of 20 ton ha^{-1}
(3) Beachcast compost with a Cd content of 1.0 mg kg^{-1} dw applied every 5–7 years at a rate of 20 ton ha^{-1}

The fractional Cd increase from each scenario is presented in Table 6.

The results show that Scenario 1 (applying beachcast compost with a Cd content of 1.5 mg kg^{-1} DW every year) would double the soil Cd level (109% increase). Scenario 2 (applying beachcast compost with a Cd level of 1.5 mg kg^{-1} dw) displayed a turning point at an application rate of 7–9 years, for which a slight decrease in soil Cd levels could be expected. A decrease in soil Cd from Scenario 3 (beachcast compost with a Cd content of 1.0 mg kg^{-1} dw) could be expected if beachcast is applied every 5–7 years. Details are presented in Table 6, where the fluctuating numbers (percentages) are due to fluctuating Cd output.

Table 6. Scenario modelling, showing changes in soil Cd fractions when applying beachcast compost with a lower Cd content than the beachcast compost in the cultivation experiment, in which the model contained 1.0 and 1.5 mg kg$^{–1}$ dw, respectively) at different time intervals (ranging from 1–9 years) to investigate when Cd would not accumulate in the soil.

		Changes in $[Cd]_{soil}$ (%)			
Treatment	***Interval***	**Change in soil Cd_{2030}** (%)	**Change in soil Cd_{2050}** (%)	**Change in soil Cd_{2070}** (%)	**Change in soil Cd_{2090}** (%)
Beachcast compost 1.5 *mg kg$^{–1}$ dw*	*Every yr.*	19	51	81	109
	7 yrs.	–0.068	+1.6	+3.3	5.1
	9 yrs.	–0.068	–0.11	–0.04	2.0
Beachcast compost 1.0 *mg kg$^{–1}$ dw*	*5 yrs.*	–0.72	0.29	1.2	2.3
	7 yrs.	–0.72	–0.91	–0.93	–0.83

The modelled scenarios indicated that soil accumulation could be avoided if using beachcast compost with Cd <1.0 mg kg$^{–1}$ dw, and applying 20,000 kg ha$^{–1}$ at 5–7 year intervals, or Cd <1.5 mg kg$^{–1}$ dw, and applying 20,000 kg ha$^{–1}$ at 7–9 year intervals. In the scenario of setting the maximum Cd input from beachcast compost to the same threshold used for biofertilisers including sewage sludge (at 0.75 g ha$^{–1}$ yr $^{–1}$), beachcast compost with a Cd content of 1.5 mg kg^{-1} dw could be applied in the amount of approximately 2000 kg ha$^{–1}$ (instead of 20,000 kg ha$^{–1}$) per year. This corresponds to a tenth of the applied amount in this study.

Discussion

This study examined the risk of long-term Cd accumulation from the agricultural use of beachcast compost, with the objective of investigating potential scenarios to avoid Cd soil accumulation (Objective 3) based on the estimated rate of Cd soil accumulation and changes in soil Cd fractions (Objectives 1 and 2). By better understanding the scale of impact of the use of beachcast in agriculture, in relation to the properties included in Cd budget/modelling, the long-term fate of Cd in soils is more predictable. This is a significant contribution of the paper.

Although the data is case-specific, the discussion contributes to thinking regarding how to manage beachcast and like resources; i.e., biomass associated with a waste–resource dilemma. Based on the results, which point at only applying beachcast compost with a Cd content of less than 1–1.5 mg kg$^{–1}$ biomass at 5–7 and 7–9 year intervals, respectively, and in small quantities (in relation to fertilisation requirements), beachcast should be seen as a supplement rather than a substitute for other fertilisers.

Multiple factors would affect the mass balance model, some of which were not included in this study. One of them is the addition of organic matter input, which would increase with continuous beachcast compost application. This could affect the transfer factor (TF, which was assumed to be constant in this model)—as organic carbon input is converted to humus over time, there is more material to immobilise metals such as Cd (Sun et al., 2021). This has been shown to reduce the plant uptake of Cd in wheat (Grüter et al., 2019). Organic matter also affects the soil structure, mainly by increasing soil porosity, the stability of aggregates, and water retention (Mininni & Santori, 1987)—all which could affect the Cd mass balance and are valuable features for sustainable agroecosystems. Numerous agricultural systems with similar crop rotations as the one used in this model (no ley or manure) are in need of such improvements in terms of carbon input (Kirchmann & Hamner, 2015). The amount of carbon input from beachcast compost in our case would be approximately 5300 kg C ha^{-1} yr^{-1}. As a reference, the addition from biowaste in the study by Michaud et al. (2020) reached approximately 4000 kg C ha^{-1} yr^{-1}.

Moreover, the model did not include various soil types or farming practices, the inclusion of which is recommended when considering management (Bengtsson et al., 2006; Cieslinski et al., 1996; Stafford et al., 2018). The content of soil organic matter affects metal binding to soils (Gustafsson et al., 2003). The precision of the predicted accumulation may improve by developing the model to include this aspect. Adjusting soil management and crop rotation could potentially lower the Cd concentration, as Cd concentration in grain is highest in wheat grown after a legume, and lowest in wheat grown after a cereal, and reduced-till or conventional cultivation has shown lower crop accumulation than direct drilling (Mench, 1998).

Grüter et al. (2019) stated that the diversity of effects that farming practices have on Cd accumulation in wheat demonstrates that only long-term field trials can show how a certain combination plays out under real-world conditions. This statement also calls for the study of common/more pragmatic farming practices of beachcast. Additional research should therefore investigate the properties of beachcast material, as the purpose of any compost (e.g., fertiliser or carbon supplement) determines its suitability (Crohn, 2016).

Furthermore, to make the comparison between beachcast compost and chemical fertiliser treatments more accurate, another choice for a realistic worst-case assumption may be preferred. Given that the EU Council's slow suggests a single limit of 60 mg Cd (kg P_2O_5)$^{-1}$ (Ulrich, 2019) that corresponds to 137 mg Cd (kg P)$^{-1}$, the parameter for the Cd content of chemical fertiliser could potentially be set to this level instead of the minimum achievable level. Moreover, the Scientific Committee on Health and Environmental Risks accepts an average content of Cd in fertilisers of 36 mg Cd (kg P_2O_5)$^{-1}$ (SCHER, 2015); equal to 82 mg Cd (kg P)$^{-1}$. If the Cd content of the chemical fertiliser in this model would have been set to this level, the parameter would have been approximately seven times higher (from 12 to 82 mg Cd (kg P)$^{-1}$). This would have changed the predicted Cd soil accumulation of the chemical fertilizer treatment, and made the difference between the two treatments (chemical fertilizer and beachcast compost) less distinctive, and perhaps more realistic (since a best-case scenario of 12 Cd (kg P)$^{-1}$) may be unrealistic).

Given the above aspects, together with Gotland’s long history and prospective future of using beachcast an agricultural resource input, there is a need for future research to include long-term field trials in order to investigate how agricultural use of beachcast may affect agroecosystems, which produce knowledge of agroecosystem management or agricultural and environmental policies.

In the meantime, strategies to minimize Cd the input may consider careful application with regards to the Cd content of the beachcast compost and amounts applied, and co-application with other fertilizers to minimize the input.

It would also be of interest to follow up on the relevance of the results with regards to management and policy decisions dealing with beachcast as a resource, as the knowledge produced in this paper provides a perspective that has not been presented either on Gotland or globally.

Conclusions

The strong link between beachcast application to soils and Cd accumulation is well-documented, and our results confirm this correlation, but the model in this study was able to predict the potential long-term accumulation. Seventy years of regular beachcast applications caused a substantial increase in Cd in the topsoil, according to the modelled experiment, due to steadily increasing Cd concentration in soil. The model could be considered an extreme local scenario, but is, nevertheless, possible. In the scenario of setting the maximum Cd input from beachcast compost to the same threshold as that of sewage sludge, at 0.75 g ha^{-1} yr^{-1}, beachcast compost with a Cd content of 1.5 mg kg^{-1} dw (the EU threshold for biofertilisers) could be applied in the amount of approximately 2000 kg ha^{-1} per year (a tenth of the applied amount in this study). Nevertheless, the long-term effects on agroecosystems from Cd soil accumulation from the continuous application of beachcast as fertiliser cannot be disregarded.

The results integrate new knowledge and perspectives on beachcast management that are relevant to agricultural and environmental policy-making. However, more knowledge of variations in Cd levels and the other chemical components of beachcast is required before any recommendations can be made. The diversity of effects that farming practices have on Cd accumulation in wheat shows that only long-term field trials under real-world conditions can confirm the actual outcome (Grüter et al., 2019). This statement also calls for the study of common farming practices of beachcast, including whether beachcast is primarily used for fertilisation, amendment, and/or mulch, as the particular application determines what properties should be evaluated to assess the suitability of a compost (Crohn, 2016). The above aspects merit further study (including long-term field trials) in the location of Gotland, given its long history and prospective future of using beachcast an agricultural resource input, to investigate how it may affect agroecosystems, and produce knowledge on agroecosystem management or agricultural–environmental policies.

The motivations behind future research on the potential agricultural uses of beachcast are two-fold and cross-scale, combining the marine and agricultural policy domains: it could help solve the environmental problem of beachcast accumulation affecting coastal/marine ecosystems, while also possibly contributing to sustainable agroecological practices.

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the conceptual idea and research design. The development and revision of model were performed by Hanna Nathaniel and Jon-Petter Gustafsson. The execution of field experiment and data collection was executed by Hann Nathaniel and Daniel Franzén. The data analysis was done by Hanna Nathaniel, Jon-Petter Gustafsson, and Daniel Franzén. The first draft of the manuscript was written by Hanna Nathaniel and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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