Science of the Total Environment 882 (2023) 163664

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Comparison of PFAS soil remediation alternatives at a civilian airport using cost-benefit analysis

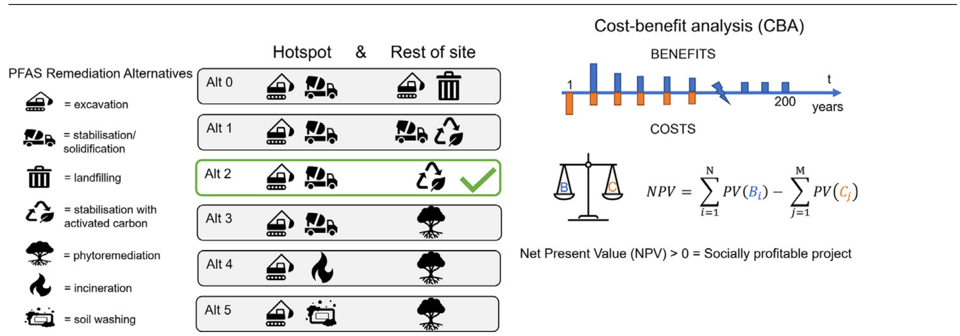
P. Drenning [a,*], Y. Volchko [a], L. Ahrens [b], L. Rosén [a], T. Söderqvist [c], J. Norrman [a]

[a] Department of Architecture and Civil Engineering, Chalmers University of Technology, SE-41296 Gothenburg, Sweden
[b] Department of Aquatic Sciences and Assessment, Swedish University of Agricultural Sciences, SE-75007 Uppsala, Sweden
[c] Holmboe & Skarp AB, Norr Källstavägen 9, SE-14896 Sorunda, Sweden

HIGHLIGHTS

- Comparison of remediation techniques for managing a PFAS contaminated site
- Probabilistic cost-benefit analysis to evaluate PFAS remediation alternatives
- PFAS in the environment is associated with high costs of inaction to society.
- Simulation of different annual avoided cost of inaction to find breakeven points
- Ex-situ S/S of hotspot and stabilization of rest of site highest ranked alternative

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Frederic Coulon

Keywords:
Cost-benefit analysis (CBA)
Per- and polyfluoroalkyl substances (PFAS)
Gentle remediation options (GRO)
Sustainable remediation
Ecosystem services
Decision-support

ABSTRACT

Contamination of soil and water systems by per- and polyfluoroalkyl substances (PFAS) due to uncontrolled use of aqueous film-forming foams (AFFFs) at firefighting training sites at civilian and military airports is a universal issue and can lead to significant human health and environmental impacts. Remediation of these sites is often complex but necessary to alleviate the PFAS burden and minimise the risks of exposure by eliminating the hotspot/source from which the PFAS spreads. This study presents a probabilistic cost-benefit analysis (CBA) for evaluating PFAS remediation alternatives, which includes monetisation of both direct costs and benefits as well as externalities. The method is applied for a case study to compare five remediation alternatives for managing PFAS contaminated soil at Stockholm Arlanda Airport in Sweden. The social profitability, or the net present value (NPV), of each remediation alternative was calculated in comparison to two reference alternatives – 'total excavation' of the site (Alt 0) or 'do nothing'. Sensitivity analyses and model scenarios were tested to account for uncertainties, including small or large PFAS spreading and simulating different values for the magnitude of annual avoided cost of inaction (i.e., aggregate benefit) from PFAS remediation. In comparison to total excavation, four of the five studied remediation alternatives resulted in a positive mean NPV. Excavation and stabilization/solidification of the hotspot on-site combined with stabilization using activated carbon for the rest of site (Alt 2) had the highest NPV for both spreading scenarios, i.e., Alt 2 was the most socially profitable alternative. Simulations of the annual avoided cost of inaction enabled estimation of the breakeven point at which a remediation alternative becomes socially profitable (NPV > 0) compared to 'do nothing'. Alt 2 had the lowest breakeven point: 7.5 and 5.75 millions of SEK/year for large and small spreading, respectively.

* Corresponding author.
E-mail address: drenning@chalmers.se (P. Drenning).

http://dx.doi.org/10.1016/j.scitotenv.2023.163664
Received 23 January 2023; Received in revised form 30 March 2023; Accepted 18 April 2023
Available online 22 April 2023

1. Introduction

Ubiquitous contamination of per- and polyfluoroalkyl substances (PFAS) in environmental media has become a critical global issue in recent years because of their persistent, bioaccumulative, highly mobile and toxic nature (ITRC, 2020a, 2020b; Wang et al., 2019). One major source of PFAS contamination is the legacy usage of PFAS-containing aqueous film-forming foams (AFFF) in firefighting operations, which has been used since at least the 1960s and gradually phased out by 2011 across Europe (Ahrens et al., 2015; Goldenman et al., 2019). The repeated use and uncontrolled release of AFFFs during firefighting has contaminated the local environment with PFAS chemicals, and firefighting training sites at airports, military facilities, etc. have been highlighted as major point sources (hotspots) of PFAS contamination (Ahrens et al., 2015; Cousins et al., 2016; Goldenman et al., 2019). AFFF sites have been linked to adverse health effects in local populations in recent epidemiological studies, e.g., (Xu et al., 2022).

Environmental fate and transport of PFAS can vary depending on their physicochemical properties as well as environmental conditions but, in general, short-chain PFAS are potentially more water soluble and mobile while long-chain PFAS tend to sorb more strongly to soil particles and can accumulate in the food chain (Ahrens et al., 2015; ITRC, 2020b). Primary exposure pathways relevant for human health risks from PFAS contamination are linked to intake of contaminated food or contaminated drinking water, which may result from elevated PFAS concentrations in groundwater (Cousins et al., 2016; Ojo et al., 2021). Treating PFAS contaminated drinking water is therefore a primary concern; however, the soil in hotspot areas such as at airports can retain PFAS and release it over a long period of time. This can result in subsequent leaching into groundwater, spreading to adjacent surface water and contamination of drinking water sources, which can cause significant harm to both human health and the environment (Cousins et al., 2016; Fenton et al., 2021; Gobelius et al., 2017; Rosenqvist et al., 2017; Sörengård et al., 2021). Indeed, the costs of inaction to society for not managing PFAS contamination in the environment are estimated to be as much as €2.1–2.4 billion annually in the Nordic countries alone, due to health impact-related costs from PFAS-contaminated drinking water (Goldenman et al., 2019). It is therefore important to also manage the hotspots of PFAS soil contamination effectively; for the longer the PFAS contamination remains in the environment without remediation, the wider it will spread and the greater the quantity of soil, groundwater and other drinking water sources that will need be treated (Goldenman et al., 2019).

PFAS exposure has been definitively linked to multiple detrimental health effects to humans, including different types of cancer, osteoporosis, liver damage, decreased fertility and increased risk of asthma, reduced immune response and endocrine disruption (ATSDR, 2021; Ojo et al., 2021; Wang et al., 2019; Xu et al., 2022). While there are still uncertainties due to a lack of data, PFAS exposure has also been shown to have toxic effects on aquatic animal species and is linked to endocrine disruption and impaired thyroid function, impaired immune responses, metabolism and reproduction disruption (Birgersson et al., 2021; Lee et al., 2020; Ojo et al., 2021; Wang et al., 2019), as well as a reduction in soil bacterial biodiversity (Cao et al., 2022). It is now clear that PFAS contamination is poorly reversible, ubiquitous in the environment, and the social costs of inaction are and will continue to be high (Goldenman et al., 2019). Remediation of PFAS contaminated sites, therefore, is crucial to mitigate the risks from PFAS exposure to both humans and ecosystems by managing the source of PFAS contamination in soil and/or spreading and exposure pathways. However, in some cases the site-specific costs of PFAS remediation may exceed the expected benefits gained from the remedial action at a particular site which warrants careful consideration when spending limited resources.

In addition, remediation is not inherently sustainable (Bardos et al., 2020; Rosén et al., 2015; Söderqvist et al., 2015) and selecting a remediation alternative to manage the risks posed by the PFAS contamination can be difficult for decision-makers due to the associated costs and e.g., potential impacts on provisioning of ecosystem services. Cost-benefit analysis (CBA) is a decision-support tool that relies on welfare economics for expressing positive (benefits) and negative (costs) effects on human well-being including both financial costs and benefits as well as positive and negative externalities (i.e., positive or negative effects on health and the environment in terms of provisioning of ecosystem services, carbon emissions, noise, traffic etc.). Using monetary units makes it possible to weigh the costs of a remedial action against associated benefits over a certain time horizon and in relation to a reference alternative. A positive net sum of discounted costs and benefits means that the remedial action entails a social profitability, whereas a negative net sum indicates social loss (Johansson and Kriström, 2018; Rosén et al., 2015; Söderqvist et al., 2015). CBA has been highlighted as a decision-support method with great potential for incorporating sustainability measures in an understandable, easy-to-use approach and account for the value of restoring or preserving soil functionality and ecosystem services (ES) (Onwubuya et al., 2009). Additionally, economic valuation of ES contributes to the decision-making process by integrating ES into decision-support and engaging potentially responsible parties to participate in both the remediation process and funding of risk mitigation measures (Harwell et al., 2021). The novelty of this study lies in its systematic approach to evaluating feasible techniques for remediating PFAS in soil, according to prevailing literature, and estimating the economic impacts of each alternative while also including impacts to the environment and taking uncertainties into account. To our knowledge, applying a probabilistic CBA methodology for evaluating and comparing PFAS remediation alternatives is unique. Given the scale of PFAS contamination and society's limited resources, demonstrating the use of CBA in a case study for a specific site also provides a valuable contribution by supporting decision-makers to cost-effectively and sustainably remediate a PFAS contaminated site.

The aim of this study is to further develop a methodology for performing a probabilistic CBA of remediation alternatives for managing PFAS contamination in soil. The CBA is illustrated through practical application to evaluate five remediation alternatives for managing the risks to human health and the environment posed by PFAS in the soil at the firefighting training site of Stockholm Arlanda Airport. The specific objectives are to: i) develop a probabilistic CBA model for five PFAS remediation alternatives, ii) estimate the costs and benefits of the remediation alternatives based on literature studies and personal communication with contractors, and by taking uncertainties in the input variables of the model into consideration; and iii) investigate the sensitivity of the CBA model regarding both parameter and model uncertainty. The CBA is carried out by means of Monte Carlo simulations and both parameter and model uncertainty are investigated. The model uncertainty is analysed by creating alternative scenarios for: a) choice of reference alternative, b) the social discount rate, c) two PFAS spreading scenarios, and d) the magnitude of avoided cost of inaction.

2. Site: Stockholm Arlanda Airport

2.1. Site description

The firefighting training site is situated at Stockholm Arlanda Airport outside of Stockholm, Sweden, where AFFF-containing PFAS was used until 2011 (Gobelius et al., 2017).

The geology consists primarily of surface layers of glacial clay underlain by sandy glacial till which varies between a depth of 1.5–8 m below the surface depending on the thickness of the clay (Rosenqvist et al., 2017). The glacial till is deposited on crystalline metamorphic rock of igneous origin. To the immediate north and northeast of Stockholm Arlanda Airport, layers of sand (glacio-fluvial or beach deposits with silt) have been deposited on top of the clay layer. The firefighting training site is located within one such area with a top layer of beach sand and silt, varying between 0.3 and 2 m in thickness, that thins out and disappears altogether closer to the landing strips southwest of the training site. Filling material of sand and gravel form the immediate surface layer of 0.5 m in the built area above the natural geological soil layers. Hydrogeological investigations have determined that there are two distinct aquifers: an unconfined aquifer in the upper layer of sand and silt above the clay and a confined aquifer in the sandy glacial till below. The upper aquifer is contaminated with PFAS and constitutes an important spreading pathway for PFAS off-site to nearby surface water systems. At the training site, the groundwater depth ranges between 1.1 and 1.8 m across the site, but the water table is at or near the surface layer in some areas. It has also been determined that the groundwater flows in a south-westerly direction, towards a nearby open ditch that is in hydraulic contact with nearby surface water but away from and not in contact with the glacio-fluvial sand deposits to the northeast of Stockholm Arlanda Airport with high hydraulic conductivity (Rosenqvist et al., 2017).

Sampling campaigns at the site have extensively investigated PFAS concentrations in soil, sediment, groundwater, surface water and aquatic organisms. Gobelius et al. (2017) took soil samples at three locations within 500 m of the site in the direction of groundwater flow to a depth 10 cm. The sum total of the 26 PFAS analysed in the soil samples ranged from 20 to 160 ng g^{-1} dry weight (dw). Groundwater samples at the same locations showed concentrations ranging from 1200 to 34,000 ng L^{-1}. A more extensive soil sampling campaign by Rosenqvist et al. (2017) analysed 40 soil samples and reported even higher maximum values with significant variation between the different types of PFAS compounds in concentration as well as spreading distance from the source (see Table S1 and Figs. S1 and S2 in Supplementary Material (SM)). The sum total of the 13 analysed PFAS compounds ranged from 0.63 ng g^{-1} to 2700 ng g^{-1} dw. They found that PFOS (a subset of PFAS compounds) made up 88 % of the PFAS compounds measured in soil with an average value of 234 ng g^{-1} dw across the site and PFHxS, PFHxA and PFOA were the next highest in concentration. An important note is the median value of 34 ng g^{-1} dw, indicating large differences in measured concentrations closer to the source (the training site hotspot) versus further downstream away from the immediate source. The depth to which the soil is contaminated with PFAS varies considerably between the immediate hotspot and soil layers throughout the rest of the site.

For comparison, preliminary guidelines have been established by the Swedish Geotechnical Institute (SGI) which provide a soil guideline value of 20 ng g^{-1} dw for PFOS for “less sensitive land use,” e.g., industrial use, and 3 ng g^{-1} dw for “sensitive land use,” e.g., residences or recreation, to protect human health and the environment (Pettersson et al., 2015). The guideline value for groundwater is 45 ng L^{-1}. The tested concentrations in both soil and groundwater greatly exceed the guideline values in many sampling locations.

2.2. Extent of PFAS contamination at the site

The size of the contaminated area is difficult to estimate, and no reliable figure could be found in existing reports. In fact, two firefighting training sites have been noted – a new and an old site – though only the newer one is included in this analysis (see the marked area H in Fig. 1). A rough approximation was made using an online mapping tool (Eniro) by delineating the square area to include the soil sampling points and the firefighting training site itself (Fig. 1). Remediation of the PFAS soil contamination for the firefighting training site at Stockholm Arlanda Airport has been separated into two components: remediation of the ‘hotspot’ and remediation of the ‘rest of site’. There are low uncertainties with respect to the size of the hotspot area at the study site; however, contamination spreading in the rest of the area is highly uncertain since PFAS are persistent, mobile and spread widely in both soil and water systems. Therefore, two different PFAS contamination scenarios were evaluated in this study to account for a ‘small’ and ‘large’ contamination spreading for the rest of the site (Fig. 1).

3. Methods

3.1. Probabilistic CBA modelling

In a CBA, cost and benefit items of remediation alternatives are monetised in comparison with a reference alternative. The cost and benefit items are discounted over a time horizon of 120 years using a real social discount rate of 3.5 %, as recommended for CBA in Sweden (STA, 2020). Present values (PV) for each alternative and the net present value (NPV) are calculated using as follows (Eqs. (1), (2)) (Söderqvist et al., 2015):

$$NPV = \sum_{i=1}^{N} PV(B_i) - \sum_{j=1}^{M} PV(C_j), \quad (1)$$

$$PV(B_i) = \sum_{t=0}^{T} \frac{1}{(1+r)^t} B_{it} \text{ and} PV(C_j) = \sum_{j=0}^{T} \frac{1}{(1+r)^t} C_{jt}, \quad (2)$$

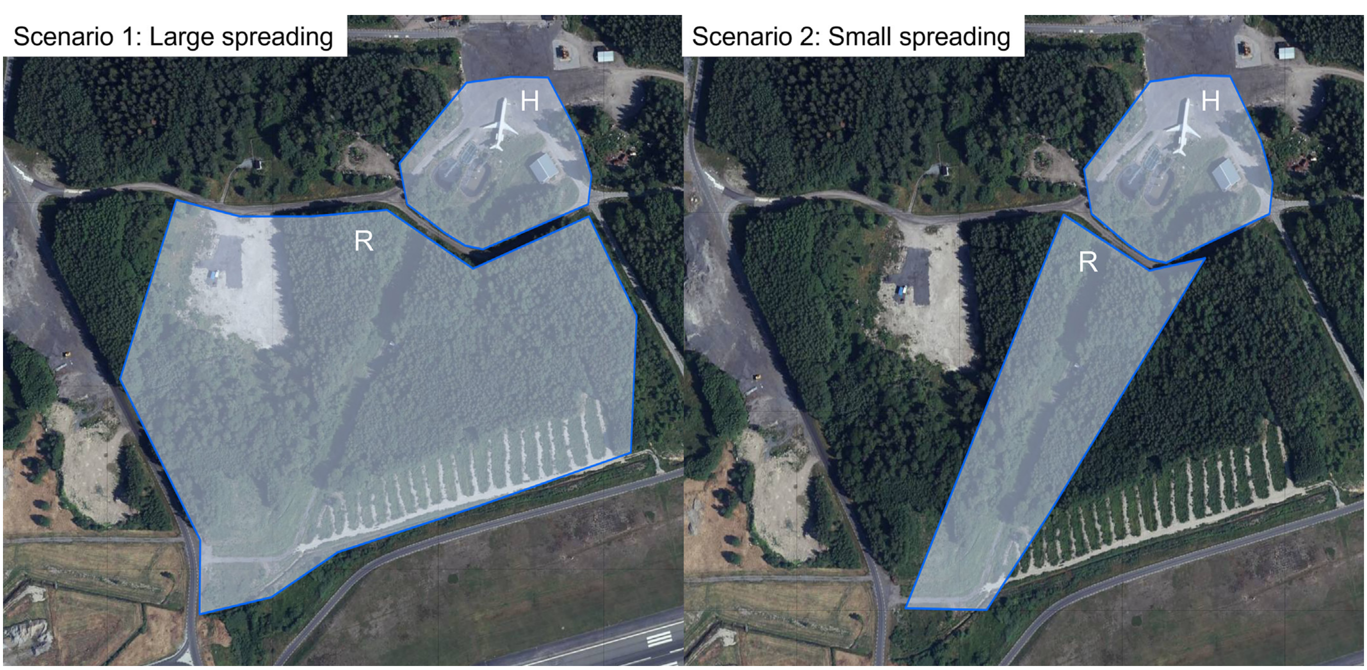


Fig. 1. Forecasted spreading of PFAS contamination in Scenario 1 and 2 based on site investigation (Rosenqvist et al., 2017). H is a hotspot area. R is the rest of the contaminated site.

where T is the time horizon, r is the social discount rate, and t is the time when benefits and costs occur for each benefit item (B_i, $i = 1 \ldots N$) and cost item (C_j, $j = 1 \ldots M$).

The most profitable remediation alternative for society is that with the highest positive *NPV*. If all the *NPVs* are <0, then the remediation alternative with the lowest negative *NPV* results in the least social loss in economic terms.

The CBA was carried out by adapting the method presented in Söderqvist et al. (2015) and Volchko et al. (2020), according to the following steps:

1. Identification of remediation alternatives, a reference alternative, the social discount rate and a relevant time horizon associated with the alternatives.
2. Identification of costs and benefits associated with each remediation alternative and defining scenarios to account for model uncertainties.
3. Quantification and monetization of costs and benefits by defining a minimum, maximum, and most likely value based on literature studies and personal contact with contractors and assigning probability distributions to input variables and cost and benefit items to represent the uncertainties in these input variables.
4. Calculating the *NPV* and associated uncertainties of each alternative by using Monte-Carlo simulations and discounting the cost and benefit items using a social discount rate and a relevant time horizon, simulating the CBA for the different defined scenarios, and investigating the results to evaluate the uncertainties in *NPVs* of the remediation alternatives and performing sensitivity analyses.
5. Concluding about the social profitability and ranking of remediation alternatives to provide recommendations as decision-support.

The cost and benefit items relevant for CBA in the remediation project and the methods used to quantify them are presented in the SM (Table S2).

The probabilistic CBA model was set up in MS Excel using the Palisade add-in software @Risk 8.2 for defining uncertainty distributions for input variables (Table S3). Monte Carlo simulations were run 10,000 times by repeatedly picking random values from the probability distributions of input variables to calculate the *NPVs* (Bedford and Cooke, 2001). The probability of each remediation alternative generating *NPV* > 0 is calculated using the RiskTarget feature of @Risk 8.2.

3.2. CBA model: base scenario

A 'base scenario' was defined as the default model settings with which to compare the remediation alternatives. The default parameters for the base scenario are a discount rate of 3.5 %, time horizon of 120 years (~4–6 generations), 7.5 MSEK for 'annual avoided cost of inaction' (in the CBA corresponding to the benefit items B2-B3, see Table S2 in SM), and 20 years for time of risk reduction by phytoextraction. Also, in the base scenario, the mean *NPVs* of Alt 1–5 (Table 2) were evaluated in comparison to the 'total excavation' remediation alternative as a reference, Alt 0, to demonstrate the positive or negative effects of each alternative compared to the conventional remediation technique, which is also the 'most likely' remediation alternative to be first considered for the site if remediation is mandated.

Alt 0 assumes total excavation of the entire site to a depth just above the clay layer (0–2.5 m), treatment of the hotspot (and backfilling) and disposal of the material from the rest of site (Table 2). Alt 0 is thus a reference situation entailing complete risk reduction, which from a duty-based ethical perspective could be argued as the most correct thing to do for achieving environmental protection targets and protecting future generations despite the potentially high costs, environmental impacts or other externalities. This reference can also represent a 'business-as-usual' case for remediation of contaminated soils by excavation and disposal, which is the most common remediation technique used in Sweden and many other countries, and is useful to evaluate against other remediation alternatives to determine whether they are more socially profitable in comparison. However, it was modified by employing on-site stabilization/solidification (S/S) ex-situ on-site (hotspot) and ex-situ off-site (rest of site), since disposing of PFAS-contaminated soil is currently not permitted at disposal sites in Sweden (SEPA, 2019).

3.3. Parameter and model uncertainties

For investigating the sensitivity of the input variables in the probabilistic CBA model, Spearman rank correlation coefficients were calculated by @Risk 8.2 (Palisade).

In addition, multiple model 'scenarios' were defined to test different model assumptions and sensitivity of model uncertainties. The following scenarios were defined and tested: a) choice of reference alternative, b) the social discount rate, c) two PFAS spreading scenarios, and d) the magnitude of annual avoided cost of inaction. The various scenarios and how they were simulated to account for uncertainties in the model are summarized in Table 1.

3.3.1. Reference alternative

Moral and legal obligations to remediate PFAS contamination suggest that a 'do nothing' option is untenable, but nevertheless is a common reference (Söderqvist et al., 2015; Volchko et al., 2020) for investigating when a project, in this case a remedial action, becomes socially profitable (*NPV* > 0). Therefore, leaving the site in its current state (i.e., 'do nothing') was considered as an alternative reference for comparing the mean *NPVs* of the remediation alternatives (including Alt 0) thus providing a different basis with which to consider the overall value of remediating a specific site.

3.3.2. Social discount rate

The sensitivity of the *NPVs* to changes in a social discount rate was tested for each studied remediation alternative Alt 1–5, compared to Alt 0. The following social discount rates were tested: 0, 1.7, 3.5, 5 and 7 %, with 3.5 % as the 'base scenario' as done in Söderqvist et al. (2015).

3.3.3. PFAS spreading

The size of the hotspot has remained constant for the remediation alternatives, however, the conceptual uncertainty in the extent of the PFAS contamination ('rest of site') has been accounted for by creating two separate scenarios – large or small spreading – as shown in Fig. 1.

3.3.4. Annual avoided cost of inaction (AACOI)

Annual avoided cost of inaction (AACOI) represents the aggregated benefit of avoided societal costs from PFAS contamination due to remediation (B2-B3, Table S2 in SM). These costs of inaction include at least costs due to negative impacts on human health (e.g., kidney cancer, all-cause mortality, increased infection risk, hypertension) and the (non-health) environment-related costs such as upgrading drinking water treatment plants, ongoing (bio)monitoring and remediation costs amongst others (Goldenman et al., 2019). For modelling purposes, a value of 7.5 MSEK was used as a fixed amount in the 'base scenario', which results in a present value of ca.

Table 1
The different scenarios for model parameters accounted for in the study. Total area sizes were considered for two studied scenarios measured using Eniro mapping tool. PERT is the PERT-beta distribution, Min is minimum, M-likely is the most likely value, Max is maximum, ha is hectares.

Scenario analysis	Parameters	Reference/comment
a) Reference alternative	i) Alt 0 – total excavation ii) 'Do nothing'	
b) Social discount rate (%)	0, 1.7, 3.5, 5 and 7 %	(STA, 2020)
c) Spreading scenarios (PERT dist.):		
- Large spreading – total area (ha)	Min: 11; Max: 15; M-likely: 13	(Gobelius et al., 2017; Rosenqvist et al., 2017)
- Small spreading – total area (ha)	Min: 3; Max: 7; M-likely: 5	
d) Annual avoided cost of inaction (MSEK)	6 simulations: 5, 7.5, 10, 12.5, 15, 25	

196.59 MSEK or €18.03 million (1€ is ca. 10.9 SEK as of December 2022). However, it is important to note that this is not an estimate of a site-specific avoided cost of inaction but rather as a tested value for PFAS remediation benefits to evaluate potential social profitability and compare alternatives. The site-specific AACOI is unknown because the reported costs of inaction are based on assumptions for large, aggregated sums for a country or the Nordic region, so a reliable value for how much of this damage is ascribed to a particular site is still prohibitively difficult to determine. Given this uncertainty, a scenario analysis was conducted to test the sensitivity of the model for different values for AACOI – 5, 7.5, 10, 12.5, 15, and 25 MSEK. The simulations were used to find the 'breakeven points' at which each remediation alternative becomes socially profitable ($NPV > 0$) in comparison to 'do nothing' that could provide valuable decision-support when evaluating potential remediation alternatives and more data is available to monetize the local impacts of PFAS contamination more accurately.

4. Results

4.1. PFAS remediation alternatives for the site

As emerging contaminants have gained widespread attention only in recent years, remediation technologies to immobilise, remove or destroy PFAS and its associate compounds are not yet well-established (Held and Reinhard, 2020; ITRC, 2018; Ok et al., 2020; Smith et al., 2016). Indeed, a combination of multiple technologies (i.e., treatment chains (Lu et al., 2020)) is often required to remediate a site effectively (ITRC, 2018; Merino et al., 2016). Gentle remediation options (GRO) – nature-based solutions using combinations of plant, bacteria, fungi and soil amendments – are considered for their potential to manage PFAS contamination as well as improve (or at least not reduce) soil functioning while producing useful biomass as part of a phytomanagement strategy (Cundy et al., 2016). Also, in defining remedial goals, it is important to consider which specific PFAS are considered to pose a risk according to the risk assessment and determine the specific 'risk driver' for the site by considering the source-pathway-receptor linkages ('contaminant linkages') and how best to manage them (Held and Reinhard, 2020; Ross et al., 2018). Many reviews on PFAS remediation options have been carried out which show that there are some promising technologies and strategies to manage PFAS contaminant linkages (Bolan et al., 2021; Held and Reinhard, 2020; ITRC, 2018; Mahinroosta and Senevirathna, 2020; Ok et al., 2020; Ross et al., 2018; Smith et al., 2016).

Five remediation alternatives were developed, where each alternative is a combination of several technologies for managing the risks posed by PFAS contamination in soils, summarized in Table 2 and described in detail in SM2.

Table 2
Overview of the remediation alternatives for PFAS-contaminated soils at the Stockholm Arlanda Airport site. REF indicates the reference alternative used in the CBA.[a]

CBA of Alt 1–5 compared to Alt 0, i.e., 'total excavation' (base scenario)		REF	Remediation alternatives evaluated against Alt 0				
		Alt 0	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5
CBA of Alt 0–5 compared to the 'do nothing' case	REF	Remediation alternatives evaluated against 'Do nothing'					
	Do nothing	Alt 0	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5
Remedial actions at the hotspot							
Excavation (before treatment)		X	X	X	X	X	X
Ex-situ stabilization/solidification (S/S) with cement and activated carbon on-site		X	X	X	X		
Ex-situ thermal treatment off-site						X	
Ex-situ soil washing On-site							X
Backfilling with the treated masses		X	X	X	X		X
Backfilling with pristine soils						X	
Remedial actions at the rest of the site							
Excavation (before treatment or disposal)		X					
In-situ stabilization/solidification (S/S) with cement and activated carbon			X				
In-situ immobilisation/stabilization with activated carbon without cement				X			
Phytoremediation with birches and spruces					X	X	X
Landfilling at a disposal site		X					
Backfilling with pristine soils		X					
Achievement of risk reduction targets (years required to manage risks)							
Hotspot	–	2	2	2	2	2	2
Rest of site	–	2	2	2	20	20	20
Long-term project management and monitoring	–	0	0	20[b]	20[b]	20[b]	20[b]

[a] CBA: cost-benefit analysis.
[b] It is assumed that risk reduction can take a shorter time, but the site may not be left without monitoring and adaptive management when using gentle remediation options (Drenning et al., 2022).

4.2. CBA results: the base scenario

The simulated mean present values of cost and benefit items for a discount rate of 3.5 % and time horizon of 120 years are shown in Table 3. These values were used in the CBA to calculate *NPVs* for the respective PFAS remediation alternatives for both large and small spreading scenarios.

4.2.1. Net present values

The outcome of the probabilistic CBA model for the 'base scenario' is shown in Fig. 2. Alt 2 (excavation and S/S of the hotspot and stabilization of PFAS at the rest of the site with activated carbon) generates the greatest mean *NPV* for both the large and small spreading scenarios, 123 MSEK and 14.1 MSEK, respectively. The results indicate that all studied remediation alternatives except for Alt 4 are associated with remediation cost savings (Table S4 in SM) compared to Alt 0. This is valid for both spreading scenarios. The ranking of the other alternatives varies depending on the spreading scenario. For the small spreading scenario, Alt 1 and Alt 2 generate an almost equally positive mean *NPV*. Alt 3 and Alt 5 generate a slight negative mean *NPV* in the small spreading scenario but have the second highest mean *NPV* in the large spreading scenario. The mean *NPV* of Alt 4 is substantially negative in both spreading scenarios.

4.2.2. Reduced negative externalities

An additional point of comparison for the remediation alternatives is the potential generation of reduced negative externalities (i.e., negative effects on health and the environment in terms of provisioning of ecosystem services, avoided carbon emissions, noise, traffic accidents etc.) as a result of the remedial action (Fig. 3). The reference alternative (Alt 0) generates substantial negative externalities due to the remedial action, and any alternative that generates reduced negative externalities will therefore result in reduced costs (shown as a 'negative cost' in Table S4). In comparison to Alt 0, all alternatives, except for Alt 4 in the small spreading scenario, are associated with reduced negative externalities during the remedial action compared to Alt 0. Alt 1 is just slightly better than the reference Alt 0 with respect to externalities during remedial action. Alt 4 is even worse than the reference alternative in the small spread scenario because of more extensive air emissions and noise from the ex-situ thermal treatment of the hotspot. However, the externalities are associated with large uncertainties (shown as error bars in Fig. 3) in the large spreading scenario in particular, and Alt 4 may generate even more negative externalities than Alt 0 in the large spread scenario too.

4.3. Uncertainty analysis

4.3.1. Parameter uncertainty

The calculated Spearman rank correlation coefficients for each studied remediation alternative are presented in Tornado charts (Figs. S5–S14, SM). Regarding uncertainties and sensitivity of input variables associated

Table 3
Summary of cost and benefit values used in the cost-benefit analysis to calculate net present values. Mean PV: the mean present value of cost and benefit items. L: Large spreading scenario. S: Small spreading scenario. The annual avoided cost of inaction (B2-B3) in Alt 0-Alt 5 is assumed to be 7.5 MSEK. The social discount rate is 3.5 %. The time horizon is 120 years.

Time horizon (years): 120 Discount rate: 3.5 %		Alt 0 S/S hotspot & disposal rest		Alt 1 S/S hotspot & S/S rest		Alt 2 S/S hotspot & Stabilization AC		Alt 3 S/S hotspot & Phytoremediation		Alt 4 T/T hotspot & Phytoremediation		Alt 5 SW hotspot & Phytoremediation	
Category	Item	Mean PV (MSEK)		Mean PV (MSEK)		Mean PV (MSEK)		Mean PV (MSEK)		Mean PV (MSEK)		Mean PV (MSEK)	
Benefit categories and items													
Spreading scenarios		L	S	L	S	L	S	L	S	L	S	L	S
B2-B3. Avoided cost of inaction	Improved health and increased provision of ecosystem services	197	197	197	197	197	197	177	177	177	177	177	177
Cost categories and items													
C1. Remediation costs	C1a-e.I. Short-term costs (total area)	109	60.0	80.4	52.1	67.5	48.6	129	75.9	322	268	129	75.3
	C1b.II,C1e.II. Long-term costs of management, monitoring (rest of the site)	0	0	0	0	7.39	7.39	7.39	7.39	7.39	7.39	7.39	7.39
	C1f. Project risks	32.1	17.3	23.4	14.9	19.6	13.9	16.8	13.1	74.4	70.8	16.6	12.9
	Total C1	141	77.3	104	67.0	94.5	69.8	154	96.4	404	346	153	95.6
C2. Impaired health due to remedial action	C2b. From transport activities and C2c. At a disposal site	0.709	0.201	0.0346	0.015-7	0.0197	0.0116	0.00854	0.00852	0.401	0.400	0	0
C3. Decreased provision of ecosystem services due to remedial action (C3a-C3c)		71.8	82.5	10.1	79.3	9.23	6.57	3.68	2.58	2.58	32.3	32.3	4.76

with the remediation alternatives in the base scenario, Alt 4 is shown to have the largest variability of the mean *NPV* (Fig. 2), where the size of the hotspot and the associated thermal treatment cost contribute most to the variability. Uncertainties regarding costs of phytoremediation contribute most to the variability of the mean *NPV* of Alt 3–5 (except for Alt 5 in the small spreading scenario) in both spreading scenarios. However, if PFAS spreading is small, hotspot size and the associated costs for soil washing of Alt 5 contribute most to the variability of the mean *NPV* of this alternative. Damage costs associated with tree clearing at the site for Alt 1 in the large spreading scenario is the input variable that contributes most to the variability in the mean *NPV* for this alternative. However, for the small spreading scenario, the size of the hotspot and the cost associated with S/S contribute most to the variability of the mean *NPV* of Alt 1.

4.3.2. Social discount rate

In the base scenario, regardless of which of the social discount rate levels is used, Alt 2 is highest ranked of the remediation alternatives with respect to *NPV* for both the large and small spreading scenarios (Table S5, SM). The next highest-ranking alternative differs in the large or small spreading scenario and varies between Alt 3 or Alt 1 being the second highest, respectively, followed closely by Alt 5. Alt 4 is the lowest ranked alternative for all the social discount rate levels and spreading extent of PFAS at the site.

4.3.3. 'Do nothing' as reference

When 'do nothing' is used as reference, all alternatives, including Alt 0 but excepting Alt 4, generate a positive mean *NPV* for the base scenario

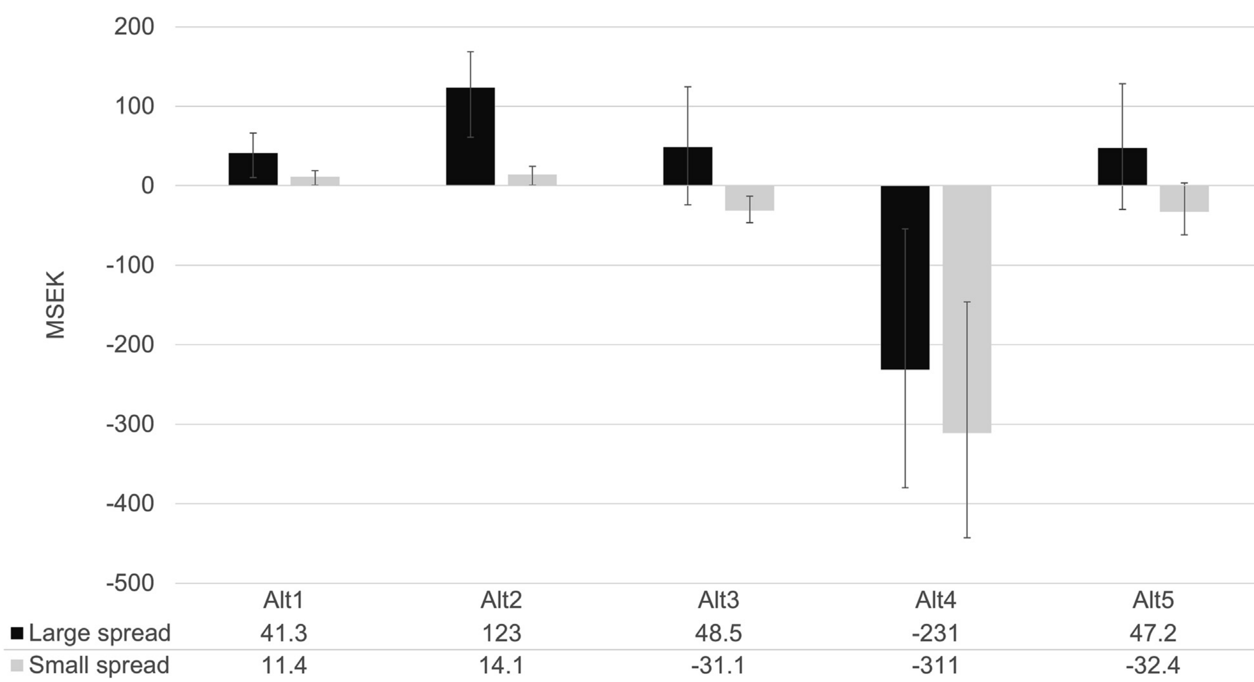


Fig. 2. The simulated mean of the net present values (NPV) for Alt 1–5 in comparison to Alt 0 as the reference alternative; the 5th and 95th percentiles are shown as error bars. The values in the data table below the chart area represent the simulated mean values of the NPV for each alternative and spreading scenario in millions of SEK (MSEK).

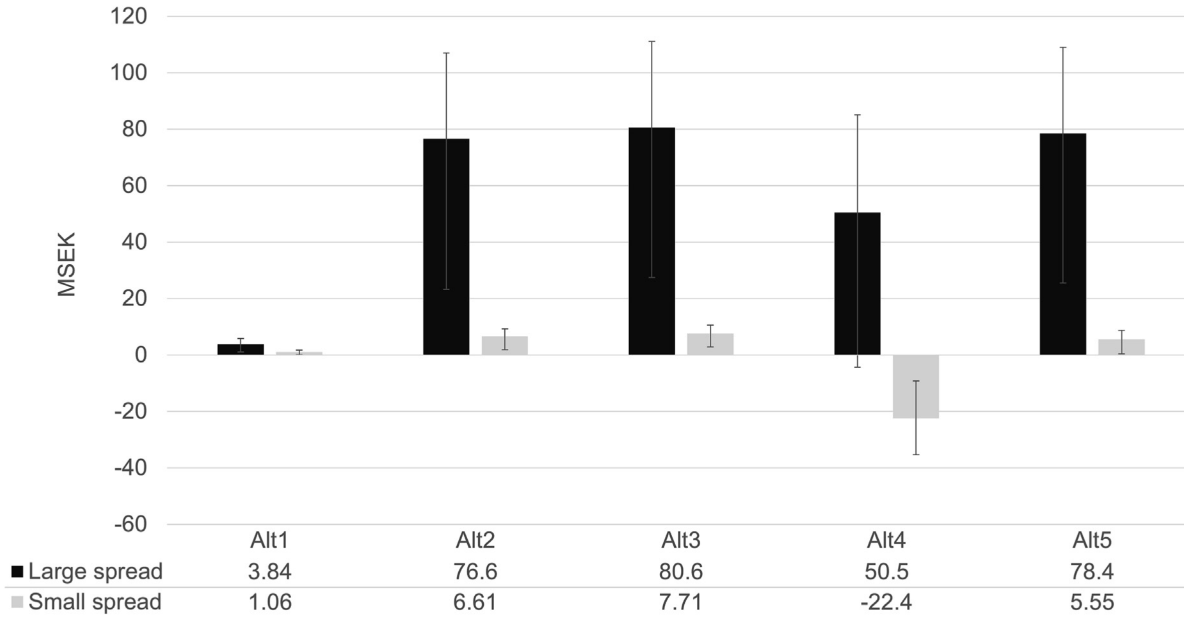


Fig. 3. Cost reductions in terms of reduced negative externalities for remediation alternatives Alt 1–5, in comparison to Alt 0. The 5th and 95th percentiles are shown as error bars. The values in the data table below the chart area represent the simulated mean values of the reduced negative externalities for each alternative and spreading scenario in millions of SEK (MSEK).

with an annual cost of inaction of 7.5 MSEK in the small spreading scenario, social discount rate of 3.5 %, and time horizon of 120 years (Fig. S13, SM). However, only Alt 2, Alt 3 and Alt 5 generate a positive mean *NPV* in the large spreading scenario, though with larger uncertainties for Alt 3 and Alt 5. The mean *NPV* for Alt 2 compared to the 'do nothing' alternative is the greatest for both spreading scenarios (95.4 MSEK and 123 MSEK for large and small spreading, respectively). All remediation alternatives generate negative externalities when compared to the 'Do nothing' reference alternative; however, the alternatives utilising gentle remediation options (GRO) without thermal treatment (Alt 2, Alt 3, Alt 5), incurred the least negative externalities (Fig. S14, SM). Tables compiling the present values (*PV*) of each cost and benefit item as well as resulting mean *NPV* for each alternative compared to the 'do nothing' reference alternative for both large and small spreading scenarios are available in the SM (Table S6).

4.3.4. Annual avoided cost of inaction

The sensitivity of the outcome of the CBA in relation to the 'annual avoided cost of inaction' (AACOI, i.e., the aggregated benefit of B2-B3) is investigated by identifying at which value of AACOI an alternative is socially profitable ($NPV > 0$) with at least 50 % probability. This value is referred to as the 'breakeven point' and is found at the cross-section with the red dashed line in Fig. 4 for the two modelled spreading scenarios (large and small spreading) compared to 'Do nothing'.

Alt 2 has the lowest value of the breakeven point: an AACOI of approximately 7.5 and 5.75 MSEK for large and small spreading of PFAS, respectively. The difference in breakeven points between alternatives is clearly distinguishable in the large PFAS spreading scenario. Alt 2 is socially profitable with a very high probability (>90 %) at an AACOI of ca. 9 MSEK, but the AACOI would have to be at least 12.5 MSEK/year to make Alt 1, Alt 3 and Alt 5 socially profitable with a probability >90 % or 20 MSEK/year for Alt 0. In the small PFAS spreading scenario, all alternatives, including Alt 0 but excepting Alt 4, have similar breakeven points of avoided cost of inaction (ca. 5.5–7 MSEK) for generating an $NPV > 0$ (for details see Table S7, SM). An avoided cost of inaction of at least 8 MSEK/year will generate a positive NPV for Alt 0, 1, 2, 3 and 5 with a probability of at least 85 % in the small spreading scenario.

5. Discussion

5.1. Ranking and associated impacts of the PFAS remediation alternatives

In this study, combinations of soil remediation technologies to manage both the hotspot and rest of site area were evaluated using CBA. Each alternative entails both distinct advantages and disadvantages, which is reflected in their resulting rankings for each modelled scenario (Table S8 in SM). An important note is that the relative rankings did not change significantly as a result of differing values simulated for AACOI, but the rankings change depending on whether the modelled PFAS spreading and resulting size of the 'rest of site' is large or small.

The intensive hotspot remediation over a short period of time (2 years) generates much of the direct health and environmental benefits from the PFAS remediation; however, the techniques differ with regard to total cost and externalities. Excavation of the hotspot followed by S/S on-site (Alt 0 and Alt 1–3) has the lowest remediation cost but requires an extensive use of cement, which is associated with large carbon emissions from production of the cement and transportation. For calculating the cost of carbon emissions, the cement is assumed to be produced in the EU and thus within the EU greenhouse gas emission trading system (see SM4.6 for calculation details). Thermal treatment (Alt 4) is both expensive and carbon intensive due primarily to transportation and energy requirement from operating the facility, which resulted in a large cost that caused this alternative to be ranked last in all tested scenarios. Soil washing (Alt 5) of the hotspot soil was estimated to be more expensive than excavation and S/S but would entail much lower negative externalities due to lower carbon emissions of the remedial action due to e.g., not requiring transportation of heavy trucks for remediation or backfilling since the treated masses are assumed to be reused on site (Table S4 in SM for respective cost and benefit estimates).

The remedial techniques considered for the 'rest of site' were more varied and the assumed time required for the remedial action ('time of risk reduction') differed between the alternatives. Alt 0–1 are assumed to achieve the risk reduction targets within the same 2-year timespan as the hotspot remediation, but the equivalent time for Alt 3–5 was estimated to be 20 years. Alt 2 uses an activated carbon stabilizing agent to achieve the rapid risk reduction but will require project management and monitoring costs for

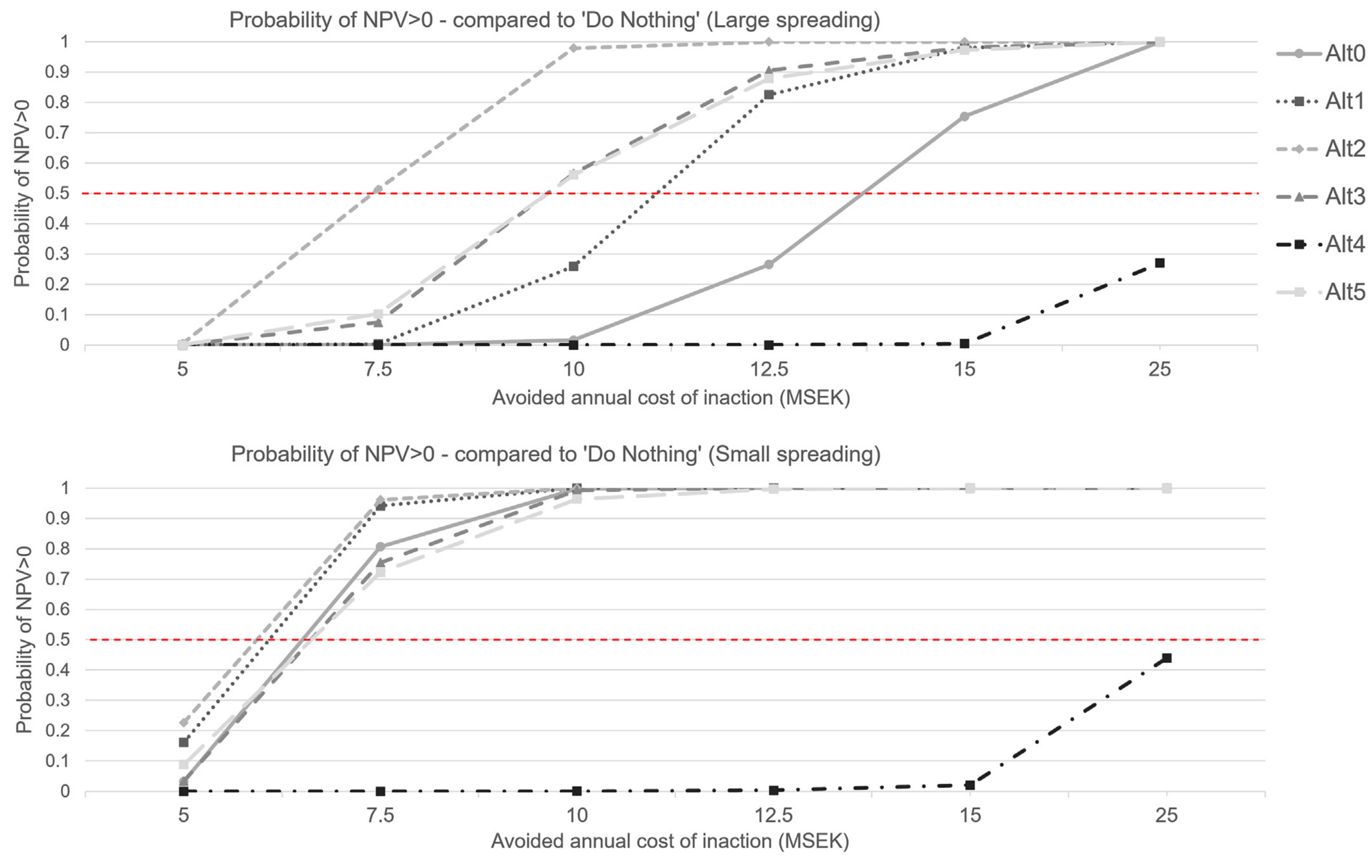


Fig. 4. Probability of NPV being positive (>0) for Alt 0–5 in comparison to 'Do nothing' for simulated values representing avoided annual cost of inaction, in millions of SEK (MSEK) given a social discount rate of 3.5 %. The red dashed line indicates the 'breakeven point' where the NPV has a >50 % probability of being >0. Note: the scale on the x-axis is not linear.

20 years. Phytoremediation (Alt 3–5) also includes these long-term costs, in addition to the long time required to achieve the risk reduction targets. Alt 0–2 were thus assumed to generate 100 % of the benefit within 2 years while Alt 3–5 generated 80 % from hotspot remediation and the remaining 20 % over the duration of the remediation time required for the rest of the site (Eq. (S1)). This partitioning favoured the faster remediation techniques, but Alt 3 and Alt 5 were still shown to consistently rank 2nd or 3rd highest in the different scenarios. Different values for the proportion of the total benefit gained from hotspot remediation were not tested but it could change with greater knowledge of the scale and severity of the PFAS spreading and impacts.

Importantly, the long time requirement for phytoremediation is an assumption for phytoextraction, which may be infeasible, but mitigation of spreading risks from short-chain PFAS through hydraulic control of groundwater via phytomanagement could be achieved in a shorter timeframe while also providing valuable ecosystem services (Evangelou and Robinson, 2022). A distinct advantage with phytomanagement is that the remedial costs are often lower than other remediation techniques and it could potentially generate a mean *NPV* closer to zero or positive if accounting for long-term additional benefits such as provision of ecosystem services and the potential production of valuable biomass, which are currently not included. For example, Wan et al. (2016) expected that the benefits of phytoremediation of a metal-contaminated soil (from e.g., cash crop production) would offset the project costs in less than seven years. The longer timeframe for GRO may not even be such a disadvantage in the Stockholm Arlanda Airport case if there are no plans for rapidly redeveloping the site for immediate profit, especially in the large PFAS spreading scenario which supports the view that GRO are well-suited for large areas where there are no time restrictions (Cundy et al., 2016). GRO may even be a profitable option for both the problem owner and society in the long-term if the present value of remediation cost savings (benefit) exceeds the present value of postponed increased property value (cost) resulting from capital costs and long-term monitoring and management activities necessary to carry out the remediation alternative (Bell, 1996). However, if there are plans for immediate development then the long timeframe of remediation alternatives that include gentle remediation via stabilization with active carbon or phytomanagement (Alt 2, 3, 5) may be a disadvantage when compared to Alt 0.

The effectiveness of each remediation alternative to manage the contamination risks is also an important aspect that must be directly addressed per alternative, especially considering the novelty of PFAS compounds. Typically, this would be considered during the selection of viable remediation alternatives to include in the CBA, which assumes that these meet the requirements with respect to their effectiveness. However, when including newer, more innovative techniques (e.g., phytomanagement) or if there are uncertainties due to the complexity of remediating PFAS, there is a risk of failure to meet the risk reduction targets. As previously noted, a primary shortcoming with phytoremediation is the long time required for phytoextraction, which may be effective only for short-chain PFAS with carbon chain length (<C6), though stabilization of longer-chain PFAS through accumulation in the roots can also help to mitigate risks (Bolan et al., 2021; Evangelou and Robinson, 2022; Gobelius et al., 2017; Huff et al., 2020). Conventional remediation techniques may also entail difficulties that limit their effectiveness when applied to remediate PFAS-contaminated soil. Immobilisation technologies like S/S have been shown to be effective in binding PFAS but a significant downside is that the contamination ultimately remains at the site, with short-chain PFAS potentially breaking through over time, and the long-term stability of amendments is still unknown which limits their use and application as a long-term solution (Bolan et al., 2021; Goldenman et al., 2019; Mahinroosta and Senevirathna, 2020; Ross et al., 2018; Sörengård et al., 2021). Thermal treatment of soil at high temperatures (>1000 °C) can destroy PFAS, but at lower temperatures

(500–600 °C) it may vaporize and generate PFAS transformation by-products that can be released into the air if not captured and treated (Held and Reinhard, 2020; Ok et al., 2020; Wang et al., 2015, 2022) Soil washing can likewise have high removal efficiencies but its effectiveness varies for individual PFAS and type of soil (Grimison et al., 2023).

One method to account for varying effectiveness is to include an 'efficiency surcharge' per alternative (Chen and Li, 2018), which could reflect the technical uncertainty by increasing the cost of the alternative by a factor (%) of failure. Similarly, the risk of failure is accounted for in this CBA including a probabilistic 'project risk' (C1f, Table S2 in SM) cost (i.e., the probability of failure multiplied by the costs of necessary additional remedial actions). The probabilistic project risk costs could thus be considered as a contingency plan in the case of the remedial action not meeting the remediation objectives in the estimated time and account for the relative uncertainty and effectiveness of the specific remediation alternatives used to manage the PFAS contamination. Linacre et al. (2005) emphasized that 'uncertainty in project success' (i.e., the possibility that complete remediation may not be realized) may significantly increase the perceived costs of phytoremediation operation for decision makers. However, the extra project risk cost due to probability of failure for phytoremediation was not shown to impact the resulting mean *NPV* or rankings of these alternatives (Alt 3–5).

5.2. Costs of inaction

A challenge in this study was to determine a reasonable value for the AACOI (B2-B3) for Stockholm Arlanda Airport. According to Goldenman et al. (2019, pg. 129), "The costs for remediating some cases of contamination run to many millions of EUR. Total costs at the European level are expected to be in the hundreds of millions of EUR as a minimum." The costs of remediation at PFAS contaminated sites will accordingly be large and weigh heavily on the resulting *NPV* for the remediation project. However, the 'costs of inaction' for not managing PFAS in the environment are estimated to be even larger – €2.1–2.4 billion annually in the Nordics from health impact-related costs due to contaminated drinking water alone (Goldenman et al., 2019)– and provide a substantial counterpoint to the high remediation costs that could even tilt the scales towards a positive *NPV* outcome for many of the remediation alternatives. Furthermore, continued inaction will lead to more sources of contamination, more people exposed, higher remediation costs, and ultimately will require more extensive remediation of soil and groundwater as PFAS spreads throughout the environment over time.

In the CBA, 7.5 MSEK was used as a base scenario for the AACOI (B2-B3), and the resulting *NPV*s in comparison to 'do nothing' for some alternatives indicate that they may indeed be socially profitable at a social discount rate of 3.5 %. In the case of negative *NPV*s, the results may imply that PFAS remediation in these cases is not socially profitable given this discount rate. A lower discount rate would result in lower breakeven points and a higher discount rate in higher breakeven points. However, remediation may still be motivated for other reasons and even be required by regulatory authorities since 'doing nothing' is not legally permissible. Also, due to the direct and indirect (e.g., inhibited recreation, contaminated fish) costs associated with PFAS contamination, the AACOI correlated with remediating Stockholm Arlanda Airport could potentially be higher.

In the Swedish context, Goldenman et al. (2019) estimate that 290,000 people in Sweden alone (ca. 47 % of the estimated total exposed Nordic population of 621,000) are exposed to PFAS above a statutory limit, which could then be roughly equated to ca. €1 billion per year of associated health-impact costs to represent 47 % of the total estimated €2.1–2.4 billion for the Nordics. The difficulty then is disaggregating this large lump sum of health impact-related costs, most of which are attributed to exposure via contaminated drinking water, and parsing the avoided costs to specific remedial actions taken at a particular PFAS contaminated site such as Stockholm Arlanda Airport. That is, what fraction of these avoided costs can be attributable to a remedial action taken at Stockholm Arlanda Airport?

The case could be made that remediation of the firefighting training site at Stockholm Arlanda Airport would result in a substantial amount of 'avoided' harm from PFAS contamination. As noted in Goldenman et al. (2019), much of the contribution of PFAS contamination to the Sweden is likely due to sites where AFFF were used, such as at civilian and military airports. Indeed, evidence from site investigations indicates that Stockholm Arlanda Airport is a significant source of PFAS spread to Lake Mälaren by as much as 2.4–5.3 kg of PFAS per year (Ahrens et al., 2015). Lake Mälaren is an important drinking water source for Stockholm and PFAS contamination has necessitated extensive investments in drinking water treatment plants in recent years to treat the PFAS contaminated drinking water with increasingly strict drinking water guidelines (Franke et al., 2021). Soil remediation, especially of the hotspot but also the rest of site, would undoubtedly mitigate these negative impacts but the fraction of the avoided health-impact costs that could be attributed to such a remedial action would require further investigation.

In comparison to the 'do nothing' reference, Alt 0, Alt 1, Alt 2, Alt 3 and Alt 5 have a high probability of generating $NPV > 0$ in the range of tested AACOI values from 5 to 15 MSEK/year, depending on the PFAS spreading scenario. The breakeven point provides an indication of when remediation may be justified from an economic standpoint and which alternative is most attractive (highest probability of $NPV > 0$) for lower expected values of avoided cost of inaction. However, given the severity of PFAS contamination and its expected impacts, the more intensive and faster remediation alternatives to rapidly mitigate risks would become more profitable in comparison to the other alternatives if the expected value of avoided cost of inaction is determined to be very high. At present, an accurate value for the cost of inaction attributable to Stockholm Arlanda Airport is unknown but this CBA provides a valuable piece of information to decision-makers by demonstrating the full range of costs and benefits and breakeven points for social profitability.

5.3. Impact of choices, assumptions and uncertainty

An early-stage CBA faces the challenge of using limited data to provide reliable decision-support. In this case, developing a probabilistic CBA for a novel application required making many assumptions due to the novelty of PFAS contamination and lack of both technical and economic data. Also, the CBA results is sensitive to choices and assumptions made in developing the model such as selection of the reference alternative and choice of discount rate.

In this case, two different reference alternatives were included in the model that serve different purposes. Alt 0 represents a modified 'business-as-usual' case entailing 'total excavation', which is a common remediation approach in Sweden and other countries. It is therefore useful as a comparison case for when remediation is mandated, and a conventional approach can be evaluated against alternatives to provide decision-support. 'Do nothing', on the other hand, is a helpful reference alternative in a CBA for obtaining indications on whether it is economically reasonable for society to spend scarce resources on remediating a particular site or rather use its resources for other purposes. It should be noted that even if it is not found to be economically reasonable to remediate a site (i.e., $NPV < 0$), remediation might still be motivated from legal and moral consideration. The choice of reference alternative in a CBA is thus context-dependent and should always be carefully considered and motivated.

The choice of discount rate is also important, especially in applications with long time horizons (Söderqvist et al., 2015). In essence, the choice of discount rate reflects the emphasis placed on future values: the higher the discount rate the lower the present value of the future benefits and costs, other things being equal (Johansson and Kriström, 2018); which is important when valuing, for example, the expected positive externalities (or avoided damage). Furthermore, the choice of discount rate can become an issue of inter-generational equity, particularly in the case of PFAS with its large current and expected future impacts, and where the expected value of some remediation projects is long into the future and can only be accurately reflected in a CBA with a suitably low, long-term discount rate, or even a declining discount rate over a long time horizon (Johansson and Kriström, 2018). The mean *NPV* for Alt 2–5, which employ GRO, vary significantly depending on the discount rate and the social profitability of each alternative can be much higher if the expected benefits from positive externalities are not heavily discounted over the remediation time period (Table S5). Still, Alt 2 is the most promising remediation option from an economic perspective, regardless of changes in the discount rate. It should be noted that a higher discount rate might be more appropriate for evaluating the profitability of these alternatives to a landowner who is more concerned with short-term impacts (Volchko et al., 2017).

5.4. Limitations of the study

A CBA is about investigating consequences for human well-being and, whenever possible, monetize them, including those caused by changes in the supply of ecosystem services. However, there might be other values that cannot be captured by a CBA, e.g., the intrinsic value of soil health or ecosystems, which suggests a need for complementary assessments in the decision-making process for making well-informed and sound decisions. Currently, the improved health and environmental benefits from the remediation alternatives are bundled into the lump sum value of avoided cost of inaction. There are, however, many wider benefits (or costs) that may result from remediation such as the loss or gain of soil functionality, which is difficult to account for in a CBA but is an important aspect of soil remediation (Chen and Li, 2018). The improvement of soil functionality and increased provision of ecosystem services could be an important benefit of using GRO that is currently neglected. Multi-criteria decision analysis is increasingly being used for evaluating positive and negative effects of remedial actions in the three domains of sustainability (environmental, social and economic) to support the decision on the most reasonable alternative taking into consideration other values which are not accounted for in a CBA (Bardos, 2014; Rosén et al., 2015; Söderqvist et al., 2015).

Assumptions were made regarding the technical applications of certain remediation technologies that impacted the CBA results. For soil washing, it was assumed that 100 % of the excavated soil was washed and reused on site, which may not be completely accurate but is favourable based on the site geology of primarily sand. Similarly, thermal treatment is assumed for the treatment of fine aggregates with the reuse of coarse aggregates on-site, but the particle size distribution in terms of proportion of fine aggregates is unknown. Also, the annual cost of phytoremediation was not possible to accurately quantify based on literature and could have affected the resulting *NPV* of Alt 3–5. The lump sum used as a present value of this cost includes total project costs (e.g., costs of establishment, operation and maintenance, biomass harvest and management) was consequently not sensitive to changes in the time required for risk reduction which could impact the present value of costs and benefits when discounted over a longer time. It is also a simplification to assume that full risk reduction will be achieved so quickly and in similar time for each hotspot remediation alternative. Other potentially viable PFAS remediation techniques such as engineered caps/covers were not included in this study but may be considered as similar to the considered containment techniques (i.e., S/S and stabilization with AC) and entail similar processes, costs, and limitations.

6. Conclusions

The following main conclusions can be drawn from this study:

- There are many uncertainties associated with PFAS contamination, including costs, benefits and effectiveness of PFAS remediation alternatives. Limitations in data and the novelty of PFAS remediation required making assumptions to compensate. Probabilistic CBA is demonstrated to be a robust method to account for uncertainties and parameter sensitivity and the model was further improved by creating multiple scenarios to test different model assumptions. The analysis provides valuable decision-support by evaluating the social profitability of different PFAS remediation alternatives.
- In general, excavation and stabilization/solidification of the hotspot on-site combined with stabilization of PFAS at the rest of the site with activated carbon (Alt 2) has the highest probability of being socially profitable (greatest mean *NPV*) and highest ranking in all scenarios. All other alternatives, except for thermal treatment of the hotspot (Alt 4), are socially profitable and entail reduced negative externalities to varying degrees compared to 'total excavation' of the entire site. The extent of PFAS spreading (large or small spreading) is shown to be the most sensitive variable in the CBA model and affect the ranking of subsequent remediation alternatives.
- Costs of inaction to society from PFAS contamination are high but associated with uncertainties, in particular how much avoided damage to human health and the environment is attributable to remediation at a particular site like Stockholm Arlanda Airport. Simulations of different values for annual avoided cost of inaction (AACOI) as an aggregated benefit to society are useful to compare breakeven points for when a remediation alternative becomes socially profitable.
- Two different reference alternatives – Alt 0 as a modified business-as-usual case entailing 'total excavation' and 'do nothing' as a common reference for economic analysis – were used for comparison to evaluate the remediation alternatives from different perspectives and to provide balanced support to decision-makers.

Funding

This work is supported by Research Council Formas (Dnr 2018-01467; Dnr 2021-01428), a Swedish government research council for sustainable development.

CRediT authorship contribution statement

The authors contributed as follows: Conceptualization: P.D., Y.V., T.S., L.R., J.N.; Methodology: P.D., Y.V., T.S., L.R., J.N.; Validation: L.A.; Formal analysis: P.D., Y.V.; Investigation: P.D., Y.V.; Visualization: P.D., Y.V.; Writing - original draft preparation: P.D., Y.V., L.A., J.N.; Writing - review and editing: P.D., Y.V., L.A., T.S., L.R., J.N.; Supervision: Y.V., L.R., J.N.; Project administration: J.N.; Funding acquisition, Y.V., L.R., J.N.

All authors have read and agreed to the published version of the manuscript.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.163664.

References

Ahrens, L., Norström, K., Viktor, T., Cousins, A.P., Josefsson, S., 2015. Stockholm arlanda airport as a source of per- and polyfluoroalkyl substances to water, sediment and fish. Chemosphere 129, 33–38. https://doi.org/10.1016/j.chemosphere.2014.03.136.
ATSDR, 2021. Toxicological Profile for Perfluoroalkyls.
Bardos, P., 2014. Progress in sustainable remediation. Remediation 25, 23–32. https://doi.org/10.1002/rem.21412.
Bardos, P., Spencer, K.L., Ward, R.D., Maco, B.H., Cundy, A.B., 2020. Integrated and sustainable management of post-industrial coasts. Front. Environ. Sci. 8, 1–14. https://doi.org/10.3389/fenvs.2020.00086.
Bedford, T., Cooke, R., 2001. Probabilistic Risk Analysis: Foundations and Methods. Cambridge University Press, New York.

Bell, R., 1996. Quantifying diminution in value due to detrimental conditions: an application to environmentally contaminated properties. Environ. Claims J. 9, 127–137.

Birgersson, L., Jouve, J., Jönsson, E., Asker, N., Andreasson, F., Golovko, O., Ahrens, L., Sturve, J., 2021. Thyroid function and immune status in perch (Perca fluviatilis) from lakes contaminated with PFASs or PCBs. Ecotoxicol. Environ. Saf. 222. https://doi.org/10.1016/j.ecoenv.2021.112495.

Bolan, N., Sarkar, B., Yan, Y., Li, Q., Wijesekara, H., Kannan, K., Tsang, D.C.W., Schauerte, M., Bosch, J., Noll, H., Ok, Y.S., Scheckel, K., Kumpiene, J., Gobindlal, K., Kah, M., Sperry, J., Kirkham, M.B., Wang, H., Tsang, Y.F., Hou, D., Rinklebe, J., 2021. Remediation of poly- and perfluoroalkyl substances (PFAS) contaminated soils – to mobilize or to immobilize or to degrade? J. Hazard. Mater. 401. https://doi.org/10.1016/j.jhazmat.2020.123892.

Cao, L., Xu, W., Wan, Z., Li, G., Zhang, F., 2022. Occurrence of PFASs and its effect on soil bacteria at a fire-training area using PFOS-restricted aqueous film-forming foams. iScience, 25 https://doi.org/10.1016/j.isci.2022.104084.

Chen, W., Li, H., 2018. Cost-effectiveness analysis for soil heavy metal contamination treatments. Water Air Soil Pollut. 229. https://doi.org/10.1007/s11270-018-3784-3.

Cousins, I.T., Vestergren, R., Wang, Z., Scheringer, M., McLachlan, M.S., 2016. The precautionary principle and chemicals management: the example of perfluoroalkyl acids in groundwater. Environ. Int. https://doi.org/10.1016/j.envint.2016.04.044.

Cundy, A.B., Bardos, R.P., Puschenreiter, M., Mench, M., Bert, V., Friesl-Hanl, W., Müller, I., Li, X.N., Weyens, N., Witters, N., Vangronsveld, J., 2016. Brownfields to green fields: realising wider benefits from practical contaminant phytomanagement strategies. J. Environ. Manag. 184, 67–77. https://doi.org/10.1016/j.jenvman.2016.03.028.

Drenning, P., Chowdhury, S., Volchko, Y., Rosén, L., Andersson-Sköld, Y., Norrman, J., 2022. A risk management framework for Gentle Remediation Options (GRO). Sci. Total Environ. 802, 149880. https://doi.org/10.1016/j.scitotenv.2021.149880.

Evangelou, M.W.H., Robinson, B.H., 2022. The phytomanagement of PFAS-contaminated land. Int. J. Environ. Res. Public Health https://doi.org/10.3390/ijerph19116817.

Fenton, S.E., Ducatman, A., Boobis, A., DeWitt, J.C., Lau, C., Ng, C., Smith, J.S., Roberts, S.M., 2021. Per- and Polyfluoroalkyl substance toxicity and human health review: current state of knowledge and strategies for informing future research. Environ. Toxicol. Chem. https://doi.org/10.1002/etc.4890.

Franke, V., Ullberg, M., McCleaf, P., Wålinder, M., Köhler, S.J., Ahrens, L., 2021. The Price of really clean water: combining nanofiltration with granular activated carbon and anion exchange resins for the removal of per- and polyfluoralkyl substances (PFASs) in drinking water production. ACS ES&T Water 1, 782–795. https://doi.org/10.1021/acsestwater.0c00141.

Gobelius, L., Lewis, J., Ahrens, L., 2017. Plant uptake of per- and Polyfluoroalkyl substances at a contaminated fire training facility to evaluate the phytoremediation potential of various plant species. Environ. Sci. Technol. 51, 12602–12610. https://doi.org/10.1021/acs.est.7b02926.

Goldenman, G., Fernandes, M., Holland, M., Tugran, T., Nordin, A., Schoumacher, C., McNeill, A., 2019. The Cost of Inaction: A Socioeconomic Analysis of Environmental and Health Impacts Linked to Exposure to PFAS, TemaNord. https://doi.org/10.21557/dsp.51953910.

Grimison, C., Knight, E.R., Nguyen, T.M.H., Nagle, N., Kabiri, S., Bräunig, J., Navarro, D.A., Kookana, R.S., Higgins, C.P., McLaughlin, M.J., Mueller, J.F., 2023. The efficacy of soil washing for the remediation of per- and poly-fluoroalkyl substances (PFASs) in the field. J. Hazard. Mater. 445. https://doi.org/10.1016/j.jhazmat.2022.130441.

Harwell, M.C., Jackson, C., Kravitz, M., Lynch, K., Tomasula, J., Neale, A., Mahoney, M., Pachon, C., Scheuermann, K., Grissom, G., Parry, K., 2021. Ecosystem services consideration in the remediation process for contaminated sites. J. Environ. Manag. 285, 112102. https://doi.org/10.1016/j.jenvman.2021.112102.

Held, T., Reinhard, M., 2020. Remediation management for local and wide-spread PFAS contaminations (TEXTE 205/2020). Umwelt Bundesamt 310.

Huff, D.K., Morris, L.A., Sutter, L., Costanza, J., Pennell, K.D., 2020. Accumulation of six PFAS compounds by woody and herbaceous plants: potential for phytoextraction. Int J Phytoremediation 22, 1538–1550. https://doi.org/10.1080/15226514.2020.1786004.

ITRC, 2018. Remediation Technologies and Methods for Per- and Polyfluoroalkyl Substances (PFAS). ITRC PFAS Fact Sheets, pp. 1–24.

ITRC, 2020a. History and Use of Per- and Polyfluoroalkyl Substances (PFAS) Found in the Environment. ITRC PFAS Fact Sheets 2000, pp. 1–4.

ITRC, 2020b. Fate and Transport of Per- and Polyfluoroalkyl Substances (PFAS). ITRC PFAS Fact Sheets 1, pp. 1–4.

Johansson, P.-O., Kriström, B., 2018. Cost-Benefit Analysis, Cambridge. Cambridge University Press, Cambridge.

Lee, J.W., Choi, K., Park, K., Seong, C., Yu, S.do, Kim, P., 2020. Adverse effects of perfluoroalkyl acids on fish and other aquatic organisms: a review. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2019.135334.

Linacre, N.A., Whiting, S.N., Angle, J.S., 2005. The impact of uncertainty on phytoremediation project costs. Int. J. Phytoremediation 7, 259–269. https://doi.org/10.1080/16226510500327103.

Lu, D., Sha, S., Luo, J., Huang, Z., Zhang Jackie, X., 2020. Treatment train approaches for the remediation of per- and polyfluoroalkyl substances (PFAS): a critical review. J. Hazard. Mater. 386, 121963. https://doi.org/10.1016/j.jhazmat.2019.121963.

Mahinroosta, R., Senevirathna, L., 2020. A review of the emerging treatment technologies for PFAS contaminated soils. J. Environ. Manag. 255, 109896. https://doi.org/10.1016/j.jenvman.2019.109896.

Merino, N., Qu, Y., Deeb, R.A., Hawley, E.L., Hoffmann, M.R., Mahendra, S., 2016. Degradation and removal methods for perfluoroalkyl and polyfluoroalkyl substances in water. Environ. Eng. Sci. 33, 615–649. https://doi.org/10.1089/ees.2016.0233.

Ojo, A.F., Peng, C., Ng, J.C., 2021. Assessing the human health risks of per- and polyfluoroalkyl substances: a need for greater focus on their interactions as mixtures. J. Hazard. Mater. 407. https://doi.org/10.1016/j.jhazmat.2020.124863.

Ok, Y.S., Rinklebe, J., Hou, D., Tsang, D.C.W., Tack, F.M.G.G., 2020. Soil and Groundwater Remediation Technologies: A Practical Guide. First edit. CRC Press, Boca Raton.

Onwubuya, K., Cundy, A., Puschenreiter, M., Kumpiene, J., Bone, B., Greaves, J., Teasdale, P., Mench, M., Tlustos, P., Mikhalovsky, S., Waite, S., Friesl-Hanl, W., Marschner, B., Müller, I., 2009. Developing decision support tools for the selection of "gentle" remediation approaches. Sci. Total Environ. 407, 6132–6142. https://doi.org/10.1016/j.scitotenv.2009.08.017.

Pettersson, M., Ländell, M., Ohlsson, Y., Kleja, D.B., Tiberg, C., 2015. Preliminära riktvärden för högfluorerade ämnen (PFAS) i mark och grundvatten, SGI.

Rosén, L., Back, P.E., Söderqvist, T., Norrman, J., Brinkhoff, P., Norberg, T., Volchko, Y., Norin, M., Bergknut, M., Döberl, G., 2015. SCORE: a novel multi-criteria decision analysis approach to assessing the sustainability of contaminated land remediation. Sci. Total Environ. 511, 621–638. https://doi.org/10.1016/j.scitotenv.2014.12.058.

Rosenqvist, L., Vestergren, R., Westberg, E., Eliaeson, K., Norström, K., Liljeberg, M., Strandberg, J., Rahmberg, M., 2017. Spridning av högfluorerade ämnen i mark från Stockholm Arlanda Airport: Förutsättningar för beräkning av platsspecifika riktvärden för mark.

Ross, I., McDonough, J., Miles, J., Storch, P., Thelakkat Kochunarayanan, P., Kalve, E., Hurst, J., Dasgupta, S.S., Burdick, J., 2018. A review of emerging technologies for remediation of PFASs. Remediation 28, 101–126. https://doi.org/10.1002/rem.21553.

SEPA, 2019. Vägledning om att riskbedöma och åtgärda PFAS-föroreningar inom förorenade områden, Rapport 6871 (In English: Guidance for Risk Assessing and Remediating PFAS Contamination at Contaminated Sites). Stockholm.

Smith, J.W.N., Beuthe, B., Dunk, M., Demeure, S., Carmona, J.M.M., Medve, A., Spence, M.J., Pancras, T., Schrauwen, G., Held, T., Baker, K., Ross, I., Slenders, H., 2016. Environmental fate and effects of polyand perfluoroalkyl substances (PFAS). CONCAWE Reports 1–107.

Söderqvist, T., Brinkhoff, P., Norberg, T., Rosén, L., Back, P.E., Norrman, J., 2015. Cost-benefit analysis as a part of sustainability assessment ofremediation alternatives for contaminated land. J. Environ. Manag. 157, 267–278. https://doi.org/10.1016/j.jenvman.2015.04.024.

Sörengård, M., Gago-Ferrero, P., Kleja, D.B., Ahrens, L., 2021. Laboratory-scale and pilot-scale stabilization and solidification (S/S) remediation of soil contaminated with per- and polyfluoroalkyl substances (PFASs). J. Hazard. Mater., 402 https://doi.org/10.1016/j.jhazmat.2020.123453.

STA, 2020. Analysmetod och samhällsekonomiska kalkylvärden för transportsektorn: ASEK 7.0. Swedish Traffic Administration.

Volchko, Y., Norrman, J., Rosén, L., Karlfeldt Fedje, K., 2017. Cost-benefit analysis of copper recovery in remediation projects: a case study from Sweden. Sci. Total Environ. 605–606, 300–314. https://doi.org/10.1016/j.scitotenv.2017.06.128.

Volchko, Y., Berggren Kleja, D., Back, P.E., Tiberg, C., Enell, A., Larsson, M., Jones, C.M., Taylor, A., Viketoft, M., Åberg, A., Dahlberg, A.K., Weiss, J., Wiberg, K., Rosén, L., 2020. Assessing costs and benefits of improved soil quality management in remediation projects: a study of an urban site contaminated with PAH and metals. Sci. Total Environ. 707. https://doi.org/10.1016/j.scitotenv.2019.135582.

Wan, X., Lei, M., Chen, T., 2016. Cost–benefit calculation of phytoremediation technology for heavy-metal-contaminated soil. Sci. Total Environ. 563–564, 796–802. https://doi.org/10.1016/j.scitotenv.2015.12.080.

Wang, F., Lu, X., Li, X.Y., Shih, K., 2015. Effectiveness and mechanisms of defluorination of perfluorinated alkyl substances by calcium compounds during waste thermal treatment. Environ. Sci. Technol. 49, 5672–5680. https://doi.org/10.1021/es506234b.

Wang, Yu., Chang, W., Wang, L., Zhang, Yinfeng, Zhang, Yuan, Wang, M., Wang, Yin, Li, P., 2019. A review of sources, multimedia distribution and health risks of novel fluorinated alternatives. Ecotoxicol. Environ. Saf. https://doi.org/10.1016/j.ecoenv.2019.109402.

Wang, J., Lin, Z., He, X., Song, M., Westerhoff, P., Doudrick, K., Hanigan, D., 2022. Critical review of thermal decomposition of per- and polyfluoroalkyl substances: mechanisms and implications for thermal treatment processes. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.2c02251.

Xu, Y., Hansson, E., Andersson, E.M., Jakobsson, K., Li, H., 2022. High exposure to perfluoroalkyl substances in drinking water is associated with increased risk of osteoporotic fractures – a cohort study from ronneby, Sweden. Environ. Res., 114796 https://doi.org/10.1016/j.envres.2022.114796.