Integrated and sustainable management of post-industrial coasts.

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Author contribution statement

PB, KS, and AC conceived of the initial idea, and outlined the brief, which was then co-developed by all authors. PB and AC led on the gentle remediation and sustainability linkages approaches, KS on coastal landfills and dredged sediment management, RW on coastal management and ecology, and BM on renewables and US-based examples. All authors contributed to manuscript writing and revision, and read and approved the submitted version. AC finalised and co-ordinated submission of the manuscript. The opinions given in this article are those of the authors, and do not necessarily reflect those of their employers.

Keywords

Risk Management, coastal management, Gentle remediation options, Sustainable Remediation, Sustainability linkage, Coastal landfill sites, Phytomanagement, Brownfield

Abstract

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The sustainable management of post-industrial coasts is a major emerging issue globally. Along such coasts, there may be a significant legacy of both contaminated land (including historic landfills and non-managed waste disposal) and contaminated sediments in and around urban and industrial areas, which require new strategies for cost-effective and integrated risk management under future sea-level rise and climate change scenarios. Here, we review current approaches to managing contamination in post-industrial coastlines, discuss emerging integrated management strategies (building on low input approaches to sustainable brownfields regeneration) and present an approach and framework for assessing and comparing different scenarios for coastal brownfield regeneration to soft re-use and other end-points. This framework can be applied to explore the opportunities for synergy and realisation of wider environmental, economic and societal benefits between coastal protection, dredged material re-use and the management of brownfield land. As such, the approach we propose supports planning and options appraisal to realise maximum benefit and value from integrated coastal management strategies.

Contribution to the field

The sustainable management of post-industrial coasts is a major emerging issue globally. Along these coasts, following decline of heavy industry, there may be a significant legacy of both contaminated land (including historic landfills and unmanaged waste disposal) and contaminated sediments in and around urban and industrial areas. These legacy, contaminated, materials require new strategies for cost-effective and integrated risk management under future sea-level rise and climate change scenarios. In this article, we review current approaches to managing contamination and legacy materials in post-industrial coastlines, discuss emerging integrated management strategies (building on low input approaches to sustainable brownfields regeneration) and review a new approach and framework for assessing and comparing different scenarios for coastal brownfield regeneration to soft re-use and other end-points. This framework can be applied to explore opportunities for synergy between different approaches and sites, and the realisation of wider environmental, economic and societal benefits between coastal protection, dredged material re-use and the management of brownfield land. As such, the method we propose supports planning and options appraisal to realise maximum resilience, benefit and value from integrated coastal management strategies.

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The sustainable management of post-industrial coasts is a major emerging issue globally. Along such coasts, there may be a significant legacy of both contaminated land (including historic landfills and non-managed waste disposal) and contaminated sediments in and around urban and industrial areas, which require new strategies for cost-effective and integrated risk management under future sea-level rise and climate change scenarios. Here, we review current approaches to managing contamination in post-industrial coastlines, discuss emerging integrated management strategies (building on low input approaches to sustainable brownfields regeneration) and present an approach and framework for assessing and comparing different scenarios for coastal brownfield regeneration to soft re-use and other end-points. This framework can be applied to explore the opportunities for synergy and realisation of wider environmental, economic and societal benefits between coastal protection, dredged material re-use and the management of brownfield land. As such, the approach we propose supports planning and options appraisal to realise maximum benefit and value from integrated coastal management strategies.

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1. Introduction.

Sea-level rise and the increasing magnitude and frequency of coastal storm surges, and consequent impacts (including coastal erosion, and saline flooding or inundation of urban areas and coastal assets), are major challenges for the sustainable development of coastal areas and communities over the 21st century. Many coastlines in areas subject to former extensive urban and industrial development (post-industrial coasts) contain a significant legacy of brownfield land[1], including areas of land contaminated with a range of toxic organic, inorganic and microbial (and other) contaminants, and land areas which have been subject to historic landfill and unmanaged waste disposal (Brand et al. 2017, O'Connor et al. 2019). Erosion, reworking and remobilisation of contaminants, solid particulates, debris (e.g., asbestos), pathogens and plastics from this land and solid waste material could pose a significant risk to human and ecological health. For each individual site, contaminant load may not be significant. However, on regional, national and global scales the problem may be underestimated (O'Shea et al. 2018). For example, in England there are > 1200 vulnerable coastal landfills with 1 in 10 of these sites at risk of erosion over the next few decades (Brand et al. 2017) and more widely across Europe, there are ca. 10,000 historic landfills containing industrial, domestic and hazardous waste in coastal and riparian areas prone to flooding and/or erosion (Wille, 2018).

In addition, industrialised coasts and estuaries may host significant volumes of historically contaminated subtidal and intertidal sediments (Vane et al., 2015). These sediments may cause continuing contamination of coastal systems even after primary contaminant discharges have ceased, due to advective sediment mixing and supply of reworked, secondary contamination from erosion of contaminated sediments elsewhere along the coast or estuary (e.g. Machado et al. 2015; Cundy and Croudace 2017; Premier et al. 2019). This diffuse legacy pollution is considered to be one of the major causes for the UK's rivers and transitional waters failing ecological and chemical water quality standards (Defra 2012). Removal or dredging, and subsequent safe disposal or beneficial re-use, of these contaminated sediments pose major ongoing challenges. These challenges may be particularly severe where dredged sediments are required for beach nourishment, land reclamation and land raising as part of climate change adaptation strategies. In addition, an expected change in coastal erosion and sedimentation patterns, including an increased frequency of extreme events, may mean that more reactive dredging is needed than currently required, whereas in other cases proactive dredging may be more appropriate to deal with the implications of long-term seasonal changes in flow (Hakstege 2013).

Achieving sustainability had been considered an integral outcome of brownfields or contaminated site management (including at coastal sites) since its inception in the 1970s, as through this process under-utilised or damaged land was returned to the land use cycle, avoiding greenfield use (Bardos et al. 2016). From the late 1990s however this assumption began to be questioned, in recognition of the realisation that poorly selected, designed or implemented remediation and site management activities may in fact cause greater impact than the contamination or other land issues that they seek to address. This has led to an emerging international literature and (recently) consensus on sustainable remediation, which has focused on promoting "the use of more sustainable practices during environmental clean-up activities, with the objective of balancing economic viability, conservation of natural resources and biodiversity, and the enhancement of the quality of life in surrounding communities" (Bardos

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[1] Sites that have been affected by the former uses of the site and surrounding land, are derelict or underused, may have real or perceived contamination problems, are mainly in developed urban areas and require intervention to bring them back to beneficial use. CABERNET, 2007

et al. 2016, ISO 2017). For coastal brownfields (that are often fragmented, may be sited in post-industrial areas subject to declining property values, and may be at real or perceived risk of flooding or erosion) remediation and regeneration for so-called “hard” re-use (e.g. housing or infrastructure developments) may be problematic. Indeed Leger et al., (2016) noted that economic circumstances and frequent policy shifts have impeded the redevelopment of brownfield land in coastal areas, and there is a need for new imaginative approaches that will help coastal communities realise the undoubted benefits of redevelopment of brownfield sites.

One such set of approaches are those combining risk management with nature-based approaches or “soft” re-use (e.g. redevelopment of brownfield as green space, habitat, or for biomass and other natural product generation). This includes the use of so-called low input or gentle remediation approaches: “risk management strategies or technologies involving plant (phyto-), fungi (myco-), and/or bacteria-based methods that result in a net gain (or at least no gross reduction) in soil function as well as effective risk management” (Cundy et al. 2016). Soft re-use has historically tended to be overlooked in brownfields management (Bardos et al. 2016). However, in response to the sustainable development vision, there is a broad agreement among stakeholders that soft re-use of brownfields can bring significant environmental, societal and economic benefits (Bardos et al. 2011; 2016; Cundy et al. 2016), as evidenced by a number of case studies and practical applications (e.g. Cundy et al. 2013; 2016, Li et al. 2019). The soft re-use approach also broadly aligns with an emergence and increased utilisation of soft-engineering coastal management approaches such as managed realignment and other habitat recreation, which offer potential synergies (or possibly conflicts in some situations) with brownfields and contaminated sediments management.

Here, we present an approach and framework for assessing and comparing different scenarios for coastal brownfield regeneration to soft re-use and other end-points, based around “sustainability linkages”, which draws on concepts and case studies from sustainable remediation and low input approaches to sustainable brownfields regeneration. Following a review of contemporary responses and challenges to the management of contaminated land and sediments in and around coastal urban and industrial areas, we examine (and present examples of) the potential synergies and wider benefits from integrated low input approaches. We then present and discuss the sustainability linkages approach, based on sustainability assessment criteria produced by the UK Sustainable Remediation Forum (SuRF-UK), as a potential planning and decisional aid to support integrated and sustainable management of post-industrial coasts.

2. Contemporary responses and challenges

Historically estuaries and coasts have frequently been areas for waste disposal due to their proximity to industrial and commercial centres, the perceived low value of coastal wetland habitats, and due to the ability of tidal flushing to rapidly dilute and disperse contaminants so reducing acute impact. This occurred through either the use of adjacent land for landfilling of solid wastes and industrial activities or the discharge of contaminated effluent streams and particulates. There are potentially millions of landfill and waste disposal sites along coastlines globally that are at risk of marine inundation, erosion or catastrophic failure. Most of these pre-date environmental regulation developed in the latter half of the 20th Century with little attempt to isolate solid, liquid or gaseous contaminants from the surrounding environment and these are generally described as ‘historic’ or ‘legacy’ landfills (Brand et al. 2017). In lower and middle income economies this is of even greater concern. Rapid economic development has been accompanied by increasing waste production and globally solid wastes are being generated faster than any other environmental pollutant (Hoornweg et al., 2013). Lack of regulation and poor infrastructure means many solid waste disposal sites are frequently uncontrolled (Gupta et al., 2015; Gu et al., 2015) and ‘open’ waste sites are a major source of marine litter, contaminate water bodies through the release of wide-ranging wastes and pollution (e.g., metals, batteries, tyres) and present significant human health risk (Ferronatto and Toretta 2019). This has recently been recognised as a significant issue in the management of plastic debris, where mismanaged land-based wastes are estimated to contribute significantly to marine plastics debris inputs and without significant infrastructure improvements to waste management, the cumulative release of plastics will increase by an order of magnitude by 2025 (Jambeck et al. 2015; Waldschlaeger et al. 2020). For 2010, the top 10 countries ranked by mass of mismanaged plastic waste were China, Indonesia, the Philippines, Vietnam, Sri Lanka, Thailand, Egypt, Malaysia, Nigeria and Bangladesh. Apart from Egypt and Malaysia, these countries all showed a percentage of mismanaged waste exceeding 75% (as a proportion of total waste), with a number handling additional waste imported for processing from Western nations. Historic and uncontrolled waste disposal sites present two significant potential contaminant pathways to the marine environment that need to be managed. Firstly, as solid wastes degrade, soluble contaminants (leachates) migrate through the waste and surrounding inter-tidal sediments before entering groundwater and the marine environment, and secondly, solid particulate wastes can be released directly to coastal waters.

As a means of managing soluble leachates there is an assumption than contaminant impact would be mitigated via natural attenuation through either the precipitation of contaminants in anoxic inter-tidal sediments and/or sorption to fine-grained minerogenic and organic material (Michalak and Kitanidis, 2002; Njue et al. 2012). The release of any remaining soluble contaminants in the leachate plume present above natural background would then be diluted by tidal flushing. However, there is evidence that this ‘do nothing’ approach has resulted in localised ‘hot spots’ of estuarine sediment contamination (Cox and Preda, 2005; O’Shea et al. 2018) and long term ammonia release (Gooddy et al. 2014). Future climate change scenarios also increase the likelihood for tidal flooding and enhanced leachate generation. However, it is generally recognised that following decades of burial leachate is likely to be relatively dilute and any release would be rapidly dispersed in coastal waters (Beaven et al. 2020; Brand and Spencer, 2020).

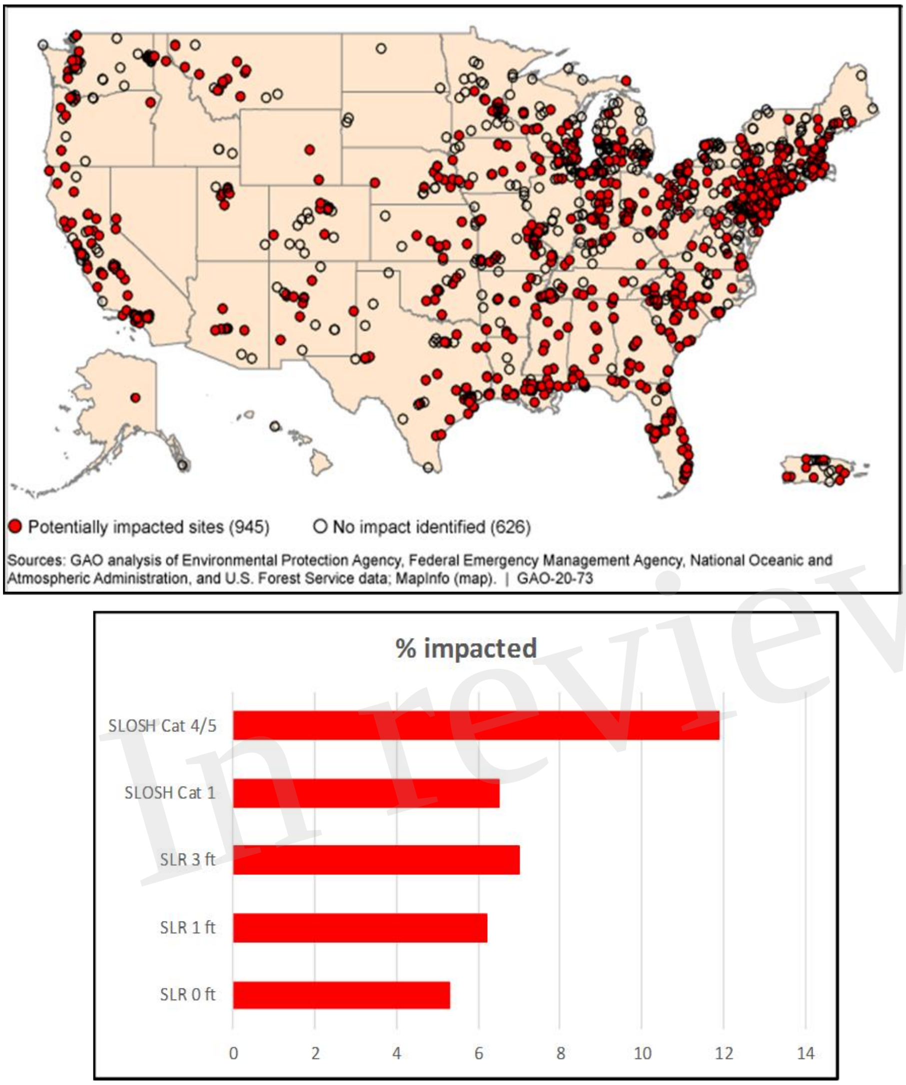
The management of solid waste release has perhaps received more consideration, and for controlled disposal sites solid waste is usually isolated from the marine environment by installing a physical barrier such as a hard engineered coastal defence or through geographic location by placing landfills on cliff tops above mean high water (Nicholls et al. 2020). However, with sea level rise and increased frequency and intensity of storm surges and coastal erosion, there are multiple scenarios for contaminant release through; 1) over-topping of barriers and inundation with saline waters, 2) damage to coastal defences and waste release, 3) catastrophic failure of coastal defences and 4) cliff failure (Beaven et al. 2020). In the UK, 1 in 10 vulnerable historic coastal landfills are at risk of erosion if coastal defences are not maintained (Brand et al. 2017) and there is also increasing evidence that extreme flood and erosion events can result in catastrophic failure and release large volumes of solid waste. For example, 13 toxic waste sites were flooded in Texas by Hurricane Harvey in 2017 (US EPA, 2017) and more recently, in New Zealand, floods washed out a closed landfill on the Fox River releasing solid wastes over an area *ca.* 1000 ha and impacting 63 km of coastline (Department of Conservation 2019). Even following decades of burial landfill waste can be highly toxic, with the release of matrix material, textiles, wood, paper, asbestos and plastics all presenting significant ecological risk (Brand and Spencer 2019; Su et al. 2019).

For coastal brownfield sites more generally, there is a risk that coastal and climatic change may undermine remediation and risk management strategies previously used at contaminated sites, particularly where risk management strategies have involved source stabilisation or pathway management (i.e. strategies where contaminants have been stabilised or managed *in-situ* and remain in the subsurface). The U.S. Sustainable Remediation Forum (SuRF) spearheaded three years of collaborative research and knowledge exchange that culminated in: Resilient Remediation: Addressing Extreme Weather and Climate Change, Creating Community Value (Maco et al. 2018). They found that “At hazardous sites, climate change and extreme weather events can undermine the effectiveness of the original site remediation design and can also impact contaminant toxicity, exposure, organism sensitivity, fate and transport, and long-term operations, management, and stewardship of remediation sites”. For example, a detailed modelling study at a Superfund site impacted by Hurricane Florence showed that, “in general, higher-infiltration events could mobilise vadose-zone residual contaminants, raising contaminant concentrations in groundwater for a prolonged period.” Further, in the US nearly two million people, the majority in low-income communities, live within 1 mile of one of 327 Superfund sites in areas prone to flooding or vulnerable to sea-level rise caused by climate change (Maco et al. 2018). In October 2019 the U.S .Government Accounting Office identified that *ca*. 60 % of all non- federal National Priorities List (most contaminated sites) are located in areas that may be impacted by potential climate change impacts of flooding, storm surge, wildfires, and sea level rise (US GAO 2019). The majority of sites are located in coastal areas (Figure 1), with 7% of sites expected to be inundated by a sea-level rise of 3 ft (0.9 m), and 11.9% at risk of flooding from Category 4 or 5 hurricane surges.

Therefore, the presence of waste and residual contamination in the coastal environment can place significant constraints on coastal managers. For example, the presence of historic landfills can preclude the selection of more sustainable coastal management approaches such as managed realignment, which adapt to sea level rise and create flood storage by moving coastal defences inland, or ‘do nothing’ approaches, where coastlines are allowed to retreat in response to natural coastal processes. In addition, estuaries are also frequently areas of significant sediment contamination resulting from decades (if not centuries) of industrial use and effluent release with pollution being a significant, long-term threat to estuarine and coastal ecosystem health (e.g. Kennish 2002). These legacy pollutants may cause deterioration in water quality and ecological health through reworking, erosion, natural advective mixing and diffusion, which may be enhanced under climate change scenarios (e.g., Machado et al., 2017), and through dredging activities whereby sediments are disturbed via mechanical means (e.g., Spencer et al., 2006). As such, contaminated sediments have the potential to be released to marine waters or deposited on coastal floodplains and wetlands (Bert et al., 2009).

Approximately 200 million m^3 of sediment is dredged annually from Europe’s harbours, ports and coastal waters, and up to 50% of this is contaminated (SedNet, 2004; Todaro et al., 2016). The European Waste Directive encourages us to view these dredged materials as a resource (Apitz 2010) and if possible either reduce their production (through e.g., management of dredge licensing) and to re-use where possible. Even contaminated sediments can be treated to immobilise or transform the contaminants, and de-water and stabilise the sediments (Todaro et al. 2016). Increasingly, these sediments can then be used for coastal protection, environmental enhancement and sustainable restoration of tidal wetlands and beaches (e.g. Martin et al., 2019). However, whilst there is enormous potential to utilise dredged material as a resource, many projects are small, piecemeal and lack long term monitoring or assessment. Most projects deal only with uncontaminated materials (Costa-Pierce and Weinstein, 2002, Martin et al.,

2019) and practices and technology uptake can vary, driven by nuances in national dredging policy and the communication difficulties associated with coupling sediment supply to suitable, local receptor sites (Ausden et al. 2018).



Sources: GAO analysis of Environmental Protection Agency, Federal Emergency Management Agency, National Oceanic and Atmospheric Administration, and U.S. Forest Service data; MapInfo (map). | GAO-20-73

Figure 1: Superfund Sites Located in Areas that May Be Impacted by Flooding, Storm Surge, Wildfires, or Sea Level Rise (top). Bottom graph shows (from top) percentage of sites impacted by Sea, Lake and Overland Surges by Hurricanes (SLOSH) of category 4 or 5, and category 1, and those expected to be inundated by a sea-level rise of 3, 1 and 0 ft (source: US GAO, 2019).

3. Low input approaches – their benefits, and towards an integrated management approach.

A variety of integrated, low input remediation / restoration approaches are possible for coastal brownfields which may offer some advantages over contemporary approaches. In broad terms remediation[2] describes the mitigation of risks from brownfields. For a risk to be present, a

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[2] Specifically, managing the risks to receptors so that there is no longer a risk of unacceptable harm. This may be via some form of intervention at the level of source, pathway or receptor

source (of hazardous substance or property), a receptor (that could be affected adversely by the contamination) and a pathway (linking the source to the receptor) must be present, as shown in Figure 2 (Tack and Bardos 2020).

A receptor might be a human, an ecologically sensitive site, surface or underground water resources, or a building. Moreover, risks to the ecosystem 'goods or services' provided by the wider environment[3] may become an increasingly important receptor to consider in many scenarios. A risk management intervention can take place at any point in the S-P-R linkage provided that it breaks the linkage, which might be by removing the source, intercepting the pathway, or modifying the receptor behaviour or location. A range of risk management / remediation options are available at different points across any particular linkage[4]. This risk-based approach to contaminated sites is termed Risk Based Land Management – RBLM (Vegter et al., 2002)

Remediation is not intrinsically sustainable. Poorly planned projects can have serious negative impacts, and so (ideally) risk management should also therefore meet sustainable development principles. Together this constitutes sustainable risk based contaminated land management, SRBLM (NICOLE/COMMON FORUM 2013).

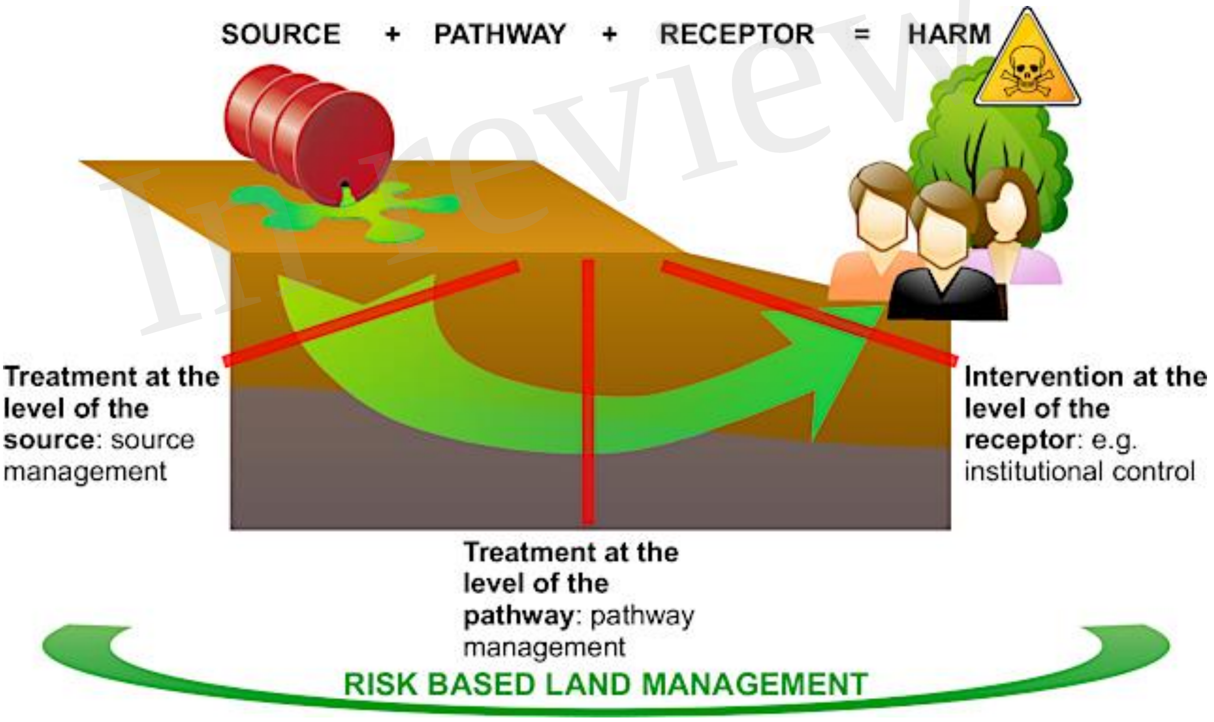

Figure 2: Risk Management along a Contaminant (S-P-R) Linkage (Tack and Bardos, 2020)

Restoration describes improving and extending the functionality of land so it can serve a wider range of purposes, which can encompass remediation, but also measures to improve soil and water quality, ecological management, and establishment of new higher value (including more sustainable) land uses. These land uses may be for buildings or other infrastructure where the

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[3] e.g. as described by the World Health Organisation: https://www.who.int/globalchange/ecosystems/en

[4] e.g. as described by *Land contamination: risk management*, https://www.gov.uk/guidance/land-contamination-how-to-manage-the-risks

soil is sealed (“hard” re-uses), or land use dependent on the soil function such as for parkland or where the soil is otherwise unsealed such as for photovoltaic arrays (“soft re-uses”). In the context of coastal brownfields soft re-uses may be particularly important as they can offer a range of ancillary services, for example flood management capacity, carbon sequestration and storage, and/or public amenity in areas where buildings and infrastructure are either no longer feasible or considered at risk. The processes of remediation, restoration and ongoing management may all be included in an overarching strategy that yields multiple benefits from the brownfield management process (Bardos *et al.* 2016), creating a greater overall value from the land re-use, a wider partnership of interested parties able to support the brownfield regeneration and greater resilience to future threats, such as climate change mitigated impacts (e.g. Maco et al., 2018).

Low input remediation measures, so called “gentle” remediation approaches or options, may be particularly advantageous given their passive nature and relatively low cost base. “Gentle” remediation options, or GRO, are defined as “risk management strategies or technologies that result in a net gain (or at least no gross reduction) in soil function as well as achieving effective risk management” (Cundy et al., 2013). They include a range of plant (phyto-), fungi (myco-), and/or bacteria-based approaches (Cundy et al., 2016, Table 1), with or without chemical additives or soil amendments, which reduce contaminant transfer to local receptors by extraction, transformation, or degradation of contaminants, or by *in-situ* stabilisation. “Gentle” remediation options are closely aligned with the concept of “nature-based solutions” for the longer-term restoration of land. Indeed, approaches such as bioremediation and phytoremediation are increasingly being used as a low input approach to coastal brownfield land remediation (Hassan et al. 2019; O’Connor et al. 2019). Phytoremediation is particularly effective where hyperaccumulater plants are used, e.g. those that have the capability of assimilating high levels of metals such as Au, Ag, Cd, Se, Ta, Cu, Co, Cr, Ni, Pb, U, As, Mn and Zn (Mahar et al., 2016) including coastal plant species such as *Phragmites australis*, *Deschampsia cespitosa*, *Festuca rubra*, *Juncus maritimus*, *Spartina alterniflora*, *Distichlis spicata*, and *Ruppia maritima* (Peer et al., 2005). In addition, where metal-excluding plants are used (with or without soil amendments), phytostabilisation shows promise as a low-cost method for contaminated dredged sediment management (e.g. Bert et al., 2008, Bert et al., 2009). Bioremediation utilises microbial activity to decrease available contaminants within degraded systems. This method is particularly effective for groundwater treatment although this is dependent on appropriate geochemical conditions, available nutrients and the abundance of microorganisms (Sam and Zabbey 2018), and does not provide the same landscape and visual amenity, nor ecosystem service benefits available from other nature-based solutions (Song et al. 2019). Phytoremediation can offer a range of benefits to coastal brownfield site remediation including lower energy input, higher material efficiency and resilience from global environmental change as well as providing a range of ecosystem service benefits such as flood protection, estuarine filtering of environmental pollutants, habitat and nursery for marine animals, and carbon sequestration and storage amongst others (Blanco-Canqui 2016; Burges et al. 2017, 2018). In spite of these benefits, nature based solutions are often only used where there is a cost benefit to implementation rather than taking into account the wider socio-economic and environmental benefits (Song et al. 2019).

Gentle Remediation Option (GRO)	Definition
Phytoextraction	The removal of metal(loid)s or organics from soils by accumulating them in the harvestable biomass of plants. When aided by use of soil amendments, this is termed *aided phytoextraction*.
Phytodegradation / phytotransformation	The use of plants (and associated microorganisms such as rhizosphere bacteria) to uptake, store and degrade organic contaminants.
Rhizodegradation	The use of plant roots and rhizosphere microorganisms to degrade organic contaminants.
Rhizofiltration	The removal of contaminants from aqueous sources by plant roots and associated microorganisms.
Phytostabilisation	Reduction in the bioavailability of contaminants by immobilisation in root systems and / or living or dead biomass in the rhizosphere soil – creating a milieu which enables the growth of a vegetation cover. When aided by use of soil amendments, this is termed *aided phytostabilisation*.
Phytovolatilisation	Use of plants to remove contaminants from the growth matrix, transform them and disperse them (or their degradation products) into the atmosphere.
Phytoexclusion	The implementation of a stable vegetation cover using excluder plants which do not accumulate contaminants in the harvestable plant biomass. Can be combined with *in situ* immobilisation (below).
In situ immobilisation	Reduction in the bioavailability of contaminants by immobilising or binding them to the soil matrix through the incorporation into the soil of organic or inorganic compounds, singly or in combination, to prevent the excessive uptake of essential elements and non-essential contaminants into the food chain.
Bioremediation	Generic term applied to a range of remediation and risk management technologies which utilise soil microbial organisms to degrade, stabilise or reduce the bioavailability of contaminants.
Mycoremediation	A form of bioremediation in which fungi-based methods are used to degrade, stabilise or reduce the bioavailability of contaminants.

Table 1: Examples of Gentle Remediation Options. Adapted and updated from Cundy et al., (2016).

Potential low input approaches to the redevelopment of coastal brownfield sites include conversion of brownfield land to coastal wetland, parkland or forest providing resilience to pressures from global environmental change (Sarkis et al., 2016; Song et al., 2019; Zhu et al., 2017). These options all provide strong aesthetic value improvement to sites (Hartig et al. 2012), as well as habitat creation (or replacement) for plants, mammals, birds and invertebrates (Harrison and Davies, 2002; Sellers et al. 2006; Woods 2012, Latham et al. 2016), increased infiltration or flood storage capacity and resultant decrease in flood risk (EPA, 2014), and low life cycle environmental footprints. They also provide a meeting/socialising space, which improves well-being, particularly important in crowded urban areas such as are found in Asia, N. America and Europe (Faivre et al., 2017). Forest planting schemes at coastal brownfield sites can help reduce noise, improve air quality and reduce heat island effects (Solecki et al. 2005; Tan et al. 2016). Importantly, given the adoption of ambitious zero net carbon targets by a number of urban areas (https://news.trust.org/packages/zero-carbon-cities/), there is significant potential for planted sites to provide a very visible contribution to integrated carbon reduction strategies, via carbon storage and sequestration, although the degree of carbon offsetting generated will depend on planting type and density, stand area, etc (e.g. Zhao et al., 2010, Tang et al., 2016, Wilkes et al, 2018). Conversion of brownfield sites to forest, coastal wetland or parkland can also have wider societal benefits improving the longer-term liveability and environmental quality for local communities (Mitchell et al. 2015). This can also strongly interface with "bluefields" strategies, around the linking or integration of abandoned or underutilised sites along rivers or other waterfronts, as part of urban waterfront regeneration initiatives (e.g. Pinch and Munt, 2002; Tolnai, 2018).

In addition, the EU has set a target of at least 20% of energy from renewable sources by 2020, with a consequent requirement for an increase in biomass fuels. The State of California has committed to procuring 50% of energy from renewables by 2050, while the State of New York's Climate Action Plan includes a goal of 100% Renewable energy by 2050. To support these targets, coastal brownfield sites can be repurposed for biomass production utilising plant species such as: *Salix* spp; *Phalaris arundinacea*; *Panicum virgatum*; *Miscanthus giganteus*; rapid growth species with a tolerance for high levels of soil contamination and a tolerance/preference for wet soils (Lord et al. 2008; Lord 2015). The autecological requirements of these species make them ideal for coastal brownfield site plantation. These species can also provide phytoremediation through removal of some soil contaminants (e.g. Zn, Cd, and Cu) (Lord et al., 2008). Infrastructure linked to coastal brownfield sites (e.g. roads, grid connections), as well as proximity to consumers and appropriate zoning make these sites ideal for potential repurposing as brightfield sites (sites for renewable energy generation) (Converse 2007), addressing three major global challenges: climate change; urban revitalisation; and contaminated land remediation (Adelaja et al. 2010).

4. Potential synergies, and maximising benefits.

As we discuss above, there are a range of synergies potentially offered by the application of low input remediation or restoration approaches for soft end-use, which utilise coastal brownfields and/or contaminated dredged materials within an integrated overall coastal management approach. A number of current and historical examples have gone part-way towards realising this synergetic management approach. These include:

- <u>Beneficial use of dredging materials and construction wastes for habitat recreation and other benefits, SE England and the Thames estuary, UK.</u> Increasingly, dredged materials from maintenance and capital dredging, but also sediments from engineered tunnelling have been used for coastal and brownfield restoration in the Thames Estuary and south east England. For example, 6 million tonnes of excavation material from London's Crossrail project has been re-used and recycled to create 670 ha of coastal wetland habitat at Wallasea Island, Blackwater Estuary, Essex, UK, and to raise the land by 1.5 m as an adaptation to sea level rise (Dixon et al., 2008; Cross 2017).
- <u>Restoration of a former landfill site for ecological and community benefit, Mersey estuary, UK.</u> Port Sunlight River Park is a 28-hectare community park space near Birkenhead in the Wirral, Merseyside, U.K. located on a capped and covered former coastal landfill site. After closure to new waste in 2006, the site was leased to the Land Trust (a UK charity) and following a £3.4 million investment was repurposed as a riverside park in 2013 (opening to the public in 2014). The River Park is managed through a partnership with a local non-profit organisation, Autism Together (a charity providing services and support to people with autism and their families), who manage the park on a day-to-day basis and lead local community engagement in park activities,

as well as providing work opportunities for local community members affected by autism. The completed park provides visitors with waterfront access (with views over the Liverpool city skyline), a variety of walks (and other leisure and recreation opportunities) and access to nature. A section of wetland in the north of the site, linking to the adjacent River Mersey mud flats, provides important habitat for water birds. Based on a qualitative sustainability assessment, Li et al, (2019) show that the establishment of the Port Sunlight River Park has clear sustainability advantages (using a range of environmental, economic and social indicators) over a baseline of having left the site under its previous management regime.

- “Designing with water” to improve storm and climate change resiliency, Boston, MA, USA. Boston, Massachusetts, has been aggressively researching options to protect the city post-Hurricane Sandy as part of its “Designing with Water” efforts (Aiken et al., 2014, Sutton-Grier et al., 2015). In 2015, Boston ran an international competition for design solutions imagining a more resilient, more sustainable, and more beautiful Boston prepared for both sea level rise and climate change up to the end of the 21st century (Sutton-Grier et al., 2015). This utilised different examples of hybrid approaches to make urban areas more resilient to climate change and storms, including Dutch “Living with Water” strategies, where planners design to accommodate flood waters in urban settings and build floating communities for flood control and socioeconomic prosperity. Successful projects were expected to help build resilience to disturbances to existing built infrastructure and to social and community networks, and do “double duty” in terms of providing flood protection in times of need whilst also providing other uses and benefits (such as recreational opportunities) when protection is not needed (Sutton-Grier et al., 2015). Outputs were used to inform revisions to building plans and zoning codes, and influence the city’s ‘Imagine Boston 2030’ strategy, Boston's first citywide plan in 50 years.
- Renewable energy on coastal brownfields for local energy generation and community benefit, San Francisco Bay, USA. A recently completed renewable energy project in the San Francisco Bay Area, the Marin Clean Energy (MCE) Solar One partnership, highlights the benefits of synergetic management approaches to coastal brownfields. Sixty acres of a remediated brownfield site were leased (by the site owners Chevron) to the Partnership for $1 per year. This land was then repurposed for solar power generation. At 10.5 megawatts capacity, the site is expected to eliminate 3,234Mt of carbon dioxide emissions per year, the equivalent to taking more than 680 cars off the road annually. As well as leveraging significant inward investment (almost two million dollars were spent on project materials purchased or rented locally), the MCE Solar One Partnership provided additional community benefits by partnering with RichmondBUILD, who are a public–private partnership focusing on training community members from low income households for skilled construction, hazardous waste removal, and renewable energy jobs. The project also includes an innovative procurement approach called “community choice energy,” in which citizens and businesses are offered an alternative to the standard energy utility for purchasing their electricity. As a result, homes and businesses benefit from a low-carbon electricity option that costs 2 to 5% less than traditional Bay Area utility rates (https://www.mcecleanenergy.org/news/press-releases/mce-solar-one-thinking-globally-building-locally/).
- Park Spoor Nord, Antwerp, Belgium. Antwerp, a major and diverse port city on the Scheldt estuary in Belgium, in common with many port cities contains a significant legacy of underused industrial and harbour space, as well as high density residential areas and limited public green space. Regeneration in the Spoor Nord area of the city

has focused on attracting investment in residential and commercial land, and generating public support for on-going regeneration. Based on local residents' feedback, green and open areas, space and light were identified as the main priorities of the regeneration process. To facilitate this, the City of Antwerp supported the restoration of a 24 ha former railway complex as an urban landscape park, integrating residential areas, a Sports centre, and green open space (parkland), to bring green public space into the densely populated Spoor Nord area, and act as a catalyst for new development and inward investment. This example is one of several considered within the EU Seventh Framework Programme project TIMBRE (http://www.timbre-project.eu/), which focused on the regeneration of large and complex contaminated "megasites" in Europe. To support this, the project developed a web-based tool (the Timbre Brownfield Prioritization Tool) which integrates sustainability assessment and multiple-criteria decision analysis (MCDA) to facilitate assessment and prioritisation of a portfolio of sites on the basis of the probability of successful and sustainable regeneration (Bartke et al, 2016).

One of the key issues in applying such approaches at a specific site or regional level, and realising as full a range of benefits as possible, is identifying the synergies or conflicts between interventions, in terms of maximising the benefits (services) from coastal brownfield restoration and dredged sediment re-use, and how this might encompass wider opportunities for better coastal management. In addition, in order to gain support for soft re-use, it is also important to not just illustrate sustainability in the redevelopment process, but also understand how it can create value for stakeholders. Here, we present an approach and framework for assessing and comparing **different scenarios for coastal brownfield regeneration to soft re-use and other end-points, to support planning and options appraisal to realise maximum benefit and value.** We use as the basis for this a "sustainability linkages" approach, based on sustainability assessment criteria produced by the UK Sustainable Remediation Forum (SuRF-UK) (CL:AIRE 2011, Li et al., 2019).

5. The "Sustainability linkages" approach

5.1 Context

Land Contamination practitioners are familiar with the source-pathway-receptor, or contaminant linkage, paradigm for providing a structure for assessing risks, evaluating them and planning a risk management response. An analogous thought process can be applied to consider the various individual considerations of a sustainability assessment, to produce a series of *sustainability linkages*. A *sustainability linkage* describes the connection between a driver (a pressure or a change), something that might be affected (i.e. a receptor) and the mechanism by which a pressure or change affects a receptor, see Figure 3. Analogous to the source-pathway-receptor model, a sustainability effect only takes place when there is also a receptor that might be affected and a mechanism ("pathway") by which this affect can happen. Li *et al.* (2019) show how individual *sustainability linkages* can be collated following site stakeholder consultation to provide a conceptual site model for sustainability for a brownfields project, using the example of a coastal legacy landfill site (the Port Sunlight River Park example discussed in section 4 above) regenerated for soft re-use as community parkland and coastal wetland. We discuss this example and the wider applicability of the sustainability linkages approach further here, within the context of the integrated management of post-industrial coasts.

The Port Sunlight Riverside Park sustainability assessment is based on UK guidance produced by the Sustainable Remediation Forum UK, an independent cross-sectoral project managed by the UK contaminated land information forum CL:AIRE (www.claire.co.uk/surfuk). This guidance offers a range of possible indicators / criteria that can be used in sustainability assessments for brownfields organised across 15 headline categories, summarised in Table 2, and has been recently updated (CL:AIRE 2020). Sustainability assessments are highly site and project specific, so the conceptual model developed for the Port Sunlight Riverside Park is unique to its context.

Table 2. SuRF-UK Headline Categories for Sustainability Indicators (CL:AIRE 2011, 2020)

Environmental	**Social**	**Economic**
ENV1: Emissions to air	SOC1: Human health and safety	ECON1: Direct economic costs and benefits
ENV2: Soil and ground conditions	SOC2: Ethics and equity	ECON2: Indirect economic costs and benefits
ENV3: Groundwater and surface water	SOC3: Neighbourhoods and locality	ECON3: Employment and employment capital
ENV4: Ecology	SOC4: Communities and community involvement	ECON4: Induced economic costs and benefits
ENV5: Natural resources and waste	SOC5: Uncertainty and evidence	ECON5: Project lifespan and flexibility

5.2 Methodology

The qualitative sustainability assessment was carried out in 2016. The aim of the sustainability assessment was to understand the economic, environmental and social benefits/disbenefits of transforming the former landfill (a brownfield site) into a public open space, managed long term. The sustainability assessment therefore compared two intervention options:

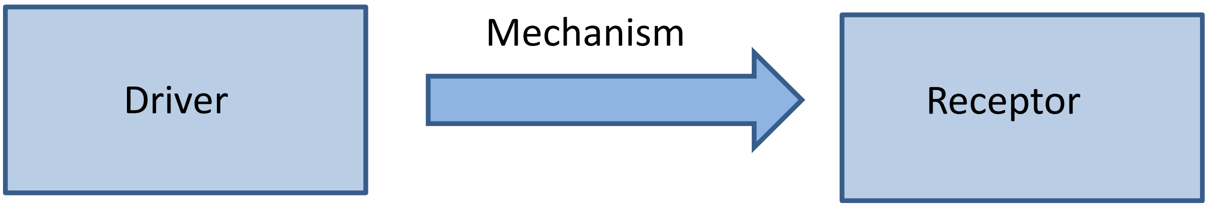
1. Establishment of the park (i.e. the transformation from a restored landfill site to park and long term management, including construction of roads, paths, landscaping, drainage and car parking; but excluding existing landfill management measures); and
2. A hypothetical "no intervention" baseline, where the site continued as a managed former landfill.

Full methodological details are given in Li et al., (2019) but in summary:

The sustainability assessment followed guidance issued by SuRF-UK. Identification and analysis of individual sustainability linkages was carried out across all of the SuRF-UK headline categories (CL:AIRE, 2011), in consultation with the Land Trust (site owner) and Autism Together (the charity that manages the site on a day to day basis on behalf of the Land Trust). Fifty individual specific sustainability linkages were identified and individually ranked. These were combined into a conceptual model for the site, which can be used to rationalise the pressures/mechanisms and receptors, show where effects are desirable or not desirable, check for possible duplicated effects and show interconnections between effects. In the case of the Port Sunlight River Park comparison: 30 pressures, 31 mechanisms and 6 receptors encapsulated the 50 linkages identified (no duplicates were found).

5.3 Results

The network diagram (conceptual model) produced for Port Sunlight River Park is shown in Figure 4. The linkages assist in making individual cause and effect chains explicit, so that different management options can be more readily compared, and different linkages can be more explicitly valued. This has the benefit of identifying and so reducing unintentional duplications of sustainability criteria, and can also highlight synergies and conflicts for different risk management or regeneration scenarios. For example, short-term greenhouse gas emissions from the operation of remediation or engineering plant may be offset in the longer-term by carbon sequestration and storage in park soils and vegetation, or "blue carbon" storage in the wetlands at the north of the site. Specific synergies can be identified between flood water storage capacity and improved habitat, inward investment creation and property value uplift, and community inclusivity, access to parkland and public health benefits, amongst others.



Health and safety risks (part of SOC1)	Materials excavation and handling on site	Site workers
Road traffic accident risk (part of SOC1)	Traffic movements from the remediation project	Local community
Exhaust emissions affecting local air quality (part of SOC3)	Traffic movements from the remediation project	Local community
Increased sense of pride / place (part of SOC4)	Improvement of the urban landscape / removal of blight	Local community
Greenhouse gas emissions (part of ENV1)	Remediation operations	Atmosphere
Property value uplift (part of ECON1)	Site improvement	Site owner
Property value uplift (part of ECON2)	Improvement of the urban landscape / removal of blight	Surrounding property owners

Figure 3: A Sustainability Linkage (a), and some possible examples (by no means exhaustive) (b). Abbreviations in left column refer to SURF-UK Sustainability Assessment Criteria (CL:AIRE 2011).

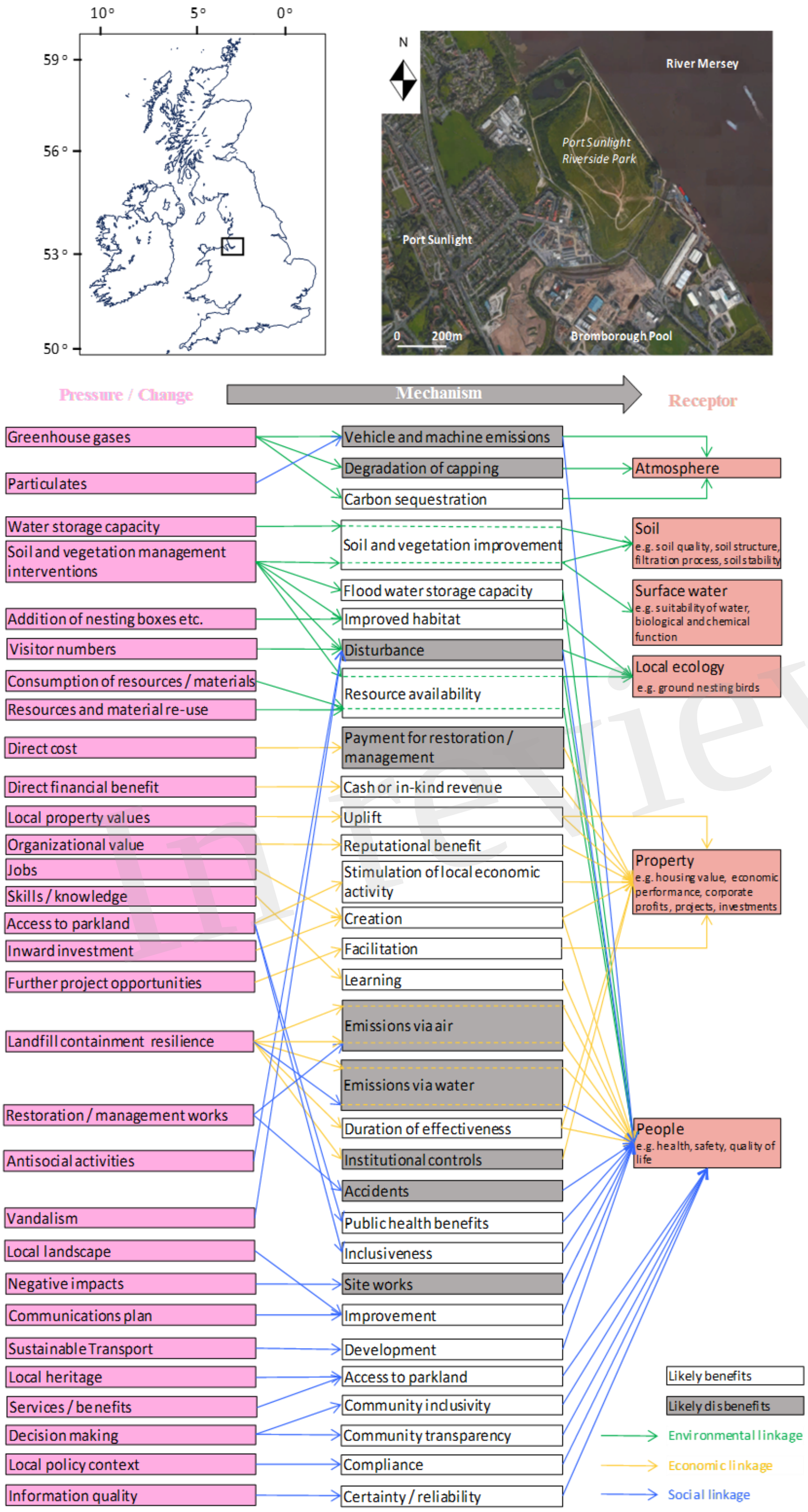


Figure 4: conceptual site model for sustainability (network diagram) for the Port Sunlight River Park (after Li et al., 2019). Mechanisms are coloured depending on whether they are considered deleterious (as grey) or beneficial (white). Linkages are shown as arrows, colour-coded to environmental, economic and social elements of sustainability, using green, yellow and blue respectively

Our suggestion is that the sustainability linkages approach can be used as a planning and decisional aid to assist a more robust valuation of the wider benefits from coastal brownfield regeneration to soft re-use and other end-points, by: (1) ensuring that any cost benefit assessment is consistent with a conceptual model of sustainability, rather than being based on a different set of premises or indicators; and (2) providing a more targeted valuation approach. For the latter point (in regards to valuation) the sustainability linkages that comprise the conceptual model can be divided into three broad groups (grouped by their ease of monetisation):

- Those linked already to some form of investment cost or return – which can be valued under a direct financial model
- Linkages that can be readily and broadly agreed to be linked to wider effects that are economically tangible and so more readily valued, for example, surrounding property value uplift, and benefits to local businesses.
- Those linkages related to wider effects that at least one stakeholder considers economically intangible, or not easy to value, such as public health benefit, value of access to nature, improved visual amenity etc.

While direct monetisation of sustainability benefits was not possible in the example given by Li et al., (2019), the conceptual site model based on sustainability linkages provides a clearer basis for understanding cause and effect for benefits and disbenefits, while also therefore providing a rationale for grouping individual effects based on their ease of valuation. This potentially provides a road map for cost-benefit assessments for different integrated coastal management approaches by (1) being able to match specific sustainability linkages to their most appropriate means of valuation, and (2) connecting the sustainability assessment and cost benefit assessment processes in a transparent (and defensible) manner. Moreover, where stakeholders have concerns about the valuation the process would be sufficiently transparent that they could precisely zero in on the points of concern and perhaps then be better able to make their own arguments.

6. Concluding remarks.

The sustainability linkages approach and framework discussed here provides a potential method for achieving a better understanding and design of combined coastal brownfields management approaches to maximise benefits and minimise risks, benchmarked against standard sustainability assessment criteria. This framework can be applied to explore the opportunities for synergy and realisation of wider environmental, economic and societal benefits between coastal protection, dredged material re-use and the management of brownfield land, as well as to support planning and options appraisal to realise maximum benefit and value from integrated coastal management strategies. The approach uses engagement with core and wider stakeholders throughout the preparation, definition and execution phases, which is critical as the effectiveness of soft re-use depends on the public's perceptions of risk and their willingness to support new uses of the sites (Levi and Kocher, 2006). There are strong synergies for these integrated soft re-use management approaches to interface with coastal flood protection and coastal habitat creation initiatives, and emerging areas such as landfill mining and resource re-use, green infrastructure approaches and city carbon neutrality targets. The unique strengths of natural infrastructure are that it can be self-maintaining, has the potential to self-repair after major damaging events, and (in the case of marsh/mangrove systems) has the ability to grow and keep pace with sea level rise (Sutton-Grier et al, 2015). Low-input approaches, appropriately designed, can generate wide environmental, economic and social benefits along post-industrial coasts, and can show enhanced resilience to sea level rise and other hydroclimatic effects induced by climate change (O' Connor et al., 2019), and can leverage a number of current brownfields resilience initiatives. In the USA for example these include the ASTM guide (in development) for Resilient remedies, and the Interstate Technology and Regulatory Council- (a 50 US state-led coalition- (ITRC)) project to develop principles, practices and case studies for Resilient Sustainable Remediation. For the latter, a recent survey by the ITRC RSR team noted that brownfields provided the best opportunity for sustainable clean up and re-use of contaminated sites: the states surveyed identified the most valuable metrics as job creation and preservation and creation of open space, including parks and marshlands.

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List of Figures:

Figure 1: Superfund Sites Located in Areas that May Be Impacted by Flooding, Storm Surge, Wildfires, or Sea Level Rise (top). Bottom graph shows (from top) percentage of sites impacted by Sea, Lake and Overland Surges by Hurricanes (SLOSH) of category 4 or 5, and category 1, and those expected to be inundated by a sea-level rise of 3, 1 and 0 ft (source: US GAO, 2019).

Figure 2: Risk Management along a Contaminant (S-P-R) Linkage (Tack and Bardos, 2020)

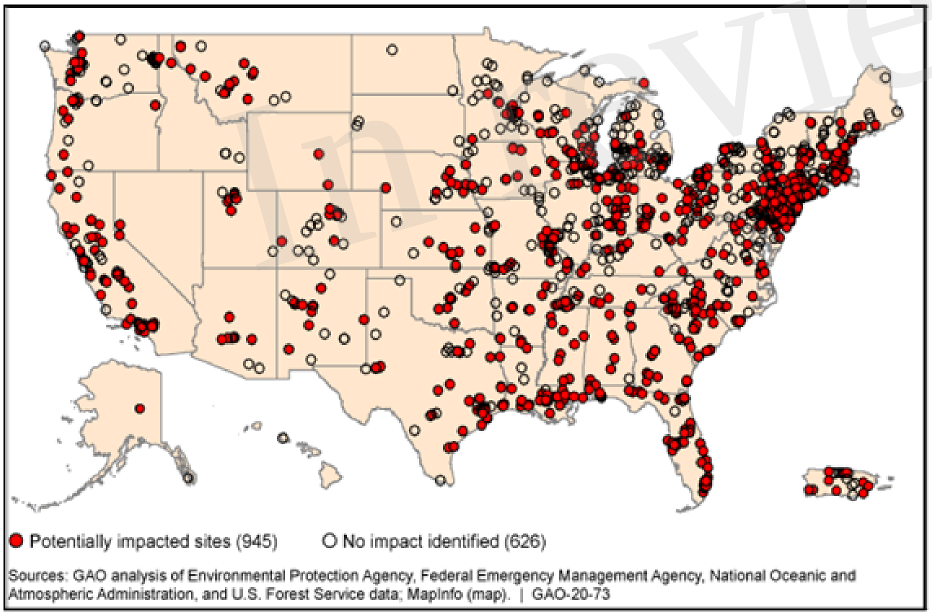
Figure 3: A Sustainability Linkage (a), and some possible examples (by no means exhaustive) (b). Abbreviations in left column refer to SURF-UK Sustainability Assessment Criteria (CL:AIRE 2011).

Figure 4: conceptual site model for sustainability (network diagram) for the Port Sunlight River Park (after Li et al., 2019). Mechanisms are coloured depending on whether they are considered deleterious (as grey) or beneficial (white). Linkages are shown as arrows, colour-coded to environmental, economic and social elements of sustainability, using green, yellow and blue respectively.

Table 1: Examples of Gentle Remediation Options. Adapted and updated from Cundy et al., (2016).

Table 2: SuRF-UK Headline Categories for Sustainability Indicators (CL:AIRE 2011, 2020)

Figure 1.TIF



Sources: GAO analysis of Environmental Protection Agency, Federal Emergency Management Agency, National Oceanic and Atmospheric Administration, and U.S. Forest Service data; MapInfo (map). | GAO-20-73

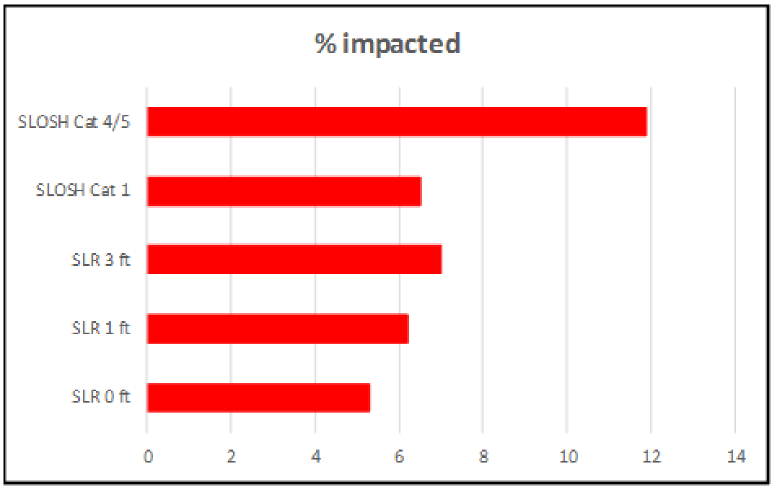


Figure 2.TIF

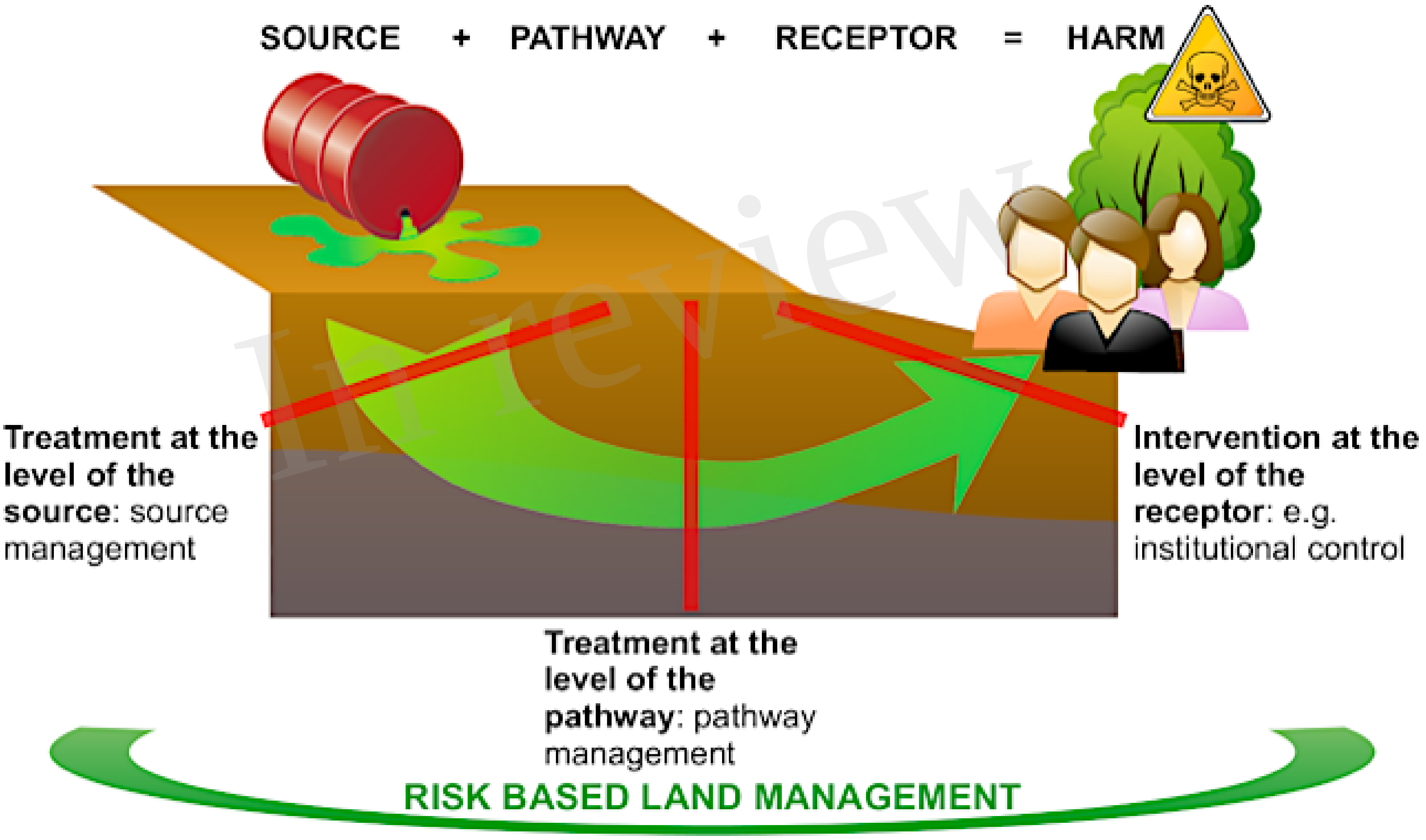
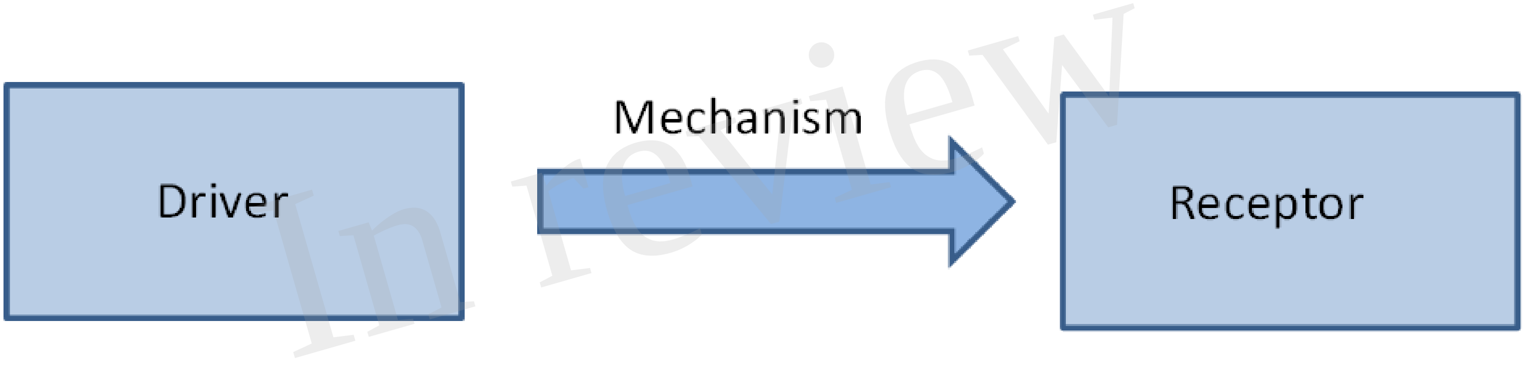
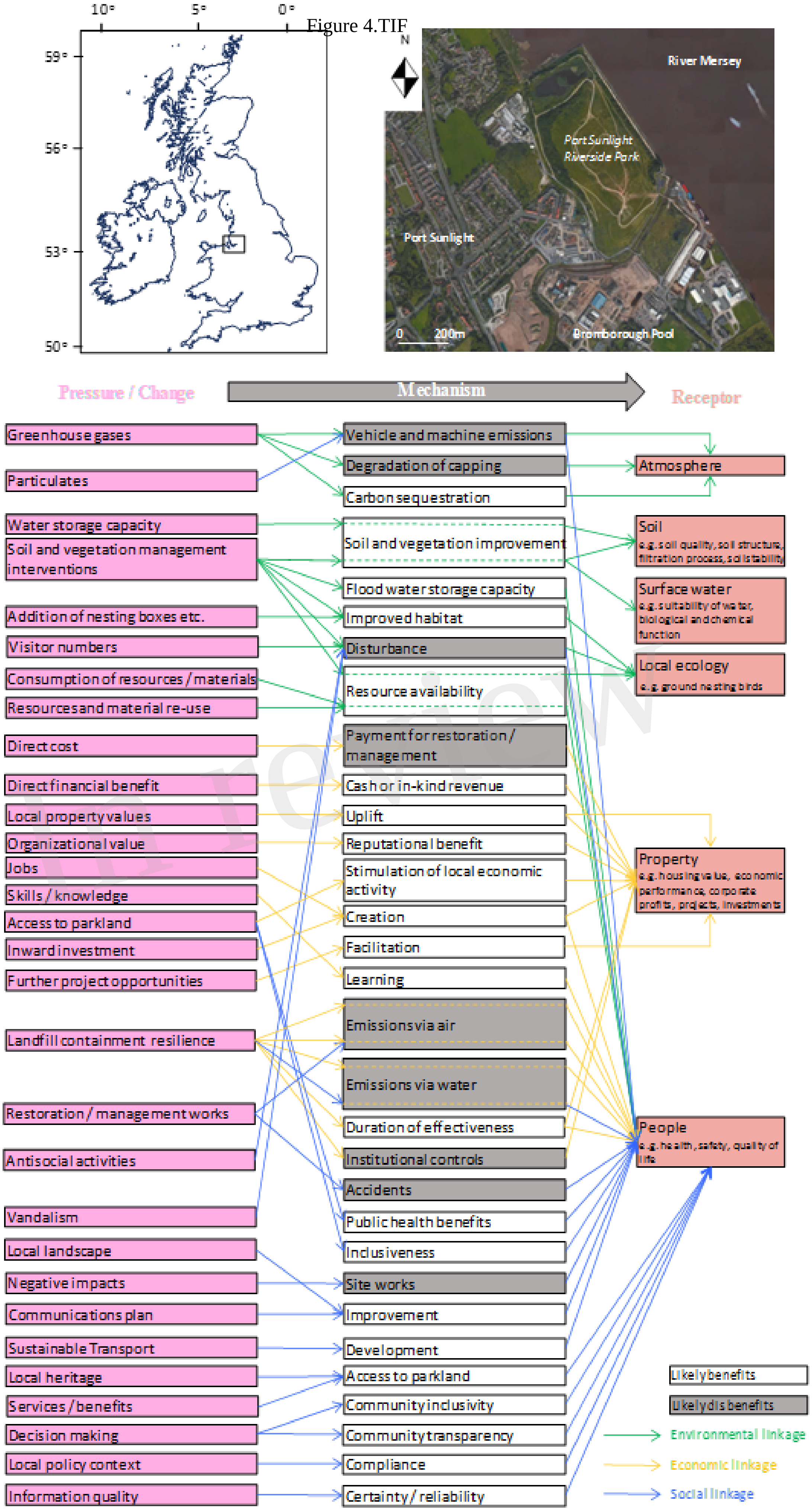

SOURCE + PATHWAY + RECEPTOR = HARM
Treatment at the level of the source: source management
Treatment at the level of the pathway: pathway management
Intervention at the level of the receptor: e.g. institutional control
RISK BASED LAND MANAGEMENT

Figure 3.TIF



Health and safety risks (part of SOC1)	Materials excavation and handling on site	Site workers
Road traffic accident risk (part of SOC1)	Traffic movements from the remediation project	Local community
Exhaust emissions affecting local air quality (part of SOC3)	Traffic movements from the remediation project	Local community
Increased sense of pride / place (part of SOC4)	Improvement of the urban landscape / removal of blight	Local community
Greenhouse gas emissions (part of ENV1)	Remediation operations	Atmosphere
Property value uplift (part of ECON1)	Site improvement	Site owner
Property value uplift (part of ECON2)	Improvement of the urban landscape / removal of blight	Surrounding property owners

Figure 4.TIF


10°
5°
0°
59°
56°
53°
50°
N
River Mersey
Port Sunlight Riverside Park
Port Sunlight
0 200m
Bromborough Pool
Pressure / Change
Mechanism
Receptor
Greenhouse gases
Particulates
Water storage capacity
Soil and vegetation management interventions
Addition of nesting boxes etc.
Visitor numbers
Consumption of resources / materials
Resources and material re-use
Direct cost
Direct financial benefit
Local property values
Organizational value
Jobs
Skills / knowledge
Access to parkland
Inward investment
Further project opportunities
Landfill containment resilience
Restoration / management works
Antisocial activities
Vandalism
Local landscape
Negative impacts
Communications plan
Sustainable Transport
Local heritage
Services / benefits
Decision making
Local policy context
Information quality
Vehicle and machine emissions
Degradation of capping
Carbon sequestration
Soil and vegetation improvement
Flood water storage capacity
Improved habitat
Disturbance
Resource availability
Payment for restoration / management
Cash or in-kind revenue
Uplift
Reputational benefit
Stimulation of local economic activity
Creation
Facilitation
Learning
Emissions via air
Emissions via water
Duration of effectiveness
Institutional controls
Accidents
Public health benefits
Inclusiveness
Site works
Improvement
Development
Access to parkland
Community inclusivity
Community transparency
Compliance
Certainty / reliability
Atmosphere
Soil
e.g. soil quality, soil structure, filtration process, soil stability
Surface water
e.g. suitability of water, biological and chemical function
Local ecology
e.g. ground nesting birds
Property
e.g. housing value, economic performance, corporate profits, projects, investments
People
e.g. health, safety, quality of life
Likely benefits
Likely disbenefits
Environmental linkage
Economic linkage
Social linkage