Developing a business case for greening hard coastal and estuarine infrastructure: preliminary results

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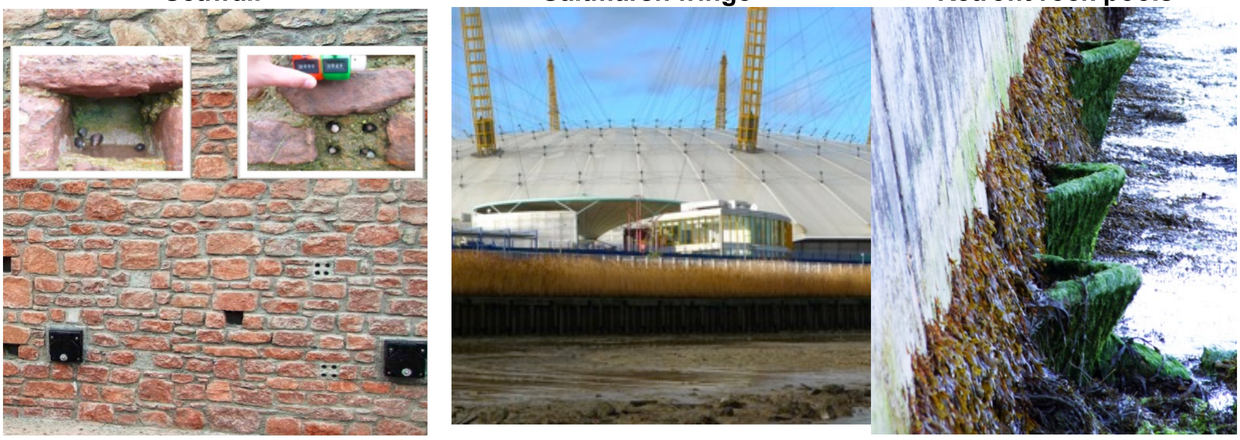
Abstract
This paper presents a new framework of critical success factors (CSF) that is being developed to aid approval of ecological enhancements and green engineering options in cities, historic conservation areas, estuaries and at the coast. This is intended to support asset managers, engineers, conservation and biodiversity teams, decision-makers, and other end-users. The CSF framework is outlined and demonstrated by assessing the engineering performance and ecosystem services benefits of ecological enhancements used in specific operational scale case studies. Where data availability permits, the costs and benefits of different greening approaches compared to 'business as usual' are assessed. Three coastal and estuarine case studies are presented to demonstrate how the framework can be applied to compare traditional engineering solutions to green-grey options. Results show that simple, inexpensive ecological enhancement and green engineering solutions can deliver more multifunctional benefits than business as usual solutions for similar or reduced costs. They also demonstrate that the CSF framework will be a powerful tool that can aid practitioners in evaluating green engineering solutions compared with business as usual.

Introduction
A potent cocktail of increasing storminess, rising sea levels and coastal urbanisation is raising demand for estuarine and coastal flood and storm alleviation infrastructure. In parallel there is a growing requirement from government for grey infrastructure, including coastal defences, to be sustainable, resilient, work with nature and to be more multi-functional, including ecosystem services provision (Environment Agency, 2012). Much of the global effort on nature-based (or working with natural processes) flood risk management, such as recreation of saltmarshes using managed realignment, have been designed and tested in rural areas, and are not directly applicable to urbanised areas where adaptation space is limited. Urbanised coastlines typically have lower biodiversity value than equivalent natural habitats (Bulleri and Chapman 2010, Gaston et al. 2013) and many of the characteristic soft sediment habitats found in estuaries have been lost due to human activities (Heery et al. 2017). There is an urgent need to identify suitable options for improving the multifunctionality of urbanised estuaries and coasts, through provision of a range of soft and hard substrate habitats on hard infrastructure. This form of "greening" extends beyond current green infrastructure and working with natural processes practices to green "grey" assets that need to remain predominately grey for their primary engineering function; we call this 'Integrated Green Grey Infrastructure' (IGGI) (after Naylor et al. 2014). At the coast, IGGI approaches may be suitable where other softer, nature-based engineering options are deemed unsuitable. Thus, IGGI measures can be used to improve the

ecological value and associated ecosystem services provided by hard infrastructure where a hard engineering solution is required (Figure 1).

Seawall **Saltmarsh fringe** **Retrofit rock pools**



Niche habitats in a flood defence scheme at Shaldon, Devon.

Structurally engineered saltmarshes in the River Thames.

Vertipools along the south coast of England (Source: Arc-Consulting)

Figure 1. Examples of estuarine and coastal ecological enhancements

Background

Over the past decade, there has been growing awareness that hard coastal and estuarine structures are poor surrogates for natural rocky shorelines worldwide (Bulleri and Chapman 2010, Scherner et al. 2013). There is increasing research and practical efforts by a few teams around the world (notably in Seattle, Sydney, Singapore, Italy, Israel, USA and the UK) to enhance hard assets for rocky shore species and to improve ecosystem service provision (e.g. see Firth et al. 2016 for a recent review) (Figure 1). Much of this work has been led by academic researchers where experimental evidence of success is overwhelmingly positive; however, widespread application of these ideas in operational coastal and estuarine flood risk schemes, has, to date, been more limited (Naylor et al. 2012, Perkol-Finkel and Sella 2015). Few government guidance documents exist on this subject (see Naylor et al. 2011 in the UK and the Living Shorelines guidance in America (Habitat.noaa.gov, 2017) for notable exceptions). Where these do exist (e.g. Estuary Edges Guidance, Environment Agency, 2008) there has been limited application elsewhere. Thus, there are gaps between academic research and practical application, particularly outside of these specific locations, both in the UK and further afield.

There is also is a dearth of information comparing the costs and benefits of ecologically enhanced infrastructure compared with ‘business as usual’ options. The absence of these data makes it challenging for practitioners to provide a sound business case for or against the inclusion of such measures as part of new build, maintenance or repair works to coastal and estuarine flood alleviation schemes. Indeed, in a recent survey of 53 engineering and environmental practitioners, 25% of all respondents wanted improved guidance, case studies and details on the costs/benefits to enable wider implementation (Naylor et al. 2016). Fifty-eight percent of respondents felt that a policy lever was required to improve uptake of greening of hard assets. Whilst there is clear practitioner willingness to improve multifunctionality (Evans et al. 2017), it is also evident that a more robust, evidence-based framework for evaluating ecological enhancements is required (Naylor et al. 2016).

Outline of This Paper

This paper reports on preliminary findings of the NERC funded Integrated Green Grey Infrastructure (IGGI) framework project, led by the University of Glasgow in partnership with the University of Oxford and a suite of national to local scale government agencies (Environment Agency, Natural England, Natural Resources Wales, Highways Agency, Historic Environment Scotland, Scottish Environmental Protection Agency, Glasgow City Council, Southampton City Council, New York City Parks) and an SME (Arc Consulting). It aims to create a decision framework to improve application of ecological enhancement design principles to hard urban, historic and river and coastal infrastructure.

Developing a Critical Success Factors (CSF) framework

The CSF framework is designed to consider the range of policy, engineering, ecological and social parameters that have been, or could be, used to support and/or improve the ecosystem services provided by hard coastal and estuarine infrastructure. The framework has been co-developed with the project partners and HR Wallingford (who were carrying out an equivalent exercise for riverine infrastructure), using an iterative, co-production approach (Reyers et al. 2015) to ensure that both engineering and ecosystem services elements are adequately addressed. This involved a series of meetings, teleconferences and workshops with project partners to co-develop the framework to ensure it is of direct value to coastal engineering, environment and engineering users.

An initial impetus for this project was to build on the recently released Benefits of Sustainable Urban Drainage (SUDs) Tool by CIRIA, the Constrution Industry Research and Information Association (BeST, CIRIA, 2015)) which is designed to assess the wider multifunctional benefits that SUDs can provide, using an ecosystem services and ecological economics framework. Our aim was to extend this approach to develop a robust, data-driven framework to assess the multifunctional benefits of different IGGI options compared to business as usual grey solutions. Key outcomes are a framework and suite of case studies that practitioners can readily use to improve the business case for including IGGI design principles in a range of operational engineering activities (i.e. new build, replacement, repairs and maintenance). The framework is designed to support existing ecosystem services and appraisal guidance documents such as the Flood and Coastal Erosion Risk Management Appraisal Guidance (Environment Agency, 2010).

Selection of Critical Success Factors

A conscious, collective decision was made by the project teams and partners to create a framework that could help overcome key barriers to uptake of IGGI measures, by providing data on engineering performance, maintenance and inspection *and* an assessment of the financial, ecosystem service and social benefits. As we are aiming to help practitioners make a more reasoned assessment of whether and how to gain approval for IGGI measures, the motivation for existing schemes, including any statutory requirements was seen as a key factor to include in the framework. These were collectively termed ‘critical success factors’ (hereafter CSF) to look at the range of drivers, motivators, constraints and opportunities, and cost and benefits compared to business as usual (Figure 2). All CSFs are discussed in the case studies developed using the framework, but only a selection are used as part of the cost benefit assessment. For example, data is gathered for “Motivation” o aid practitioner understanding of the drivers behind a particular scheme rather than to be included quantitatively.

Framework and Case Study Development

The framework was developed as an iterative process in close coordination with the project partners and HR Wallingford. First, case studies were solicited from key project partners and a review of the existing evidence on CSFs was made. Key criterion for case studies were good data on the costs of adding the IGGI measure (so a comparison to business as usual could be made) and there needed to be ecological data allowing comparison between the ecological enhancement and a control or business as usual option. Those that did not meet these criteria were developed into ‘Art of the Possible’ examples to showcase innovation, where the CSF Framework could not be fully applied.

The case studies provided baseline data that were used to develop criteria for each critical success factor used in the framework. Data limitations meant that the framework is primarily qualitative, though some parameters (e.g. capital costs of adding an IGGI measure) are quantified where possible. Where site-specific data were lacking or limited, supporting data were gathered using expert judgement or wider evidence; a data quality table was used to capture this variability. This approach is consistent with the new EA appraisal tools (Environment Agency, 2016).

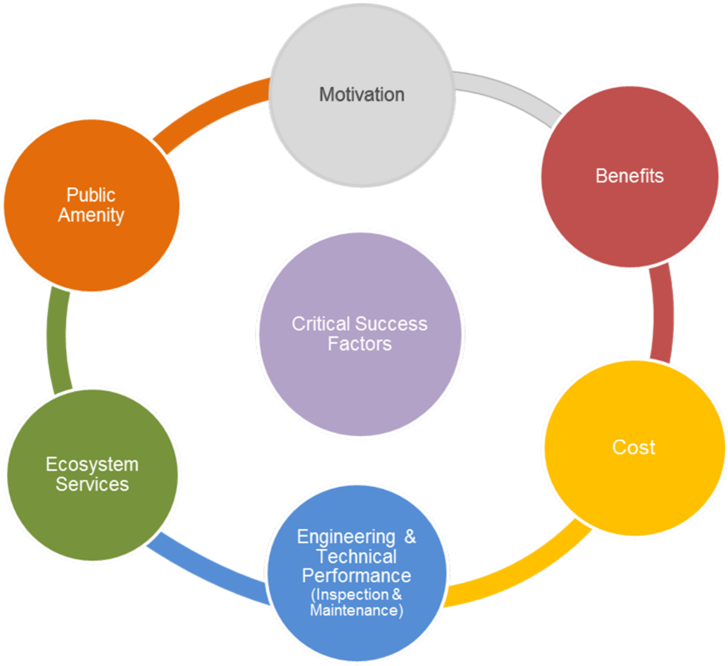


Figure 2. Critical success factors underpinning the decision support framework.

Engineering performance maintenance and inspection

The case studies below show how we used the CSF Framework to detail key aspects of working examples and how issues of uncertainty were addressed within these projects. From discussion with engineers and environmental practitioners it became clear that common factors limiting the uptake of IGGI approaches (and green infrastructure more broadly) were a level of risk aversion and limited information showing how the asset is influenced, for maintenance and inspection as well as performance. These are key in assuring funders that the project can be successful in the long-term.

The functionality of the asset is, of course, of primary importance meaning that performance compared to the traditional 'business as usual' approach(es) is a primary issue. For many business-as-usual examples, the performance baselines are well established and asset managers will have quick and easy access to data. In comparison, most comparative IGGI measures are relatively untested in the field. We therefore chose case studies scrutinised with at least some degree of scientific rigour, using information from suppliers, contractors, PhD studies or scientific papers, and converting data to common metrics (e.g. cost per metre of seawall) where needed. Extrapolations and assumptions were done with expert guidance, particularly where there was a risk that performance, design life, asset resilience, maintenance or inspection may be negatively impacted. In these cases we attempted to determine the circumstances under which this may occur and how it might be avoided or mitigated, or where further expert judgement should be sought.

Cost

Project costs are key to any prospective project manager and the CSF framework enables them to determine how and to what degree including IGGI measures might influence the business case. Data for business as usual options are often available from previous examples and industry guides, and extrapolation under expert guidance can provide quantitative and qualitative figures for an IGGI measure, enabling comparisons to be made. In addition to direct costs, and business as usual costs, the framework considers longer-term costs, including possible changes to asset resilience and inspection/maintenance costs.

Ecosystem Services (ES)

GI and IGGI projects can be generally described as ecological enhancement measures and may incorporate an implied effort to broadly mimic local natural habitats in some way, or more explicitly declared efforts to replace particular ecosystems, perhaps lost through the project or identified in strategic biodiversity plans and policy. The CSF helps identify what the ecological aims are for individual projects, how they can be met and ways in which they can be enhanced. The case studies all had data that compared the ecological outcomes of IGGI measures with control scenarios; these data informed the ES assessment.

Public Amenity
Within ecosystem services and GI research, the amenity benefits of 'naturalising' urbanised areas are increasing acknowledged. For this reason it is drawn out from the ecologically focused ES measure and used at its broadest, i.e. not only pleasantness of space but also additional Social-economically valuable elements. For example, access to third party funding (including Corporate Social Responsibility activities or funding from community payback schemes), improved favourability within planning and permitting processes, to foster community support/stewardship, streamline resources/reduce costs and carbon footprint, generate income and develop business opportunities.

Demonstrating the critical success factors framework

Three case studies are used here to illustrate how the CSF framework can be applied to different types of coastal and estuarine engineering works:

1. Replacement new build: A hard coastal defence scheme under construction
2. Repair works: A softer, green engineering repair scheme for an existing estuarine coastal defence
3. Maintenance: A change in maintenance regime of an estuarine earth embankment flood defences to optimise mowing for key pollinator species

In each case, a table summarising the values assigned to each CSF with an explanation of how they were derived. Data quality is also evaluated for each case study.

Case Study 1 New build hard coastal defences: Hartlepool

Background

In response to a 'hold the line' policy, the Headland Foreshore Coastal Defence Scheme, is replacing and upgrading existing but poor-condition defences for 562 residential and commercial properties as well as important cultural heritage assets at Hartlepool in north east England, UK. This is an exposed, north-east facing open coast subject to a strong storm wave climate where wave overtopping is a key flood risk. Funded via the Project for Accelerated Growth (PAG) Scheme, with support from the Environment Agency, Hartlepool Borough Council and PD Ports, the scheme is currently underway. A particular challenge was concern for loss of habitat and/or quality of foreshore feeding grounds for internationally important water bird populations (the scheme lies within a Special Protection Area, Ramsar site and SSSI). Emplacement of a seawall and granite rock armour revetment on the foreshore, coupled with coastal squeeze in response to sea level rise, posed a challenge under the Habitats Regulations, which required no adverse impacts on the water bird habitats (Naylor et al., under review).

Several measures were taken to minimise the ecological impact of the revetment during construction and during the design life of the structure (80-100 years). This included adjusting the timing and footprint of construction works, and material choice and design modifications of the sea wall and rock revetment to improve physical habitat complexity (after Coombes et al. 2015 and Firth et al. 2013). Additionally, apprporate use of rock armour could provide additional three-dimensional habitat to help mitigate the expected habitat losses associated with coastal squeeze. Budget limitations meant that any mitigation measures adopted needed to be cost-effective, could not be in any way detrimental to the primary engineering function of the defence, nor delay the construction. These constraints limited the choice of material for the rock revetment to granite.

Key IGGI design alterations for the rock revetment involved choosing the most ecologically suitable granite (light coloured and coarse grained), infilling some void spaces with limestone to improve habitat suitability for certain species (after Coombes et al. 2009) and where possible, positioning boulders to optimise their water-holding capacity to maximise intertidal refuge (Firth et al. 2013). The rock revetment is a mixture of 'passively enhanced' rock armour (via positioning) and 'normal' rock armour comprised of pink granite with carboniferous limestone fill material. Preliminary surveys conducted 12-18 months post deployment (Naylor et al. under review) suggest that the passively enhanced rock armour has improved ecological outcomes compared to areas without enhancement.

Application of the CSF Framework

A business-as-usual scenario (of non-enhanced rock revetment) was not an option for this scheme as ecological mitigation was a statutory requirement. We therefore compared other options that were considered during the scheme appraisal (e.g. traditional rock armour) to the final adopted, enhanced approach. As only some elements of the revetment were enhanced on-site, comparisons of ecological success between 'normal' and enhanced rock armour are possible. Each CSF used to compare the IGGI measure with 'business as usual' is summarised in Table 2.

Table 1. Critical success factors for the Hartlepool scheme

	Data Quality	Business-as-usual (standard rock armour)	IGGI measure (rock armour material and placement)	CSF Value
Engineering	Quantitative	Design life: 80-100yr Resilience: to storms Maintenance: as required Inspection: annual	No change	No change[2]
Public amenity	Qualitative	Maintained	Maintained	No change
Ecosystem Services	Quantitative	At risk	Maintained	Positive[3]
Direct Cost[1]	Quantitative		Marginal increase[4]	Slight negative
Cost Benefit	Mixed			**Net positive**

[1]Capex cost compared to business as usual
[2]The scheme was not damaged by the January 2017 East coast surge.
[3]Minimised ecological impact; increased rate of colonisation and abundance of species of food interest to protected birds so far; ecological mitigation against coastal squeeze.
[4]Marginal increase due to slight increases in material costs and operator training time

The overall cost benefit for Hartlepool shows that, in as little as 18 months post-installation, the benefits of the IGGI measure already outweigh the minimal increase in cost. Further monitoring is on-going. It also demonstrates that IGGI measures can be simple and inexpensive, with minimal impact on standard engineering construction or design practice.

Case Study 2 Softer engineering repair works: Vegetated terraces

Background

Because of the extensive network of sea defences already in place along the UK coastline, the opportunities for innovations in greening of grey infrastructure are often higher for repair and maintenance works than for replacement or new build. The cost of repair and maintenance of estuarine structures, for example, is already an issue and much of the 2100km of flood defences raised after the 1953 North Sea flood event is approaching the end of its design life (Temmerman et al, 2013). This requires strategic thinking about flood risk management options in a changing climate, and in the meantime, address short-term, localised repairs to existing engineering assets. For example, there are opportunities for IGGI measures to be adopted during the repair and maintenance of existing defences whilst more sustainable adaptation options are being considered.

In this example twelve experimental stone gabion and clay filled terraces were installed in Essex in 2012 by the Environment Agency as part of sea wall repair works. The works intended to protect the toe from wave action and to enhance habitat provision by re-establishing lost salt marsh. The clay was excavated locally and the borrow pits were designed to create additional saline lagoon and/or freshwater habitats. Over 22 months of monitoring it was found that each terrace provided a narrow strip of otherwise unavailable sediment substratum with the potential to support salt marsh vegetation. Though salt marsh development can take time to fully develop (Mossman et al. 2012) seven of the twelve terraces showed increased colonisation by salt marsh plant species (Cousins et al., 2016). Factors such as the tidal height of the gabion, the proximity to existing salt marsh, exposure and sediment compaction were all found to be important factors influencing the ecological success of the design. The long-term ecological resilience of this type of IGGI measure to sea level rise requires further study, to assess whether species migrate into the sedimentary habitat that was created. Monitoring in 2016 found continued plant colonisation and maintained physical integrity on the majority of the terraces, including a further 3 terraces not surveyed in Cousins et al, 2016.

Application of the CSF framework

Each CSF used to compare the IGGI measure with 'business as usual' is summarised in Table 3.

Table 2. Critical success factors for Vegetated terraces

	Data Quality	Business as Usual (Essex blocks)	IGGI measure (vegetated terraces)	CSF Value
Engineering	Quantitative	Performance: meets expected design life Resilience: withstands storms Maintenance: as required Inspection: 6 monthly	Potential to improve performance – via wave attenuation	Potential positive[1]
Public amenity	Qualitative	Low	Improve -enhanced landscape	No change[2]
Ecosystem Services	Quantitative	Limited habitat	Improved – increased salt marsh habitat	Positive[3]
Direct Cost[4]	Quantitative	From Scheme option appraisal	Marginal increase	
Cost Benefit	Mixed			**Net positive**

[1]no loss of structural integrity under storm conditions in 2013 (Cousins et al., 2016); saltmarsh fringe may attenuate waves; otherwise no change in performance after 22 months.
[2]no amenity data were available; benefits may include improved aesthetics and fish habitat
[3]mitigation of lost habitat was achieved (Cousins et al., 2016)
[4]evaluation of costs is currently being conducted

Case Study 3 Altered maintenance regime: Mowing for Wildlife

Background

In England the Environment Agency maintains around 1,000km of coastal defences, including sea wall embankment and 1,700km of raised walls and embankments under third party ownership. These raised banks vary in width from 2-5m to 10-15m and are engineered to protect against tidal flooding. Their grassed crest and landward-facing slopes (Figure 4) provide terrestrial habitat for a range of plant and invertebrate species (Gardiner et al., 2015). They are periodically mown (at least once a year, sometimes up to 6 times per year) to facilitate inspection work, maintain surface soil integrity and limit tree and shrub growth (Environment Agency, 2009). Changes to the timing and frequency of mowing can significantly improve plant, animal and insect populations (Gardiner et al, 2015).

A. Business as usual **B. Changed mowing management**

Figure 4. Examples of mown and unmown earth embankment coastal flood defences, Canvey Island, Essex, UK (September 2016)

In an attempt to address declining pollinator populations (see National Pollinator Strategy, 2014) the Environment Agency undertook a number of trials on embankments in Canvey Island. Since 2012, cutting regimes were changed on a 4 km stretch from a minimum of 2 cuts a year to 1 cut, delayed until after 15th September to allow for bee foraging and nesting habitats. In addition, a large section of the landward folding/berm (in places 20-30m wide) next to Canvey Wick SSSI (a flower-rich brownfield site) was left uncut.

Monitoring has shown significant increases in bee species richness and their plant food species on the 1-cut regime compared to the 2-cut regime. One UK Biodiversity Action Plan Priority species of bee (*Bombus humilis*) was twelve times more common on the single cut areas (Gardiner & Vetori, 2015). This intervention has since been expanded to include 15km of sea wall in the outer Thames Estuary, and the practice is now incorporated into the Thames Estuary Asset Management (2100) Programme of tidal flood defence works (Gardiner & Vetori, 2015)).

Application of the CSF framework

Each CSF used to compare the IGGI measure with 'business as usual' is summarised in Table 4.

Table 3. Critical success factors for Mowing for Wildlife

	Data Quality	Business as Usual (mowed earth embankment)	IGGI measure (Mowing for wildlife)	CSF Value
Engineering	Quantitative	Performance: meets expected design life Resilience: to storms Maintenance: as required Inspection: 6 monthly	No change	No change[1]
Public amenity	Qualitative	Low amenity value (except for those preferring short grass)	Mixed – uncut grass = "unappealing", vs. Increased interest and support for wildlife	Slight positive[2]
Ecosystem Services	Quantitative	Limited habitat	Improved – increased pollinator habitat and populations	Positive[3]
Direct Cost	Quantitative		Decrease	Positive[4]
Cost Benefit	Mixed			**Net positive**

[1]engineering performance is not adversely affected by altered mowing regimes (EA, 2009).
[2]assuming widespread support for pollinators vs. expressed local dislike of longer grass
[3]increased number of target bee species
[4]reduced cost associated with lower-frequency mowing, estimated to be £250 per km per reduced cut

Discussion and Conclusions

The purpose of the CSF framework is to strengthen any business case for where there is potential to adopt IGGI measures and to provide a platform upon which other innovative measures can be transparently evaluated compared to business as usual 'grey engineering' solutions. It was developed to address a key gap hindering the ability to compare different IGGI measures and traditional grey engineering solutions. Crucially, development of a quantitative framework and the cost benefit assessments of individual case studies were hampered by a lack of suitable data (Table 5). For example, none of the case studies had any robust amenity data.

This means that the actual assessment of cost benefits, especially the ecosystem service and amenity, are conservative estimates as many factors are unknown or are drawn from wider supporting information. The framework presented here thus provides a first step towards achieving this goal, providing a transparent process by which existing or future schemes can be compared with traditional grey solutions. It is recommended that future projects adopting IGGI measures try to secure funding and partnerships with organisations who can assist with designing comprehensive before and after monitoring, to evaluate success (or failure) across all of the critical success factors. This level of data would enable improved assessments of IGGI approaches compared with grey engineering solutions. There are an increasing number of mechanisms to evaluate Ecosystem Services beyond the production of useable or edible material. IGGIframe provides an accessible mechanism to evaluate and demonstrate the wider social values, where they are measured.

Table 4. Comparative assessment of data quality between case studies

	Data quality/quantity						
	Site specific data			Expert judgement		Wider evidence	
Data type	No data	Limited reported sources	Strong reported sources	Some expert judgement	Multiple expert opinion	Some sources	Multiple sources
Case Study 1: Hartlepool[1]							
Economic			+	+			
Engineering		+		+			
Environmental[2]		+					++
Case Study 2: Vegetated Terraces							
Economic				+			
Engineering			++				
Environmental			++			++	
Case Study 3: Altered Mowing							
Economic			++				
Engineering				++			
Environmental			++			++	

[1]Preliminary results as scheme is under construction;
[2]Environmental combines ecosystem services and social amenity

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