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WP1 Developing an Asset Register for the Turks and Caicos Coastal-Marine Area

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Summary

Natural Capital assessment, accounting and mapping approaches provide valuable tools that enhance the capabilities of decision-makers and local communities when managing marine resources.

Natural Capital approaches are investigated in this study of the shallow marine coastal areas of the Turks and Caicos Islands to create a Natural Capital Asset Register for the first time. The work builds on the marine evidence base of the Turks and Caicos Islands, using key scientific literature and mapping products to develop the Asset Register for twelve benthic habitat classes. The dominant habitat assets are sand (43.59% study area), sparse seagrass (24.78%) and dense seagrass (12.28%), which together account for over 80% of the shallow marine coastal area of the Turks and Caicos Islands.

An Asset-service matrix was created for habitat assets and species assets following a review of literature generated from 310 individual pieces of evidence from 65 sources. This showed the linkages between habitat and species assets and the ecosystem services they provide. In total, nine habitat assets were linked to sixteen services in the habitat Asset-service matrix and nine species assets were linked to seven services in the species Asset-service matrix. Linkages were not possible for all assets or all services due to evidence gaps, highlighting a need for further research in those areas.

Combined use of the habitat Asset-Service Matrix and benthic habitat maps enabled the creation of maps showing ecosystem service delivery of three types of service across the shallow marine coastal seas of the Turks and Caicos Islands. Maps created showed the delivery of two regulating services, carbon storage, erosion and flood protection; one provisioning service, habitat provision for adult and juvenile groupers; and one cultural service, snorkelling activity. The ecosystem service delivery maps highlighted areas where many services are provided by the same habitat assets, such as in the seagrass areas, that may prove useful for decision-makers and local communities and their understanding on these areas.

The approaches used in the study have numerous benefits, including making good use of existing marine evidence and highlighting areas with multiple ecosystem benefits, and will likely form the baseline for future work involving assessments of asset condition, development of asset indicators and future monitoring strategies. The study makes recommendations for future work, focusing on the knowledge gaps and refinements of current approaches to improve the accuracy of and confidence in a Natural Capital Asset Register, Asset-service matrix and ecosystem service delivery maps.

Contents

1 Introduction

This report has been delivered as part of the Darwin Plus funded project DPLUS119 '*Technical assistance programme for effective coastal-marine management in the Turks and Caicos Islands*'. Darwin Plus is funded by the UK Government. Led by JNCC and working in partnership with the Government of the Turks and Caicos Islands Department of Environment and Coastal Resources (DECR) and the South Atlantic Environment Research Institute (SAERI), the project aims to improve the evidence base in the marine and coastal environments in order to support sustainable coastal and marine management approaches in the islands. Working with local communities, science professionals and decision-makers, the project will provide in-depth support and capacity building in using information management systems, natural capital approaches, undertaking environmental status and vulnerability assessments and developing indicators to monitor changes in marine and coastal habitats. Project outputs will support decision making, maximising the use and value of existing data, and support implementation of a new TCIG Environment Strategy. For further information, please visit https://jncc.gov.uk/our-work/turks-caicos-islands-marine-coastal-management/.

1.1 The Natural Capital Approach

The natural capital approach in the marine context is described by Hooper *et al.* (2019, p2) as "a somewhat broad term that encompasses assessment of the quantity, quality, function and value of environmental assets and the goods and services that flow from them, with the aim of ensuring the sustainable use of natural resources. Fundamentally, the approach is based on recognising the contribution of nature to human welfare, and hence improving the manner in which the natural environment is traded-off against other things that are important to society. The concept of value is central to the natural capital approach, as it seeks to better integrate environmental and economic information and thus to redress the historic trend in which natural capital and ecosystem services were undervalued and overexploited. Equally important is documenting ecological status as the characteristics of assets are usually only partially reflected in monetary values."

In seeking to integrate nature more effectively into decision-making processes, the natural capital approach has adopted terminology for the natural environment that is closely related to that used in the economic thinking that drives much policy making. The three principal elements of this typology are: (i) natural capital assets; (ii) ecosystem services; and (iii) goods and benefits. Figure 1 provides definitions of, and a schematic of the connections between, these elements. Recognised methodologies for natural capital assessments are also beginning to emerge, which focus on recording the status of assets, services and benefits and using maps from Geographical Information System (GIS) layers to represent the information spatially. The main methods and tools are shown in Figure 2.

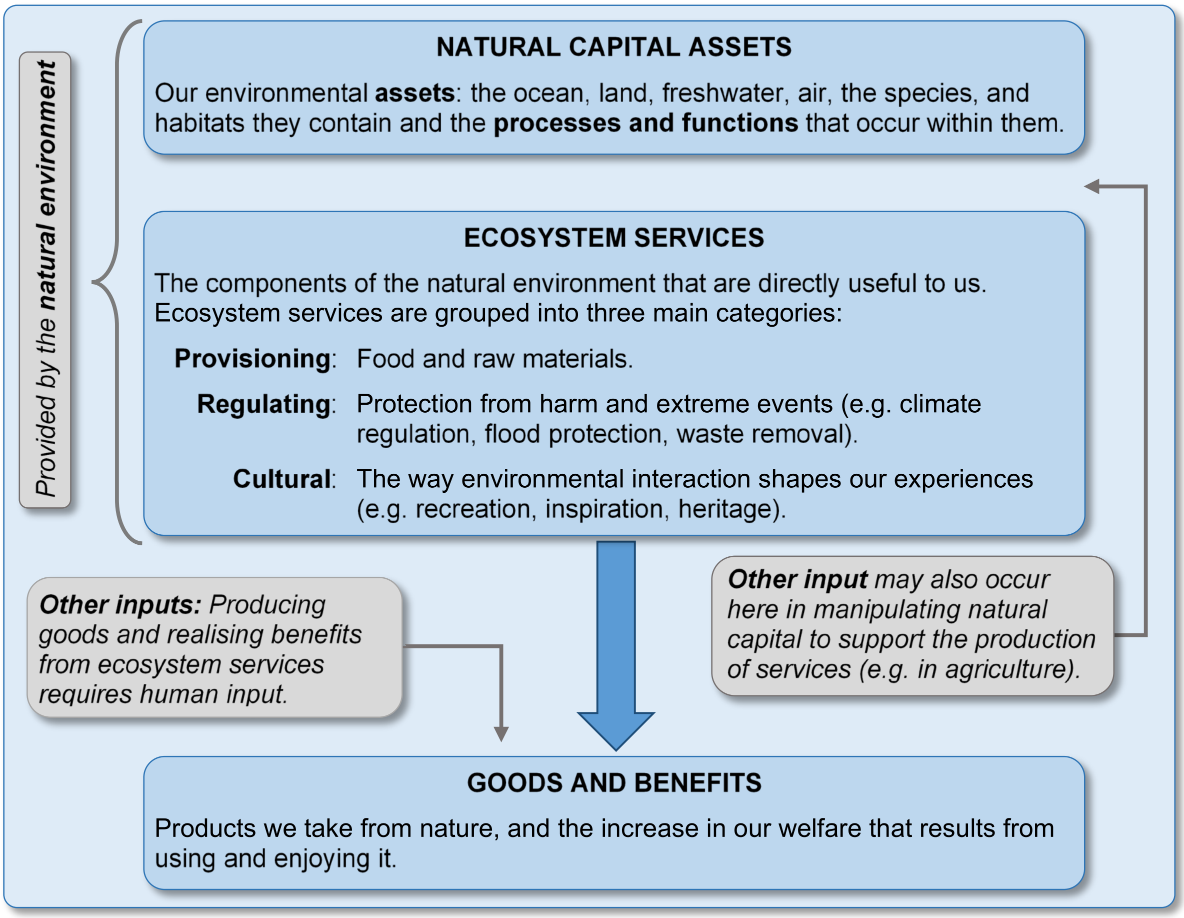

Figure 1. The main elements of the natural capital system (adapted from Hooper & Austen 2020).

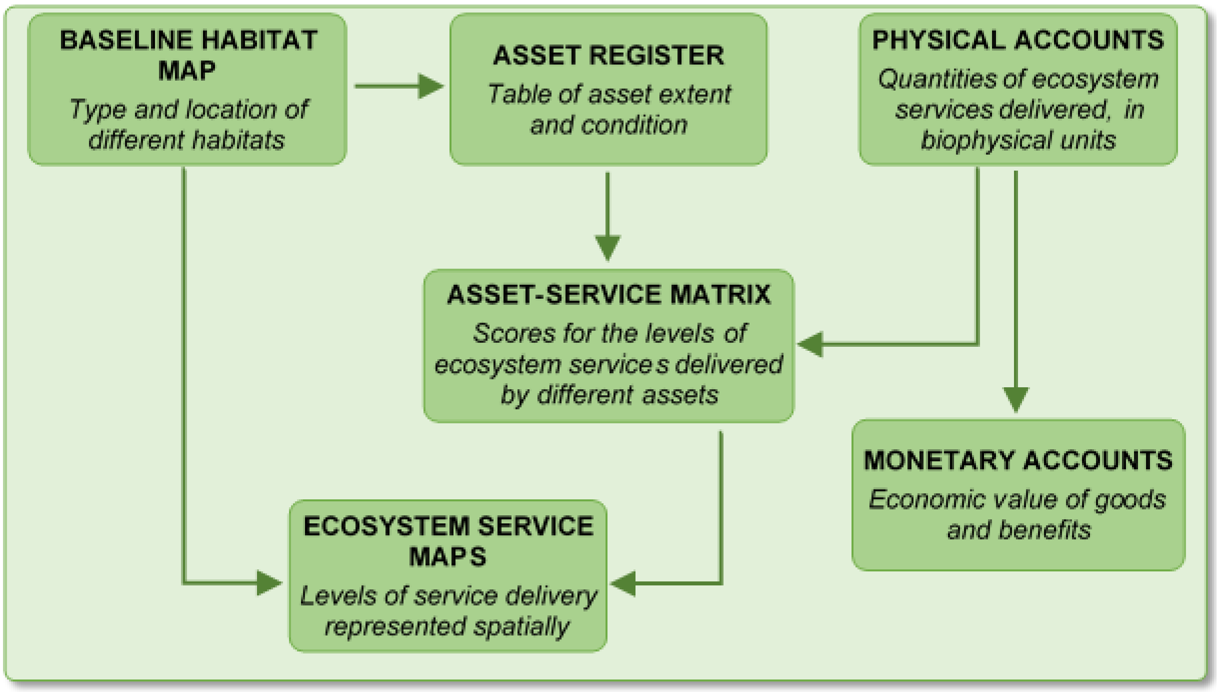

Figure 2. A generalised schematic of the tools for organising and reporting natural capital information.

Natural capital assessments that follow the general approach outlined in Figure 2 are becoming commonplace in land management, with JNCC alone involved in projects to map natural capital and ecosystem services in Chile, Columbia, and Peru. Examples are also emerging of the use of the asset registers and ecosystem service mapping in marine management, including in relation to coastal zone planning (Verutes *et al.* 2017; North Devon Biosphere Reserve 2020), and in the development of byelaws to protect important habitats from damaging fishing activity (Ashley *et al.* 2020; Sussex IFCA 2020). The techniques have also been explored within the Turks and Caicos Islands (TCI), for example in mapping the ecological values, including those for ecosystem services, for terrestrial and marine habitats in East Caicos (Wood 2016). This work builds on such preliminary approaches.

1.2 Project aims, objectives and tasks

The overarching aim of this work is to contribute to the provision of practical tools for, and enhanced capabilities of decision-makers and local communities to understand, natural capital approaches. The specific objectives are:

- To create a Natural Capital Asset Register for the TCI marine and coastal environment, incorporating outputs from the previous JNCC TCI Natural Capital Accounting - Initial review (Eftec & JNCC, 2018, 2019), and drawing on tools already developed by JNCC.
- To undertake a systematic literature search to identify links between marine and coastal habitats (assets) present in the TCIs and ecosystem services and benefits, using examples from the Caribbean where available.
- To develop ecosystem service maps using The Nature Conservancy habitat map and outputs from the TCI Asset Register for a minimum of three ecosystem services within the Provisioning, Regulation and Maintenance, and Cultural service categories.

The key steps in the project were, firstly, the creation of an overarching conceptual framework to define the scope of the asset register and ensure its connection to the existing natural capital accounts. Development of the asset register itself required definition of the benthic asset classes and calculation of the extent of each using GIS layers. Understanding the connections between assets and the services they provide required the sourcing and systematic synthesis of the available evidence before the level of ecosystem service supply by individual habitats could be mapped.

In the remainder of this report, the methods for each part of the process are described (Method) and the outputs presented (Sample outputs), which are then discussed collectively (Discussion) before conclusions are drawn and recommendations made (Conclusions and next steps).

2 Methods

An asset register is the first building block of a natural capital assessment, and is, simply, "*an inventory of the natural assets in an area and their condition,*" which should be presented using maps and GIS layers where possible (Natural Capital Committee 2017). Condition has not been included in this assessment, as that is the focus of a separate work package of the wider project. The utility of an asset register for management purposes is enhanced by making the connection between assets and the ecosystem services they supply, which will ultimately link to the goods and benefits to which economic values can be attributed. These connections are documented in an asset-service matrix, which provides the level of service delivery by each habitat on a 4-point scale where appropriate evidence could be found. The asset-service matrix then forms the basis of maps of ecosystem service delivery from specific habitats, which can support visualisation of important areas within the TCI marine-coastal system.

The following sections describe in more detail the individual steps undertaken, from the conceptual framework, creation of the baseline habitat map, and generation of the asset-service matrix, to mapping ecosystem service delivery. The outputs themselves are then presented in section 3 (Sample outputs).

2.1 Conceptual framework

The first step in developing the asset register was to ensure that it could be linked to the Natural Capital Accounts prepared for the TCI (Eftec & JNCC, 2018, 2019). To achieve this, a conceptual framework was developed (Figure 2), which connected the goods and benefits quantified within the accounts to the underlying species and habitats responsible for their supply. Certain services not directly connected to the goods and benefits within the accounts were also included. This was to increase the usefulness of the framework in other contexts, particularly in highlighting regulating services that may become important in management contexts such as addressing water quality issues. The framework had five principal elements:

- *Habitats:* The high-level habitats present within the TCI marine-coastal area.
- *Species:* The main target species for fisheries, together with additional charismatic species that support important cultural services.
- *Supporting Services*: Key functions provided by marine habitats that explain intermediate steps in the link to goods and benefits.
- *Final Services*: The services that contribute directly to the supply of goods and benefits. These are mostly described using definitions from the Common International Classification of Ecosystem Services (CICES), with the descriptions and terms used in the natural capital accounts also included for clarity.
- *Goods and Benefits*: For which economic values have been calculated within the accounts or are expected to be in later iterations (although these may not be complete in all cases for marine elements).

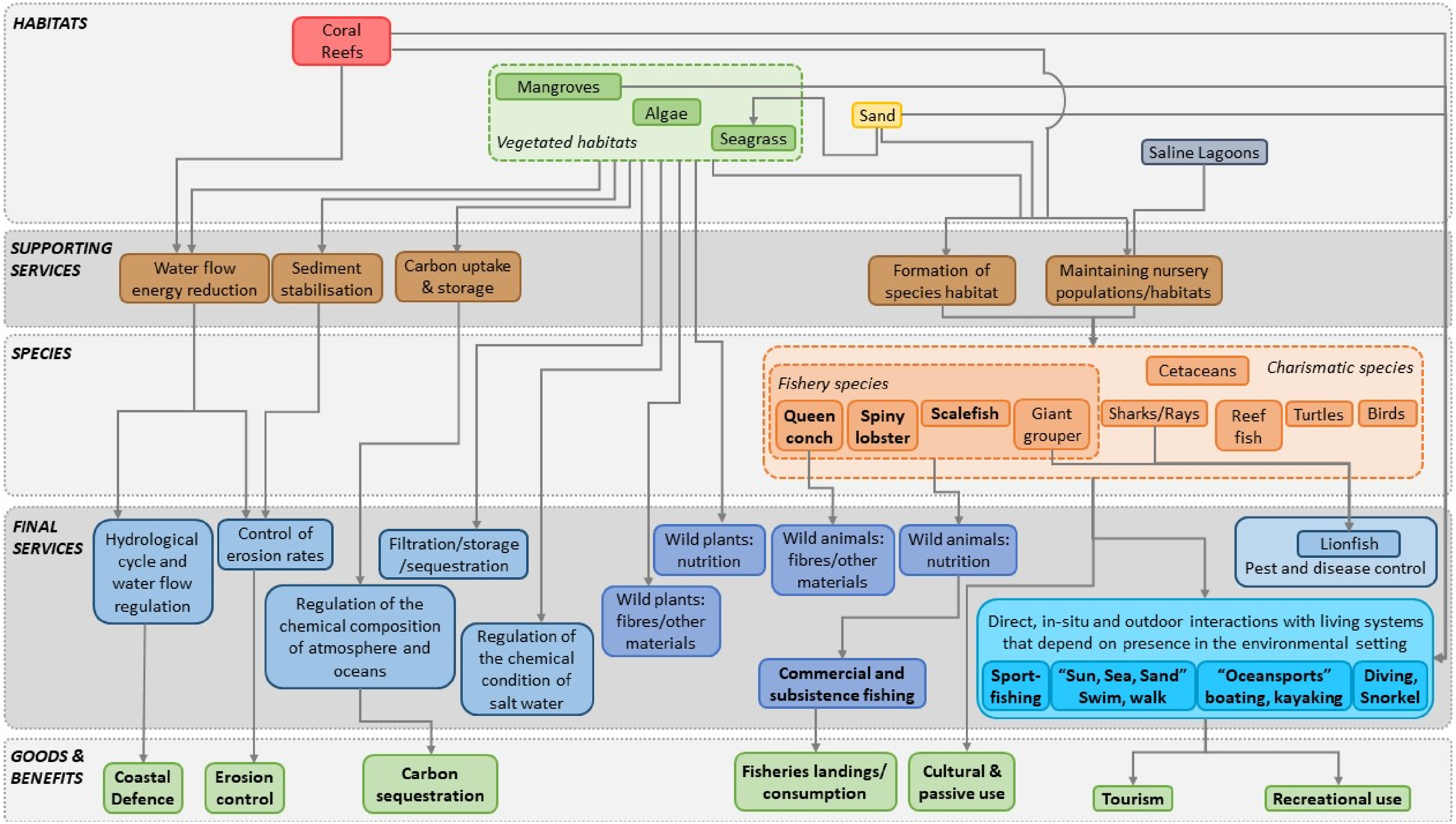

Figure 3. The conceptual framework linking habitats, species, services and goods and benefits. **Bold type** indicates services and benefits referred to in the natural capital accounts (Eftec & JNCC 2019).

2.2 Benthic habitat extent

The fundamental information within an asset register is the quantity of the different assets for the area of interest. The conceptual framework (Figure 3) considers high-level habitats, but the final asset register should be to a higher resolution where possible, reflecting available data and potential differences in ecosystem service delivery between sub-habitats.

2.2.1 Habitat classes

The assets for which extents have been calculated are those included within the TCI benthic habitat map GIS shapefiles[1], produced and provided by The Nature Conservancy Caribbean Division Science Team (Schill *et al.* 2020, November 2020 update). Details of the characteristics of the individual habitat classes are given in Table 1. The characteristics were taken from draft descriptions provided by The Nature Conservancy, which have subsequently been updated are due to be published soon (Schill *et al.* In review). The complete descriptions are available online (https://tnc.app.box.com/s/i9at8fnh19tdtn1lismuvk646ym810s3).

Table 1. Descriptions of the benthic habitats contained within the TCI benthic habitat GIS shapefiles, as provided by The Nature Conservancy.

Benthic type	**Characteristics**
(A) Hardbottom reef	
Coral/Algae	Presence of live coral colonies or structure that is extensive or patchy with or without a living coral veneer. Gorgonians and sparse seagrass and/or algae dominate the substrate between coral colonies.
Reef Crest	Found in shallow water break zones (<2m) between back and fore reef. Typically creates a lagoon. The benthic cover consists of coral build up and turf/calcareous algae. Large fleshy macro-algae are largely absent, and only small coral colonies are typically observed.
Reef Back	Landward side of reef crest - typically has a lot of rubble. Shallow zone 2-3m depth then transitions into lagoon. Skeletal rubble originating from reef structures and bonded by coralline algae to form a semi-consolidated framework with patchy macro-algae. Typically found on the sheltered margins landward of the reef crest. This habitat may also be found surrounding, or atop, carbonate frameworks.
Reef Fore	Typically found on the exposed seaward slope of the reef crest - area of high slope, then transitions into mixed assemblages >8m depth. Moderately rugose frameworks with sparse coral cover (typically <10%). Colonies are predominantly small (sub-meter) in size. The coral community is composed primarily of *Siderastrea*, *Montastrea*, *Diploria*, and *Colpophyllia spp*. *Crustose coralline* algae and fleshy algae (*Sargassum, Dictyota*) along with gorgonians dominate the remainder of substrate.
Spur and Groove	Coral ridges beyond the fore reef at deeper depths >10m) separated by sand channels. Marked as a feature in the geomorphic zones

[1] Available from Turks and Caicos Data Portal: https://dataportal.gov.tc/

Benthic type	Characteristics
(B) Hardbottom Non-reef	
Dense Algae	Typically found beyond the Fore reef at deeper depths (>8m) - darker algal heavy areas with mixed assemblages. Reef framework and scoured hardground with a dominant cover of gorgonians with sponges and macroalgae occupying most of the remaining substrate. The coral structure may or may not have a living coral veneer. The reef maintains the coral form. Live coral cover is patchy (< 15 % overall).
Sparse Algae	Typically found beyond the Fore reef at deeper depths (>8m) - less dark than hard bottom dense algae with more sand and open areas. Scoured hardground dominated by a veneer of turf algae with remaining substrate sparsely covered with *scleractinian* coral, hydrocoral, gorgonians, and sponges.
(C) Unconsolidated sediment	
Dense Seagrass	Dense meadows of seagrass in lagoon and sheltered areas interspersed with macroalgae (>60% cover). Community is dominated by *Thallassia testudinum* but other seagrasses (principally *Syrongodium filiforme*) and calcareous macroalgae (*Halimeda sp*.) contribute significantly to cover. Typically, does not grow > 10m depth.
Sparse Seagrass	Sparse meadows of seagrass interspersed with macroalgae (<40% space cover). The seagrass community is often dominated by *Thallasia testudinum* but other seagrasses (principally *Syringodium filiforme*) and macroalgae (*Halimeda sp*.) as well as fleshy macroalgae, such as *Padina* contribute to cover. Cyanobacteria often form dense mats between macroalgal stalks covering the underlying sandy substrate.
Sand	Unconsolidated sand or sediment bottom with little to invertebrate, seagrass or macroalgal cover that can occur at all depths and in all geomorphological zones. Grain size is influenced by sediment transport during strong wave events, with sediment grading finer towards the low energy back reef. Shallow sand can occur < 5 m typically found within embayments and lagoons where sediments are often muddier. Sometimes found as a halo around shallow reef patches. Offshore sediments tend to become more skeletal. Sand channels often form in between spur and groove reefs. Grain size is influenced by sediment transport during strong wave events, with sediment grading finer towards the low energy back reef.
Muddy Bottom/Estuarine	Inland coastal lagoons, estuaries, and dredged areas. Can also be found at river mouths that dump sediment and silt.
Dredged	Active dredging locations for facilitating boat traffic.

2.2.2 Calculating benthic habitat extents

Habitat areas were calculated from the TCI coastal and marine GIS layers using ArcGIS 10.1. These data are available from the Turks and Caicos Data Portal [2]. The polygons were checked using the Identify tool, and the attribute tables examined. No pre-existing

[2] https://dataportal.gov.tc/

measurement information was available for the benthic habitats layer and so a method previously used by JNCC was employed to determine the extent of individual habitats. This method involved reprojection of data layers, using the Projections and Transformations tool, the benthic habitat layer's coordinate system from Web Mercator Equal Area Auxiliary Sphere to the North American Datum 1983 Zone 19N Universal Transverse Mercator projection. Then, a column called area metres square was added to the map layer's attribute table, to contain the habitat extents. Once this was complete, the Calculate Geometry tool was used to generate the habitat extents, setting it first to metres square to populate the area column. The Field Calculator tool was then used to convert the measurement to square kilometres. Once this had been done, the attribute tables were exported and then converted to spreadsheets using the table to Excel conversion tool.

2.3 Asset-Service matrix

2.3.1 Literature review process

A literature review was undertaken to generate the necessary evidence to create the asset-service matrix summarising the level of delivery of ecosystem services by key habitats and species. The first step was to identify literature from the TCI. Ecosystem services can be context dependent and so local evidence increases confidence that the correct level has been attributed and ensures that the most relevant services are prioritised. Identification of relevant literature was through a basic keyword search in Google Scholar, with subsequent 'snowballing' as new literature was identified within sources detected by the initial search. This method was used because the objective was to obtain as much literature on the TCI as possible, including both peer-reviewed and grey literature. A systematic review protocol was not employed because replicability was not a high priority in this instance. Systematic reviews are highly resource intensive and are challenging to implement effectively in contexts such as this where the necessary search strings become highly complex. Also, grey literature is often missing from the databases that are appropriate for systematic review protocols. Additionally, while the process of developing the conceptual framework had generated some idea of the most relevant ecosystem services, it was important to retain the option for additional services to be identified during the process, which was allowed for in a flexible search approach.

The information obtained from the literature review was recorded systematically in a spreadsheet. One line was used per species/habitat – ecosystem service combination (subsequently referred to as 'asset-service relationships'), to allow as much detail as possible to be retained (for example the habitat preferences of individual turtle species rather than for the group collectively) and to facilitate organisation of the information for the summary outputs. Where the reports/papers examined referred to secondary sources, this information was included within the spreadsheet. The cited references were not examined directly, under the assumption that the findings of the external literature had been reported accurately. A complete description of the individual fields used to record the extracted data is given in Table 2, and the references used are listed in Appendix 1.

The focus of the literature review was to attribute the relative level of service delivery by different species and habitats, on a 4-point categorical scale from negligible to high. Where possible, quantitative information was used to determine the category. For example, the relative abundance of a particular species in different habitats was used to indicate the level of delivery of the supporting service of habitat provision. Where quantified information was not available, a qualitative approach was used, principally extracting key descriptive words and phrases, such as 'exceptional' or 'rarely found'. The process of attributing levels of service delivery was unavoidably subjective. Even where quantified data were presented these were not collected for the purposes of calculating ecosystem service delivery, and so expert judgement was still required to define the boundaries between service level categories. A brief justification for the ecosystem service level given was included within the evidence spreadsheet.

Understanding the reliability of the evidence is important for marine resource management, and so a confidence level was given for each of the asset-service relationships identified. There is no accepted method for attributing confidence, and other studies have used the assumption that peer-reviewed evidence is the most reliable (Potts *et al.* 2014). However, in this case, high confidence was attributed to local studies, as these related directly to the TCI context. Local knowledge (such as information obtained from engagement with fishermen) was included within the high confidence category. Local studies may be of variable quality, but the majority of the research used in compiling the asset-service matrix was published in peer-reviewed journals, proceedings of academic conferences or as dissertations through recognised universities, suggesting that the standard of the work was sufficiently high. Confidence was reduced in circumstances where: (i) studies were from the wider region or global in scope; (ii) it was difficult to attribute a relative level of service delivery from the information available; (iii) the information contained within a local study was quite generic and its provenance was not clear; (iv) and/or the source literature was particularly dated. Again, the assumptions made in attributing a particular confidence level were given for each asset-service relationship.

Table 2. The extent component of the asset register for Turks and Caicos shallow marine-coastal habitats.

Field Header	Description
Line ref	A sequential line number, to facilitate referencing to the specific piece of information used in determining an ecosystem service delivery score.
Full citation	The complete citation for the evidence source.
Short ref	The lead author and date (to facilitate subsequent referencing).
Publication Year	The year of publication.
Location	Where the study took place (the name of the individual country where applicable, or, for studies from multiple locations, the name of the region or noting that it was global in scope).
Species/Habitat	The species or habitat providing the service to which the evidence refers, providing as much detail as possible but using a systematic format to facilitate sorting; for example, different reef areas would be described as Coral (fringing reef) or Coral (spur and groove), and Nassau grouper labelled as Fish (grouper, *Epinephalus striatus*).
Research type	Whether the study was a primary, empirical assessment or a review.
Service category	The main category of service to which the evidence referred (Supporting, Provisioning, Regulating, Cultural).
Service class	More detail of the type of service, based on a shorthand to represent CICES service categories, and again with detailed but systematic labels. For example, nursery areas for queen conch were described as Habitat provision (conch) – juvenile.

Field Header	Description
Quantified	The amount for any quantified information related to the level of service delivery, where this was provided.
Unit	The unit for any quantified information.
Service level	The categorical level of service delivery by the species or habitat (High, Moderate, Low, Negligible), based on expert judgement of the quantitative and qualitative information provided in the source.
Confidence	The degree of confidence that the service level has been attributed appropriately (High, Moderate, Low).
Service level justification	Notes to explain why a particular service delivery level was chosen.
Confidence level justification	Notes to explain why a particular confidence level was chosen.
Notes	Wider notes, primarily verbatim extracts of the relevant evidence from the source, including reference to secondary sources.

2.3.2 Creating the matrix

The evidence extraction process ensured that as much detail as possible was retained, so that the evidence base was comprehensive, easy to use, more likely to retain its relevance in other contexts, and provided a clear audit trail. However, in order to produce a manageable and relevant final asset-service matrix it was necessary to condense the individual items of evidence. At this stage, all species and habitats were retained, although groupers and turtles were considered collectively rather than to species level. This created a longlist of assets, after which it was necessary to aggregate all the evidence for particular asset-service relationships, which required re-assessment of the levels of service delivery and confidence.

Where there was a single source for an asset-service relationship, the service delivery and confidence levels were taken from that source. Similarly, if multiple sources agreed on the level of service delivery, this was taken as the category for the aggregation. Where sources suggested different service levels, a subjective judgement was necessary on whether to take the highest, mid-point, or majority level of service delivery from those individual assessments. The latter was preferred, although there was a maximum of four different studies feeding into any one aggregated asset-service relationship. The confidence level reflected the level of agreement between different sources (i.e. was high where different sources gave consistent levels of service delivery, but low where sources disagreed). A second spreadsheet in the evidence workbook was created to record the outcome of this aggregation process, which included recording the number of individual sources (and their line references), the degree of agreement between multiple sources, and notes on how the final service delivery and confidence levels were obtained.

The output from the aggregation process was then converted into the matrix format (with species/habitats in individual rows against columns for the individual ecosystem services). The format used followed that of Potts *et al.* (2014), using colours to represent ecosystem service delivery level, and numbers to represent the confidence score.

For this preliminary version of the matrix, the asset categories reflected the way habitats had been described within the original literature sources. In order to relate the matrix to the baseline asset map, it was necessary to match the habitat types from the literature review to The Nature Conservancy's classification used for the benthic map. No distinction could be made between dense and sparse seagrass or between dense and sparse algae, as the literature did not contain sufficient evidence to attribute relative service delivery levels. Therefore, these were combined into a single category each for seagrass and algae, onto which onto the appropriate habitat types identified in the literature review were easily mapped. The process of determining which sub-types of coral reef matched the map classes relied on expert judgement based on the descriptions provided by The Nature Conservancy (see Table 1).

At this stage, a new matrix was created for which evidence was removed for those habitats not within the benthic classification. This included the removal of salinas, wetland, mangrove, and pond habitats, and beaches as the latter were not distinguished from subtidal sand. There remains the potential to reinstate these habitat types if they can be clearly delineated within an appropriate habitat map, particularly in terms of distinguishing between freshwater and saline waterbodies and making the distinction between mangroves and terrestrial shrubs and trees found close to estuary banks. Categories described as gorgonian plain and hard substrate were also removed, as it was not clear how these could be related to the habitat classification, and shallow near shore waters were excluded as the water column was out of scope.

Similarly, evidence was not used where: (i) the service described was too generic (e.g. "habitat provision" in general rather than for a particular species or group of species); or (ii) for which there was little clear information (e.g. the role of seagrass and parrotfish in disease control); (iii) where the evidence base for a species was a single line reference (e.g. seagrass as a habitat for juvenile snapper with no relative comparator); and (iv) where it was difficult to attribute the service to a particular habitat featuring in the baseline TCI habitat map (e.g. if it related to a particular coral species rather than reef types in general). While this evidence was not carried forward into the final matrix, it was retained within the supporting evidence workbook.

Having developed this final matrix framework, a brief wider literature review was undertaken to determine whether other literature was available from the wider Caribbean and internationally that would fill any gaps, repeating the process for the TCI lit review as described in Section 2.3.1 above. Where no further evidence was found, the matrix cell was described as 'not assessed'. The opportunity exists to use the expert judgment of stakeholders within the TCI to complete additional cells within the matrix, although that is outside the scope of the current project.

The final matrix (presented in Section 3.2) provides the level of service that a generic habitat or species of a particular type has the potential to deliver. Actual service delivery may be affected by local factors such as habitat condition, current speed, water temperature and depth. Assessments with this level of detail require empirical data collection, which is beyond the scope of this work. The implications of the assumptions made, and issues encountered in compiling the matrix are discussed further in Section 4.

2.4 Mapping potential ecosystem service delivery

The process of creating maps of the potential ecosystem service delivery was relatively straightforward. Within the GIS, the attribute table from the habitat mapping (Section 2.2.2) was joined to the asset-service matrix, allowing the service delivery scores to be used to create the new map shown below (Section 3.3.2).

3 Sample outputs

In the sections that follow, the outputs from the processes described in Section 2 (Methods) are presented, which include the asset register extent table, asset-service matrices for habitats and species, the benthic habitat map, and maps of the potential level of delivery of four ecosystem services, namely carbon storage, erosion and flood protection, habitat provision for groupers, and snorkelling activities.

3.1 Asset register extent table

The first element of the asset register, the summary of the area of each major habitat, is given in Table 3, and demonstrates the dominance of sand and seagrass substrates. Total area calculation are based on data from November 2020 that was converted from a shapefile to a raster layer. As such, different approaches to raster conversion and the use of newer data layers have produced slightly different area estimated across different projects, including DPLUS108. Future updates will aim to use the same raster conversion methods so as to ensure consistency in area estimates.

Table 3. The extent component of the asset register for the Turks and Caicos shallow marine-coastal habitats.

Habitat type	Habitat extent (km^2)	Percentage of total benthic area
Sand	3216.3	43.59
Seagrass (Total)	**2735.17**	**37.06**
Seagrass Sparse	1828.52	24.78
Seagrass Dense	906.65	12.28
Coral/Algae	497.25	6.73
Hardbottom Algae (total)	**791.48**	**10.72**
Hardbottom Sparse Algae	417.31	5.65
Hardbottom Dense Algae	374.17	5.07
Spur and Groove	53.62	0.76
Reef Fore	30.41	0.41
Reef Back	22.33	0.3
Reef Crest	4.07	0.05
Muddy Bottom	26.86	0.36
Dredged	0.82	0.01

3.2 Asset-service matrix

The literature review generated 310 individual pieces of evidence from 65 sources (see Appendix 1), which were used to derive the asset-service matrix (Table 4). For habitats, the categories of ecosystem service for which evidence was obtained relate primarily to habitat provision (for both adults and juveniles of key species), as well as carbon uptake and storage, and moderation of erosion and flood risk. Information on specific cultural services was limited, and evidence was found primarily for tourism in general. The importance of particular marine animals to scuba diving experiences is highlighted in the species matrix, as well as their contribution to fisheries. The possible use of genetic material from queen conch and resilient coral species is also included. Pest control is the one regulating service to feature in the species matrix, in the context of potential lionfish predation.

Gaps remain in the matrix even for asset-service relationships that appear self-evident because cells were only completed where these could be substantiated by documented evidence that was obtained during the time available for the literature review. For example, while reefs will add to the recreational experience of scuba divers, the study included in the literature review focussed on the relative value of particular species rather than the habitat. Carbon uptake by seagrass is also included as ‘not assessed’ because the references obtained all related specifically to the storage element of sequestration. Similarly, appropriate references were not found for carbon uptake or storage by algae or for carbon storage within coral reefs. Carbon cycles are complex and depend on species and wider environmental conditions, which would require a more detailed literature review supported by improved understanding of key ecological parameters (such as algal species). Additional resource to focus on specific services deemed to be of particular importance would potentially allow such gaps to be filled, and/or the matrix could be augmented with local expert judgment.

Table 4. The asset-service matrix for Turks and Caicos shallow marine-coastal areas.

Key

Service delivery
- High
- Moderate
- Low
- Negligible
- Not assessed (no documented evidence was found during the time available for the literature review)

Confidence
- 3 High
- 2 Moderate
- 1 Low

Bold numbers with asterisks (e.g. **2***) reflect TCI studies

(a) Habitats

	SUPPORTING							REGULATING							CULTURAL	
	Carbon		*Habitat provision*							*Nursery habitat provision*						
	Carbon uptake	Carbon storage	Queen conch	Spiny lobster	Grouper	Reef fish	Turtle	Erosion/ Flood protection	Filtration/storage/ sequestration	Queen conch	Spiny lobster	Grouper	Shark	Turtle	Tourism	Snorkelling
Dense/sparse algae			3*	1	1			1		1*	2*	1*				1
Dense/sparse seagrass		1	3*	1	1	2	3*	1	1	1*	2*	2*	3*	2*		1
Sand		2	3*	1	1		3*	1		1*				3*	3*	1
Coral/Algae			1*	3*	2*	2*	3*	1		1*	1	2*		1*		1
Reef Crest	3*		2	2	2*	3*		1*				2*		1*	3*	
Reef Back			2	2	2	2		2*		3*		2*				
Reef Fore	3*		2	3*	2*	3*	3*	2*				2*		3*	3*	
Spur and Groove	3*				2*	3*		1*				2*		3*	3*	

(b) Species

	PROVISIONING			REGULATING	CULTURAL		
	Food from wild animals	Materials from wild animals	Genetic material for establishing animal populations	Pest control (lionfish)	Scuba diving	Sportfishing	Option value (genetic material)
Coral					1		1
Fish (bonefish, *Albula vulpes*)	1*					3*	
Fish (grouper, *E. striatus, M. venenosa*)	3*			1*	3*		
Fish (grouper, other)	3*			1*	1		
Fish (reef fish)	1*				3		
Queen conch (*Strombus gigas*)	2*	1*	3*				
Reef shark					3*		
Spiny Lobster (*Panulirus argus*)	2*				3*		
Turtle	2*	2*			3*		

3.3 Mapping outputs

3.3.1 Benthic habitat map

The TCI support a broad range of benthic habitats in the shallow marine-coastal areas (Figure 4). The extents of these habitats are shown in Table 3. Using both the extent information and spatial distribution visible in the maps, it is clear that sand and seagrass habitats, both dense and sparse, dominate the shallow marine-coastal areas of the islands. Just outside of these areas of seagrass and sand, moving further offshore, are areas of hardbottom reef. These reef fringes are different across the islands, being narrower across the western and northern edges and wider, with more extensive spatial coverage across the north-eastern, eastern, and south-eastern areas of the islands. The reef fringes are made up of different communities broadly dividing into two groups: coral dominated habitats, including Coral/algae, reef fore, crest and back, and algae-dominated habitats, including hardbottom sparse and dense algae. The narrower reef fringes, in the western and northern areas, seem to support more of the coral dominated habitats, while the broader reef fringes, across the north-eastern, eastern and south-eastern areas, seem to support both the algae-dominated habitats (to landward) and the coral-dominated habitats (to seaward). Where the coral-dominated habitats in these broader areas drop off into deeper areas there are distinct spur and groove systems along the eastern edges of shallow marine-coastal areas. Figure 4 also includes the current and proposed protected areas, obtained by using the shapefiles available from the Department of Environment and Coastal Resources Turks and Caicos Data Portal.

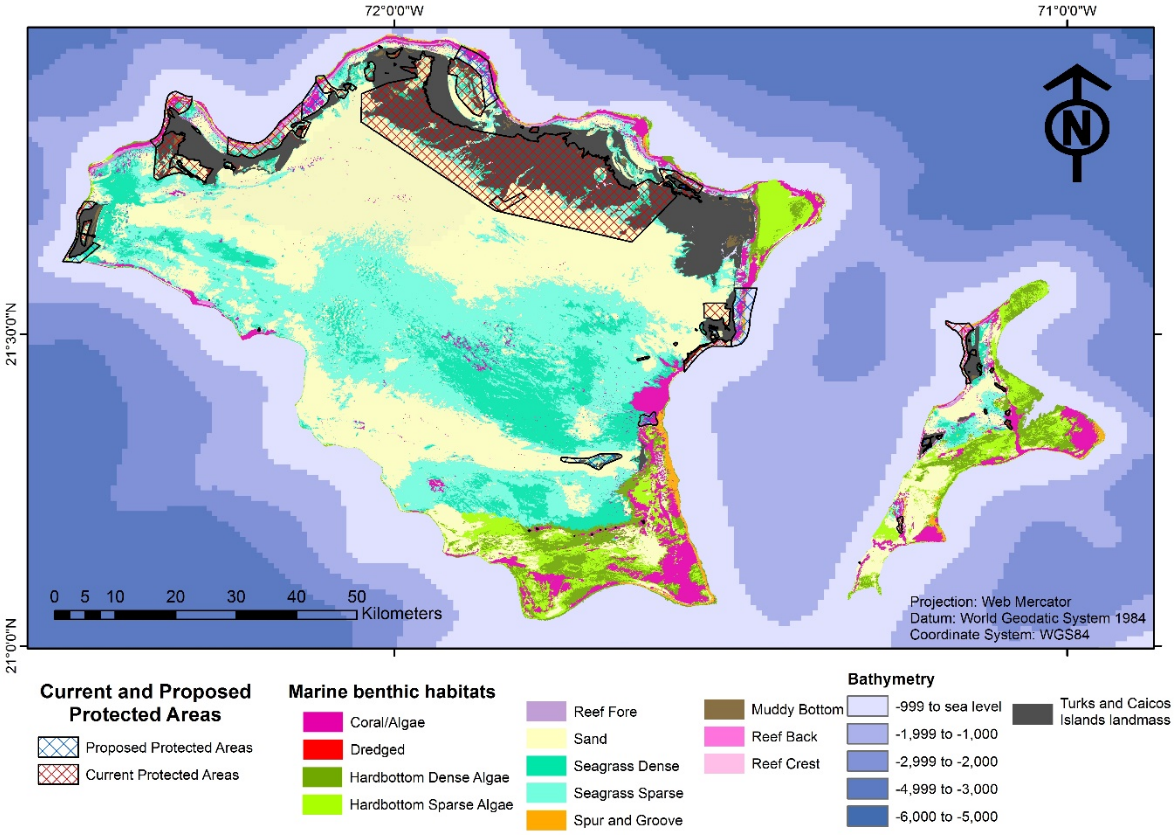

Figure 4. Benthic habitat map of the shallow marine-coastal habitats of the Turks and Caicos Islands and the sites of key marine protected areas. Bathymetry data from GEBCO2014.

3.3.2 Potential ecosystem service delivery maps

By linking the spatial data from the benthic habitat map (Figure 4) with the asset-service matrix (Table 4) it is possible to visualise areas where ecosystem services may be delivered by the shallow marine-coastal areas of the TCI. It is important to note that this provides an assessment of the possibility for ecosystem service delivery. It does not reflect what is actually being delivered because it does not account for factors such as the condition of the habitat asset. For example, at locations where habitat assets are in poor condition the delivery of ecosystem services from those assets is potentially below that which would be expected from the matrix. Therefore, the ecosystem service delivery maps shown here indicate the potential for the underlying habitat assets to deliver those services to the economy of the TCI.

The first map for potential ecosystem service delivery shows areas where marine carbon storage, i.e. ‘blue carbon’, is likely to be highest over the shallow marine-coastal areas of the TCI (Figure 5). The habitat assets delivering carbon storage here are all seagrass beds, dense and sparse (score of 3 indicates medium storage), and sand areas (score of 2 indicates low storage). The carbon storage potential of mangroves and all reef habitats, both coral-dominated and algae-dominated, was not assessed for this study due to insufficient available literature on the subject. This presents a data gap for future studies to explore.

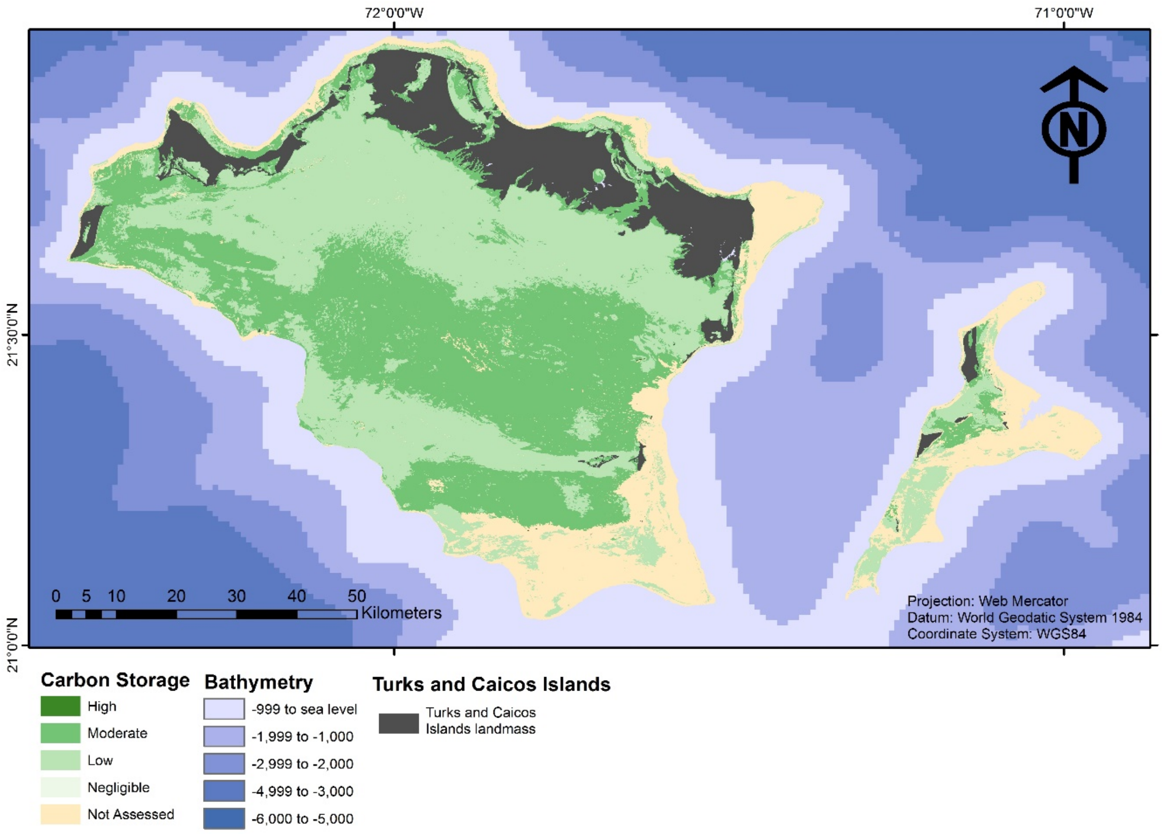

Figure 5. Relative carbon storage potential of shallow marine-coastal habitats of the Turks and Caicos Islands. Bathymetry data from GEBCO2014.

The second map for potential ecosystem service delivery shows areas where the relative erosion and flood protection is likely to be highest over the shallow marine-coastal areas of the TCI (Figure 6). The habitat assets delivering the highest levels of erosion and flood protection are all the seagrass beds, dense and sparse, and fore reef and reef crest habitats (score of 4 indicates high erosion and flood protection). All other habitat assets deliver low or negligible levels of erosion and flood protection.

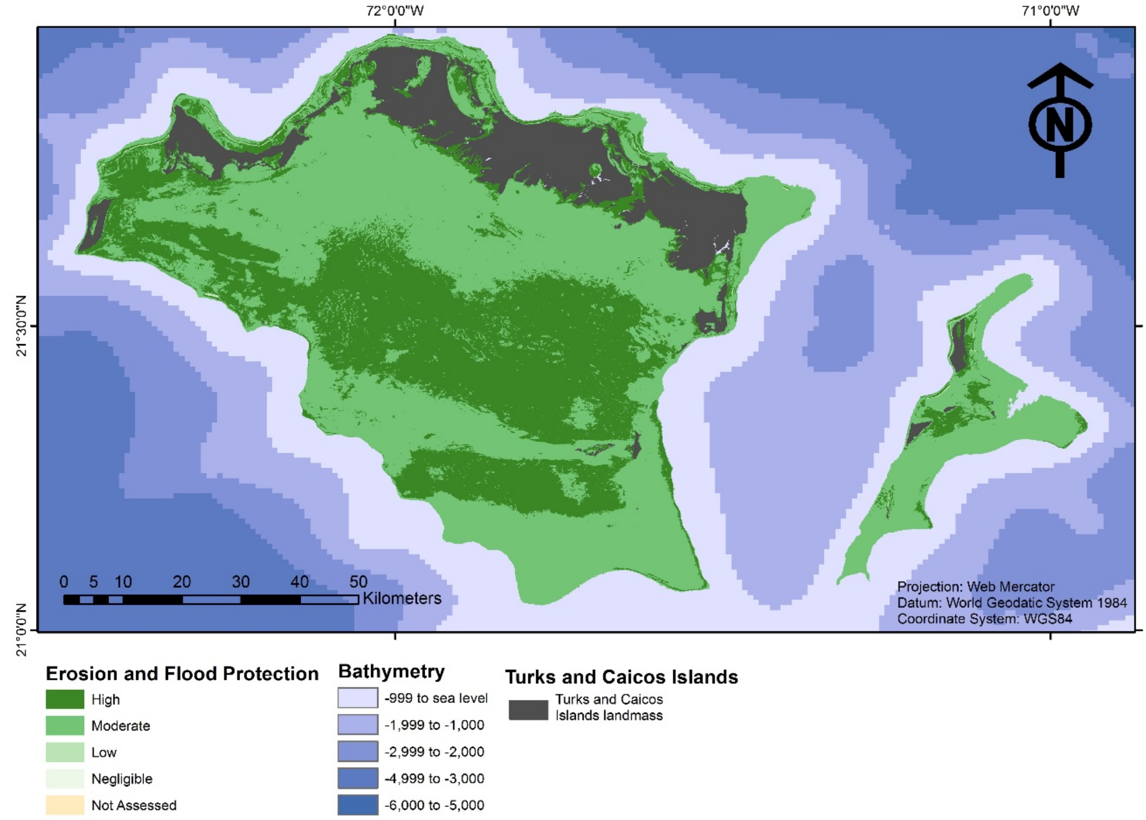

Figure 6. Relative erosion and flood protection potential of shallow marine-coastal habitats of the Turks and Caicos Islands. Bathymetry data from GEBCO2014.

The third set of maps for potential ecosystem service delivery shows areas where the habitat provision of grouper fish is likely to be highest over the shallow marine-coastal areas of the TCI (Figure 7). The maps have been divided to show the habitat provision for both the juvenile in one map and adult groupers in the other map. Not only do the maps show areas where habitat provision is highest for groupers but also that this differs depending on the life stage of the grouper. For the juvenile fish, the habitat assets delivering the highest levels of habitat provision are all the seagrass beds, dense and sparse, and fore reef and spur and groove habitats (scores of 4 indicates high habitat provision). For adult fish, however, the highest levels occur in the algae-dominated reef areas, dense and sparse, as well as in the fore reef and spur and groove habitats (scores of 4), with a shift away from the seagrass beds where there is only low delivery of habitat provisioning for adult groupers (score of 2). These differences are clear to see in the ecosystem service delivery map (Figure 7) and highlight the importance of the life stage of target fish species when considering where the habitat provision services are most beneficial for locating those fish.

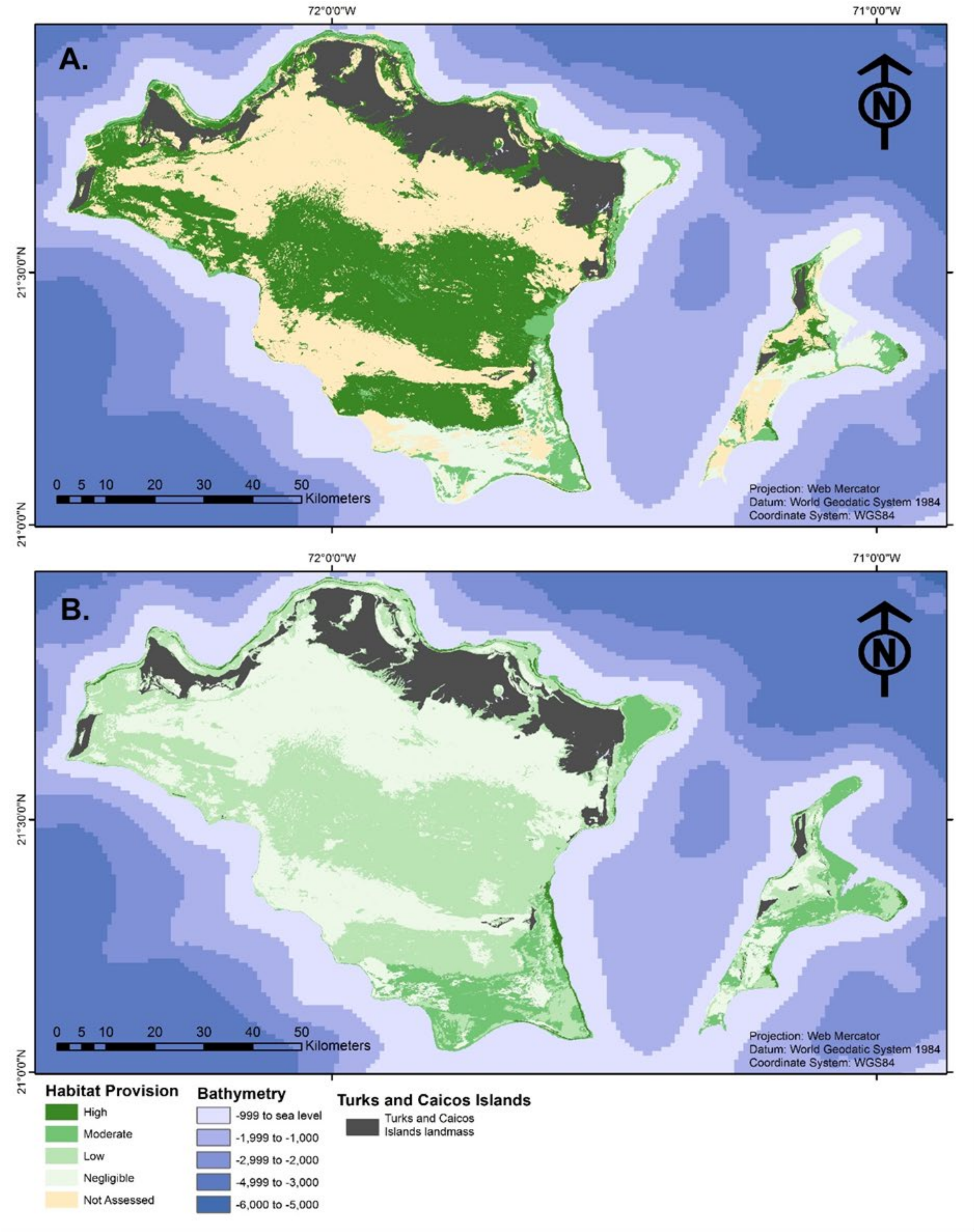

Figure 7. Relative habitat provision potential of shallow marine-coastal marine habitats of the Turks and Caicos Islands for juvenile grouper fish (A) and adult grouper fish (B). Bathymetry data from GEBCO2014.

The final example map shows areas where the potential ecosystem service delivery is likely to be highest for snorkelling activities over the shallow marine-coastal areas of the TCI (Figure 7). Snorkelling can provide a cultural service that may be used under the banner of tourism. The habitat assets delivering the highest levels of snorkelling are coral/algae areas and sand habitats (scores of 4 indicates high snorkelling potential). Lower levels of service are provided by seagrass beds, dense and sparse, and algae-dominated reef habitats, dense and sparse (scores of 2 indicate low snorkelling potential). The snorkelling potential of all reef structures, including fore, crest and back reefs, as well as spur and groove systems, was not assessed for this study due to insufficient available literature on the subject. This presents another data gap for future studies to explore.

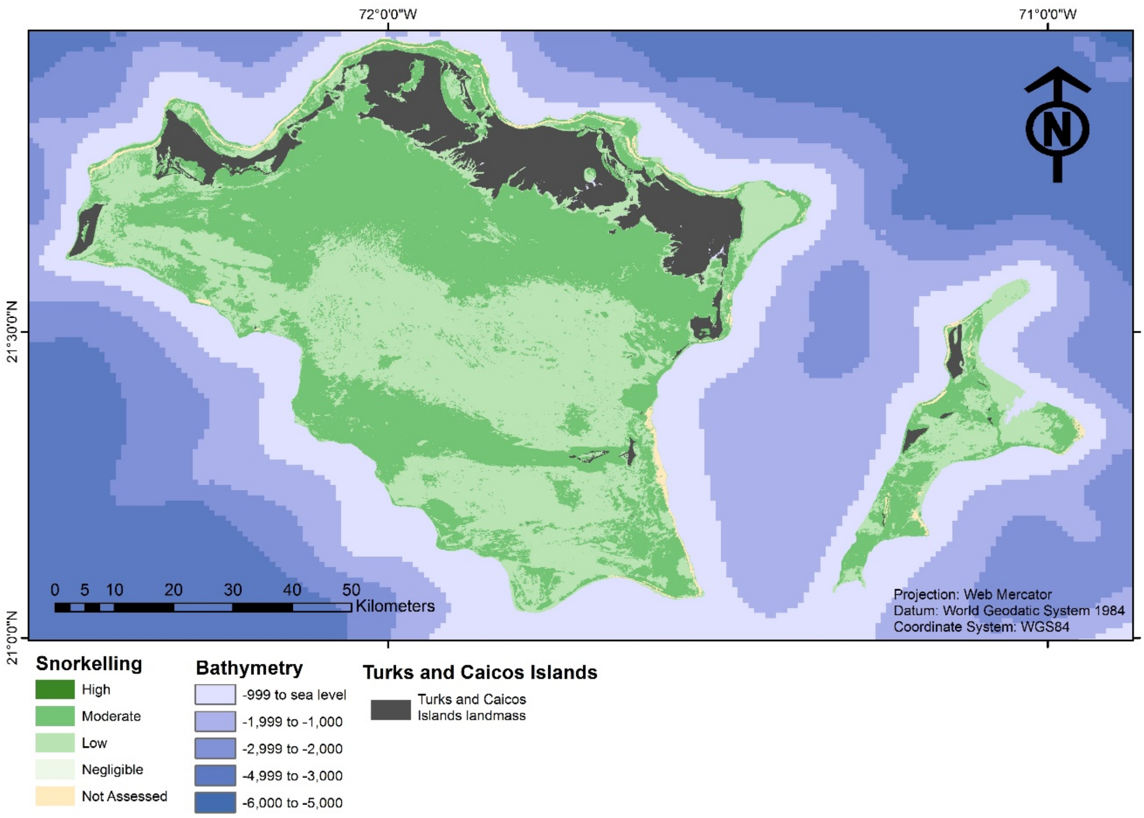

Figure 8. Relative snorkelling activity potential of shallow marine-coastal marine habitats of the Turks and Caicos Islands. Bathymetry data from GEBCO2014.

4 Discussion

Linking ecosystem service delivery to generic habitat classes provides a useful approach to developing natural capital asset registers for several reasons. Initially it enables us to make use of existing marine evidence on habitats, such as habitat maps and more detailed survey data, to begin to understand the ecosystem service delivery of those habitats and species that inhabit them. This in turn enables us to consider the existing management policies, including conservation, fishing, development strategies, already associated with those habitats alongside our understanding of the delivery of ecosystem services from those habitats. This can act as a powerful addition to aid decision making for most management plans as well as a better consideration of the value of the ecosystem services that benthic habitats can provide.

It is also useful to use spatial data from habitat maps to visualise where natural capital assets occur and the relative levels of provision of ecosystem services they can deliver. By making associations between ecosystem service delivery and generic habitat classes, a new powerful method is created to communicate the most relevant information to decision makers and stakeholders in a readily assessable form. This form is widely communicable and may be easily interpreted by stakeholders with varying levels of experience interpreting digital data. The evidence base is not complete, and there remains the potential to increase the detail of, and confidence in, the relationships between assets and services through additional literature review and/or using local expert judgment. Furthermore, by updating the underlying evidence products as new evidence emerges, i.e. when maps, survey data and asset service matrices are generated, the approach can be kept up-to-date and flexible to meet future changes to the evidence base and demands of policy.

The results of this study demonstrate the importance of benthic habitats from the perspective of providing high levels of ecosystem services rather than just the composition of their biological assemblages or geomorphological structure. For example, consider the seagrass beds which occupy 37% of the shallow marine-coastal areas of the TCI (when sparse and dense seagrass areas are combined). After only the sand habitat, the seagrass beds occupy the largest area of seabed of the shallow marine-coastal areas of the Turks and Caicos Islands. The ecosystem service provision maps showed that the seagrass beds have potential for carbon storage (medium service provision), erosion and flood protection (high service provision) and habitat provision for juvenile grouper fish (high service provision). This information improves our understanding of the importance of the seagrass habitat from different perspectives and can add value to any decision-making process involving this seabed asset.

There are, however, some issues with this current approach of linking ecosystem service delivery to generic habitat classes that deserve consideration. For example, it has not been possible to provide a complete matrix that includes the level of delivery of all ecosystem services by all assets, as the evidence base is incomplete. Certain ecosystem services were omitted from the matrix as the evidence was unclear even though they are likely to be of interest in the TCI management context. Disease control is a regulating service that considers how particular species, habitats or environmental processes can restrict the transmission of disease. This is very important in context of coral disease (as well as more widely in terms of diseases affecting, for example, fish species and seagrass). However, the natural mechanisms of controlling coral disease are not well understood. Research that suggests some coral colonies may be more resistant (Wright *et al.* 2017) and indicate an important role of parrotfish predation in the overall composition of microbial communities on coral reefs (Ezzat *et al.* 2020). Without clearer evidence on the role of natural factors in disease control, this service could not be included in the matrix.

Other services were included within the matrix, but with low levels of confidence due to conflicting evidence. Pest control in the context of controlling non-native lionfish is one example. Large groupers are known to eat lionfish (Maljkovic *et al.* 2008), but studies including those from the Bahamas (Anton *et al.* 2014) suggest that the presence of native predators does not affect lionfish abundance, and hence they do not provide significant levels of pest control. Instead, research indicates that environmental factors not related to habitat and potentially not under management control (particularly wave exposure) have a large influence on lionfish density (Anton *et al.* 2014; Valdivia *et al.* 2014). However, the limitations on lionfish predation by species such as grouper may be a factor of their overexploitation, as studies from sites with particularly high grouper abundance do provide some evidence of reduced lionfish presence (Mumby *et al.* 2011). Thus, this issue is a relevant consideration as part of future resource management.

Similarly, the potential future use of genetic resources is included in the matrix. Corals that show resilience to threats from environmental change will be of significant regional conservation interest (Sealey *et al.* 2019) and hence there is the potential for corals in the TCI (which have shown such resilience) to supply genetic material more widely (Kelley *et al.* 2020). However, it is again difficult to attribute the level of supply of this service with any confidence using the existing evidence base.

There are also some limitations to the approach more generally, particularly that using broad benthic classes requires the assumption of homogeneity within individual habitat types.

Research within the TCI suggests that this assumption may hold true for hard coral community structures, but less so for benthic composition (Dikou *et al.* 2009), and there are significant variations in the proportion of live coral cover (Goreau *et al.* 2008). Also, the importance of, and impacts on, individual species are masked when using broad habitat classes. For example, staghorn (*Acropora palmata*) and elkhorn (*A. cervicornis*) coral species have a key role in reducing wave energy, as a reef fish habitat, and in adding value to snorkelling excursions, and are in decline both locally and regionally (Goreau *et al.* 2008; Schelten *et al.* 2004; Logan & Sealey 2013), but these species cannot be extracted from the wider reef habitat types.

Conversely, in some instances the habitat data is at a higher resolution than the understanding of ecosystem service delivery. The TCI benthic maps distinguish between sparse and dense coverage of both seagrass and algae, but evidence of how density affects service delivery is lacking. The need to understand the variability of ecosystem services within and between seagrass meadows has been highlighted elsewhere (Nordlund *et al.* 2018).

The populations of mobile species such as fish vary between sites around the TCI (Hoshino *et al.* 2003). Habitat for fishery species relies on ecological processes and factors such as depth and current flow as well as habitat type (Stoner 2003) and can be context dependent. The habitat preference of juvenile lobsters, for example, depends on what is available (Acosta & Butler 1997). Also, ecosystem services for population regulation and maintenance, such as spawning aggregations (Rudd 2003) and shark nursery areas (Henderson *et al.* 2010), may only be supplied at very specific sites rather than by the habitat in general. Species occurrence in specific habitats may also be related to factors other than habitat suitability. For example, that larger groupers are observed on deeper reefs may be due to fishing restrictions that prevent spear fishing using scuba, and hence limit exploitation to shallower depths (Tupper 2002), rather than being a factor of depth *per se*. Queen conch abundance has also been shown to vary in different algal plain sites depending on whether these are protected or exploited (Tewfik & Bene 2000). This context dependency also arises in terms of direct uses by people. Sand flats, in general, may be popular areas for snorkelling, but their importance is likely to decline with reduced accessibility, so delivery of this ecosystem service is likely to be less in the centre of the bank compared to areas closer to shore.

These issues do not negate the usefulness of the overarching approach or the initial outputs for broad-scale benthic categories, which already highlight the habitats and services of most importance, and hence where future effort (in both management and research) should focus. Improving the outputs requires additional, local-scale data from which the role of spatial configuration in ecosystem service delivery can be better understood. Improved understanding of spatial configuration will allow additional rules, and hence GIS layers, to be developed that can refine existing ecosystem service delivery maps. This should include recognition of synergistic effects. It is already known that seagrass beds store more carbon when in proximity to coral reefs (Guerra-Vargas *et al.* 2020), and biomass of adult reef fish is higher in systems with mangroves (Mumby *et al.* 2004), but this is not yet captured in the broad-scale approach. Additional local data will improve confidence overall. At present, the evidence for asset-service relationships is obtained from research generally carried out for other purposes and may come from only a single site because that is all that was necessary for the original aim of the research.

5 Conclusions and next steps

Marine natural capital assets were characterised in the TCI using existing marine evidence and this enabled the development of an asset register, Asset-service matrix and ecosystem service delivery maps of the TCI. This achieved all three of the aims of this study (see Project aims, objectives and tasks). Outputs showed the range of benthic habitats in the shallow marine-coastal areas of the TCI and the ecosystem services they have the potential to deliver. Presenting a selection of four of these services showcased a spatial approach to presenting this information, which may have benefits to decision-makers and stakeholders working in policy, management and development areas. These approaches can also provide a baseline for further investigation of stocks and flows of natural capital in the TCI, including an assessment of condition and the development of indicators and natural capital monitoring strategies for the future.

To increase confidence and utility of the approaches in this study, further development is recommended in a few key areas:

1. This work used the best available evidence to generate the baseline habitat map, but this was derived from remote sensing techniques developed for the wider region. Local ground-truthing would increase confidence that the baseline habitats were accurately represented.
2. There is the potential to increase the evidence base to improve understanding of the provision of ecosystem services from benthic habitats, including:
    - Regulating service of disease control;
    - Regulating service of pest control;
    - Provision of genetic resources;
    - Carbon uptake and storage of reef habitats, both coral-dominated and algae-dominated habitats;
    - Filtration, sequestration and storage functions of all habitats except seagrass beds in the TCI;
    - Tourism related activities for reef and seagrass beds, including the snorkelling potential of all reef structures, including fore, crest and back reefs, as well as spur and groove systems.
3. Additional understanding of the effect of the relative density of seagrass beds and algae in reef habitats, both of which were recorded as ‘sparse’ and ‘dense’ in the benthic habitat map, on the provision of ecosystem services could be useful in determining the levels of provision.
4. An increased understanding of local effects on ecosystem service provision to include habitat-to-habitat effects when adjacent to each other, providing refined information of potential synergies, additive and negative effects.
5. Refinement of ecosystem service provision to reflect the sources of the services, e.g. biological taxa and where they are distributed across the seafloor, rather than habitat-wide assumptions of service provision.
6. Finally, a better understanding of context-dependence of natural assets would be beneficial in highlighting where there are actual benefits from ecosystem services provided by assets rather than simply the inference that services can be provided in an area even though there is no uptake of that service.

References

Acosta, C.A. & Butler IV, M.J. 1997. Role of mangrove habitat as a nursery for juvenile spiny lobster, *Panulirus argus*, in Belize. *Marine and freshwater research*, **48(8)**, 721-728.

Anton, A., Simpson, M.S. & Vu, I. 2014. Environmental and biotic correlates to lionfish invasion success in Bahamian coral reefs. *PloS one*, **9(9)**, e106229.

Ashley, M., Rees, S., Mullier, T., Reed, B., Cartwright, A., Holmes, L. & Sheehan, E. 2020. Isles of Scilly Natural Capital Asset and Risk Register to Inform Management of Isles of Scilly Fisheries Resources. A report by research staff the Marine Institute at the University of Plymouth. Retrieved from https://secure.toolkitfiles.co.uk/clients/19937/sitedata/pdfs/SCILL-E-Report-2020.pdf

Dikou, A., Ackerman, C., Banks, C., Dempsey, A., Fox, M., Gins, M., ... & Thomas, L. 2009. Ecological assessment to detect imminent change in coral reefs of Admiral Cockburn Land and Sea National Park, Turks, and Caicos Islands. *Marine Ecology*, **30(4)**, 425-436.

Eftec & JNCC. 2018. *Turks and Caicos Islands Natural Capital Accounting- Initial Review.* November 2018. Retrieved from https://data.jncc.gov.uk/data/0766c05e-0cfb-4510-81cd-b768701bce32/ot-nca-sup-cbn-19-tci-nca-Nov2018.pdf

Eftec & JNCC. 2019. *Annex – TCI 2018 NCA An update to the initial Natural Capital Accounts for TCI*. May 2019. Retrieved from https://data.jncc.gov.uk/data/0766c05e-0cfb-4510-81cd-b768701bce32/ot-nca-sup-cbn-21-TCI-nca-jun-2019.pdf

Ezzat, L., Lamy, T., Maher, R. L., Munsterman, K.S., Landfield, K.M., Schmeltzer, E.R., ... & Burkepile, D.E. 2020. Parrotfish predation drives distinct microbial communities in reef-building corals. *Animal Microbiome*, **2(1)**, 5.

Goreau, T.J., Fisher, T., Perez, F., Lockhart, K., Hibbert, M. & Lewin, A. 2008. Turks and Caicos Islands 2006 coral reef assessment: Large-scale environmental and ecological interactions and their management implications. *Revista de Biología Tropical*, **56(1),** 25-49.

Guerra-Vargas, L.A., Gillis, L.G. & Mancera-Pineda, J.E. 2020. Stronger Together: Do Coral Reefs Enhance Seagrass Meadows "Blue Carbon" Potential?. *Frontiers in Marine Science*, **7(628)**, 1-15.

Henderson, A.C., McClellan, K. & Calosso, M. 2010. Preliminary assessment of a possible lemon shark nursery in the Turks and Caicos Islands, British West Indies. *Caribbean Journal of Science*, **46(1)**, 29-38.

Hooper, T. & Austen, M. 2020. *Application of the natural capital approach to Sustainability Appraisal*. *Final Report*. October 2020. Report prepared as part of the South West Partnership for the Environment and Economic Prosperity (SWEEP) and the Marine Pioneer programme. Retrieved from https://www.northdevonbiosphere.org.uk/uploads/1/5/4/4/15448192/sustainability_appraisal_final_report.pdf

Hooper, T., Ashley, M., Börger, T., Langmead, O., Marcone, O., Rees, S., Rendon, O., Beaumont, N., Attrill, M. & Austen, M. 2019. *Application of the natural capital approach to the marine environment to aid decision-making. Phase 1 Final Report.* Report prepared for the Department for Environment Food and Rural Affairs (project code ME5115). Retrieved from http://randd.defra.gov.uk/Document.aspx?Document=14440_FinalreportPhase1.pdf

Hoshino, K., Brandt, M., Manfrino, C., Riegl, B. & Steiner, S.C. 2003. Assessment of the coral reefs of the Turks and Caicos Islands (Part 2: Fish communities). *Atoll Research Bulletin*, **496(26)**, 480-499.

Kelley, E.R., Sleith, R.S., Matz, M.V. & Wright, R.M. 2020. Gene expression associated with disease resistance and long-term growth in a reef-building coral. *bioRxiv*, 1-22, https://doi.org/10.1101/2020.08.12.248286

Logan, A. & Sealey, K.S. 2013. The Reefs of the Turks and Caicos Islands. In C Shepherd (Ed.), *Coral Reefs of the United Kingdom's Overseas Territories* (volume 4., pp. 97-114). Dordrecht: Springer, https://doi.org/10.1007/978-94-007-5965-7_9

Loss, S. C. T. 2020. *Wider Caribbean Working Group (WCWG) eBulletin*. Retrieved from https://www.ukotcf.org.uk/wp-content/uploads/2020/10/WCWG-eBulletin-SCTLD-28.pdf

Maljkovic, A., Van Leeuwen, T.E. & Cove, S.N. 2008. Predation on the invasive red lionfish, Pterois volitans (Pisces: Scorpaenidae), by native groupers in the Bahamas. *Coral Reefs*, **27(3)**, 501, retrieved from https://www.researchgate.net/profile/Aleksandra-Maljkovic/publication/230554941_Predation_on_the_invasive_red_lionfish_Pterois_volitans_Pisces_Scorpaenidae_by_native_groupers_in_the_Bahamas/links/0fcfd50153895348cd000000/Predation-on-the-invasive-red-lionfish-Pterois-volitans-Pisces-Scorpaenidae-by-native-groupers-in-the-Bahamas.pdf

Mumby, P.J., Harborne, A.R. & Brumbaugh, D.R. 2011. Grouper as a natural biocontrol of invasive lionfish. *PloS one*, **6(6)**, e21510.

Mumby, P.J., Edwards, A.J., Arias-González, J.E., Lindeman, K.C., Blackwell, P.G., Gall, A., ... & Llewellyn, G. 2004. Mangroves enhance the biomass of coral reef fish communities in the Caribbean. *Nature*, **427(6974)**, 533-536.

Natural Capital Committee. 2017. *How to do it: a natural capital workbook*. 30pp. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/957503/ncc-natural-capital-workbook.pdf

Nordlund, L.M., Jackson, E.L., Nakaoka, M., Samper-Villarreal, J., Beca-Carretero, P. & Creed, J.C. 2018. Seagrass ecosystem services–What's next? *Marine pollution bulletin*, **134**, 145-151.

North Devon Biosphere Reserve. 2020. *North Devon Marine Natural Capital Plan. Final Report*. June 2020. Retrieved from https://www.northdevonbiosphere.org.uk/uploads/1/5/4/4/15448192/north_devon_marine_plan_final_version_approval__1_.pdf

Potts, T., Burdon, D., Jackson, E., Atkins, J., Saunders, J., Hastings, E. & Langmead, O. (2014). Do marine protected areas deliver flows of ecosystem services to support human welfare? *Marine Policy*, **44**, 139-148.

Rudd, M.A. 2003. *Institutional analysis of marine reserves and fisheries governance policy experiments: a case study of Nassau grouper conservation in the Turks and Caicos Islands*. The Netherlands: Wageningen Universiteit.

Schelten, C.K., Brown, S., Gurbisz, C.B., Kautz, B. & Lentz, J. A. (5th Gulf and Caribbean Fisheries Institute). 2004. *Status of* Acropora palmata *populations off the coast of South*

Caicos, Turks, and Caicos Islands. Retrieved from https://oceanrep.geomar.de/48877/1/gcfi_57-46.pdf

Schill, S. R., Pollock, F. J., Lüthje, F., Li, J., Knapp, D., Kington, J., McDonald, T., McNulty, V. P., Escovar-Fadul, X. & Asner, G. 2020. Caribbean shallow benthic habitat maps from Dove satellite imagery for conservation and marine planning. https://dataportal.gov.tc/dataset/benthic-habitat-map-tci

Schill, S.R., McNulty, V.P. Pollock, F.J., Fritjof, L., Jiwei L., Knapp, D., Kington, J., McDonald, T., Raber, G.T., Escovar-Fadul, X. & Asner, G. In review. Regional-scale high-resolution benthic habitat data from PlanetScope imagery for conservation decision-making and marine planning, Remote Sensing. http://dataportal.gov.tc/reports/The-Nature-Conservancy-Benthic-Habitat-Map-classes.pdf

Sealey, K.S., Wood, K. & Logan, A. 2019. The Turks and Caicos Islands. In C Shepherd (Ed.), *World Seas: An Environmental Evaluation* (2nd Edition, 617-635). Academic Press
Stoner, A. W. 2003. What constitutes essential nursery habitat for a marine species? A case study of habitat form and function for queen conch. *Marine Ecology Progress Series*, **257**, 275-289.

Sussex IFCA. 2020. *Sussex IFCA District Nearshore Trawling Byelaw 2019 Impact Assessment (IA No: SXIFCA007).* Retrieved from https://secure.toolkitfiles.co.uk/clients/34087/sitedata/files/consultations/Nearshore-TrawlingByelaw-IA.pdf

Stoner, A.W. 2003. What constitutes essential nursery habitat for a marine species? A case study of habitat form and function for queen conch. Marine Ecology Progress Series, 257, pp.275-289

Tewfik, A. & Béné, C. (Proceedings of the 51st Gulf and Caribbean Fisheries Institute). 2000. *Densities and age structure of fished versus protected populations of queen conch (*Strombus gigas L.*) in the Turks and Caicos Islands*. **51(3)**, 60-79. Retrieved from http://aquaticcommons.org/13340/1/gcfi_51-3.pdf

Tupper, M. (Proceedings of the 53rd Gulf and Caribbean Fisheries Institute). 2002. Essential fish habitat and marine reserves for groupers in the Turks and Caicos Islands. 606-622, retrieved from http://aquaticcommons.org/13534/1/gcfi_53-51.pdf

Valdivia, A., Bruno, J.F., Cox, C.E., Hackerott, S. & Green, S.J. 2014. Re-examining the relationship between invasive lionfish and native grouper in the Caribbean. *PeerJ*, **2**, e348.

Verutes, G.M., Arkema, K.K., Clarke-Samuels, C., Wood, S.A., Rosenthal, A., Rosado, S., Canto, M., Bood, N. & Ruckelshaus, M. 2017. Integrated planning that safeguards ecosystems and balances multiple objectives in coastal Belize. *International Journal of Biodiversity Science, Ecosystem Services & Management*, **13(3)**, 1-17.

Wood, K.M. 2016. A Multi-Criteria Evaluation Model for Rapid Assessment and GIS Mapping of Ecological Values for Informed Land Use in Small-Island Developing States. (PhD thesis). Harvard University.

Wright, R.M., Kenkel, C.D., Dunn, C.E., Shilling, E.N., Bay, L.K. & Matz, M.V. 2017. Intraspecific Differences in Molecular Stress Responses and Coral Pathobiome Contribute to Mortality under Bacterial Challenge in Acropora Millepora. *Scientific Reports,* **7(2609),** 1-13, retrieved from https://www.nature.com/articles/s41598-017-02685-1.pdf

Appendix 1 – Literature reviewed for the asset-service matrix

Acosta, C.A. & Butler IV, M.J. 1997. Role of mangrove habitat as a nursery for juvenile spiny lobster, *Panulirus argus*, in Belize. *Marine and freshwater research*, **48(8)**, 721-728.

Anton, A., Simpson, M.S. & Vu, I. 2014. Environmental and biotic correlates to lionfish invasion success in Bahamian coral reefs. *PloS one*, **9(9)**, e106229.

Baker, S., Paddock, J., Smith, A.M., Unsworth, R.K., Cullen-Unsworth, L.C. & Hertler, H. 2015. An ecosystems perspective for food security in the Caribbean: seagrass meadows in the Turks and Caicos Islands. *Ecosystem Services*, **11**, 12-21.

Bates, N.R. 2002. Seasonal variability of the effect of coral reefs on seawater CO2 and air—sea CO2 exchange. *Limnology and Oceanography*, **47(1)**, 43-52.

Bates, N.R., Samuels, L. & Merlivat, L. 2001. Biogeochemical and physical factors influencing seawater ƒCO2 and air-sea CO2 exchange on the Bermuda coral reef. *Limnology and Oceanography*, **46(4)**, 833-846.

Bechhofer, J. & Henderson, A.C. 2018. Transient nocturnal site fidelity in juvenile green (*Chelonia mydas*) and hawksbill (*Eretmochelys imbricata*) sea turtles on the shallow nearshore coral reefs of South Caicos, Turks and Caicos Islands. *Tropical Zoology*, **31(1)**, 44-54.

Bos, A. R., Clark, S. & Gore, S. (54th Gulf and Caribbean Fisheries Institute). 2003. Preliminary observations on habitat use of juvenile Caribbean spiny lobster (*Panulirus argus*) in South Caicos, Turks & Caicos Islands, 230-240. Retrieved from http://aquaticcommons.org/13558/1/gcfi_54-17.pdf

Chambault, P., Dalleau, M., Nicet, J.B., Mouquet, P., Ballorain, K., Jean, C., ... & Bourjea, J. 2020. Contrasted habitats and individual plasticity drive the fine scale movements of juvenile green turtles in coastal ecosystems. *Movement ecology*, **8(1)**, 1-15.

Claydon, J.A.B. & Kroetz, A.M. 2008. The distribution of early juvenile groupers around South Caicos, Turks and Caicos Islands. *Proceedings of the Gulf and Caribbean Fisheries Institute*, **60**, 345-350.

Clerveaux, W & Danylchuk, A. (54th Gulf and Caribbean Fisheries Institute). 2003. Visual assessment of queen conch (*Strombus gigas*) stocks in the Turks and Caicos Islands: cross-checking yield estimates. 260-269. Retrieved from http://aquaticcommons.org/13560/1/gcfi_54-19.pdf

Danylchuck, A., Rudd, M.A., Giles, I. & Baldwin, K. (54th Gulf and Caribbean Fisheries Institute). 2003. Size-Dependent Habitat Use of Juvenile Queen Conch (*Strombus gigas*) in East Harbour Lobster and Conch Reserve. Turks and Caicos Islands, BWI. 240-249. Retrieved from https://core.ac.uk/download/pdf/19540619.pdf

Dikou, A., Ackerman, C., Banks, C., Dempsey, A., Fox, M., Gins, M., ... & Thomas, L. 2009. Ecological assessment to detect imminent change in coral reefs of Admiral Cockburn Land and Sea National Park, Turks and Caicos Islands. *Marine Ecology*, **30(4)**, 425-436.

Doherty, P.D., Broderick, A.C., Godley, B.J., Hart, K.A., Phillips, Q., Sanghera, A., ... & Richardson, P.B. 2020. Spatial Ecology of Sub-Adult Green Turtles in Coastal Waters of the

Turks and Caicos Islands: Implications for Conservation Management. *Frontiers in Marine Science*, **7**, 690.

Ezzat, L., Lamy, T., Maher, R.L., Munsterman, K.S., Landfield, K.M., Schmeltzer, E.R., ... & Burkepile, D.E. 2020. Parrotfish predation drives distinct microbial communities in reef-building corals. *Animal Microbiome*, **2(1)**, 5.

Ferrario, F., Beck, M.W., Storlazzi, C.D., Micheli, F., Shepard, C.C. & Airoldi, L. 2014. The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nature communications*, **5(1)**, 1-9.

Fourqurean, J.W., Duarte, C.M., Kennedy, H., Marbà, N., Holmer, M., Mateo, M.A., ... & Serrano, O. 2012. Seagrass ecosystems as a globally significant carbon stock. *Nature geoscience*, **5(7)**, 505-509.

Gatewood, J.B. & Cameron, C.M. 2009. *Belonger perceptions of tourism and its impacts in the Turks and Caicos Islands.* Germany: Lehigh University.

Gedan, K.B., Kirwan, M.L., Wolanski, E., Barbier, E.B. & Silliman, B.R. 2011. The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. *Climatic change*, **106(1)**, 7-29.

Giglio, V.J., Luiz, O.J. & Schiavetti, A. 2015. Marine life preferences and perceptions among recreational divers in Brazilian coral reefs. *Tourism Management*, **51**, 49-57.

Goreau, T.J., Fisher, T., Perez, F., Lockhart, K., Hibbert, M. & Lewin, A. 2008. Turks and Caicos Islands 2006 coral reef assessment: Large-scale environmental and ecological interactions and their management implications. *Revista de Biología Tropical* **56(1)**, 25-49.

Graham, N.A.J. & Nash, K.L. 2013. The importance of structural complexity in coral reef ecosystems. *Coral reefs*, **32(2)**, 315-326.

Guerra-Vargas, L.A., Gillis, L.G. & Mancera-Pineda, J.E. 2020. Stronger Together: Do Coral Reefs Enhance Seagrass Meadows "Blue Carbon" Potential? *Frontiers in Marine Science*, **7(628),** 1-15.

Gullström, M., Lyimo, L.D., Dahl, M., Samuelsson, G.S., Eggertsen, M., Anderberg, E., ... & Björk, M. 2018. Blue carbon storage in tropical seagrass meadows relates to carbonate stock dynamics, plant–sediment processes, and landscape context: insights from the western Indian Ocean. *Ecosystems*, **21(3)**, 551-566.

Harborne, A.R., Mumby, P.J., Micheli, F., Perry, C.T., Dahlgren, C.P., Holmes, K.E. & Brumbaugh, D.R. 2006. The functional value of Caribbean coral reef, seagrass and mangrove habitats to ecosystem processes. *Advances in marine biology*, **50**, 57-189.

Henderson, A.C., McClellan, K. & Calosso, M. 2010. Preliminary assessment of a possible lemon shark nursery in the Turks & Caicos Islands, British West Indies. *Caribbean Journal of Science*, **46(1)**, 29-38.

Hesse, K.O. 1979. Movement and migration of the queen conch, *Strombus gigas*, in the Turks and Caicos Islands. *Bulletin of Marine Science*, **29(3)**, 303-311.

Hilton, G.M., Cleeves, T., Murray, T., Hughes, B. & Williams, E.G. 2000. Wetland birds in Turks and Caicos Islands II: wetland bird communities. *Wildfowl*, **51(51)**, 127-138.

Hoshino, K., Brandt, M., Manfrino, C., Riegl, B. & Steiner, S. C. 2003. Assessment of the coral reefs of the Turks and Caicos Islands (Part 2: Fish communities). *Atoll Research Bulletin*, **496(26)**, 480.

Johnson, B., Gore, S. & Lockhart, K. (Proceedings of the 63rd Gulf and Caribbean Fisheries Institute). 2011. Red Lionfish (*Pterois volitans*) Control Strategies in the Caribbean UK Overseas Territories (Cayman Islands, Virgin Islands, and Turks and Caicos), 331-333. Retrieved from http://aquaticcommons.org/21263/1/GCFI_63-65.pdf

Kelley, E.R., Sleith, R.S., Matz, M.V. & Wright, R.M. 2020. Gene expression associated with disease resistance and long-term growth in a reef-building coral. *bioRxiv*.

Landsman, S.J., Jadot, C., Ashley, M. & Claydon, J.A. (Proceedings of the 61st Gulf and Caribbean Fisheries Institute). 2009. Investigation of the Nassau grouper (*Epinephelus striatus*) fishery in the Turks and Caicos Islands: implications for conservation and management. 82-90. Retrieved from http://aquaticcommons.org/15701/1/GCFI_61-12.pdf

Lefcheck, J.S., Hughes, B.B., Johnson, A.J., Pfirrmann, B.W., Rasher, D.B., Smyth, A.R., ... & Orth, R.J. 2019. Are coastal habitats important nurseries? A meta-analysis. *Conservation Letters*, **12(4)**, e12645.

Logan, A. & Sealey, K.S. 2013. The Reefs of the Turks and Caicos Islands. In C Shepherd (Ed.), *Coral Reefs of the United Kingdom's Overseas Territories* (volume 4., pp. 97-114). Dordrecht: Springer, https://doi.org/10.1007/978-94-007-5965-7_9

Maljkovic, A., Van Leeuwen, T.E. & Cove, S.N. 2008. Predation on the invasive red lionfish, *Pterois volitans* (Pisces: Scorpaenidae), by native groupers in the Bahamas. *Coral Reefs*, **27(3)**, 501, retrieved from https://www.researchgate.net/profile/Aleksandra-Maljkovic/publication/230554941_Predation_on_the_invasive_red_lionfish_Pterois_volitans_Pisces_Scorpaenidae_by_native_groupers_in_the_Bahamas/links/0fcfd50153895348cd000000/Predation-on-the-invasive-red-lionfish-Pterois-volitans-Pisces-Scorpaenidae-by-native-groupers-in-the-Bahamas.pdf

Medley, P.A. & Ninnes, C.H. 1999. A stock assessment for the conch (*Strombus gigas L.*) fishery in the Turks and Caicos Islands. *Bulletin of Marine Science*, **64(3)**, 399-406.

Mtwana Nordlund, L., Koch, E.W., Barbier, E.B. & Creed, J.C. 2016. Seagrass ecosystem services and their variability across genera and geographical regions. *PLoS One*, **11(10)**, e0163091.

Mumby, P.J., Broad, K., Brumbaugh, D.R., Dahlgren, C.P., Harborne, A.R., Hastings, A., ... & Sanchirico, J.N. 2008. Coral reef habitats as surrogates of species, ecological functions, and ecosystem services. *Conservation Biology*, **22(4)**, 941-951.

Mumby, P.J., Edwards, A.J., Arias-González, J.E., Lindeman, K.C., Blackwell, P.G., Gall, A., ... & Llewellyn, G. 2004. Mangroves enhance the biomass of coral reef fish communities in the Caribbean. *Nature*, **427(6974)**, 533-536.

Mumby, P.J., Harborne, A.R. & Brumbaugh, D.R. 2011. Grouper as a natural biocontrol of invasive lionfish. *PloS one*, **6(6)**, e21510.

Nagelkerken, I.S.J.M., Blaber, S.J.M., Bouillon, S., Green, P., Haywood, M., Kirton, L.G., ... & Somerfield, P.J. 2008. The habitat function of mangroves for terrestrial and marine fauna: a review. *Aquatic botany*, **89(2)**, 155-185.

Overcash, D.L. 2011. Capturing fisher input on regulatory change in the Turks and Caicos Islands marine turtle fishery and assessing the possibility of co-management (PhD Thesis). Duke University: North Carolina.

Paterson, S.E. 1998. Group occurrence of great barracuda (*Sphyraena barracuda*) in the Turks and Caicos Islands. *Bulletin of Marine Science*, **63(3)**, 633-638.

Pienkowski, M.W., Pienkowski, A.E. & Manco, B.N. 2005. Birds on the outer cays of the Turks and Caicos Islands. *Journal of Caribbean Ornithology*, **18**, 31-43.

Richardson, P.B., Bruford, M.W., Calosso, M.C., Campbell, L.M., Clerveaux, W., Formia, A., ... & Broderick, A.C. 2009. Marine turtles in the Turks and Caicos Islands: remnant rookeries, regionally significant foraging stocks, and a major turtle fishery. *Chelonian Conservation and Biology*, **8(2)**, 192-207.

Rudd, M.A. 2001. The effects of seafood import tariffs on market demand for Nassau grouper in the Turks and Caicos Islands. *Proceedings of the Gulf and Caribbean Fisheries Institute*, **55**, 178-190.

Rudd, M.A. 2001. The non-extractive economic value of spiny lobster, *Panulirus argus*, in the Turks and Caicos Islands. *Environmental Conservation* **28(3)**, 226-234.

Rudd, M.A. 2003. Fisheries landings and trade of the Turks and Caicos Islands. *Fisheries Centre Research Reports*, **11(6)**, 149-161.

Rudd, M.A. 2003. *Institutional analysis of marine reserves and fisheries governance policy experiments: a case study of Nassau grouper conservation in the Turks and Caicos Islands*. The Netherlands: Wageningen Universiteit.

Rudd, M.A. & Tupper, M.H. 2002. The impact of Nassau grouper size and abundance on scuba diver site selection and MPA economics. *Coastal Management*, **30(2)**, 133-151.

Rudd, M.A., Danylchuk, A., Gore, S.A. & Tupper, M.H. 2001. Are marine protected areas in the Turks and Caicos Islands ecologically or economically valuable? *Economics of Marine Protected Areas*, **9**, 198-211.

Sealey, K.S., Wood, K. & Logan, A. 2019. The Turks and Caicos Islands. In C Shepherd (Ed.), *World Seas: An Environmental Evaluation* (2nd Edition, 617-635). Academic Press.

Serafy, J.E., Shideler, G.S., Araújo, R.J. & Nagelkerken, I. 2015. Mangroves enhance reef fish abundance at the Caribbean regional scale. *PloS one*, **10(11)**, e0142022.

Stoner, A.W. 2003. What constitutes essential nursery habitat for a marine species? A case study of habitat form and function for queen conch. *Marine Ecology Progress Series*, **257**, 275-289.

Stringell, T.B., Calosso, M.C., Claydon, J.A., Clerveaux, W., Godley, B.J., Phillips, Q., ... & Broderick, A.C. 2010. Loggerhead turtles in the Turks and Caicos Islands, *Caribbean Marine Turtle Newsletter*, **127**, 23-25.

Taylor, O. & Medley, P. 2003. Turks and Caicos Islands Field Report. *Participatory Fisheries Stock Assessment project*, *7947*.

Tewfik, A. & Béné, C. (Gulf and Caribbean Fisheries Institute). 2000. *Densities and age structure of fished versus protected populations of queen conch (*Strombus gigas L.*) in the*

Turks and Caicos Islands. **51(3)**, 60-79. Retrieved from http://aquaticcommons.org/13340/1/gcfi_51-3.pdf

Tupper, M. (Proceedings of the 53rd Gulf and Caribbean Fisheries Institute). 2002. Essential fish habitat and marine reserves for groupers in the Turks & Caicos Islands. 606-622, retrieved from http://aquaticcommons.org/13534/1/gcfi_53-51.pdf

Uyarra, M.C., Watkinson, A.R. & Cote, I.M. 2009. Managing dive tourism for the sustainable use of coral reefs: validating diver perceptions of attractive site features. *Environmental management*, **43(1)**, 1-16.

Valdivia, A., Bruno, J.F., Cox, C.E., Hackerott, S. & Green, S.J. 2014. Re-examining the relationship between invasive lionfish and native grouper in the Caribbean. *PeerJ*, **2**, e348.

Ware, J.R., Smith, S.V. & Reaka-Kudla, M.L. 1992. Coral reefs: sources or sinks of atmospheric CO 2? *Coral reefs*, **11(3)**, 127-130.

Watanabe, A. & Nakamura, T. 2019. Carbon dynamics in coral reefs. In T Kuwae and M Hori (Eds,). *Blue Carbon in Shallow Coastal Ecosystems* (pp. 273-293). Singapore: Springer.

Wilderman, E. (2015). *The life history of the hawksbill sea turtle (*Eretmochelys imbricata*) and an observational study of Caribbean hawksbills in Grand Turk, The Turks and Caicos Islands*. Retrieved from https://www.academia.edu/28454650/The_life_history_of_the_hawksbill_sea_turtle_Eretmochelys_imbricata_and_an_observational_study_of_Caribbean_hawksbills_in_Grand_Turk_The_Turks_and_Caicos_Islands

Wood Environment & Infrastructure Solutions UK Limited & JNCC. 2020. *The Role of Mangroves in Coastal Protection*. Retrieved from https://data.jncc.gov.uk/data/586618ac-a29d-488b-9beb-2d8fb61bb0c1/wood-the-role-of-mangroves-in-coastal-protection.pdf

Wright, R.M., Kenkel, C.D., Dunn, C.E., Shilling, E.N., Bay, L.K. & Matz, M.V. 2017. Intraspecific Differences in Molecular Stress Responses and Coral Pathobiome Contribute to Mortality under Bacterial Challenge in Acropora Millepora. *Scientific Reports,* **7(2609),** 1-13, retrieved from https://www.nature.com/articles/s41598-017-02685-1.pdf

Zhang, K., Liu, H., Li, Y., Xu, H., Shen, J., Rhome, J. & Smith III, T.J. 2012. The role of mangroves in attenuating storm surges. *Estuarine, Coastal and Shelf Science*, **102**, 11-23.