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ORIGINAL PAPER

Applying Geographic Information Systems to ecosystem services valuation and mapping in Trinidad and Tobago

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Abstract Consideration of the spatial dimension in the provision of ecosystem services is fundamental for the calculation of the economic value of ecosystem services and the distribution across beneficiaries and ecosystems. In the context of Small Island Developing States, the islands of Trinidad and Tobago are characterized by a rich natural capital, which lies at the source of the provision of all ecosystem services. Such natural capital, however, is threatened by a range of anthropogenic pressures. This paper builds upon state-of-the-art benefit transfer techniques and Geographic Information Systems to provide the first maps of the value of three key ecosystem services in Trinidad and Tobago. Result estimates indicate that the mean value of carbon sequestration by terrestrial and coastal ecosystems amounts to 65 US$/ha/year. Mean values for coastal recreation and shoreline coastal protection are estimated in 6468 and 924 US$/ha/year, respectively. We discuss how this spatially explicit valuation exercise may feed into Trinidad and Tobago's National Spatial Development Plan, thus contributing toward a more sustainable use of the country's natural capital.

Keywords Ecosystem services · Geographic Information Systems · Spatial economic valuation · Meta-analysis · Value transfer

JEL Classification Q51 · Q57

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1 Introduction

The economic valuation of ecosystem services (ES) is broadly accepted as a useful tool to inform development- and conservation-related decisions on the wide societal implications of different scenarios, thus enhancing our collective choices regarding the management of natural resources and the environment. Unfortunately, the critically valuable ecosystem services tend not to be economically valued, as their benefits are often not reflected in the prices of goods and services in markets. This occurs not only because some of these goods are public goods, that is, non-excludable (owners cannot prevent others from enjoying it) and non-rival (providing the good to more people can be done at zero cost), but also because of the existence of market failures even when the goods are not public. Over the last two decades, the economic valuation of ES has attracted increasing attention worldwide. International initiatives such as the Millennium Ecosystems Assessment (http://www.millenniumassessment.org), which launched its main report in 2005 (MA 2005), The Economics of Ecosystems and Biodiversity (TEEB; http://www.teebweb.org), which was initiated in 2007 under the leadership of UNEP and the European Commission, and the "Project for Ecosystem Services" (ProEcoServ; http://www.proecoserv.org) led by the United Nations Environment Programme have substantially contributed to move the discussion forward in this field.

Various primary valuation techniques are available in the toolbox of environmental economists to capture the non-market benefits humans derive from natural and environmental resources. Two major categories of valuation techniques are stated preference methods, which rely on the simulation of a market through a questionnaire administered to a sample of the affected population (e.g., contingent valuation method, choice experiments) and revealed preference methods, which seek to elicit preferences and implicit prices from actual, observed, market-based information that is indirectly linked to the ecosystem service in question (e.g., travel cost method, hedonic pricing). Environmental managers and decision-makers also increasingly rely on secondary ES valuations (i.e., value transfer) as a second-best assessment of ecosystem benefits (Johnston et al. 2015). In this context, value (or benefit) transfer refers to the procedure of drawing inferences on the unobserved monetary value of ecosystem goods or services in a policy site by borrowing existing valuation estimates from comparable study sites. Though widely used also in developed countries, the use of secondary valuation techniques is particularly relevant in the context of developing countries, where the lack of ES valuation expertise and the financial resources necessary for a primary valuation study are often limiting factors (Chaikumbung et al. 2016).

A fundamental issue that both primary and secondary ES valuation exercises need to address relates to the level of complexity with is due to the inherently spatial nature of ES flow (Eade and Moran 1996; Troy and Wilson 2006). As a matter of fact, the consideration of the spatial dimension with respect to the provision of ecosystem services (on the supply side) as well as the underlying distribution of benefits (on the demand side) is a fundamental element in the calculation of the aggregated economic value of these services as well as its spatial distribution across relevant areas and/or populations. The importance of explicitly accounting for the spatial distribution of ES provision is testified by the increasingly large number of related international initiatives and scientific publications on the subject, including the recently launched "Mapping and assessing ecosystems and their services for policy and decision making" European Horizon-2020 project (http://www.esmeralda-project.eu) and the Special Issue of the journal Ecosystem Services on Best Practices for Mapping Ecosystem Services (http://www.sciencedirect.com/science/journal/22120416/13). Recent studies show that the transfer of per-hectare or per-household point estimates is inadequate to assess the distribution of values over the investigated natural asset unless spatial patterns in the market, geographic context, and systematic variation in public preferences over space are considered (Johnston and Rosenberger 2010; Smith 2018). A range of techniques has been proposed, for instance, to take into account the spatial dependence of stated preferences and the resulting welfare estimates in value transfer (Campbell et al. 2008, 2009), including distance decay effects (Bateman et al. 2011; Jørgensen et al. 2013), or for developing spatially explicit meta-analytical value transfer functions (Brander et al. 2012; Ghermandi and Nunes 2013; Ghermandi 2015).

Primary and secondary valuation of ecosystem services presents particular challenges in the context of Small Island Developing States (SIDS). The Guidance Manual on Valuation and Accounting of Ecosystem Services for Small Island Developing States (UNEP 2014) highlights how properly devised economic valuation and accounting of island ecosystem services can improve cost–benefit analysis and policy appraisal in SIDS, bearing in mind on one hand the strong dependency of SIDS economies on their rich natural environment and, on the other hand, the fragility and vulnerability of their ecosystems.

The present study focuses on the economic valuation and spatially explicit mapping of selected ecosystem service benefits in the small island developing state of Trinidad and Tobago. First, the study sets out to investigate and preliminarily screen the available information on key ecosystem services and available data from previous ES valuation studies. This stage is necessary to identify the scope, methodology and sources of information for the ES value mapping exercise. While the Total Economic Value (TEV) framework (TEEB 2010) provides a useful point of departure for the study, valuation of all components of the TEV requires a large-scale research effort, which is beyond the scope of the present study. A useful approach, which is followed in the present work, consists of first identifying the different values and then proceeding to focus on the ones that are most important and that are capable of being valued with reasonable accuracy (TEEB 2013).

Second, the required data and information regarding the selected ecosystem services is collected in all necessary details. This step includes the spatially explicit characterization of the provision-shed for the key selected ecosystem services with the aid of Geographic Information Systems (GIS), as well as the identification, collection, and assessment of the relevant information regarding the socio-economic, institutional, and environmental context in Trinidad and Tobago, in which such services are expressed.

Third, the study implements a range of methodologies that value and map the provision of three key ecosystem services in Trinidad and Tobago, namely: carbon sequestration by coastal ecosystems (i.e., mangroves, coastal marshes, and seagrasses) and terrestrial forest ecosystems; coastal recreation; and shoreline coastal protection. Using available data, the study demonstrates how the benefits of ecosystem services can be made spatially explicit combining economic valuation techniques with GIS and geospatial platforms.

The study concludes discussing how the results of the presented economic valuation and ES value mapping exercises can potentially help increase the magnitude and level of integration of regional environmental policies, including the development of a National Spatial Development Plan, and consequently potentially contribute to guide Trinidad and Tobago towards a sustainable growth path.

2 Ecosystem service valuations in Trinidad and Tobago

The Republic of Trinidad and Tobago is a Small Island Developing State (SIDS) in the Caribbean region, which covers a total land area of about 5130 km^2 with an estimated corresponding coastline length of 362 km and a population of about 1.33 million people (UNEP 2014). Trinidad and Tobago's Exclusive Economic Zone (EEZ) covers 77,500 km^2. The country is known as the most industrialized country of the Caribbean, with its economy strongly dependent on the petroleum and natural gas sectors, with the energy sector accounting for around 34.9% of the country's Gross Domestic Product. Although Trinidad and Tobago has successfully diversified its oil and gas industry, this sector is expected to be exhausted by 2025–2030 if no new resources are discovered so that government's central imperative is innovation and diversification of the non-resource base. This is where incorporating the value of other kinds of assets such as biodiversity and ecosystem services into economic decision-making becomes critical for the country's sustainable future.

The islands of Trinidad and Tobago are well known for the richness of their natural environment and biodiversity. A number of natural ecosystems are found on the island, including forests, inland freshwater systems, coastal and marine ecosystems (such as coral reefs, mangrove swamps, seagrass beds and open ocean), savannas, karst landforms, and man-made/induced systems (such as secondary forests, agricultural lands and freshwater dams) (Environmental Management Authority 2012). Local ecosystems show a substantial spatial heterogeneity (Fig. 1). Relief features are concentrated in the north of Trinidad, with the Northern Range covering approximately 25% of the island's extension and being covered by a variety of tropical forests (Girvan and Teelucksingh 2012). The majority of emergent wetland ecosystems are located along the west coast of Trinidad, including Caroni swamp—the largest mangrove swamp in the country, which alone accounts for 60% of the total mangrove area (Shah et al. 2013). A notable exception is the Nariva swamp on the island's east coast. Submerged wetlands such as coral reefs and seagrass beds are, on the other hand, primarily located in the island of Tobago. Tobago's coral reefs fringe about half of the island's shoreline and support an important tourism sector, especially in areas such as the Buccoo Reefs and the Bon Accord Lagoon (Burke et al. 2008). In addition to being home of much of the country's rich marine and terrestrial biodiversity, the coastal zone has been the focus of much development, which has led to ecological stress and land-use conversion due to the needs for land suitable to the development of industrial sectors, such as maritime transport and tourism, agriculture, and residential areas (Tompkins and Adger 2002).

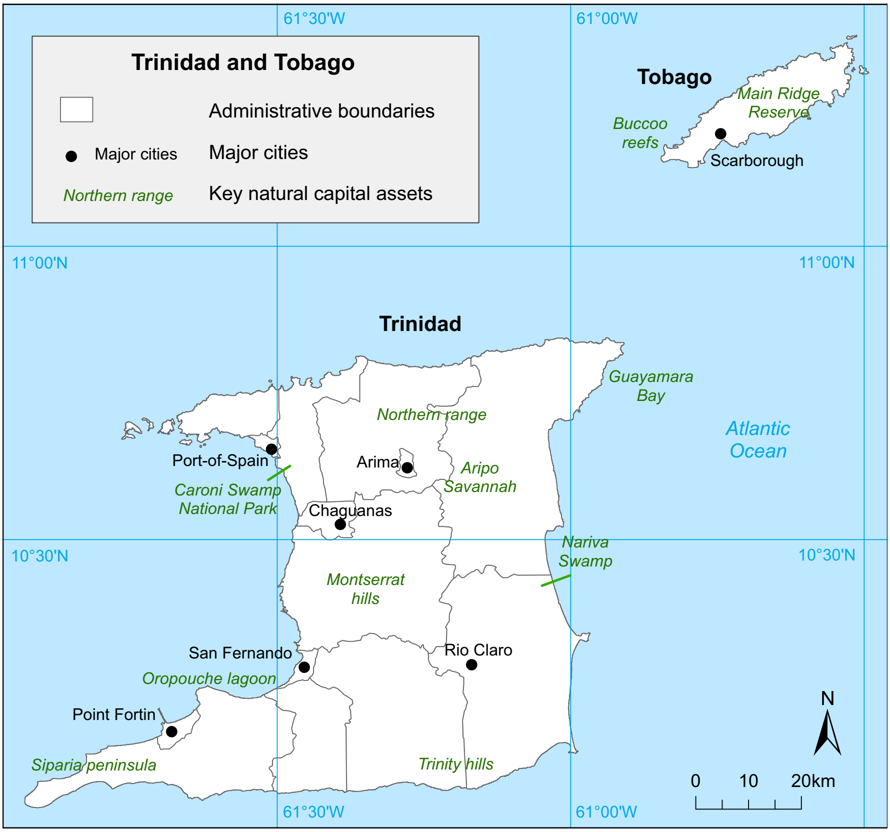

Fig. 1 Map of Trinidad and Tobago with major cities and key natural capital assets

Trinidad and Tobago was chosen as a case-study location for ProEcoServ, with pilot sites in Nariva Swamp, the Northern Range, and south-west Tobago. Previous reports produced in the context of this international initiative with an economic ES valuation component focused on the value of pollination in the Nariva Swamp, water supply in Tobago, erosion prevention by the Northern Range forests, and carbon storage (Girvan and Teelucksingh 2012; Girvan 2015). ProEcoServ focuses on the ways through which ES can be integrated across different scales and has as one of its main objectives the development of GIS-based ecosystem service maps and a decision support system for inclusion in the new Trinidad and Tobago National Physical Development Plan.

The policy avenue presented by the National Physical Development Plan is one that is necessary for greater sustainability in a small island state such as Trinidad and Tobago that, over the last two decades, has lacked an updated national physical development plan. As governments change frequently and each has its own policy, this absence has resulted in numerous ad hoc plans and policies with overlapping principles and recommendations. The Town and Country Planning Division (TCPD) of the Ministry of Planning and Development has recognized this disparity and has attempted to harmonize all aspects of development through policy statements coordinated within the National Spatial Development Strategy (NSDS 2014). The NSDS acknowledges the value of ‘essential ecosystem services’ and reinforces the need to integrate spatial planning into the decision-making process.

The Ministry, through the TCPD, has proposed the use of Strategic Environmental Assessment (SEA) as one of the first steps in incorporating ecosystem service maps into the planning process. This is because SEA is undertaken much earlier in the decision-making process than the more commonly used but generally reactive Environmental Impact Assessment process required by the Environmental Management Authority (EMA) and occurs at a much broader development planning level and brings longer term thinking into the picture. The expectation is that incorporating ecosystem services maps into SEA decision making is the first step to changing the way nature is valued, and a positive way to plan for the future.

Prior to the ProEcoServ initiative, ES in Trinidad and Tobago have been the object of a limited number of valuation studies. A total of six studies were identified that conducted primary valuations of the benefits of ecosystems in Trinidad and Tobago (Table 1). Out of them, three focused on the valuation of coastal and marine ecosystems, in particular coral reefs, and three on wetland ecosystems (Nariva and Caroni swamps). Valued ES include cultural services (e.g., support for tourism and recreation, and passive uses), regulating services (e.g., shoreline coastal protection), and provisioning services (e.g., fishing).

The present study builds upon the information that is available from these and other primary valuation studies that were conducted in comparable contexts with the following goals: (1) to adapt such information, where necessary, to the specific environmental and socio-economic context of Trinidad and Tobago, taking into account key factors including income levels and the impacts on ecosystem services—i.e., the environmental impact; and (2) to make the economic value of selected ecosystem services spatially explicit using a geospatial platform and creating ecosystem service value maps. The focus of the study is on three ecosystem services that were identified in the investigated previous primary valuation studies to be of key importance in the context of Trinidad and Tobago, namely (1) carbon sequestration, (2) coastal recreation, and (3) shoreline coastal protection.

3 Materials and methods

3.1 Carbon sequestration by forest and coastal ecosystems

The benefits of the regulating service of carbon sequestration provided by terrestrial, coastal and marine ecosystems are expressed in the form of mitigation of climate change. Coastal ecosystems are increasingly recognized for their important role in sequestering and storing carbon dioxide from the atmosphere: such service is generally referred to under the term “blue carbon” (Nellemann et al. 2009). Among vegetated coastal habitats, mangroves, salt marshes and seagrasses are known to be substantially more efficient per unit area than terrestrial forests in sequestering and burying carbon dioxide (McLeod et al. 2011). Girvan and Teelucksingh (2012) rely on the estimates of average organic carbon soil storage provided by Seepersad (2010) for various types

Table 1 Overview of primary ecosystem service valuations in Trinidad and Tobago. *Source*: Modified from UNEP (2014)

Study site	Valued scenario	Estimated value	Valuation method	Commissioned by (year)	Valued ES	Beneficiaries	References
Nariva swamp	WTP for wetland protection	Not specified	CVM	Government (2004)	Protection of wildlife, vegetation and habitat	Local residents; Georgia residents (non-users)	Allen (2004)
Tobago's coastal waters	WTP for water quality improvement	(1) US$44.09 snorkelers (2) US$13.85 non-snorkelers	CE	Research (2010)	Recreation	Local residents; tourists	Beharry-Borg and Scarpa (2010)
Buccoo Reef Marine Park	WTP to prevent deterioration	(1) 1.2 million US$ quality reduced (2) 2.5 million US$ no quality change (3) 0.9 million US$ quality reduced + double users (4) 1.7 million US$ no quality change + double users	CVM	Government (2000)	Non-extractive and passive uses	Local residents; tourists	Brown et al. (2000)

Table 1 continued

Study site	Valued scenario	Estimated value	Valuation method	Commissioned by (year)	Valued ES	Beneficiaries	References
Coral reefs in Tobago	(1) total economic impacts from reef-associated tourism (2) direct impact of fisheries (3) avoided damage from coastal protection	(1) US$43.5 million/year (2) US$0.7-1.1 million/year (3) US$18-33 million/year	ADC, MP	NGO; International Organization (2008)	Tourism and recreation; fishing; shoreline protection	Local residents; tourists	Burke et al. (2008)
Nariva swamp	WTP for conservation	US$56 per household	CVM	Research (2005)	Non-extractive uses	Local residents	Pemberton and Mader-Charles (2005)
Caroni swamp	CS for non-extractive recreation activities	(1) US$80,462/year birdwatching (locals) (2) US$80,510/year birdwatching (tourists) (3) US$12,626/year sport fishing and hunting	TCM	Government (1980)	Recreation	Local residents	Ramdial (1980)

WTP willingness to pay, *CS* consumer surplus, *CVM* contingent valuation method, *CE* choice experiment, *ADC* avoided damage cost, *MP* market prices, *TCM* travel cost method

Table 2 Estimated average carbon sequestration rates by vegetated coastal habitats and tropical forests. *Source*: Modified from McLeod et al. (2011)

Ecosystem	Carbon burial rate (±SE) [gC/m^2/year]
Salt marshes	218 ± 24
Mangroves	226 ± 39
Seagrasses	138 ± 38
Tropical forests	4.0 ± 0.5

SE standard error

of forests and soils to assess the total carbon storage in terrestrial tropical forests in Trinidad and Tobago in 19,170 thousand metric tonnes. Using the average market price of carbon in the European Union Emissions Trading Scheme (EU-ETS) during the year 2011, Girvan and Teelucksingh (2012) estimate the average value of the carbon storage service provided by Trinidad and Tobago's tropical forests in 1088 US$ per hectare.

In the present study we consider the carbon sequestration service provided by four different ecosystem types in Trinidad and Tobago: (1) mangroves; (2) salt marshes and swamps; (3) seagrasses; and (4) tropical forests. In the absence of local, experimental estimates of the carbon sequestration rates provided by the investigated ecosystems, we rely on global average carbon sequestration rates for the four ecosystem types to estimate the carbon fluxes per unit of area (Table 2).

The carbon sequestration rates from Table 2 were associated in a spatially explicit way with the land cover types and distribution of coastal ecosystems in Trinidad and Tobago, as obtained from a range of sources. For the main island of Trinidad, the study relies on the land use map of Trinidad by Jordan (2010). The land cover refers to the year 2000. For Tobago and minor islands around Trinidad, the land use cover presented by the ESA GlobCover Version 2.3 2009 300 m resolution Land Cover Map (http://www.edenextdata.com/?q=content/esa-globcover-version-23-2009-300m-resolution-land-cover-map-0) is used to map carbon sequestration values. The land use data in this map refers to the years 2005-2006. The geographical distribution of seagrasses in Trinidad and Tobago is derived from the UNEP-WCMC Global Distribution of Seagrasses (UNEP-WCMC and Short 2005; Green and Short 2003). The only seagrass fields identified by the UNEP-WCMC map in the Trinidad and Tobago region are in the south-west coast of the island of Tobago.

To estimate carbon fluxes in broken forests (sparse forests) and mixed land-use types involving a forest or salt marsh/swamp component, the following assumptions were made: (1) carbon sequestration in broken forests (sparse forests) is assumed to amount to 75% of that of dense forests; (2) mixed land-use types are assumed to be composed by the individual land use types in equal amounts (i.e., a mix of two land use types, combining a dense forest component with another non-forest or swamp ecosystem type, is assumed to yield 50% of the carbon sequestration of a dense forest); (3) carbon sequestration from agricultural land use and other non-forest vegetated ecosystems (such as scrub and grassland) is not considered in the present study which focuses exclusively on forest and coastal blue carbon sinks.

A micro-economic valuation of the benefits of carbon sequestration by coastal ecosystems and tropical forests may rely on prices per unit of carbon, multiplied by the ecosystem-specific carbon sequestration rate per unit of area. The appropriate monetary measure per unit of carbon is the social cost of carbon. The social cost of carbon captures the net present value of the cumulative, global impact of one additional ton of carbon emitted to the atmosphere today over its residence time in the atmosphere, typically 100 years or longer (Watkiss et al. 2005). The social cost of carbon can be interpreted as the value of resulting climate damage, measured at the margin. Since the benefits of carbon sequestration and storage are not limited to a specific region but are felt globally, the social cost of carbon does not have spatial variation.

Monetary estimates of the social cost of carbon are the outcome of Integrated Assessment Models (IAMs), which capture the complex linkages between greenhouse gas emissions, greenhouse gas atmospheric concentrations, temperature change and monetary costs of climate change damage to society. A number of models and approaches have been applied in the literature to the estimation of the social cost of carbon, resulting in a wide range of magnitudes (Tol 2018). Van den Bergh and Botzen (2014) took a critical look at the current range of published estimates of the social cost of carbon, and particularly at cost categories that omitted from prior studies, discounting, and uncertainties about damage costs and risk aversion. They conclude that most previous estimates grossly underestimate the true social cost of carbon. In this study, we rely on their proposed lower bound estimate of the social cost of carbon of 125 US$/ton CO_2 to value in monetary the yearly flux of carbon from the four ecosystem types presented in Table 2.

3.2 Coastal recreation

From a welfare perspective, the cultural services provided by marine and coastal systems through their support of recreational activities generate positive welfare impacts, which may be felt at the local, regional or global level but, because of their public good nature, are not reflected in the current markets and respective price signals. In other words, the current market prices, in their wide range of market goods and services, fail to embed a substantial fraction of the beneficial contribution that marine and coastal system have for society. Since market prices do not reflect the broad range of ecosystem services, decision-making will be inefficient and fail to preserve or defend these values.

A review of primary non-market valuation studies of ecosystem services in Trinidad and Tobago (see Table 1) reveals substantial gaps of information regarding the economic value of several of the ecosystem services provided by coastal and marine ecosystems, including coastal recreation and shoreline coastal protection. In this context, we rely in the present section on the application of a state-of-the-art meta-analytical value transfer methodology, integrated with GIS tools, to provide a spatially explicit assessment of the values of the coastal recreation services provided along the coastline of the Trinidad and Tobago islands. Bearing in mind the limitation of a value transfer exercise, which is always to be considered as a second-best strategy in the absence of a primary valuation study gathering time-, location- and stakeholder-specific information, value transfer is increasingly accepted as a useful strategy when a valuation is not available or feasible.

In the present application to Trinidad and Tobago, the value transfer exercise is aimed at: (1) providing a first, spatially explicit estimate of the regional and local economic importance of the ecosystem services for which primary data is lacking; (2) allowing for the identification of priority areas where it may be worthwhile to focus future primary valuation studies; and (3) providing policy-relevant information and a robust, econometrically estimated model on which to evaluate alternative future policy and management scenarios.

The econometric and GIS techniques used in this study were first proposed by Ghermandi and Nunes (2013) and demonstrated in the mapping of global coastal recreation values, at a spatial resolution of 0.5° of longitude/latitude. For the present application, all geospatial layers, which underlie the analysis in Ghermandi and Nunes (2013) were downscaled to grid cells with a resolution of 1 km × 1 km so that the application to Trinidad and Tobago provides a sufficiently detailed image of the spatial distribution of values. The re-scaled and re-projected layers (and the respective sources) include: population density (CIESIN, Gridded Population of the World, v.2; sedac.ciesin.columbia.edu/plue/gpw), accessibility (European Commission, Global Accessibility Maps; bioval.jrc.ec.europa.eu/products/gam), human development impact (GLOBIO project; www.globio.info), anthropogenic pressure from nutrients pollution (Halpern et al. 2008), heating degree months (own calculation based on data from the Community Climate System Model; http://www.ccsm.ucar.edu), and marine biodiversity (Ocean Biogeographic Information System, OBIS; www.iobis.org). Unlike in Ghermandi and Nunes (2013), given the higher spatial resolution of the study, an additional effort was done to characterize the land-use in each grid cell, distinguishing between coral reefs (World Resources Institute, Reefs at Risk revisited; http://www.wri.org/publication/reefs-risk-revisited), estuarine mangrove ecosystems, beaches, and other land-use types.

The meta-analytical value transfer function defined in Ghermandi and Nunes (2013) was subsequently applied to each of the 1 km × 1 km grid cells along the coastline of Trinidad and Tobago as follows:

$$\ln(y) = 4.830 + 1.050 \cdot Estuary + 1.860 \cdot Beach + 1.667 \cdot Reef + 0.454 \cdot PopDens + 1.972 \cdot LDI - 0.239 \cdot Pressure - 0.534 \cdot Access + 0.290 \cdot MarBio - 0.008 \cdot HDM$$

where y is the value in US$/ha/year in each of the coastal grid cells; *Estuary, Beach* and *Reef* are dummy variables reflecting the local land cover; *PopDens* is local population density (in inhabitants per km^2); *LDI* is a dummy capturing grid cells with a low development impact; *Pressure* identifies anthropogenic pressure through nutrient pollution in coastal waters (in ton/km^2/year); *Access* is measured through the travel time (in h) to the nearest large city; *MarBio* reflects the local marine biodiversity through the Shannon index of biodiversity; and *HDM* is heating degree months (in °C). The variables *PopDens*, *Pressure* and *Access* are introduced in logarithmic units. Population density, anthropogenic pressure and marine biodiversity variables were evaluated within a 20 km buffer in each of the grid cells of Trinidad and Tobago's coastline. Values are calculated within a 2 km swath of land, moving inland from the shoreline, with the understanding that most coastal recreational activities that are of relevance for this study take place within this area. For a more thorough discussion of the meta-regression variables and results, as well as for an interpretation of the constant term, the reader may refer to Ghermandi and Nunes (2013).

3.3 Shoreline coastal protection

Coastal wetlands, mangroves and near-shore coral reefs provide crucial benefits to coastal communities by protecting them from flooding and storm surges, both seasonal and idiosyncratic storm events. The benefits from this ecosystem service may include prevention of loss of life, damage to housing, infrastructure and food sources, and prevention of saltwater intrusion. This has been shown to be particularly important in the case of poor, vulnerable communities, which recent research shows to be often the most critically dependent on the provision of ecosystem services, among others due to their limited options to replace foregone services by natural ecosystems with man-made options.

Four main types of coastal habitats present in Trinidad and Tobago are understood to provide significant services for shoreline coastal protection: these are coral reefs, mangroves, coastal wetlands and seagrasses. Mangrove forests protect inland communities and freshwater resources from saltwater intrusion during storms, and protect near shore settlements from erosion, their roots helping to hold the sediment in place and slowing down water flow (Orth et al. 2006). Coral reefs and mangroves also minimize the impact of storms by reducing wind action, wave action and currents and coral reef structures buffer shorelines against waves, storms and floods (Adger et al. 2005). Wetlands and seagrasses found in coastal areas often function as storm buffers, dissipating both storm energy and wave energy (Costanza et al. 2008; Orth et al. 2006). Due to a lack of primary valuations in the literature regarding the shoreline coastal protection values of seagrasses, this coastal habitat is not included in the present analysis.

Similarly to the valuation exercise for coastal recreation services, the spatially explicit valuation of the shoreline coastal protection services of coastal and marine ecosystems in Trinidad and Tobago is performed using a combination of meta-analytical value transfer and GIS techniques. The methodology applied in the present exercise, was proposed and tested by Rao et al. (2015) for the spatial economic analysis of shoreline protection values, at the global scale, with a resolution of 0.5° of longitude/latitude. Consistently with the assumptions made for the coastal recreation service, all geospatial layers, which underlie the analysis in Rao et al. (2015) were downscaled to grid cells with a resolution of 1 km × 1 km so that the application to Trinidad and Tobago provides a sufficiently detailed image of the spatial distribution of values. In addition to the human development and land-use layers previously described, storm frequency and wind speed layers (International Best Track Archive for Climate Stewardship; Knapp et al. 2010) were re-scaled for the present analysis.

The meta-analytical value transfer function defined in Rao et al. (2015) was subsequently applied to each of the grid cells along the coastline of Trinidad and Tobago as follows:

$$\ln(y) = 4.061 - 1.473 \cdot Mangrove - 0.652 \cdot Reef - 1.515 \cdot LDI + 0.056 \cdot Storms - 0.056 \cdot WindSpeed + 0.026 \cdot (Mangrove \cdot WindSpeed) + 0.076 \cdot (Reef \cdot WindSpeed)$$

where y is the value in US$/ha/year in each of the coastal grid cells; *Mangrove* and *Reef* are dummy variables reflecting the presence of the shoreline protection ecosystem service, with coastal wetlands as the omitted variable; *LDI* is a dummy capturing grid cells with low development impact; *Storms* and *WindSpeed* represent respectively the frequency of storms and their wind speed as derived from Knapp et al. (2010). The meta-regression model includes two interaction terms between ecosystem types and the wind speed variable. For the analysis and mapping, coastal ecosystems located within 2 km from the shoreline were included, after considering that shoreline coastal protection services decline with the distance from the shore. For a more thorough discussion of the meta-regression variables and results, as well as for an interpretation of the constant term, the reader may refer to Rao et al. (2015).

4 Results

Figure 2 shows the results of the valuation and mapping exercise for the (a) carbon sequestration, (b) coastal recreation, and (c) shoreline coastal protection services. The spatial resolution of the carbon sequestration map is 300 m × 300 m, while the other service values are mapped at a 1 km × 1 km resolution.

On average, the economic value of carbon sequestration services provided by coastal ecosystems and tropical forests in Trinidad and Tobago are estimated to range between 3 and 1035 US$/hectare/year over 34,577 grid cells with non-zero values. The mean (± SD) and median values are, respectively, 65 ± 214 and 18 US$/hectare/year. The highest values are found in proximity of the largest coastal wetland ecosystems in Trinidad, such as the Caroni swamp (north-west), the Nariva swamp (east), and the Oropouche Lagoon (south-west). The carbon sequestration service is also significantly present in areas of tropical forests such as the Northern Range (north), Trinity Hills

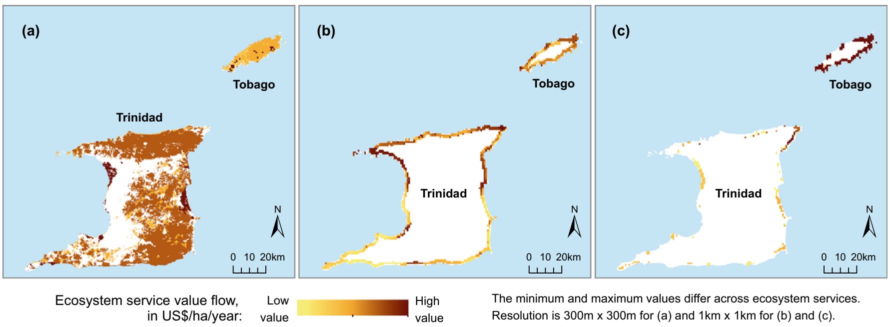

Fig. 2 Maps of **a** carbon sequestration, **b** coastal recreation and **c** shoreline coastal protection values in Trinidad and Tobago

(south-east) and, to a lesser extent, in the Siparia peninsula (south-west) and Montserrat Hills (center). Lower values are found in the more urbanized areas in the center and west of the island. In Tobago, carbon sequestration values are rather uniformly distributed over the entire island, with peaks in correspondence of mangrove wetlands and seagrasses, particularly in the south-west of the island.

The mean (± SD) and median values of the recreation service provided by coastal and marine ecosystems in Trinidad and Tobago are estimated in, respectively, 6468 ± 17,335 and 2495 US$/hectare/year. Values range between 85 and 390,428 US$/hectare/year over 965 individual grid cells. The spatial distribution of values is shown in Fig. 2 and is determined by the combination of the local values of the explanatory variables (i.e., population density, human development, anthropogenic pressure, site accessibility, marine biodiversity and climate). Although more pristine (i.e., less developed) areas tend to be highly valued by recreationists, the highest values are found close to large urban centers, where accessibility and proximity to the market of recreationists are highest. In Trinidad, high values are found in proximity of the largest urban concentrations, including Laventille, Port of Spain and Chaguanas (north-west), and San Fernando (center-west). High recreation values are also observed along the north and north-west coastline, where several popular bathing beaches are present. In Tobago, high values are found in particular along the south-west coastline, where renowned tourism attractions such as the Buccoo Reef and Bon Accord Lagoon are located, and in the north-east of the island, where several popular diving sites are concentrated.

The mean (± SD) and median values of the shoreline coastal protection service provided by coastal and marine ecosystems in Trinidad and Tobago are estimated in, respectively, 924 ± 863 and 397 US$/hectare/year. Values range between 11 and 1808 US$/hectare/year over 322 grid cells. The identified shoreline coastal protection services are located in concordance with coastal ecosystems such as coral reefs, mangroves, salt marshes and swamps. High values are found along the entire coast of Tobago, following the distribution of coral reefs and mangrove ecosystems, along the north-east coast of Trinidad in proximity and south of Guayamara Bay, and in correspondence to large coastal wetland ecosystems such as the Caroni swamp (north-west) and the Nariva swamp (east). The economic values reported in the map are determined by the combination of the local values of the different explanatory variables that are included in the meta-regression model. As expected, the modelled values tend to increase with local human development (e.g., presence of coastal infrastructure), number of storms and wind speed.

5 Discussion and conclusion

The sustainable management of natural capital and the underlying ecosystem goods and services requires a comprehensive understanding of the drivers of economic value change and how these interact with the different ecosystem services under consideration in their spatial, socio-economic and environmental context. In the present study we demonstrate how available, secondary sources of information on ecosystem services distribution and economic values can be successfully used in a spatial economic analysis in the context of a severe lack of primary sources. In the context of the economic valuation of ecosystem services in Trinidad and Tobago performed in the framework of the ProEcoServ project, the present study focuses on three key ecosystem services—i.e., carbon sequestration by coastal ecosystems and tropical forests, coastal recreation, and shoreline coastal protection—to produce the first maps of ecosystem service value distribution in Trinidad and Tobago.

In the context of Trinidad and Tobago, the assessment of the spatial distribution of ecosystem service values may help to compare, and ultimately prioritise, alternative areas for action. Different strategic approaches are possible here. A conservative approach may focus, for instance, on investing in the protection of areas that produce a relatively high economic value in all of the investigated ecosystem services, say at least as high as the national average. A different approach may look at maximizing the diversity of the national portfolio of ecosystem goods and services, thus promoting investment in those areas where the provision of the three ecosystem services is unbalanced, with one ecosystem service value dominating the other two. This may result in the creation of "vulnerability" maps, where vulnerability is expressed in terms of one area's overall dependence on one individual ecosystem service. A third approach might concentrate the attention on areas that deliver the highest combined economic value flow for all three services. Such information can be useful, for instance, in identifying priority areas for nature conservation projects, or for more in-depth analyses (e.g., as target sites for primary economic valuations of selected ecosystem services).

For the sake of illustration, Fig. 3 shows how the three different approaches described in the previous paragraph may lead to different priority setting for the conservation of ecosystem services in Trinidad and Tobago. As a first step, we calculated the aggregated value flows (in US$/year) for each of the 15 administrative subdivisions of Trinidad and Tobago. Figure 3a identifies the regions in Trinidad and Tobago, in which the ecosystem service value flow is higher than the national average for each of the three services under consideration in this study. Only two regions meet this criterion (Tobago and Sangre Grande). Figure 3b identifies the six regions in which the value flow of at least one of the three ecosystem service is in the top quartile nationwide. In addition to Tobago and Sangre Grande, these include Diego Martin (due to a high coastal recreation value flow), Mayaro/Rio Claro, San Juan-Laventille, and Siparia (due to high coastal shoreline protection and carbon sequestration values

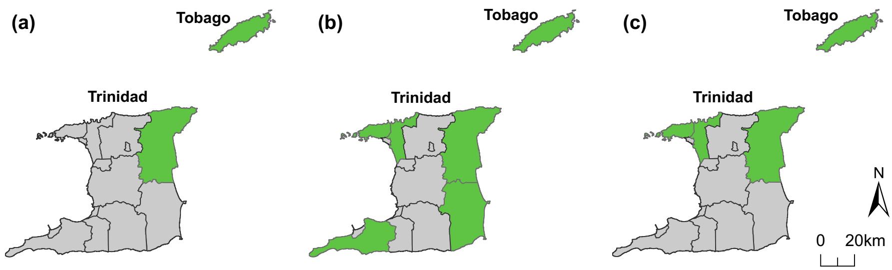

Fig. 3 Priority regions for the preservation of ecosystem services in Trinidad and Tobago, according to three different conservation strategies: **a** ES flow value higher than national average for each ES; **b** ES flow value in top quartile for at least one ES; **c** aggregated ES flow value in top quartile

and in spite of a lower than average coastal recreation value). Finally, in Fig. 3c the four regions providing the largest total flow of ecosystem service values are shown (Diego Martin, San Juan-Laventille, Sangre Grande, and Tobago). In all four regions that largest values are associated to coastal recreation.

The results of the present study support the notion that ascribing values to the provision of ecosystem goods and services in a spatially explicit way is a fundamental tool to support the decision-making process. While a number of other studies have been produced to map recipients of benefits from ES, this study is one of the few focussed on mapping areas that generate such services. While the former are useful to design more equitable public revenue collection systems for ES conservation, the latter are more geared towards improving the protection regime of areas generating multiple ES flows. The visualization of the spatial distribution of values in ecosystem service value maps may thus allow, for instance, for the identification of areas that are particularly valuable for one or multiple services (e.g., coral reefs for recreation and coastal shoreline protection; mangroves for shoreline coastal protection and carbon sequestration). This information can then play a key role in comparing alternative investment actions in ecosystem goods and services and evaluating the trade-offs that are associated with them, such as the identification of winners and losers from each action. Furthermore, the analysis of the spatial distribution of ecosystem service values may provide an additional, science-based argument to invest in payment for ecosystem service schemes.

Among the limitations of the study, one should consider that the elicited ES value maps are based either on secondary data, which represent a second-best strategy to evaluate policy impacts (Liu et al. 2011), or on literature-derived carbon sequestration flows, the precision of which is not empirically tested in the local context of Trinidad and Tobago due to the lack of suitable on-site experimental studies. Moreover, the maps provide a snapshot of the current provision of ecosystem services and do not reflect the dynamic nature of ES provision over time. While such dynamics can be incorporated in the investigated models through changes in land cover and in the explanatory variables of the meta-regression models, such analysis is beyond the scope of the present paper.

The importance of the concepts developed in the present study for the sustainable management of Trinidad and Tobago's natural capital was reaffirmed by the fact that, during the course of this study, the Parliament of the Republic of Trinidad and Tobago has prepared the way for implementation of ecosystem services maps by approving new legislation (Act No. 10 of 2014) titled 'The Planning and Facilitation of Development Act, 2014'. The legislation generated a National Spatial Development Strategy (NSDS), which includes a section on ecosystem services policy and maps. The current government's Vision 2030 National Development Strategy 2016–2030 states that this document is being reviewed and updated.

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